The effect of self-luminous electronic displays on melatonin

by

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

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ABSTRACT

Circadian rhythms are biological processes that occur cyclically over a 24-hour period, an example being the sleep/wake cycle. Ideally, the sleep/wake cycle is synchronized to the naturally occurring light/dark pattern created by the rising and setting of the sun. If synchronized, individuals are awake during periods of light and asleep during periods of dark. However, due to various social and economic pressures, individuals are required to be awake during times when they would normally be sleeping. Another trend on the rise is the widespread use of self-luminous electronic devices such as computer displays, televisions, and tablet devices. These devices are used throughout the day, including the nighttime just before bed. These displays are commonly lit with light-emitting diodes (LEDs) that emit light at short-wavelengths. Melatonin, a hormone produced at night under conditions of darkness, can be suppressed when exposure to short-wavelength light occurs. Disruption of circadian rhythms has been associated with health maladies such as obesity and diabetes. Two experiments were conducted to gain a better understanding of the effect of light from self-luminous displays, more specifically light from a tablet device and a television, on melatonin levels in the early part of the night. The impact of the light from these displays on performance, subjective sleepiness, and display preference was also assessed.

Thirteen subjects were exposed to light from a self-luminous tablet device (the Apple iPad). Subjects were exposed to three experimental conditions over three nights, each one-week apart. The conditions were 1) tablet-only set to the highest brightness level, 2) tablet viewed through orange-tinted safety glasses (dark control; optical radiation < 525-nm ≈ 0), and 3) tablet viewed through clear safety glassed equipped with blue LEDs, thus providing 40 lux of 470-nm light at the cornea. For the tablet plus blue LED condition, 1-hr and 2-hrs of exposure resulted in suppression values statistically greater than zero. Suppression after 1-hr exposure to the tablet-only was not statistically greater than zero, but did reach significance after 2-hrs of exposure. Predictions made using the phototransduction model and data from the Dimesimeter were close to the measured melatonin suppression values after one hour. Performance decreased (increased reaction time) over the course of the night for each of the three conditions.

During another experiment, sixteen subjects were exposed to light from a television. Eight subjects viewed the display from 6 ft, and eight viewed the display from 9 ft. Subjects were exposed to four lighting conditions over four nights, each one-week apart. The four lighting conditions consisted of three different correlated color temperature (CCT) settings (12,000 K, 6500 K, and 2700 K) and a dark control (12,000 K plus orange-tinted safety glasses). It was predicted, using the phototransduction model and Dimesimeter data, that the melatonin suppression resulting from the TV exposure would be low. Statistically significant suppression was not observed for any of the lighting conditions at either viewing distance, and KSS responses increased over the course of the night for all four conditions. Subjective ratings of picture quality and color were significantly lower when the TV was viewed through the orange-tinted glasses.

The results from these studies suggest that, depending on the duration of exposure, light provided by a self-luminous display may suppress melatonin. Recording actual light exposures and using the model of phototransduction, predictions can be made regarding the impact of these displays. Manufacturers can use this information to produce displays that minimize the risk of nocturnal melatonin suppression.

1. Introduction and Historical Review

1.1 Visual System

Light is defined as radiant energy capable of eliciting a visual response, corresponding to the portion of the electromagnetic spectrum from 380-780 nanometers (nm). In other words, the visual system does not function in the absence of light. The visual system consists of the eye and brain, which work together to obtain and interpret an image.

1.1.1 Eye

The eye is a spherical structure consisting of several components that function to provide a focused image on the retina (Boyce, 2003). The transparent portion of the sclera (white part of the eye) is the cornea, which is where light enters the eye. Two-thirds of the refraction necessary to focus an image occurs at the air-cornea interface; thus making it the most powerful lens of the visual system (Hubel, 1988). Functions of the choroid include absorbing stray light, providing oxygen and nutrients to the retina, and formation of the ciliary body. The iris, which is the muscle that gives the eye its color, controls the size of the pupil. Pupil size is important because the pupil allows light to enter the eye. The pupil is a hole and appears black due to the absorption of pigments by the retina (Boyce, 2003). Located behind the pupil and iris is the crystalline lens, which absorbs ultraviolet radiation and is where the remaining refraction for focus occurs. Ciliary muscles allow the lens to change its shape to sharpen the image formed on the retina.

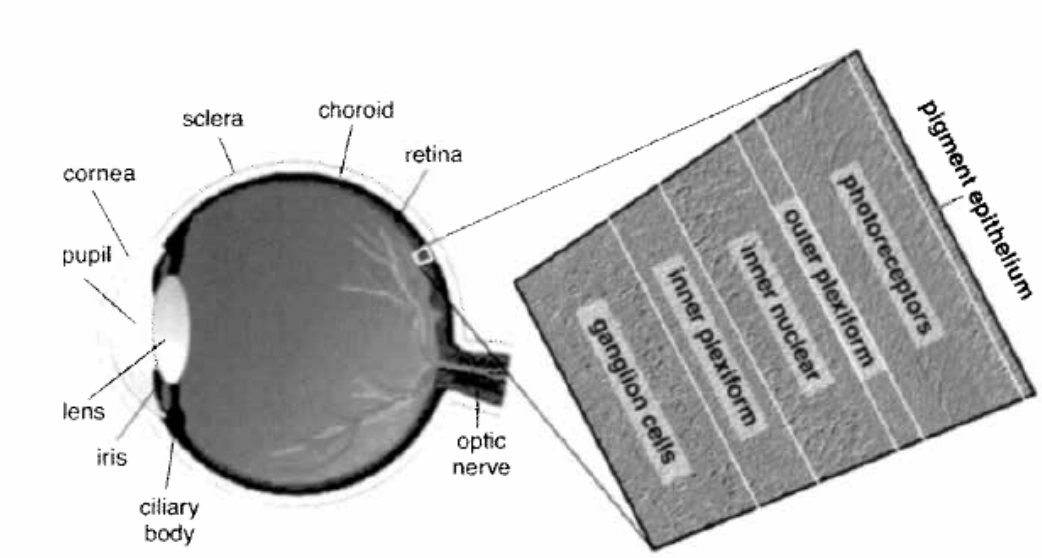

Figure 1: Anatomy of the human eye (Kolb, 2003).

An extension of the brain and the optic nerve, the retina is where the processing of an image begins. Signals are sent from the eye, along the optic nerve, to the lateral geniculate nucleus (LGN) of the visual cortex. A diagram of the structure of the eye is provided in Figure 1.

1.1.2 Human Retina

The retina, which is approximately 0.5mm thick, lines the back of the eye and is where image processing begins. The retina has been compared to a three-layer cake consisting of three layers of nerve cell bodies: the photoreceptors, the inner nuclear layer (INL), and the ganglion cell layer (GCL). Between these layers, in the outer plexiform layer (OPL) and the inner plexiform layer (IPL), are synaptic connections (Kolb, 2003). Light must pass through the entire retina to excite the photoreceptive nerve cells. Signals are passed forward towards the ganglion cells that then send the signals to the brain for further processing. The anatomy of the retina is illustrated in Figure 2.

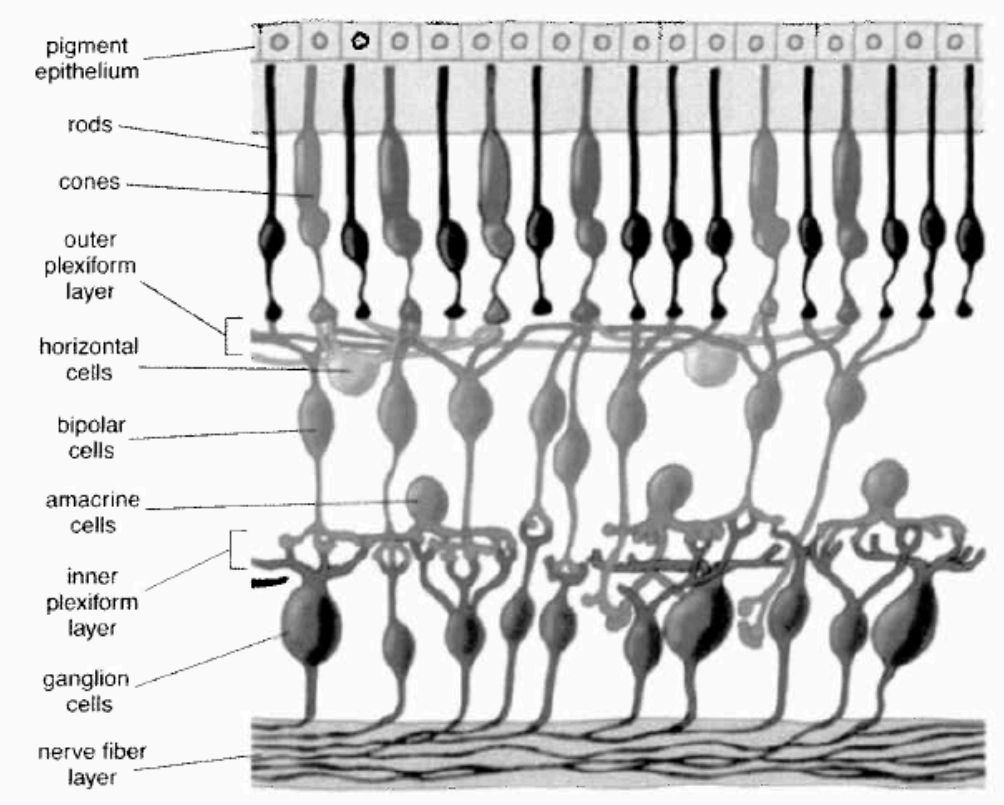

Figure 2: Anatomy of the human retina (Kolb, 2003).

1.1.2.1 Photoreceptors

Photoreceptors are the nerve cells that lie at the back of the retina, and are divided into two categories, rods and cones. Spectral sensitivity refers to the region of the visible spectrum that the photopigment contained within the cell is most sensitive to. All rods contain the same photopigment, and thus have the same spectral sensitivity (peak = 507nm). Rhodopsin responds to dim light (Hubel, 1988), and for this reason, rods are important for nighttime vision. Three types of cones exist in the retina; long (L), medium (M), and short (S)-wavelength cones with peak spectral sensitivities of 564, 533, and 437nm respectively (Lee, 2004). Cones are essential for daytime and color vision, and are concentrated in the center of the retina.

In the absence of light, photoreceptors release the neurotransmitter glutamate. When light exposure occurs, the photoreceptor hyperpolarizes preventing the flow of sodium out of the cell and the production of glutamate is inhibited (Hubel, 1988). Also,

during light exposure, the photoreceptor undergoes bleaching. During the bleaching process, a photon is absorbed by a photopigment thus chemically altering its structure to a less photosensitive formation. During a process involving enzymes and vitamin A, the photopigment is regenerated to its photosensitive conformation (Lucas, 2006). This process would not occur without another structure, the retinal pigment epithelium.

1.1.2.2 Retinal Pigment Epithelium

The photoreceptors are in contact with the retinal pigment epithelium (RPE), the dark outer layer of the retina. This layer contains melanin, which provides a continuous supply of vitamin A to the photoreceptors and also absorbs stray light (Kolb, 2003).

1.1.2.3 Inner Nuclear Layer

Between the RPE and the INL is the OPL. Synaptic connections between photoreceptors, bipolar cells, and horizontal cells occur in the OPL. The INL of the retina is the location of the cell bodies of bipolar, horizontal, and amacrine cells. These cells function as collector cells for the signals sent from the photoreceptors (Boyce, 2003). Bipolar cells form connections with and receive input from rods and cones. These cells can synapse with a single photoreceptor or form several synaptic connections (Hubel, 1988). Bipolar cells exist in two types, one type hyperpolarizes in response to light (OFF response) and the other depolarizes (ON response) (Masland, 2001).

Also present in the INL are horizontal cells. Horizontal cells function as a link between the photoreceptors and bipolar cells (Hubel, 1988). Several photoreceptors are in contact with a single horizontal cell over a wide area. Horizontal cells are said to enhance the contrast between adjacent regions of light and dark (Masland, 2001).

Amacrine cells link bipolar and retinal ganglion cells (RGCs). Rod bipolar cells rely on AII and A18 amacrine cells to transmit signals to ganglion cells (Kolb, 2003). While some connections exist between bipolar cells and ganglion cells directly, the majority of the connections between bipolar and ganglion cells involve amacrine cells.

1.1.2.4 Ganglion Cell Layer

The synaptic layer between the INL and GCL is the IPL, which is the location of synaptic connections between bipolar cells, amacrine cells, and ganglion cells. The GCL is the outermost layer of the retina towards the vitreous humor (Kolb, 2003). As was previously mentioned, RGCs receive signals from bipolar and amacrine cells. The RGCs then transmit signals to the brain via the optic nerve. RGCs have center-surround organization of their receptive fields that allow signal transmission to increase or decrease depending upon where the stimulus is provided. ON-center responses occur when light is presented to the receptive field center, and OFF-center responses occur when light is presented to the surround (Kolb, 2003).

A subset of ganglion cells, the intrinsically photosensitive retinal ganglion cell (ipRGC) has been identified as a primary non-visual photoreceptor. However, these cells have also shown visual responses. Dacey et al. (2005) found that a population of ipRGC exhibits an S-Off, (L+M)-S color opponent response. These cells have also been observed to project to the LGN, more specifically the dorsal and ventral portions (Dacey et al., 2005; Brown et al., 2010). Brown et al. (2010) also observed the ability of these cells to sustain visual responses in rodless, coneless mice, in addition to their contribution to the coding of irradiance (Brown et al., 2010). This photoreceptor will be discussed in section 1.2.2.1.

1.1.3 Color Opponency

Human color vision is divided into three different channels, an achromatic (luminance) channel and the red-green (R-G) and blue-yellow (B-Y) opponent channels. These channels are formed at the bipolar cell level. The achromatic channel receives input only from L-and M-cones and increases in activity with increasing irradiance (Boyce, 2003). Parasol ganglion cells contribute to the luminance channel by receiving summed input from L- and M-cones via ON- and OFF-diffuse bipolar cells (Lee, 2004).

The R-G opponent channel is the product of input from the M-cone versus the sum of the input from L- and S-cones. Midget ganglion cells, which project to the parvocellular (PC) layer of the LGN, are thought to be critical to the R-G channel. An

L- or M-cone connects to a midget bipolar cell, which then connects to a midget ganglion cell (Lee, 2004). Midget ganglion cells have a center-surround organization. A red-ON cell receives excitatory L-cone input to its center and inhibitory M-cone input to its surround, while a green-ON cell receives M-cone input to its center and L-cone input to its surround.

The B-Y opponent channel is the sum of the L- and M-cones versus the input from the S-cones (Dacey, 1996; Dacey, 2000). The small bistratified ganglion cell is critical to the B-Y channel by providing a blue-ON/yellow-OFF response. This cell receives ON-input from the S-cone bipolar and OFF-input from bipolar cells that synapse with L- and M-cones (Lee, 2004). It is also thought that a blue-OFF signal could be transmitted via S-cone connections to midget bipolar cells (Dacey, 2000). This blue-OFF/yellow-ON opponent signal, however, is rare compared to the blue-ON signal.

Research conducted by Boynton and Gordon (1965) demonstrate how these processes affect our perceptions of color. During their experiment, subjects were presented with a monochromatic light stimulus and were asked to describe its appearance using only red, green, yellow, and blue. Colors were very rarely described as red-green or yellow-blue, but yellow-red and green-blue were used quite frequently (Boynton & Gordon, 1965). If the signal received from the M-cones is greater than that from L- and S-cones, then green is perceived, and red is perceived when the combined signal from L- and S-cones is greater. Blue is perceived when the S-cone signal is greater than the combined signal from L- and M-cones, and yellow is perceived when the opposite happens.

1.2 Circadian Timing System

The visual system is not the only system that is affected by light. Patterns of light and dark are strong zeitgebers, or timegivers, for circadian rhythms (Boyce, 2003; Arendt, 1995). Circadian rhythms are biological processes that occur cyclically over an approximately 24-hour cycle [Latin terms *circa*, about and *dies*, day]. In humans, circadian rhythms have an intrinsic period of approximately 24.2 hours (Czeisler, 1999). Body temperature, hormone secretion, blood pressure, heart rate, and excretion are

examples of circadian rhythms (Refinetti, 2006). Perhaps one of the most obvious circadian rhythms is that of the sleep/wake cycle, synchronized to the natural light/dark pattern created by the rising and setting of the sun. The circadian timing system (CTS) is the neural system responsible for the generation and regulation of circadian rhythms. Three components compose the CTS: a master clock (pacemaker), entrainment (afferent) pathways, and output (efferent) pathways.

1.2.1 Master Clock

The master biological clock of the human circadian timing system is located in the suprachiasmatic nuclei (SCN) of the anterior hypothalamus of the brain (Reppert & Weaver, 2002). The SCN receive input from the retinohypothalamic tract (RHT) and geniculohypothalamic tract (GHT). Although environmental factors may influence the SCN, they will still exhibit rhythmicity after these factors are removed. The SCN are composed of small, densely packed cells and neurons. Various circadian oscillators that exist throughout the body, including other areas in the brain and peripheral organs such as the liver and kidneys, are synchronized to the SCN. In rats, lesioning of the SCN was observed to abolish the rhythms of drinking and behavioral activity. Research has also shown that complete destruction of the SCN eliminates circadian rhythmicity (Refinetti, 2006). Non-photic input, such as meals, social contact, temperature, and physical activity can influence the SCN. Various non-photic receptors exist, such as cold- and warm-sensitive cells of the skin body core, which transmit information to the SCN. However, under normal conditions, photic input received by the SCN are the most powerful entraining signal for the circadian timing system.

1.2.2 Entrainment Pathways

The RHT and GHT are the two pathways through which photic information is transmitted to the SCN. The GHT originates in the intergeniculate leaflet (IGL), the area of the brain that receives input from the retina. The RHT, on the other hand, originates in the retina and projects directly to the SCN (Edelstein & Amir, 1999). The

focus of this thesis is on melatonin suppression that can occur from the transmission of photic information to the SCN via the RHT.

1.2.2.1 Photoreceptors

Phototransduction is the conversion of a light signal to an electrical/neural signal that is transmitted to the brain. While the classic photoreceptors, rods and cones, play a role, they are not solely responsible for circadian phototransduction. Provencio et al. (2000) discovered melanopsin, a vertebrate opsin that is found in the inner retina. The distribution of melanopsin in the inner retina resembles that of a class of RGC that directly innervate the SCN (Provencio et al., 2000). Of the 1.5 million RGCs found in the human retina, only 0.2% contain melanopsin (Dacey et al., 2005). Berson, Dunn, and Takao (2002) discovered that the majority of the RGCs innvervating the SCN are intrinsically photosensitive (ipRGCs). The cell bodies of the ipRGCs are located in the ganglion cell layer, and the dendrites terminate in the OFF (and ON) layers of the IPL of the retina. Unlike the classic photoreceptors, these cells depolarize in response to light. This depolarizing response persists when synaptic release is blocked from all other photoreceptors and was observed among ganglion cells that directly project to the SCN. The ipRGCs also retained their photosensitivity when isolated from the retina (Berson et al., 2002). It was also observed by Berson et al. (2002) that the ipRGCs have a peak sensitivity matching the predicted peak sensitivity of a retinal-based pigment, likely melanopsin. The ipRGC peaks at 482nm and bears a resemblance to the peak sensitivity for circadian entrainment in rodents (Berson et al., 2002). In addition to their photosensitivity, the ipRGCs appear to have color-opponent receptive fields, as evidenced by responses to a light stimulus recorded from the lateral geniculate nucleus (LGN). Research conducted since the discovery of the ipRGC suggests that there are five types of ipRGC (Schmidt et al., 2011). Type 1 ipRGCs are the cells responsible for the entrainment of circadian rhythms. Cells in type 1 have the highest levels of melanopsin and exhibit the greatest photosensitivity. Although research on types 2-5 is still in the early stages, it is thought that the non-type 1 cells are important for the visual responses previously mentioned (Schmidt et al., 2011).

1.2.3 Output Pathways

The major output centers of the SCN are the subparaventricular zone (SPZ) and dorsomedial nucleus of the hypothalamus (DMH), as shown in Figure 3. This region of the brain is responsible for a variety of functions, such as the regulation of the sleep/wake rhythm, feeding, locomotor activity, and secretion of corticosteroids (Saper, Cano, & Scammell, 2005).

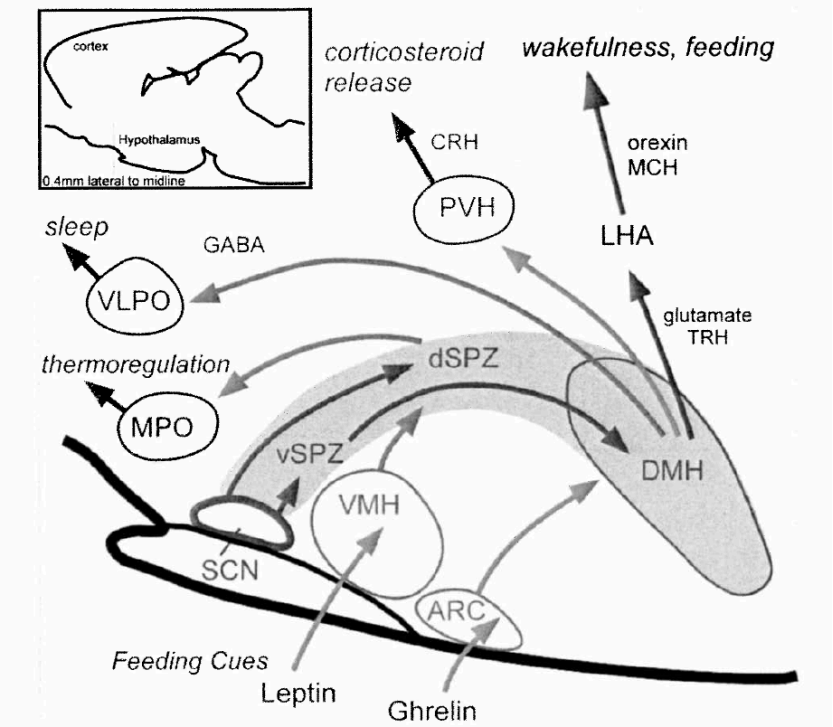

Figure 3: **Output pathways from the SCN (Saper et al., 2005).**

1.2.3.1 Melatonin

The pineal gland is a small organ that produces and secretes melatonin. Melatonin (N-acetyl-5-methoxytryptamine) is often referred to as the "darkness hormone" because it is produced and secreted at night and in darkness. Peak concentration of melatonin typically occurs between 02:00 and 04:00, with onset occurring around 21:00-22:00 and offset around 07:00-09:00 (Arendt, 1995). The melatonin rhythm is endogenous but can be affected by light/dark patterns. Lesions of the SCN abolish the rhythm of melatonin, and an intact SCN are required for the

entraining effects of melatonin to manifest (Arendt, 1995). It was observed by Lewy, Wehr, Goodwin, Newsome, and Markey (1980) that light exposure is capable of suppressing melatonin. The closed loop system between melatonin, the pineal gland, and the SCN is the reason melatonin is used as a phase marker of the circadian pacemaker.

1.2.4 Phase-shifting and Acute Effects of Light

Light can impact the circadian system in two ways, phase-shifting of the circadian clock and acutely affecting biological rhythms, such as melatonin, electroencephalogram (EEG)/alertness, and sleepiness. Phase-shifting, advancing or delaying the circadian clock, cannot be determined until at least twenty-four hours after a light exposure whereas the acute effects of light, such as increased alertness or acute melatonin suppression, are more immediate.

1.2.5 Characteristics of Light Affecting the Circadian System

The effectiveness of light on the circadian system is dependent upon the quantity, timing, spectrum, spatial distribution, and duration of light exposure as well as light history (Rea, Figueiro, & Bullough, 2002).

1.2.5.1 Quantity

Compared to the visual system, the circadian system is less sensitive to light. Thus, a greater quantity of light is needed to elicit a circadian response. Several studies have been conducted to evaluate the relationship between illuminance and suppression of melatonin. Many of these studies used fluorescent lamps as the light source (McIntyre, Norman, Burrows, & Armstrong, 1989; Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000; Rüger, Gordijn, Beersma, de Bries, & Daan, 2003). McIntyre et al. (1989) exposed subjects to the same fluorescent light source at five different illuminance values (200, 350, 500, 1000, and 3,000 lux), each one-week apart. Illuminance is the quantity of light incident on a given area. The desired illuminance values for this

experiment were obtained by having the participants sit farther or closer to the light source. In other words, when exposed to 200 lux of light, the participants were seated farther away than when they were exposed to 3,000 lux. Results from this experiment indicate that the impact of light on the circadian system is intensity dependent, with suppression of melatonin increasing as illuminance increased from 200 to 3000 lux.

Zeitzer et al. (2000) and Cajochen, Zeitzer, Czeisler, & Dijk (2000) exposed subjects to a range of illuminance values from 3 to 9100 lux provided by cool white, overhead fluorescent lamps, the results of which are provided in Figure 4. The duration of this exposure was 6.5 hours. In general, as illuminance values increased, the percentage of melatonin suppression also increased until a saturated response for melatonin suppression was observed at illuminance values greater than or equal to 200 lux. A similar trend was observed for the phase shifting effect of light, with a saturating effect occurring at 500 lux or greater and little to no effect at illuminance values less than 15 lux (Zeitzer et al., 2000). Similar results were obtained by Cajochen et al. (2000). Mean illuminance values of the low, middle and high light level groups were 23, 230, and 3190 lux respectively (Cajochen et al., 2000). Significantly lower melatonin concentrations and subjective sleepiness, as indicated by the Karolinska Sleepiness Scale (KSS) and Karolinska Drowsiness Test (KDT), were observed among the group exposed to the high light levels compared to the low light level group. Significantly greater alertness, as indicated by a decrease in slow eye movements and a decrease in theta-alpha activity during EEG recordings, was observed among the middle and high light level groups (Cajochen et al., 2000). These results suggest an increase in suppression and alertness with increasing illuminance.

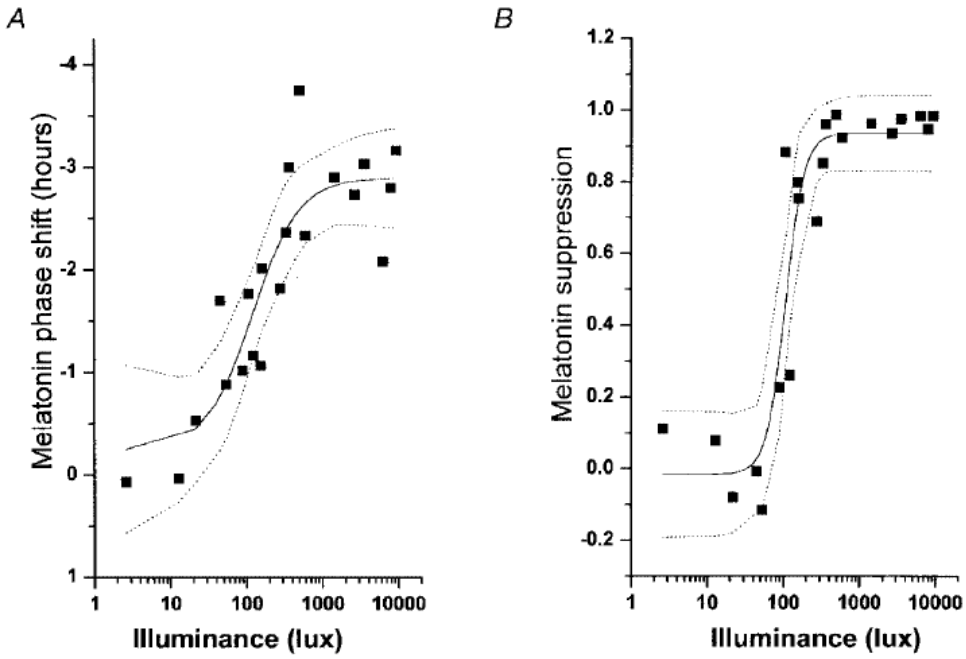

Figure 4: **Effect of illuminance at the eye on circadian phase shift and melatonin suppression (from Zeitzer et al., 2000).**

Results of a study conducted by Campbell & Dawson (1990) agree with the previously discussed KSS and alertness results obtained by Cajochen et al. (2000). Sleepiness and performance efficiency were assessed during two simulated night shifts (23:00 – 07:00) during the experiment (Campbell & Dawson, 1990). During the first night shift, all subjects were exposed to 10-20 lux. On the second night, subjects were either exposed to 10-20, 100, or 1000 lux. Every two hours during the work shift, alertness was measured by EEG recording. Performance was assessed in a subset of the subjects once an hour via a logical reasoning test, an index of spatial manipulation and processing abilities (Manikin Test), and a psychomotor test (Wilkinson 4-choice reaction test), in addition to the continuous vigilance task they were asked to perform. No significant difference was observed between the 10-20 and 100 lux groups for any of the measured variables. During the second night shift, the 1000 lux group was able to maintain wakefulness significantly longer than the dim group and showed significant improvement on the Manikin Test and logical reasoning task (Campbell & Dawson, 1990). Melatonin concentration was not assessed during this study.

Rüger et al. (2003) determined that phase-shifts in dim light melatonin onset (DLMO) and drop in core body temperature (CBT) can occur after a four-hour exposure to 5000 lux at the eye. Acute effects on melatonin, CBT, and subjective sleepiness were also observed after the light exposure. Compared to dim light, statistically significant melatonin suppression and higher CBT were observed after the 5000 lux exposure. Subjects also reported feeling less sleepy during the 5000 lux exposure, as indicated by the KSS (Rüger et al., 2003).

While the phase-shifting results of Rüger et al. (2003) were observed after exposure to light levels not normally encountered indoors, phase-shifting can occur after exposure to lower illuminance levels. Boivin, Duffy, Kronauer, and Czeisler (1996) conducted an experiment during which subjects were either exposed to 0.03 (control), 180, 1260, or 9500 lux of light for five hours on three consecutive days. Statistically significant phase advances in the CBT rhythm were observed after exposure to each condition, except the control, with the greatest advance occurring after the 9500 lux exposure (4.49 ± 0.36 hours). A phase delay of 1.05 ± 0.38 hours was observed after exposure to the control condition. More recently, Gooley et al. (2011) observed suppression of melatonin and delay of DLMO after exposure to approximately 200 lux in the 8 hours prior to bedtime. Onset occurred 23 minutes before the schedule sleep time in the 200 lux group and 1 hour 57 minutes before scheduled sleep in the dim light group (less than 3 lux) (Gooley et al., 2011). These results, in conjunction with those obtained by Boivin et al. (1996), suggest that the amount of light typically exposed to while indoors, around 100 lux, is of sufficient quantity to impact the circadian system.

The research described above involves light provided by fluorescent lamps, however, fluorescent lighting is not the only technology for which quantity of light is important. West et al. (2011) exposed subjects to 90 minutes of light from blue light emitting diodes (LED). Eight different irradiances, from 0.1 – 600 $\mu W/cm^2$ were used during this experiment compared to 40 $\mu W/cm^2$ from a 4000 K fluorescent lamp. Irradiance values greater than or equal to 20 $\mu W/cm^2$ from the blue LED significantly suppressed melatonin while values less than 20 $\mu W/cm^2$ and the fluorescent condition did not (West et al., 2011). As irradiance increased, the amount of melatonin suppression also increased. Figueiro, Lesniak, and Rea (2011a) conducted a study

investigating the impact of 470-nm light on melatonin suppression. During this experiment, subjects were exposed to six corneal irradiances ranging from 0 to 72 $\mu W/cm^2$ for ninety minutes. Statistically reliable melatonin suppression was observed after a ninety-minute exposure to $2\mu W/cm^2$ (1.2 lux) of 470 nm-light. In general, as irradiance increased, melatonin suppression also increased. An increase in suppression was also observed as the duration of exposure increased from zero to ninety-minutes. This study, as well as the other research described, illustrates that the effect of light on the circadian system is dependent upon the quantity of light provided.

1.2.5.2 Timing

The circadian system is sensitive to light throughout the day, with the least sensitivity around the time of CBT_{min}. Phase advances occur when light is presented after CBT_{min} while light before CBT_{min} results in a phase delay (Figure 5) (Jewett et al., 1997). Phase shifting results, however, do not occur until hours after a light exposure. More immediate effects of light are suppression of melatonin and increased alertness (Boyce, 2003). Lewy, Sack, Miller, and Hoban (1987) found that light provided in the morning advances the melatonin rhythm whereas light in the evening results in a delay. Similar results were observed for the CBT rhythm. A phase response curve (PRC) proposed by Khalsa, Jewett, Cajochen, and Czeisler (2003) illustrates the occurrence of a phase delay when light was presented before CBTmin (evening), and a phase advance when light exposure occurred after CBTmin (morning).

Light can be used as a treatment for some circadian disorders, such as delayed sleep phase disorder (DSPD). Individuals who experience DSPD have difficulty sleeping and waking at conventional clock times. Rosenthal et al. (1990) exposed subjects to 2500 lux of full spectrum fluorescent lighting for two hours in the morning, and limited their nighttime light exposure by having the subjects wear dark glasses from 16:00 until dusk. Compared to a control condition, 300 lux in the morning and clear glasses at night, alertness and sleep time significantly improved after the 2500 lux exposure. In other words, the participants felt more alert in the morning and reported going to bed earlier. A significant advance of CBTmin was also observed (Rosenthal et

al., 1990). From this study, it can be concluded that the phase-shifting effect of the light exposure was beneficial to the DSPD individuals participating in the study.

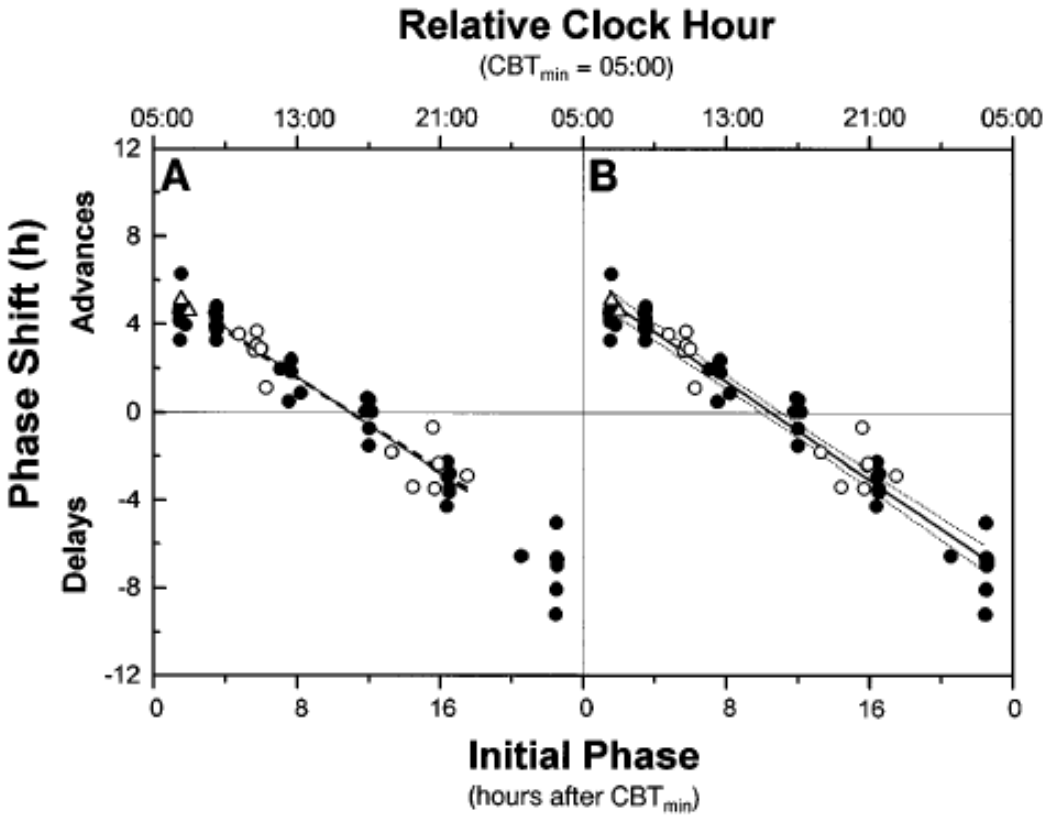

Figure 5: Timing of light exposure and the circadian phase relationship (from Jewett et al., 1997).

1.2.5.3 Spectrum

Spectrum also determines the impact a light source will have on the circadian system. Prior to the discovery of the ipRGCs, it was thought that only the classic photoreceptors influenced the circadian system, as measured through melatonin suppression. To determine an action spectrum for melatonin suppression, Brainard et al. (2001) exposed subjects to eight wavelengths of light between 440 and 600 nm. The monochromatic light stimulus was provided from 02:00 to 03:30 with at least seven days between exposures. Results from this experiment showed an increased sensitivity of the circadian system to short-wavelengths (446-477 nm) (Brainard et al., 2001). In a similar experiment conducted by Thapan, Arendt, and Skene (2001), an action spectrum was

established that also illustrated short-wavelength sensitivity. In addition to illustrating the sensitivity of the circadian system to short-wavelength light, these experiments resulted in support for a non-rod, non-cone photoreceptor involved in circadian phototransduction.

1.2.5.4 Spatial Distribution

A commonality between the visual system and the circadian system is that light must reach the retina to elicit a response. Glickman et al. (2003) conducted an experiment to assess the impact of light on melatonin when it was presented to the superior, inferior, and full retina. Results showed significantly greater suppression when light was incident on the inferior and full retina compared to the superior region (Glickman et al., 2003). One study exposed the nasal and temporal regions of the retina to light. While suppression of melatonin was observed for both regions of the retina, greater suppression was observed for the nasal area (Rüger, Gordijn, Beersma, de Vries, & Daan, 2005). Research regarding the spatial sensitivity of the circadian system is conflicting. Consistent results regarding melatonin suppression have been shown when light was provided by means of a light table (Rea, Bullough, & Figueiro, 2001), light box (McIntyre et al., 1989), uniformly illuminated field of view (Brainard et al., 2001; Thapan et al., 2001), and overhead fluorescent luminaires (Zeitzer et al., 2000).

1.2.5.5 Duration

The circadian system is less sensitive and slower to respond to light than the visual system. Thus, the duration of light exposure is involved in determining the impact light will have on the circadian system. Lewy et al. (1980) observed suppression of melatonin within ten minutes of exposure to 2500 lux of incandescent light. Melatonin concentration returned to pre-exposure levels within forty-minutes after the light exposure (Lewy et al., 1980). Results from McIntyre et al. (1989) suggest that melatonin suppression is dependent upon the intensity of the light source. From this experiment, it is suggested that as illuminance at the eye decreases, the duration of

exposure needed to produce a desired response increases (McIntyre et al., 1989). The results from two experiments (McIntyre et al., 1989) with similar procedures are provided in Figure 6. One can conclude from Figure 6 that to achieve a desired amount of melatonin suppression, the duration of exposure is determined by the illuminance at the eye.

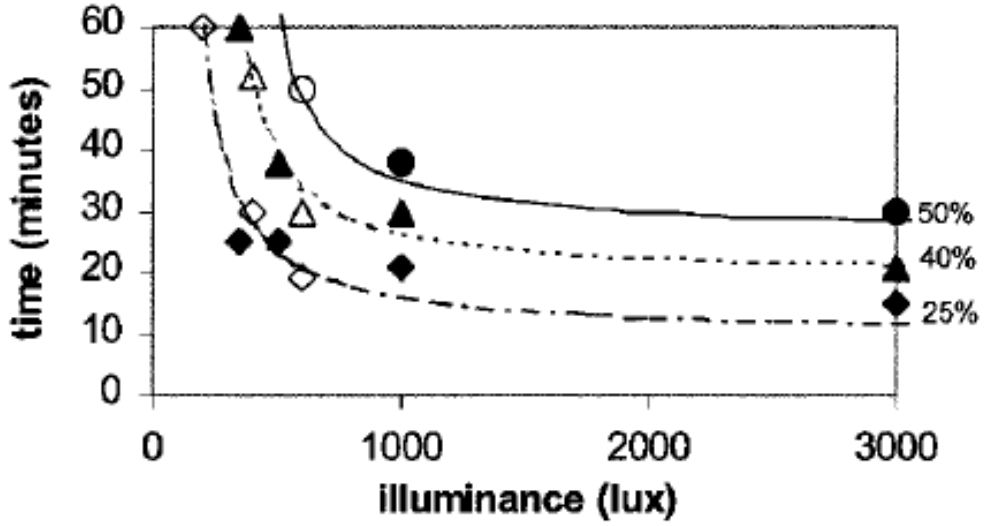

Figure 6: **Illuminace and duration of exposure necessary to suppress melatonin (Rea et al., 2002; modeled from McIntyre et al., 1989).**

1.2.5.6 Light History

Prior light history is also a factor in determining the impact of light on the circadian system. Hébert, Martin, Lee, and Eastman (2002) conducted an experiment during which subjects were exposed to bright light for a week and a dim light for a week. The bright light week consisted of four hours of light exposure by either going outside or using light boxes. During the dim week, subjects were instructed to minimize their time outdoors, and when they were outdoors they were instructed to wear dark welder's goggles (Hébert et al., 2002). At the end of each week, saliva samples were collected for analysis. Significantly greater suppression was observed after the dim week compared to the bright week. When participants were exposed to more light, less suppression of melatonin occurred. Similar results were obtained during a study conducted by Smith, Schoen, and Czeisler (2004). During the experiment two groups

were exposed to a 6.5-hour light stimulus following three days of exposure to either 200 lux or 0.5 lux during the day. While suppression was observed in both groups, suppression was significantly greater in the 0.5 lux group than the 200 lux group (Smith et al., 2004). The amplitude of the melatonin profile was also reduced in the 200 lux condition. Results from these two experiments suggest that prior light history can affect melatonin suppression by altering the sensitivity of the circadian system to light at night.

1.3 Phototransduction by the Human Circadian System

In 2005, Rea et al. proposed a mathematical model that predicts the stimulus to (circadian light; CL) and response (circadian stimulus; CS) from the human circadian system for a given spectral power distribution (SPD) and light level (Rea, Figueiro, & Bullough, 2005; Rea, Figueiro, Bierman, & Bullough, 2010; Rea, Figueiro, Bierman, & Hamner, 2011a). This model accounts for the response from the classic photoreceptors (rods and cones) as well as that of the ipRGCs. Spectral opponency and rod inhibition are also included in the model (Rea et al., 2005). A device has been created that is capable of continuously recording activity and light exposure (Bierman, Klein, & Rea, 2005). This device collects data that are used as the input to the phototransduction model and can further our understanding of light's impact on the circadian system.

1.3.1 Spectral Opponency

As was previously mentioned, humans have two color opponent channels. When channels are opponent, light in one spectral region can increase a response while light from another region can decrease it. To test the idea of spectral opponency, Figueiro, Bullough, Parsons, and Rea (2004) exposed subjects to a monochromatic (470 nm) and polychromatic (mercury vapor) light source. If circadian phototransduction were additive, the mercury vapor lamp would result in suppression values greater than or equal to the 470 nm light. The 470 nm condition, however, resulted in significantly greater suppression than the mercury vapor lamp. Figueiro, Bullough, Bierman, and Rea (2005) also conducted an experiment in which subjects were exposed to two spectra

from a mercury vapor lamp. One spectrum consisted of only a 436 nm component while the second spectrum consisted of a 436 nm component combined with 546 and 578 nm components. If the circadian system were additive, the 436 plus 546 and 578 nm light would have resulted in greater melatonin suppression than when the 436 nm light was presented alone. However, the opposite occurred. Although 436 nm irradiance values were similar for each spectra, greater suppression was observed for the 436 nm light alone than for the 436 plus 546 and 578 nm (Figueiro et al., 2005), indicating that spectral opponency may play a role in circadian phototransduction.

1.3.2 Mathematical Model

In the 2005 model, CS is calculated and quantified as circadian spectrally weighted irradiance (W/m^2) (Rea et al., 2005). A change in nomenclature, however, occurred in 2010 and CS became circadian light (CL). CL further evolved into CL_A, a value more comparable to photopic illuminance (Rea et al., 2010). CL_A is a normalized value of CL where 1000 CL_A from an incandescent source is equivalent to 1000 lux. Also in 2010, CS became a measure of the relative effectiveness of a stimulus in terms of melatonin suppression. CS values are transformed CL_A values from 0 to 0.7, threshold to saturation (Rea et al., 2010). The following equations are used to calculate CL_A and CS respectively (Rea et al., 2011a):

$$CL_A = 1622\left[\int M_{c\lambda}P\lambda d\lambda \lhd \left(a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda}P\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda}P\lambda d\lambda\right) - a_{rod}\left(1 - e^{\frac{-\int V'_\lambda P\lambda d\lambda}{RodSat}}\right)\right)\right]. \quad \text{(Eq.1)}$$

$$CS = .7 \times \left(1 - \left(\frac{1}{1 + \left(\frac{CL_A}{355.7}\right)^{1.1026}}\right)\right). \quad \text{(Eq. 2)}$$

1.3.2.1 Response of the ipRGCs

As was previously discussed in section 1.2.2.1, a subset of ganglion cells has been discovered that exhibit photosensitivity. In addition to the classic photoreceptors, the ipRGCs play an important role in the circadian entrainment of humans. As was previously mentioned, light is the most potent entrainment cue for the circadian system. In mice with severe degeneration of rods and cones and certain blind humans, light remained effective at entraining the circadian system (Berson, 2003).

These cells project directly to the SCN and are less sensitive to light than the classic photoreceptors. Unlike the classic photoreceptors, the ipRGCs depolarize in response to light. Melanopsin is thought to be the photopigment contained within these cells (Provencio et al., 2000). Since it is clear that the ipRGCs play a role in circadian phototransduction, they are represented in the mathematical model. The portion of the CL_A formula representing the response from the ipRGCs is shown in Equation 3:

$$CL_1 = \int M_{C\lambda} P_\lambda d\lambda. \qquad \text{(Eq. 3)}$$

where $M_{c\lambda}$ is spectral efficiency function of the ipRGC corrected for transmittance of the crystalline lens, and P_λ is the SPD of the light source.

1.3.2.2 Modeling Spectral Opponency

While the action spectrum of the ipRGCS peaks at 482 nm, the action spectrum for melatonin suppression peaks at 460 nm. The spectral sensitivity shorter than 482 nm suggests the participation of another photoreceptor, the S-cone. Results obtained by Figueiro et al. (2004) and Figueiro et al. (2005) (refer to section 1.3.1) suggest a spectral opponent response of the circadian system to light. Thus, spectral opponency was also included in the formula to calculate CL_A. The spectral opponency of a light source is calculated using the following equation:

$$CL_2 = a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda} P_\lambda - k\frac{V_\lambda}{mp_\lambda} P_\lambda d\lambda\right). \qquad \text{(Eq. 4)}$$

where constants a_{b-y} and k are equal to 0.6201 and 0.2616 respectively. The first constant, a_{b-y}, reflects the threshold of the b-y response. The value of k sets the cross-

point of the b-y channel at 507 nm (Rea et al., 2011a). At high light levels and wavelengths greater than 507 nm, the SCN are receiving input from the ipRGCs only due to the loss of rod inhibition. In Equation 4, the spectral sensitivity of the S-cone (Sλ) and the photopic luminous efficiency function (Vλ) are divided by the macular pigment transmittance. This is done to better represent the input of the photoreceptors from the peripheral retina (Rea et al., 2011a).

1.3.2.3 Rod Inhibition

Rods contribute to circadian phototransduction by setting a high threshold via shunting inhibition of the AII amacrine cells. A signal is not transmitted to the SCN from the ipRGCs until rod inhibition is overcome. As light levels increase, the response from the ipRGCs and cones increases and rod inhibition saturates. A18 amacrine cells contribute to the loss of rod inhibition. A18 amacrine cells are signaled to release rod inhibition by receiving a hyperpolarizing OFF response from the S-cone bipolar. The following equation reflects the involvement of the rods:

$$CL_3 = a_{rod}\left(1-e^{\frac{-\int V'\lambda P\lambda d\lambda}{RodSat}}\right). \quad \text{(Eq. 5)}$$

where a_{rod} is the rod threshold, RodSat is equal to the half-saturation constant for rod bleaching. These values are 3.2347 and 6.5 W/m^2 respectively. V'λ is the scotopic luminous efficiency function (Rea et al., 2011a).

1.3.3 Health and Well-being

As was previously mentioned, light is capable of suppressing melatonin and suppression can be mathematically predicted. Until this point, however, the importance of determining the impact light will have on the circadian system has not been explained. Due to various social and economic pressures, some individuals are required to be awake when they would normally be sleeping, thus often exposing them to light at night. Risk of breast cancer is increased among those who frequently do not sleep during the time when melatonin levels are typically highest, such as night-shift workers. Breast cancer risk is increased sixty percent in women who have worked the graveyard shift (one shift

= 8 hours) for at least one extended period of time in the ten years prior to diagnosis (Davis, Mirick, & Stevens, 2001). The increased risk of cancer among night-shift workers is thought to be the result of exposure to light at night, which can reduce melatonin concentrations. It is unknown, however, if this increased risk is solely the result of melatonin suppression or disruption of circadian rhythms. Removal of the pineal gland, which produces and secretes melatonin, enhances tumor growth in animals. These effects have been reversed by administration of melatonin, thus suggesting that melatonin may have oncostatic effects (Brzezinski, 1997). In rats, only twenty percent of those injected with melatonin developed tumors compared to 79 percent of the vehicle-injected rats after 140 days (Tamarkin et al., 1981). Research has also shown that constant light exposure can increase the growth of human breast cancer tissue when implanted into a rodent (Stevens, 2005). Melatonin appears to have oncostatic benefits, thus causing concern for individuals exposed to light at night that may reduce melatonin levels.

Night shift workers are not the only population who should be concerned with light exposure at night. When compared to the winter, adolescents are exposed to a significantly greater amount of light in the spring (Figueiro & Rea, 2010). DLMO and sleep onset were significantly later in the spring than winter. Since adolescents typically attend school at the same time everyday, later bedtimes can lead to shorter sleep durations. In fact, significantly shorter sleep durations in the spring were observed in the experiment conducted by Figueiro and Rea (2010). In addition to adolescents, significant sleep loss, the product of reduced or fragmented sleep, occurs among one-third of normal adults due to professional and familial obligations (Bonnet & Arand, 1995). As a result of their work schedule, night-shift workers report having poorer daytime sleep, reduced nighttime alertness and performance, and an increased accident rate compared to those who work the day shift (Rajaratnam & Arendt, 2001). Sleep deprivation is also linked with the disruption of various hormone secretions. For example, decreased levels of leptin (the hormone responsible for suppressing appetite) were observed after four hours of sleep for a period of six days. Ghrelin, which is released by the stomach to stimulate appetite, was observed to increase after a period of reduced sleep time (Van Cauter, Knutson, Leproult, & Spiegel, 2005). From the

research described above, it can be concluded that maintaining adequate sleep is essential for an individual to maintain good health and well-being.

Suppression of melatonin may occur as the result of exposure to light at night, and may result in a phase delay of the circadian clock. Since work and familial obligations often require individuals to wake at the same time each day, later bedtimes may lead to shorter sleep durations and sleep deprivation. The ability to predict the circadian impact of personal light exposures, such as exposure to light from a self-luminous display, is critical. Improving our understanding of the effects these displays have can potentially lead to recommendations to avoid sleep deprivation and melatonin suppression as a result of display use, thus aiding the maintenance of proper health and well-being.

1.4 Self-luminous Electronic Displays

A trend on the rise is the use of self-luminous electronic devices. In 2011, over 66 million tablet devices were sold globally. That is a 260 percent increase from the 18 million sold in 2010. Also in 2011, 260 million television sets were sold worldwide (WorldTVPC, 2012). From mid-December 2011 to early January 2012, the percentage of U.S. adults owning tablet devices nearly doubled from 10 to 19 percent (Rainie, 2012). Fifteen million iPads were sold during the 2011 holiday quarter, which is more than twice the number of iPads sold at the same time the previous year (Wingfield, 2012). Many of these devices are used throughout the day, including the hours proceeding bedtime. According to the 2011 National Sleep Foundation-Sleep in America Poll, 60% of the respondents use a television in their bedroom, 39% use a cell phone, and 36% use a computer or laptop (WB&A Market Research, 2011). Sixty-one percent of Americans report using their laptop or computer within the hour prior to sleep (WB&A Market Research, 2011). Of the individuals who use a cell phone in their bedroom, 21% send a text message almost every night. These same individuals are less likely to report getting a good night's sleep (WB&A Market Research, 2011). Since these devices are so common and are used throughout the day, including nighttime, it is important to understand the impact they may have on circadian rhythms, such as acute suppression of melatonin, phase shifting of DLMO, and delayed sleep.

1.4.1 Self-luminous Display Specifications

There are many different types of displays available on the market; examples include liquid crystal displays (LCDs), plasma displays, and cathode ray tube (CRT) displays. Displays can be further separated into two categories, passive or emissive. Emissive displays (plasma and CRT) produce their own light and passive displays (LCDs) modify the light that passes through it (Anderson, 2005). The design and performance of these displays is based on the human visual system and the environment within which they are being viewed (Anderson, 2005). A common specification provided for self-luminous displays is brightness. In the display manufacturing industry, brightness is defined as the "luminance of white colour in the center of the screen", measured in candelas per meter squared (cd/m^2) (Anderson, 2005). Luminance is the amount of light emitted from the area of a source in a given direction. As luminance increases the amount of light emitted from the screen increases, thus providing more light for the viewer. Plasma displays are considered to be the brightest commercially available device. Luminance values of plasma displays can range from 500 to 1200 cd/m^2 (Anderson, 2005). CRTs typically have luminance values around 90 to 150 cd/m^2, and LCD luminance values fall in the range of 400 to 500 cd/m^2. Luminance values ranging from 150-250 cd/m^2 are considered suitable for typical office work, but televisions and public displays benefit from higher values (Anderson, 2005).

1.4.2 Self-luminous Displays and Sleep

1.4.2.1 Behavior

Research has been conducted to determine the impact of having a television, gaming device, and/or an Internet connection on the sleep habits of adolescents. More specifically, information was obtained regarding their time to bed, time up, time spent in bed, and overall tiredness by having the adolescents complete a subjective questionnaire (Van den Bulck, 2004). Results from the study conducted by Van den Bulck (2004) illustrate that all three media-use variables under investigation (television viewing,

computer game playing, and Internet use) lead to later bed times and less time spent in bed. Information regarding specific activities and duration of use was not collected, however, the frequency at which the media were used was collected. Those reporting more frequent use of televisions and the Internet also reported later bedtimes on weekends and weekdays and increased levels of tiredness (Van den Bulck, 2004). Similar results were obtained by Suganuma et al. (2007) who assessed the impact of different durations of media use on sleep. Suganuma et al. (2007) found that long bouts of media use are associated with reports of insufficient sleep. On average, heavy media users (3.5 hours or more a night) have shorter sleep durations than light media users (less than 2.5 hours a night). Fifty-five percent of subjects in this study reported postponing their bedtime to either watch television or use the Internet (Suganuma et al., 2007). From these results, as well as the results from Van den Bulck (2004), it was concluded that television viewing should not be the only cause for concern since other forms of media are being used which may have a similar effect. It was also concluded that these forms of media-use do not have a fixed duration, meaning that the individual chooses the time when they will start and stop using these devices. No circadian markers were measured during either of these studies.

Similar results were obtained during a study conducted by Calamaro, Mason, and Ratcliffe (2009). This study reported that, on average, adolescents engage in four types of activities involving self-luminous displays after 21:00. Those that reported using the most devices had a significant decrease in the hours of sleep each night and significant sleep disturbance during school hours (Calamaro et al., 2009). Calamaro, Yang, Ratcliffe, and Chasens (2012) also conducted a study with a younger sample of subjects (6 to 10 years of age), for which similar results were reported (Calamaro et al., 2012). Questions were asked regarding sleep habits, the bedroom environment, and caffeine. Those that reported having a television, computer, and telephone in the bedroom received forty-five minutes less sleep than those that did not have any technology in their room (Calamaro et al., 2012). It is unclear, however, if this decrease in the amount of sleep is caused solely by technology use or a technology/caffeine combination. It should be noted that the four previously mentioned studies were designed to determine the relationship between media use and sleep quality. Questionnaires were used as the

method of data collection. No quantitative measurement or analysis of the displays was obtained.

Higuchi, Motohashi, Liu, and Maeda (2005) conducted a study to determine the effects of playing a game using a bright display on multiple sleep variables, such as sleep latency and subjective sleepiness. One task was a shooting game (considered exciting) and the other was a simple addition task (considered boring). The displays were set to two different light levels, 45 and 15 lux when measured at the eye 45 cm from the display (Higuchi et al., 2005). The bright display (45 lux) was white with a luminance of 120 cd/m^2, and the dark display (15 lux) was black with a luminance of 0.5 cd/m^2. Although no interaction was observed between display brightness and task in any measurement, the exciting task was observed to increase sleep latency and decrease subjective sleepiness (Higuchi et al., 2005). These results suggest that the task for which the display is used may negatively affect an individuals sleep habits.

1.4.2.2 Circadian Markers

LCD displays, since they do not produce their own light, are also equipped with a backlight. Stefani et al. (2010) compared two displays with different backlight technologies, one with an LED-backlight and the other with a CCFL (cold cathode fluorescent lamp) backlight. The SPDs of both displays are provided in Figure 7. It was determined that the short-wavelength (464nm) irradiance of the LED-lit display was twice as much as that of the CCFL-lit display (Stefani et al., 2010). Both displays were the same size (24-inches diagonal), resolution (1920x1200), and intensity (250 cd/m^2). These displays were also evaluated in terms of their effects on humans after five hours of exposure (Cajochen et al., 2011). Subjective sleepiness, as indicated by KSS, was significantly lower for the LED display and reaction times were decreased by approximately 8.5% compared to the 2.5% reduction for the CCFL display. Melatonin levels obtained when the LED display was used were significantly lower than the CCFL display at 21:15, 22:15, 22:45, and 23:15 (Figure 8) (Cajochen et al, 2011). These results suggest that newer displays using LEDs as backlight can provide a stimulus sufficient enough to suppress melatonin when used at night.

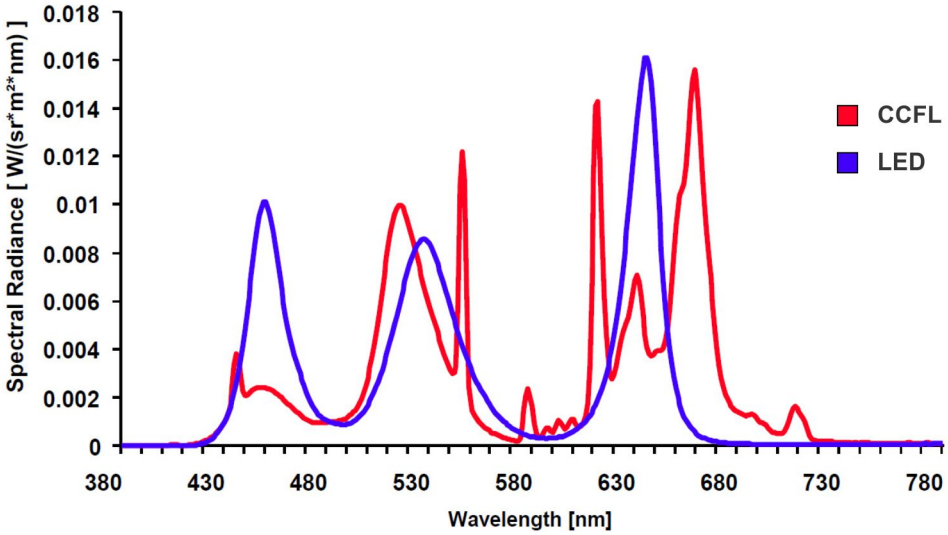

Figure 7: **SPDs of the LED and CCFL backlit displays used (adapted from Stefani et al., 2010).**

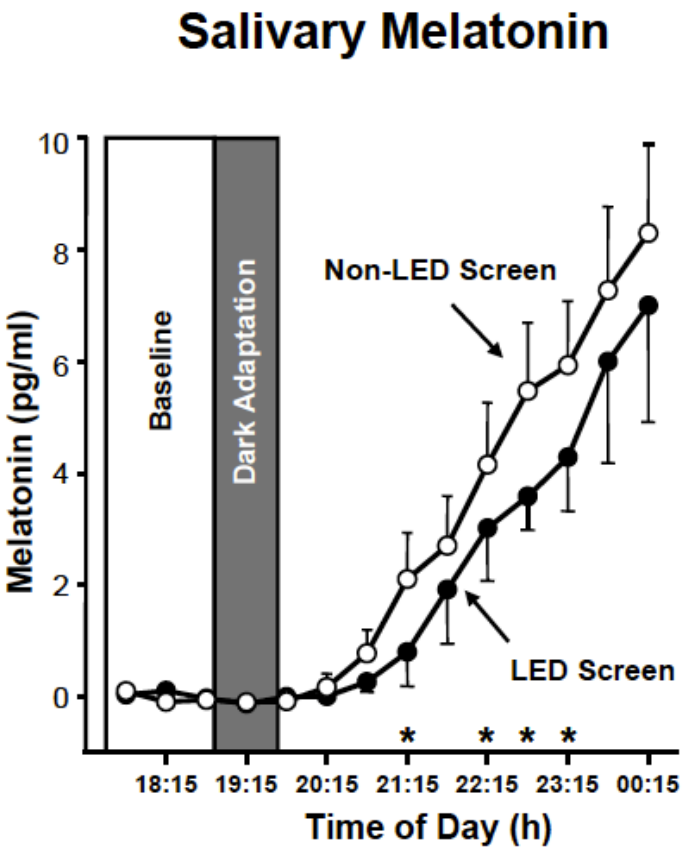

Figure 8: **Melatonin concentration during baseline, dark adaptation, and during display exposure (Cajochen et al., 2011).**

It has been well documented that the use of self-luminous displays can lead to a decrease in the amount of time spent asleep, but these studies (Van den Bulck, 2004; Suganuma et al., 2007; and Calamaro et al., 2012) offer little explanation as to why. Higuchi, Motohashi, Liu, Ahara, and Kaneko (2003) conducted a study during which seven males performed tasks on a video display terminal (VDT) at night. The displays discussed in section 1.4.2.1 that were used by Higuchi et al. (2005) were also used for this experiment. Results showed that salivary melatonin was suppressed after performing the exciting VDT task on a bright display (Figure 9). The combination of task and display is thought to have caused this result. An exciting task or emotionally arousing task may lead to increased pupil diameter as a result of increased activation of the sympathetic nervous system (Bradley, Miccoli, Escrig, & Lang, 2008). Increasing pupil diameter allows a greater amount of light to enter the eye, which may provide a greater stimulus for the circadian system, as evidenced by increased suppression of melatonin.

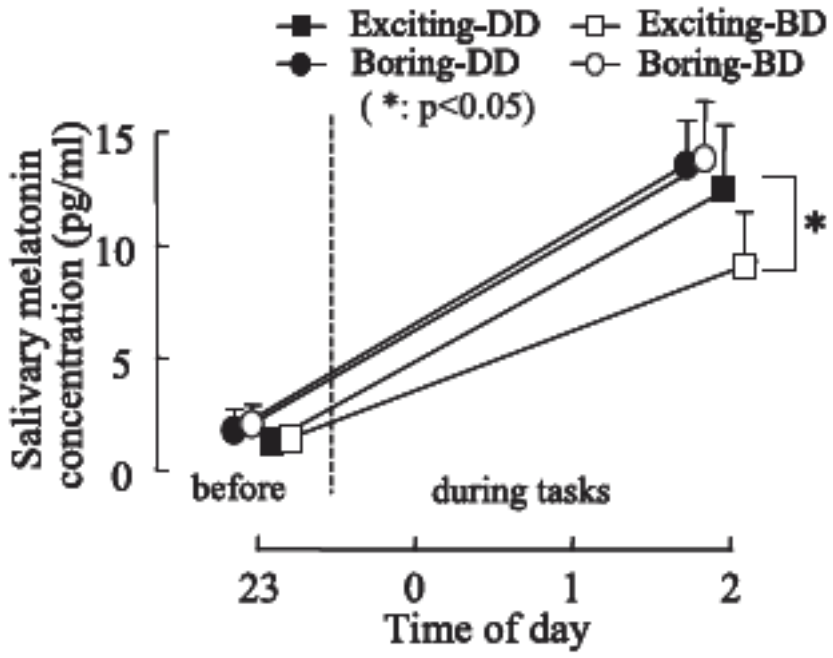

Figure 9: **Melatonin concentrations before and after complete of a video display terminal (VDT) task (Higuchi et al., 2003).**

Figueiro, Wood, Plitnick, and Rea (2011b) also observed a reduction in melatonin level after exposure to a self-luminous device, but the reduction was not significant. The displays used were 19-inch Dell Trinitron and Gateway CRT monitors calibrated to 7 lux at the eye at a distance of 51 cm. During the experiment, subjects were exposed to three different conditions: computer screen only, computer screen plus blue-light goggles (40 lux of 470 nm light), and computer screen plus orange-tinted glasses (filtering out radiation below 525 nm). The 470 nm-light goggles had been shown to suppress melatonin in a previous experiment whereas the orange-tinted glasses acted as a dark control by filtering out radiation that may have an affect on nocturnal melatonin suppression. Based on the model proposed by Rea et al. (2005), 7 lux would not be a sufficient quantity of light for melatonin suppression. However, throughout the experiment the subjects were given the freedom to engage in the task of their choice, so the actual illuminance at the eye deviated from the calibrated level and varied between subjects. A portion of the subjects wore the Daysimeter to measure the actual light exposure. Mean ± standard deviation (STDEV) photopic light levels experienced by the subjects who wore the Daysimeter were to 28 ± 12 lux at the eye, and CS values were 0.19 ± 0.08 (Figueiro et al., 2011b). Significant suppression was only observed after exposure to the computer and 470nm-light goggles. The computer screen only condition did result in a slightly greater reduction of melatonin than the orange glasses and computer screen (Figueiro et al., 2011b). The results of this experiment, provided in Figure 10, only apply to one type of computer screen, so results may differ for the newer technologies that are often larger and brighter than CRT displays.

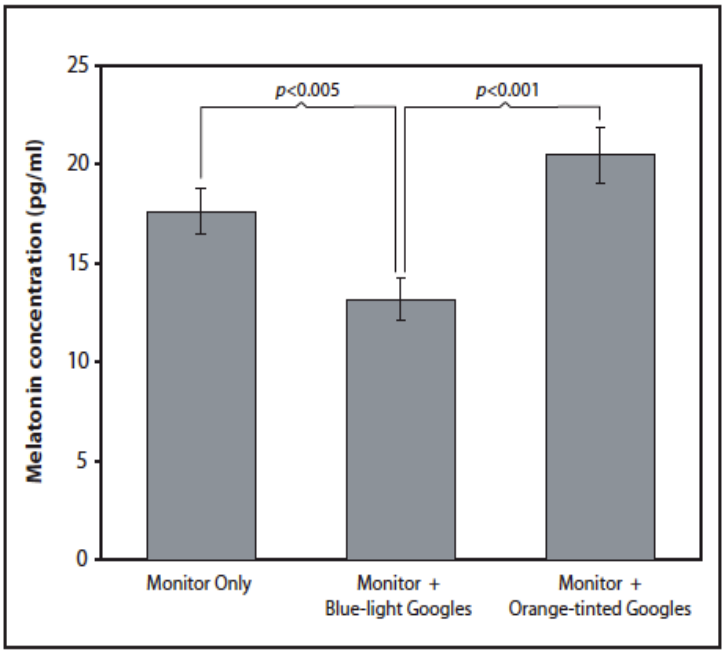

Figure 10: **Mean ± SEM melatonin concentration after exposure to a CRT monitor only, monitor plus blue-light goggles, and monitor plus orange-tinted goggles (Figueiro et al., 2011).**

1.4.2.3 Summary

In modern society it is difficult to identify someone who has not used a self-luminous display of some type. These displays, which are used during the day as well as at night, have been shown to have a negative impact on sleep and their use can result in later bedtimes and shorter sleep durations (Van den Bulck, 2004; Suganuma et al., 2007). Displays of this type are also a source of light at night and are capable of influencing circadian markers, such as melatonin. Light at night and sleep restriction may be hazardous to one's health and well-being, as discussed in section 1.3.3. Therefore, as brighter and larger displays are being produced, it is important to understand the impact self-luminous displays can have on the circadian system.

1.5 Thesis Goals

Goals of this thesis were to:

- Determine whether two types of self-luminous displays impact melatonin

- Investigate the relationship between light level and time
- Test the effectiveness of the model in predicting melatonin suppression
- Investigate the acceptance of different CCTs when watching TV
- Investigate whether light from a tablet device can improve performance (short-term reaction times)
- Investigate whether light from a TV can reduce subjective sleepiness (KSS)

1.6 Pilot Data

Pilot data were collected consisting of two components, a survey regarding display usage and measurement of the light provided by self-luminous displays. These studies were determined to gain a better understanding of what type of displays are commonly used as well as when throughout the day. Pilot data were also collected to better understand the impact light from displays might have on melatonin suppression using the phototransduction model, prior to assessing the impact of displays using human subjects. The two components are discussed in more detail in the following sections.

1.6.1 Methods

The Lighting Research Center (LRC) created an on-line survey to gain a better understanding of self-luminous display usage. Individuals completing the survey were instructed to choose which of the following displays they use: non-flat and flat screen computer monitors, non-flat and flat screen televisions, tablets, and smart phones. Questions were also asked regarding how long the display is used per day, viewing distance, display size, last time used before bed, and the most frequent task for which the display was used. The individuals were instructed to select the most appropriate answer provided in the pull-down menu for each question. The participants were also asked to provide their age, gender, and typical bedtime. Participants were recruited via e-mail,

Facebook, and word of mouth. A link to the survey was also provided on the LRC's homepage. A total of 288 responses were obtained.

1.6.1.1 Survey Results

Of the individuals who completed the survey, 45.49% were male and 54.51% were female. The majority of the participants ranged from 18 to 60 years of age (59.38%: ages 18-40, 29.86%: ages 41-60). The three most commonly reported bedtimes were 22:00, 23:00, and 0:00 (20.49%, 34.38%, and 19.10% respectively).

The three devices that received the most responses were flat-screen computers (95.49%), flat-screen televisions (61.81%), and smart-phones (47.22%). All of these devices appear to be used throughout the day, including right before bedtime (20:00 – 0:00). The majority of those using flat-screen computers reported having displays in the size range of 13 to 21 inches (80.72%), and they were most commonly viewed from a distance of 1-2 ft. (62.18%). Most flat-screen television sizes ranged from 21-60 inches (23.03%: 21-32 inches, 48.88%: 32-48 inches, and 20.79%: 48-60 inches), and were mostly viewed at a distance greater than 4 ft. (86.52%). The most common size for a smart-phone ranged from 2-4 inches (66.18%). Viewing distance for a smart-phone ranged from 4 inches to more than 8 inches.

The most frequent task reported for flat-screen televisions was movies/TV (91.57%). Office work (i.e. Excel, Word, etc.) was the most frequent task observed for flat-screen computers (56.00%). The most frequent task among smart-phone users was e-mail (31.62%). Flat-screen computers appear to be the device that the most time is spent using each day (more than 4 hours). Flat-screen televisions and smart-phones appear to be used typically around 1-2 hours each day. The complete set of results is provided in Appendix A.

1.6.2 Display Measurements

In order to better understand the impact self-luminous displays have on melatonin suppression, the impact of thirteen different displays on predicted melatonin

suppression was assessed. The displays were measured under several different conditions, as illustrated in Table 1 of Appendix B. For this experiment, the settings that are normally viewed when the device is in use were considered standard. The displays were also measured when set to full brightness and when the red, green, blue (RGB) combination of the display was altered to full blue and no blue. A white screen and black screen were measured for each display at each condition. The luminance of the displays was measured using a Minolta LS-100 Luminance Meter (Japan). In addition to brightness, black level is provided among the technical specifications and is the luminance when the screen is entirely black (Anderson, 2005). The luminance of the display also affects the illuminance at the eye, which was measured using a Gigahertz-Optik $X9_1$ Photometer (Turkenfeld, Germany). The distance at which the illuminance was measured was based on responses to the previously mentioned survey. The distances selected for this experiment (Appendix B, Table 2) and summaries of the displays measured (Appendix B, Table 3) are provided in Appendix B. Pupil diameter while viewing the display from this distance was also measured using a device called the Pupilometer. The Pupilometer consists of a set of calipers with two LEDs attached. When held up to the eye, the LEDs appear as two red disks. The individual using the Pupilometer was instructed to move the disks closer together to the point where they were tangent. The distance indicated on the caliper was the pupil diameter. An Ocean Optics USB650 Spectroradiometer was used to obtain the SPD of the different displays. The luminance, illuminance, pupil diameter, and SPD of the displays were measured for each condition. Each display was measured in an environment where the only light in the room was from the display itself. The data obtained was used in conjunction with the circadian phototransduction model proposed by Rea et al. (2011a) to determine the CL_A and CS predicted from exposure to the displays.

1.6.2.1 Display Measurement Results

As would be expected, the luminance for the white screen was greater than the luminance of the black screen for each device, and the luminance of each display was greater when set to full brightness than when set to the standard brightness setting (Table

1). The standard viewing condition for the iMac, Dell, Toshiba, and Gateway computers was full brightness, so no difference was observed for these devices from one condition to another. CL_A and CS values varied depending upon device type. For the white screen, the devices viewed from a closer distance (computers and cell phones) had higher CL_A and CS values than the devices viewed from farther away (televisions). CL_A and CS values were greater when the device was set to full brightness (Table 2) than when set to the standard condition (Table 1).

Manufacturer	Device type	CL_A		CS	
		Black	White	Black	White
Sanyo	Television	0.00	25.62	0.00	0.0365
Sharp	Television	0.03	48.14	0.00002	0.0695
Vizio	Television	0.15	6.43	0.0001	0.0083
Apple iMac	Computer	2.70	342.23	0.0032	0.3426
Dell	Computer	11.55	180.38	0.0156	0.2248
Toshiba	Computer	5.98	92.64	0.0076	0.1294
Gateway	Computer	1.64	62.82	0.0018	0.0902
Archos	Tablet	1.83	20.37	0.0021	0.0287
Asus	Tablet	3.71	27.69	0.0045	0.0396
iPad	Tablet	0.83	6.65	0.0009	0.0086
iPhone 4 (w/screen protector)	Cell phone	0.03	4.65	0.00002	0.0058
LG	Cell phone	1.61	5.61	0.0018	0.0071
iPhone 3GS	Cell phone	0.21	1.46	0.0002	0.0016

Table 1: **CL_A and CS when viewed under the standard setting.**

Manufacturer	Device type	CL_A		CS	
		Black	White	Black	White
Sanyo	Television	4.53	30.45	0.0057	0.0437
Sharp	Television	0.07	53.04	0.00006	0.0765
Vizio	Television	0.84	48.23	0.0009	0.0696
Apple iMac	Computer	2.70	342.23	0.0032	0.3426
Dell	Computer	11.55	180.38	0.0156	0.2248
Toshiba	Computer	5.98	92.64	0.0076	0.1294
Gateway	Computer	1.64	62.82	0.0018	0.0902
Archos	Tablet	3.06	28.82	0.0037	0.0412
Asus	Tablet	7.06	135.83	0.0092	0.1799
iPad	Tablet	1.61	60.95	0.0018	0.0876
iPhone 4 (w/screen protector)	Cell phone	4.63	21.30	0.0058	0.0301
LG	Cell phone	1.72	5.47	0.0019	0.0069
iPhone 3GS	Cell phone	9.7689	102.02	0.013000	0.1410

Table 2: **CL_A and CS when viewed at full brightness, standard white point.**

Manufacturer	Device type	CL_A		CS	
		Black	White	Black	White
Sanyo	Television	8.92	27.32	0.0118	0.0390
Sharp	Television	0.07	69.47	0.00006	0.0992
Vizio	Television	0.23	43.01	0.0002	0.0621

Table 3: **CL_A and CS when viewed at full brightness, white point shift to full blue.**

Manufacturer	Device type	CL_A		CS	
		Black	White	Black	White
Sanyo	Television	2.95	18.16	0.0035	0.0254
Sharp	Television	0.15	37.46	0.0001	0.0540
Vizio	Television	0.55	35.96	0.0006	0.0518

Table 4: **CL_A and CS when viewed at full brightness, white point shift to no blue.**

Change was also observed among the displays of which the RGB combination was altered (Tables 2, 3 & 4). When compared to the standard RGB settings, the Sharp television increased CL_A and CS when the white balance was changed to full blue and decreased when the white balance was shifted to no blue. These results are due to the increased illuminance at the eye when changed to full blue and decreased illuminance when changed to no blue. The Sanyo and Vizio televisions decreased in CL_A and CS when the white balance was decreased to no blue, but also decreased when the white balance increased to full blue.

1.6.2.2 Results Summary

Self-luminous display devices are used throughout the day, including the hours just before bed. Television displays tend to be larger than computer displays, tablets, and cell phones. The viewing distance for televisions, however, is typically greater than 4 ft. Of the televisions analyzed, no CS value was above the 15% threshold. Fifteen percent is used as a reliable threshold because the uncertainty in measuring melatonin is ± 12.7 % (Figueiro et al., 2006a). The only displays for which the CS value was above 15% were computer displays and a tablet device. Computer displays are the second largest type of display and are viewed from only 1 to 2 ft. Tablet devices are also viewed from 1 to 2 ft, however tablets have smaller displays than computers (10.1 inches for example). As the distance from the displays increases, the impact of the display decreases (see Table 5 and Table 6 of Appendix B). CL_A and CS decreased for each display as the distance from the display increased.

1.6.3 Pilot Data Conclusions

The results indicate that self-luminous displays may have an impact on melatonin suppression after just one hour of exposure, especially during times when the displays are set to full brightness. Many displays, however, are not viewed at full brightness and come equipped with light sensors. These light sensors automatically dim the displays in response to changes in the ambient light level, so when the ambient lighting decreases the brightness of the display also decreases. Although the technical specifications of several displays refer to completely black and white screens, the user does not typically view these conditions. Further research should be conducted analyzing self-luminous displays in more "real life" situations.

2. Hypotheses

2.1 Tablet Study

The following hypotheses were tested:

- Exposure to a tablet plus 470 nm-light goggles is expected to result in melatonin suppression that is greater than the suppression resulting from exposure to light from the tablet itself.
- As the duration of exposure increases from one-hour to two-hours, melatonin suppression is expected to increase for the tablet plus 470 nm-light goggle and tablet-only conditions.
- Performance is expected to decrease (increase in reaction time) over the course of the night. This decrease in performance is expected to be less for the tablet plus 470 nm-light goggle conditions compared to the tablet-only and tablet plus orange-tinted glasses condition.

2.2 TV Study

The following hypothesis were tested:

- Based on model calculation melatonin suppression will be low for all conditions. Although it will be low, it is expected to be greater for the 12,000 K and 6500 K conditions compared the 2700 K condition.
- Greater suppression is also expected among individuals seated closer to the display (6 ft) because they will be exposed to a higher light levels than the individuals seated 9 ft from the TV.
- KSS responses are expected to increase throughout the night with lower responses (less tired) occurring for the 12,000 K and 6500 K conditions compared to the 12,000 K plus orange-tinted glasses condition.
- Subjective ratings of picture quality and picture color are expected to be lower for the 12,000 K plus orange-tinted glasses condition than for the 12,000 K condition.

3. Method

3.1 Tablet Study

3.1.1 Objective

The objective of this study was to evaluate the effect of light from a tablet device as well as the duration of light exposure on nocturnal melatonin levels. Cajochen et al. (2011) observed a reduction in reaction time after exposure to an LED-backlit display. Another objective of this study was to evaluate the effect of light from a tablet device on performance.

3.1.2 Location

The experiment was conducted at Rensselaer Polytechnic Institute's (RPI) LRC, located in Troy, NY. Subjects were allowed to leave the test area to use the bathroom; otherwise they were instructed to remain at their assigned desk space. Blackout shades were drawn in the test room to prevent exposure to stray light. Red LED traffic lights (λ = 630nm) were positioned in the test room behind the subjects, in the hallway, and in the restrooms. Although the illumination provided by these lights was dim (less than 2 lux at the cornea), the subjects and experimenters were able to safely navigate the test facility.

3.1.3 Light Conditions

Three lighting conditions were provided in a single test room. In one condition, subjects viewed their tablet through goggles designed to deliver 40 lux (40 $\mu W/cm^2$) of short-wavelength (blue; $\approx$ 470 nm) light at the eye. The 470nm-light goggles were constructed by mounting two LEDs, one above and one below the field of view, to each lens of a pair of clear safety goggles. In order to minimize discomfort glare, polycarbonate translucent tape was used to diffuse the LEDs. A second condition involved viewing the tablet through orange-tinted safety glasses. These glasses (SAF-T-

CURE® Orange UV Filter) filtered out optical radiation below 525 nm. The third condition was exposure to light from the tablet only. The tablet selected for this study was the Apple iPad, either generation 1 or 2. The display of the iPad is approximately 9.7 inches diagonally and is backlit with LEDs. The screen resolution is 1024 x 728 pixels at 132 pixels per inch (Apple Inc., 2011). Each iPad was viewed while set to full brightness during each experimental session. The relative SPDs of the iPad display and the 470 nm-light goggles, as well as the transmittance of the orange-tinted glasses, is provided in Figure 11.

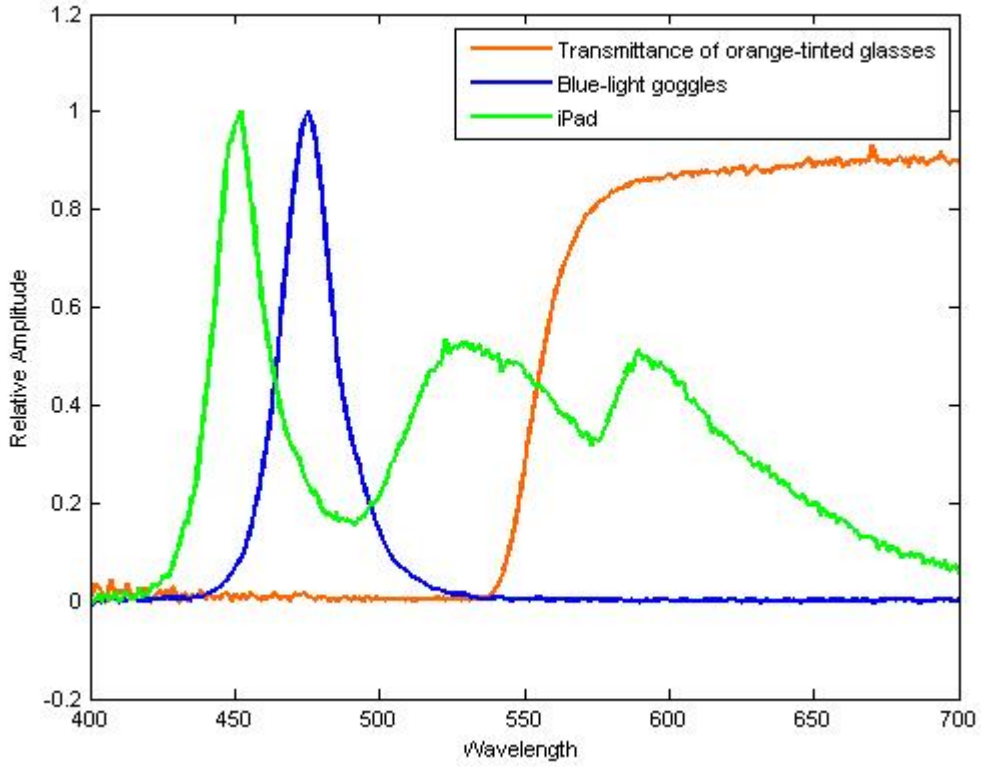

Figure 11: **Relative amplitude of the iPad display, 470nm-light goggles, and transmittance of the orange-tinted glasses.**

3.1.3.1 Goggle calibration

Prior to each session, the goggles were calibrated using an ultraviolet-visible (UV-VIS) optical fiber from Oriel Instruments (Stratford, CT). The fiber, which measures irradiance, was equipped with a cosine correcting lambertian diffuser on one

end. A standard lamp (28V, 71W halogen incandescent lamp no. 12) was used to calibrate the measurement system. The lamp was run at a constant current of 2.53A and voltage limit of 28V. To obtain a calibration factor, the relative SPD of the standard lamp was measured at a distance of one meter from the light source. The raw counts from the measurement were divided by the defined SPD of the standard lamp resulting in a calibration factor. A calibrated relative SPD was obtained by dividing the difference between a dark measurement and measured raw counts by the calibration factor. If the system was calibrated correctly, the irradiance calculated from the calibrated relative SPD should equal the irradiance of the standard lamp.

Upon successful calibration of the measurement system, the 470 nm-light goggles were measured. A rigid stand was used to hold the goggles in position and simulate how they would be worn during the experiment, as shown in Figure 12. An optical fiber was positioned behind the goggles at the approximate location of the human pupil. The irradiances of the left and right lens were measured independently and the voltage from a remote, 9V battery adjusted so that a mean illuminance of 40 lux was achieved. Average irradiances of the left and right lens were 0.38 and 0.41 W/m^2 respectively.

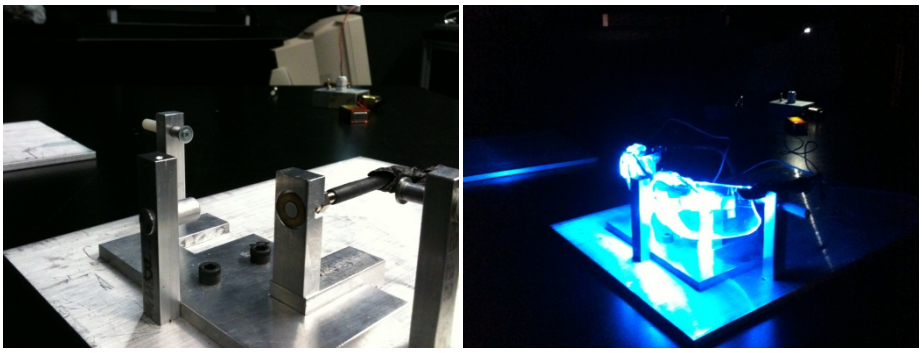

Figure 12: **Photograph of the 470nm-light goggle calibration setup.**

3.1.3.2 Transmittance of the Orange-tinted Glasses

Prior to the first experimental session, the transmittance of the orange-tinted glasses was measured. The same measurement system described in section 3.1.3.1 was used during the procedure to determine transmittance. The relative SPD of a standard

lamp (28V, 71W halogen incandescent lamp no. 12) was measured twice, once with the orange-tinted glasses in front of the lambertian diffuser and once without. Transmittance was determined by dividing the SPD of only the standard lamp by the SPD of the lamp with the orange-tinted glasses.

3.1.4 Subjects

Thirteen subjects were recruited to participate in the study. Potential participants were recruited by e-mail, web posting and word-of-mouth. Individuals were excluded from participation if they reported themselves as being a smoker and/or indicated having any major health problems such as heart disease, diabetes, and high blood pressure. Individuals were also excluded if they were taking over the counter melatonin or prescription medication. Examples of medication that would lead to exclusion include blood pressure medicine, antidepressants, beta-blockers, and sleep medicine. Those taking oral contraceptive were allowed to participate. To ensure they were not extreme early or extreme late types, potential subjects were asked to complete a Munich Chronotype Questionnaire (MCTQ) (Roenneberg, Wirz-Justice, & Merrow, 2003). This criterion was selected to help ensure that the subjects would produce melatonin between the hours of 23:00 and 01:00, the period of data collection. The mean ± standard deviation (SD) age of the subjects was 18.9 ± 5.2 years, and the mean ± SD MCTQ score of the subjects was 3.5 ± 1.3.

3.1.5 Experimental parameters

3.1.5.1 Independent Variables

The independent variables in this experiment were the three lighting conditions, the 470nm-light goggles plus tablet, orange-tinted glasses plus tablet, and tablet-only. The orange-tinted glasses served as a "dark" control condition because the optical radiation that may have the strongest effect on melatonin (less than 525nm) was filtered out. Previous research has predicted that 40 lux of 470nm-light provided as a stimulus is above threshold and below saturation for melatonin suppression (Rea et al., 2005).

Based on this research, the 470nm-light goggles plus tablet served as a "true-positive" condition. Light exposure from the tablet-only served as the third lighting condition. Each participant used an Apple iPad during the experimental sessions set to full brightness. Duration of light exposure, 1-hour and 2-hours, was also an independent variable of this experiment.

3.1.5.2 Dependent Variables

One dependent variable of the experiment was melatonin concentration, from which suppression was calculated. Another dependent variable was performance as measured through a reaction time test. Prior to the start of the experiment, each subject installed Western Labs Limited's Touch Reflex application for the Apple iPhone and iPad. When the application was launched on the iPad, the user was first instructed to change the settings so that the task would be achromatic. Screen shots of the Touch Reflex application are provided in Figure 13.

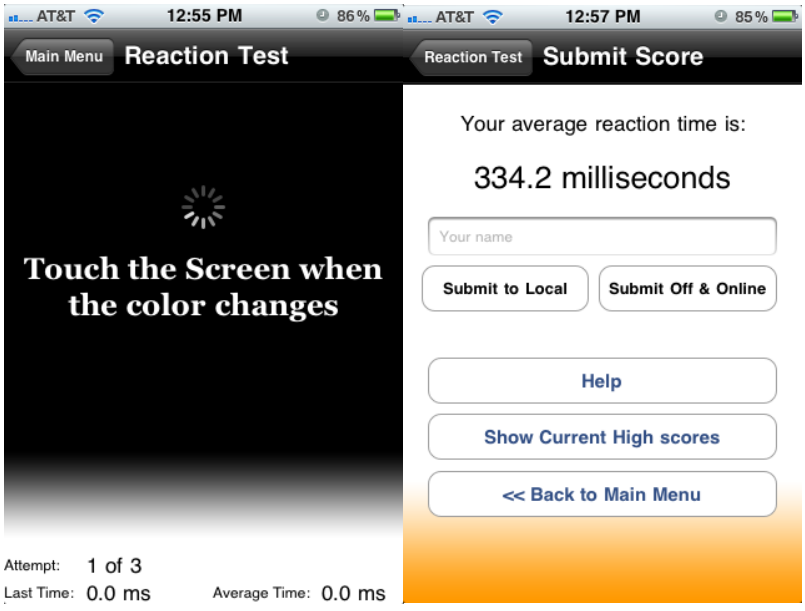

Figure 13: Screen shots of the Touch Reflex Reaction Test.

3.1.5.3 Extraneous variables

During the experiment, subjects were free to perform the tasks of their choice on their iPad. They were also allowed to sit in whatever position was comfortable for them. In other words, distance from the iPad was not held constant throughout the experiment. Since distance and task were not controlled, the actual light exposures from the iPad varied across subjects. While the iPads were in use, "spot" light measurements of display luminance (cd/m^2) and illuminance (lux) at the eye were recorded. Luminance measurements were made using a Minolta LS-100 (Japan) luminance meter and illuminance measurements were made using a Gigahert-Optik $X9_1$ (Turkenfeld, Germany) photometer. A luminance and illuminance measurement was recorded for each subject at 23:00 and 0:00 during each session. From these measurements, an average was obtained.

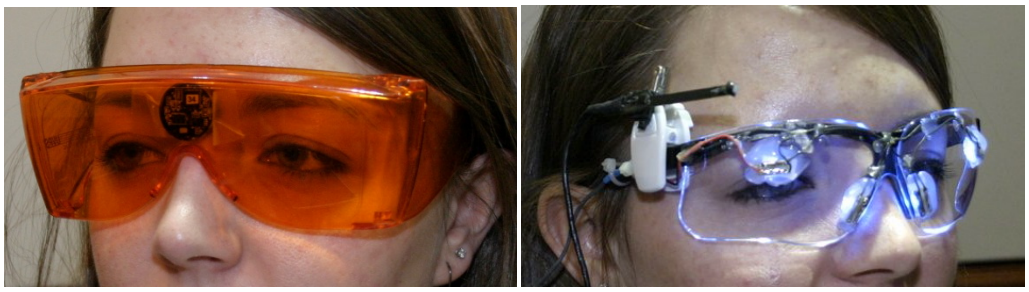

Figure 14: **Dimesimeter locations for the orange-tinted glasses and 470nm-light goggle conditions.**

In order to more accurately record individual light exposures, each subject wore a Dimesimeter. The location of the Dimesimeter during the orange-tinted glasses and 470 nm-light goggle conditions is illustrated in Figure 14. The Dimesimeter is a small (~ 2 cm in diameter) measurement device that continuously records light and activity (Figueiro, Hamner, Bierman, & Rea, 2012). The device is equipped with an integrated circuit sensor array consisting of optical filters for the RGB and infrared (IR) measurement channels with peak spectral responses of 615 nm, 530 nm, 460 nm, and 855nm respectively. Each channel includes an integrating digital-to-analog converter that transforms the raw analog signals from each channel into digital counts. The IR signals are removed from each of the remaining channels to reduce the response outside

the visible range. Raw signals are integrated over a 50 millisecond (ms) or 250 ms period, corresponding to a resolution of 1 lux and 0.2 lux respectively. At the end of the logging interval, the average counts for the RGB channels are stored on the Dimesimeter's memory. The data from the Dimesimeter were downloaded after each data collection period for post processing to determine lux, CL_A, and CS. Each Dimesimeter was calibrated prior to the experimental sessions. During the calibration process, the Dimesimeter and a calibrated illuminance meter were placed at an equivalent distance from a 750 W tungsten-halogen lamp. The devices were oriented so that their sensors were receiving the direct light generated by the source. After recording for five minutes, the data were downloaded to a computer. The measured values from the RGB channels were then averaged in order to determine the R', G', and B' calibration constants; which are the ratios of the illuminance meter reading to the average Dimesimeter output for each channel.

3.1.6 Procedure

Thirteen subjects experienced each of the three lighting conditions, one week apart. During the week prior to the experimental session (Friday night), the subjects were asked to maintain a 23:00 to 07:00 sleep schedule. This required them to go to bed no later than 23:00 and wake-up no later than 07:00. In order to verify compliance, all thirteen subjects were asked to keep sleep logs during these weeks. Seven of the subjects were also asked to call into the laboratory at 07:30 and 08:30 each morning to ensure they were awake. The remaining six subjects were attending high school each day at the same time, so they were not expected to call in. On the day of the experiment, all subjects were asked to refrain from napping and consuming caffeinated products (coffee, tea, soda, etc.) In order to counterbalance the lighting conditions the subjects were randomly divided into three groups. At the end of three weeks, all thirteen subjects had experienced all three lighting conditions.

Subjects arrived at the LRC at 22:30 the night of the experimental session and were all seated in the same test room. From 22:30 until 23:00 the subjects remained in dim red light (less than 2 lux at the cornea). The red light was provided by two red LED

traffic lights (λ = 630nm) that were positioned behind the subjects. Although the light level was low, there was enough light for the subjects and experimenters to safely navigate the test room. At 23:00, before exposure to the iPad, a saliva sample was collected. Saliva samples were collected using the salivette system (ALPCO Diagnostics, Salem NH, USA). In order to provide a saliva sample, subjects were instructed to remove a cotton cylinder from a plastic test-tube and chew it until saturated. When saturated, the subjects were asked to return the cotton to the tube, avoiding touching it with their hands. The sample was then collected and spun in a centrifuge for 5 minutes at 3000g to remove the saliva from the cotton. The cotton was discarded and saliva immediately frozen (-20°C). After the completion of the first saliva sample, the subjects were instructed to complete the reaction test on their tablet. The experimenter recorded the average reaction time for each subject after the test was complete. After completing the reaction test, the subjects were given the freedom to engage in whichever tasks they desired until 01:00. Saliva samples were collected at 00:00 and 01:00, and the reaction test was repeated every half hour for a total of six trials.

3.2 TV Study

3.2.1 Objective

The objective of this experiment was to investigate the effect of light, more specifically, the impact of light level, and CCT, from a television (TV) on melatonin levels.

3.2.2 Location

The experiment was conducted at the LRC, located in Troy, NY. Subjects were instructed to remain in their assigned seat unless they needed to leave the test area to use the restroom. Blackout shades were drawn in the test room to prevent exposure to stray light. Red LED traffic lights (maximum λ = 630 nm) were positioned in the test room behind the subjects, in the hallway, and in the restrooms. Although the illumination

provided by these lights was dim (less than 2 lux at the cornea), the subjects and experimenters were able to safely navigate the test facility.

3.2.3 Light Conditions

Both TVs (Sharp Aquos, LC-70LE734U) were set up in the same room facing opposite directions. The 70-inch, LED-backlit TVs were equipped with three different CCT settings that would become three of the experimental conditions. The CCTs provided were 12000 K, 6500 K, and 2700 K, the SPDs of which are provided in Figure 15. During the fourth lighting condition, the subjects were exposed to the 12000 K setting while wearing orange-tinted safety glasses (SAF-T-CURE® Orange Ultraviolet (UV) Filter). The only additional lighting in the room was from red LED lights located behind the subjects (less than 2 lux at the cornea). A photograph of the experimental setup is provided in Figure 16.

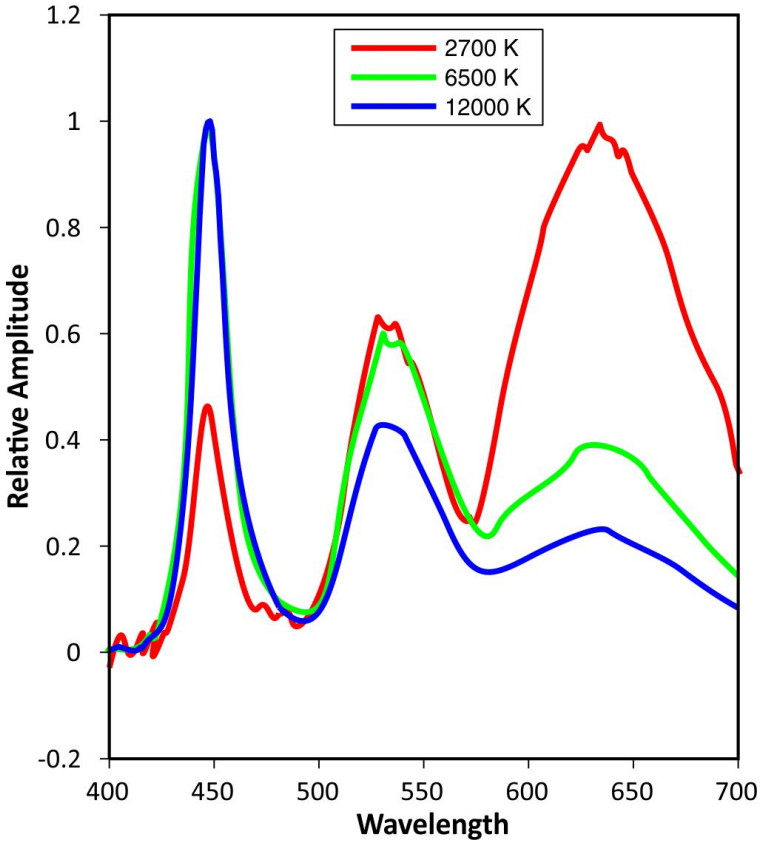

Figure 15: Relative SPDs of the three different CCT settings of the TV.

Figure 16: Photograph of the experimental setup during the TV study.

3.2.4 Subjects

Sixteen subjects were selected to participate in the experiment. Subjects were recruited via e-mail, web posting, and word-of-mouth. Those individuals who reported smoking or having major health problems such as heart disease, diabetes, and high blood pressure were excluded from participation. Individuals were also excluded if they reported taking prescription medication and/or over the counter melatonin and had traveled across two or more time zones within the month prior to the start of the experiment. Females taking oral contraceptive were allowed to participate. Potential subjects were asked to complete the MCTQ (Roenneberg et al., 2003). The MCTQ was used to ensure no extreme late or extreme early types were allowed to participate in the experiment. The mean ± SD age of the participants was 23.8 ± 12.0 years, and the mean ± SD MCTQ was 3.0 ± 1.3.

3.2.5 Experimental Parameters

3.2.5.1 Independent Variables

Four lighting conditions were provided, in a counterbalanced order, to the subjects. The subjects viewed the TVs at three different CCT settings, 12,000 K, 6500 K, and 2700 K. The 12,000 K setting was also viewed while wearing orange-tinted safety glasses. This condition was used as a dark control because the glasses filter out optical radiation below 525 nm that may otherwise have an effect on the circadian system (Rea et al., 2005; 2011a).

Light level was also an independent variable. The sixteen selected participants were randomly divided into two groups of eight, with one group viewing one TV and the second group viewing another. The two groups were further divided into "high" light level and "low" light level groups. The "high" light level group was seated 6 feet from the TV, and the "low" light level group was seated 9 feet away.

3.2.5.2 Dependent Variables

Melatonin concentration after 45 and 90 minutes of exposure was the dependent variable for this experiment. The participants were also asked to complete a subjective questionnaire as part of the experiment. They were asked to rate how they liked the overall picture of the TV and how they liked the color of the picture using a -3 to 3 scale (-3 = don't like it at all and 3 = like it a lot). Subjects were also asked to rate whether or not they would purchase the TV using the same scale (-3 = definitely no and 3 = definitely yes). A question was also asked regarding whether or not the picture was white. If the response was no, the subjects were instructed to choose whether it looked blue, green, or orange, and indicate how much of that color it appeared using a 1 to 4 scale (1 = slightly and 4 = a lot). The KSS was also used to evaluate their level of sleepiness throughout the experiment. Participants were asked to indicate how sleepy they felt using a 1 to 9 scale with decreasing alertness as number increased. All subjective ratings were completed three times, at the beginning, middle, and end of the experiment session.

3.2.5.3 Extraneous Variables

The movie viewed during the experimental sessions was not held constant throughout the experiment. In other words, a different movie was shown during each session. Three movies were selected that provided comparable stimulation to the circadian system, as determined by predictions made prior to experimentation. Toy Story, Toy Story 2, and Toy Story 3 were the movies shown on nights one, two, and three respectively. Toy Story was viewed under the 12,000 K setting on night one with one group of eight wearing orange-tinted glasses. This condition was repeated on night four with the orange-tinted glasses being worn by the remaining eight subjects.

Measurements were made prior to the experiment to determine how illuminance would change as one moved away from the center of the TV. One experimenter held an illuminance meter at eye level while another experimenter recorded the value. An illuminance measurement was made at eight locations, four chairs in the 6 ft row and four chairs in the 9 ft row. As shown in Table 5, *a priori* measurements revealed that the individuals on the end of a row (chairs 1 and 4) would be exposed to lower light levels than the individuals in the center of the row (chairs 2 and 3). For this reason, the subjects wore Dimesimeters during the experimental session. *A priori* Dimesimeter data for the movies that would be shown during the experimental sessions are provided in Table 6. An explanation of the Dimesimeter calibration process is provided in section 3.1.5.3.

Location	Illuminance (lux)	
	6 ft	9 ft
Chair 1	11.2	7.3
Chair 2	16.0	8.4
Chair 3	16.0	8.3
Chair 4	11.9	6.8

Table 5: **Illuminance at the eye for eight seats viewing the TV.**

		12,000K		
		Toy Story	Toy Story 2	Toy Story 3
6 ft	Lux	16.98 ± 6.60	16.48 ± 5.50	14.80 ± 7.24
	CL_A	20.00 ± 8.72	20.85 ± 9.54	18.03 ± 8.62
	CS	0.028 ± 0.013	0.029 ± 0.014	0.025 ± 0.013
9 ft	Lux	8.36 ± 3.40	9.44 ± 3.22	8.54 ± 4.35
	CL_A	10.67 ± 4.90	11.57 ± 5.11	10.50 ± 5.25
	CS	0.014 ± 0.007	0.016 ± 0.013	0.014 ± 0.008

Table 6: ***A priori*** **Dimesimeter data for the movies shown during the experimental sessions.**

3.2.6 Procedure

Sixteen subjects experienced each of the four spectral conditions, one week apart. During the week prior to the experimental session (Friday night), the subjects were asked to maintain a 23:00 to 7:00 sleep schedule. This required them to go to bed no later than 23:00 and wake-up no later than 7:00. In order to verify compliance, all sixteen subjects were asked to keep sleep logs during these weeks. On the day of the experiment, all subjects were asked to refrain from napping and consuming caffeinated products (coffee, tea, soda, etc.) In order to counterbalance the lighting conditions the subjects were randomly divided into four groups (two light levels on two TVs). At the end of four weeks, eight subjects had experienced all four spectral conditions at 6ft and eight subjects experienced the conditions at 9ft.

Subjects arrived at the LRC at 22:30 the night of the experimental session and were all seated in the same test room. From 22:30 until 23:00 the subjects remained in dim red light (less than 2 lux at the cornea). The red light was provided by two red LED traffic lights (maximum $\lambda = 630$nm) that were positioned behind the subjects. Although the light level was low, there was enough light for the subjects and experimenters to safely navigate the test room. At 23:00, before turning on the TV and starting the movie, a saliva sample was collected. Saliva samples were collected using the salivette system (ALPCO Diagnostics, Salem NH, USA). In order to provide a saliva sample, subjects

were instructed to remove a cotton cylinder from a plastic test-tube and chew it until saturated. When saturated, the subjects were asked to return the cotton to the tube, avoiding touching it with their hands. The sample was then collected and spun in a centrifuge for 5 minutes at 3000g to remove the saliva from the cotton. The cotton was discarded and saliva immediately frozen (-20°C). After the completion of the first saliva sample, the experimenter turned on the TV and started the movie. At this time, the first subjective questionnaire was completed. Saliva samples and subjective questionnaires were also completed at 23:45 and 00:30.

4. Results

4.1 Tablet Study

4.1.1 Data Analysis

4.1.1.1 Saliva Radioimmunoassay

Saliva samples were assayed using a radioimmunoassay kit from Labor Diagnostika Nord, (Nordhorn, Germany). The limit of detection for the assay was 0.9 pg/ml, and the intra and inter-assay coefficients of variability were 11.4% and 12.7% respectively.

4.1.1.2 Melatonin Suppression

An adjusted dark value was calculated to account for the natural rise of melatonin that occurs while in the dark as well as the variation in melatonin concentration that occurs from week-to-week. For this experiment, the orange-tinted glasses night was considered the dark night. The adjusted dark time was calculated using the formula provided in Equation 6.

$$A = C_{Tn,D}(C_{T1,Lm}/C_{T1,D}). \quad \text{(Eq. 6)}$$

where:

A = adjusted dark value

T_n = time of saliva sample; n = 1 (23:00), 2 (0:00), or 3 (1:00)

$C_{Tn,D}$ = concentration of the last saliva sample of the dark night, with n = 2 (1 hour) or 3 (2 hours)

$C_{T1,Lm}$ = concentration of the first saliva sample of the light condition, with m = 1 (tablet-only) or 2 (tablet plus blue-light goggles)

$C_{T1,D}$ = concentration of the first sample of the dark night.

Suppression (S) was calculated for each of the remaining twelve subjects by using the formula in Equation 7.

$$S = 1 - (C_{Tn,Lm}/A). \quad \text{(Eq. 7)}$$

4.1.1.3 Dimesimeter Data

Upon completion of each experimental session, the data from each Dimesimeter were downloaded onto a computer for post processing to determine photopic illuminance (lux), CL_A and CS. In order to obtain accurate illuminance values for a variety of light sources, each measurement channel was optimized. The optimization process resulted in a set of three dimensionless constants, W_R, W_G, and W_B (values provided in Table 7). These constants are used to minimize f1' error, the degree to which the spectral response of the RGB sensor matches V(λ). The output of each measurement channel is multiplied by its corresponding calibration (R', G', and B'; see section 3.1.5.3) and optimization constants, and the sum of these three products is the estimated photopic illuminance (Equation 8). The f1' error adjustments, however, are based only upon the overall spectral sensitivity to CIE standard illuminant A (incandescent tungsten filament lamp). Due to the fact that individuals encounter a variety of light sources in addition to illuminant A, the factor F was included as an adjustment to minimize overall measurement error and was applied to each calibration constant. A weighting factor (W_i) was applied to represent the expected frequency with which certain light sources would be encountered. The formula used to determine F is provided in Equation 9.

Constant	Value
W_R	0.334060
W_G	0.645098
W_B	-0.013336

Table 7: Constants used to optimize the Dimesimeter RGB sensor to V(λ).

$$E_{Dime}[lux] = R' * w_R * C_R + G' * w_G * C_G + B' * w_B * C_B \quad \text{(Eq. 8)}$$

$$F = \sum_{i=1}^{9} W_i * \frac{\int SPD(\lambda)_i * V(\lambda) * d(\lambda)}{E_{Dime}} \quad . \qquad \text{(Eq. 9)}$$

where:

$SPD(\lambda)_i$ = spectral power distribution of source i

$V(\lambda)$ = photopic luminous efficiency function

$E_{Dime\ I}$ = Dimesimeter estimated photopic illuminance

W_i = weighting given to light source i

CL_A is also determined from data obtained by the Dimesimeter (Equations 10 and 11). The measurement channels of the Dimesimeter were further optimized to responses that approximate the different photoreceptor sensitivities (Equation 12). A list of the weighting values for the different photoreceptors is provided in Table 8. Table 9 contains a list of the constants used to calculate CL_A. These constants were re-optimized to minimize the error between the CL_A estimated by the Dimesimeter and the value determined from the phototransduction model. The error minimized by this optimization is provided in Equation 13. Once calculated, CL_A is then used to determine CS using the formula provided in Equation 14.

If $S_{mac} > k * V_{mac}$

$$CL_{ADime} = A * \left[M + a_{b-y} * (S_{mac} - k * V_{mac}) - a_{rod} * 683 * (1 - e^{\left(\frac{-V'}{6.5*683}\right)} \right] . \qquad \text{(Eq. 10)}$$

else

$$CL_{ADime} = A * M . \qquad \text{(Eq. 11)}$$

Approximated photoreceptor response = $w_R * C_R * R' + w_g * C_g * G' + w_B * C_B * B'$. (Eq. 12)

Photoreceptor response curve	Symbol	W_R	W_G	W_B
S_{cone}/macula	S_{mac}	0.004902	-0.077333	0.293393
V(λ)/macula	V_{mac}	0.300981	0.736231	0.320870
Melanopsin	M	-0.009224	0.097292	0.320870
V'(λ)	V'	-0.028144	0.390077	0.199808
V(λ)	V	0.334060	0.645098	-0.013336

Table 8: Weighting functions based on the photoreceptor response curve.

Constant	Value
$a_{b\text{-}y}$	0.447
a_{rod}	3.13
k	.253
A	2.46

Table 9: Constants used in the $CL_{A\ Dime}$ calculation.

$$\text{Error} = \sum_{j=1}^{7}\sum_{i=1}^{9} W_i * \left|(CL_{A(Dime)i,j} - CL_{Ai,j})/CL_{Ai,j}\right| \quad \text{(Eq. 13)}$$

where:

j = one of seven light levels (10, 31.6, 100, 316, 1000, 3160, and 10000 lux)

i = one of nine spectrum (incandescent, daylight, three fluorescent, and four phosphor converted white LEDs)

W_i = specifies the weighting factor

$$CS = .7 \times \left(1 - \left(\frac{1}{1 + \left(\frac{CL_A}{355.7}\right)^{1.1026}}\right)\right) \quad \text{(Eq. 14)}$$

The Dimesimeter was programmed to record data every 30 seconds. A photopic illuminance, CL_A, and CS value were provided for every 30-second data collection interval. Illuminance and CL_A values were averaged to provide a value corresponding to one hour and two-hours of exposure. CS values were only provided for 1-hour of exposure since the phototransduction model proposed by Rea et al. (2005; 2011a) is based upon a one hour light exposure duration.

4.1.1.4 Reaction Time

To perform the reaction time test, the subjects were instructed to start a new game and tap their iPad display once they noticed the display change from black to white. The display change occurred three times, and then an average reaction time (in milliseconds) was reported. Subjects were asked to complete one reaction test trial every half hour for the duration of the experiment. After each trial, an experimenter recorded the average reaction time.

4.1.1.5 Statistical Analysis

A 3 x 2 factor (one control and two experimental conditions at two sample times) repeated measures analysis of variance (ANOVA) was performed on the raw melatonin concentrations of 10 subjects. The first sample, collected at 23:00, was not included in this analysis. For the reaction time data, a 3 x 6 factor (one control and two experimental conditions at six trials) was performed. Post-hoc two-tailed student's t-tests were also performed when appropriate. Adjustments were made for multiple comparisons using the Bonferroni correction.

4.1.2 Results

4.1.2.1 "Spot" Light Measurements

As was mentioned previously, subjects were allowed to perform the task of their choice during the experimental sessions. For this reason, illuminance and luminance varied from subject to subject. Illuminance values ranged from 1.54 to 43.63 lux and luminance values ranged from 1.41 to 184.50 cd/m^2. Mean [median] ± STDEV illuminance and luminance values from all 13 subjects after three weeks were 15.70[10.30] ± 14.23 lux and 76.86[73.26] ± 65.59 cd/m^2 respectively.

4.1.2.2 Model Predictions

Predicted melatonin suppression was calculated for the three lighting conditions using the CL_A data obtained from the Dimesimeter. Since the Dimesimeter was worn outside the 470nm-light goggles, the CL_A for 40 lux of 470 nm-light was added to the Dimesimeter CL_A during post processing. CS values were calculated for each lighting condition using the data gathered by the Dimesimeter. Pupil diameter was not measured during the experiment, so an adjusted CS was also calculated assuming a larger pupil diameter of 4 mm. The mean [median] ± standard error of the mean (SEM) CS values for the tablet plus blue LED and tablet-only conditions assuming a 2.3 mm pupil were 0.46[0.46] ± 0.0013 and 0.03[0.02] ± 0.007 respectively. These values increased to 0.61[0.61] ± 0.001 and 0.07[0.06] ± 0.016 when pupil diameter was increased to 4 mm. It was also assumed that, by removing the wavelengths of light that most affect the circadian system, the tablet plus orange-tinted glasses condition would not produce the stimulus necessary to suppress melatonin. When assuming a 2.3 mm pupil diameter and using the Dimesimeter CL_A data, the mean[median] ± SEM CS value for this condition was 0.002[0.002] ± 0.0004, and increased to 0.006[0.005] ± 0.001.

		Illuminance (lux)	CL_A	CS 2.3mm pupil	CS 4mm pupil	Measured Suppression (%)
1 hour	Tablet + blue LEDs	59.14 [55.15] ± 4.99	647.89 [648.14] ± 4.89	0.46 [0.46] ± 0.0013	0.61 [0.61] ± 0.001	48 [46] ± 4
	Tablet + orange-tinted goggles*	9.82 [9.35] ± 1.87	1.47 [1.31] ± 0.31	0.002 [0.002] ± 0.0004	0.006 [0.005] ± 0.001	NA
	Tablet-only	17.60 [13.40] ± 3.78	18.61 [13.21] ± 4.61	0.03 [0.02] ± 0.007	0.07 [0.06] ± 0.016	7 [2] ± 4
2 hours	Tablet + blue LEDs	57.48 [54.44] ± 3.75	645.86 [645.42] ± 3.45	NA	NA	66 [68] ± 4
	Tablet + orange-tinted goggles*	9.88 [8.35] ± 1.63	1.54 [1.15] ± 0.29	NA	NA	NA
	Tablet-only	16.01 [14.23] ± 2.67	17.05 [13.91] ± 3.51	NA	NA	23 [27] ± 6

Table 10: Mean [median] ± standard error of the mean (SEM) Dimesimeter light measurements, CS values, and measured melatonin suppression. * The tablet with the orange-tinted goggle condition was used as the dark control.

4.1.2.3 Melatonin

Results from the 3 x 2 factor ANOVA performed on the raw melatonin concentrations revealed a significant main effect of light (($F_{2,18}$) = 26.197, $p < 0.001$), and time (($F_{1,9}$) = 5.788, $p = 0.040$), as well as a significant light x time interaction (($F_{2,18}$) = 13.491, $p < 0.001$). Thirteen subjects completed the experiment, however, two subjects did not provide a sufficient quantity of saliva for analysis at 00:00, and one did not provide a sufficient quantity at 01:00. For this reason, two subjects were omitted from the one-hour analysis and one subject was omitted from the two-hour analysis. The mean[median] ± SEM suppression values for the tablet plus blue LED and tablet-only conditions are provided in Table 10 and Figure 17.

Two-tailed, one-sample t-tests were used to determine whether or not the results were statistically reliable. Mean [median] ± SEM percent melatonin suppression values of 48[46] ± 4 and 66[68] ± 4 were significantly greater than zero at 00:00 ($t(10) = 14.990$, $p < 0.001$) and at 01:00 ($t(11) = 16.102$, $p < 0.001$) respectively. Mean [median] ± SEM percent suppression values for the tablet-only condition were 7[2] ± 4 and 23[27] ± 6 after one hour and two-hours respectively. Although suppression for the tablet only condition was not significantly greater than zero after one hour exposure ($t(10) = 1.797$,

p = 0.103), suppression after two hours of exposure was significantly greater than zero (t(11) = 3.394, p = 0.006).

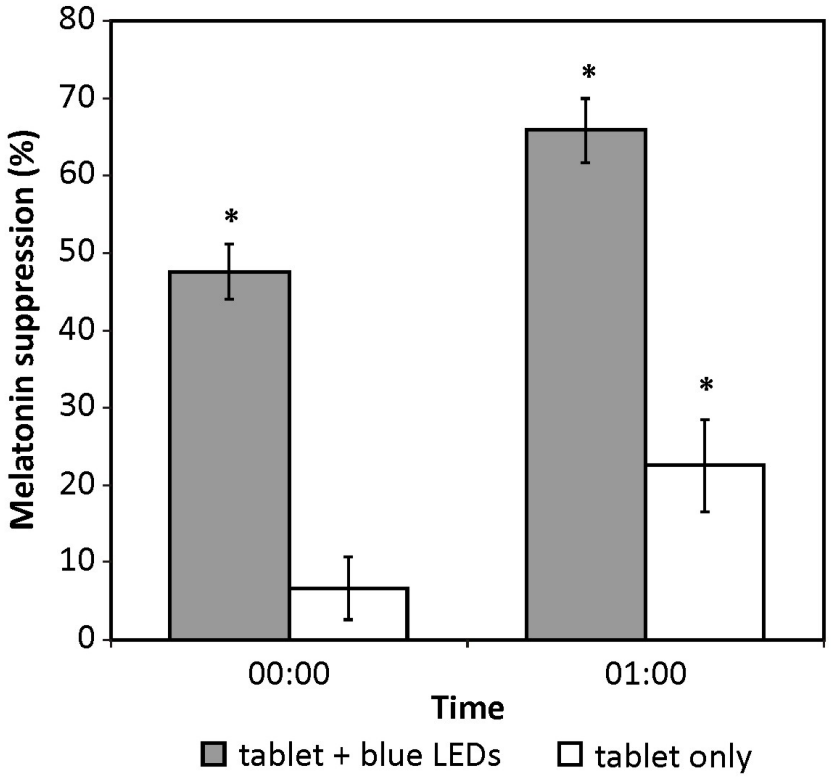

Figure 17: Mean ± SEM suppression values for the tablet + blue LEDs and tablet only conditions.

4.1.2.4 Reaction time

The mean ± SEM reaction times for each condition during the two-hour exposure period are provided in Figure 18. A repeated measures ANOVA using the mean reaction times revealed a statistically significant main effect of time (($F_{5,60}$) = 3.49, p = 0.04). The only significant difference was observed between trial three and trial four. The mean reaction time for trial three (307.13ms) was significantly greater than the mean for trial four (329.53ms) (p = 0.05). The effect of light (($F_{2,24}$) = 0.41, p = 0.67) and the interaction between light and time (($F_{10,120}$) = 1.55, p = 0.13) were not statistically significant.

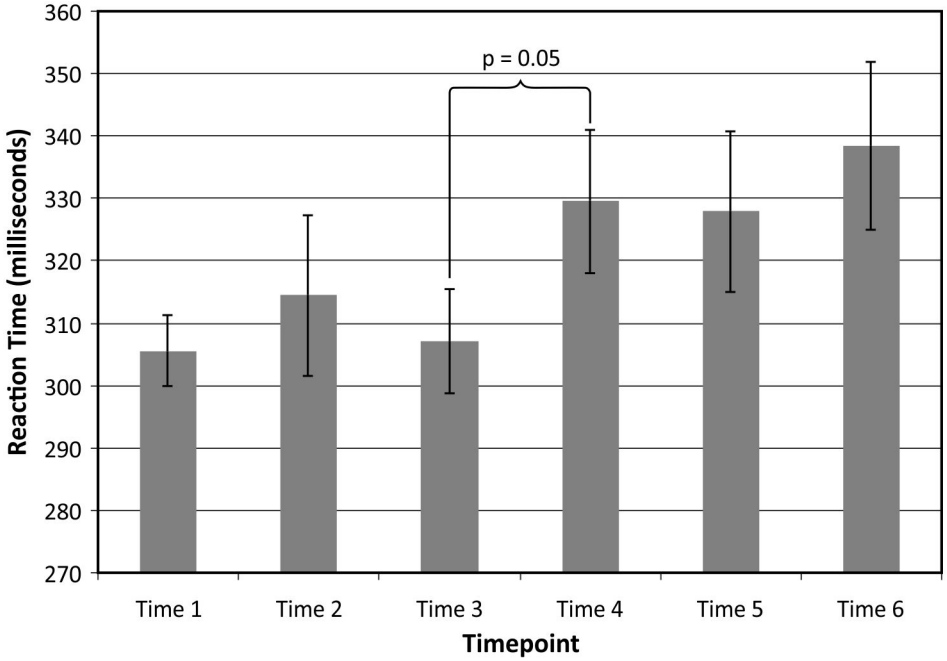

Figure 18: Mean ± SEM reaction time values.

4.2 TV Study

4.2.1 Data Analysis

4.2.1.1 Saliva Radioimmunoassay

Saliva samples were assayed using a radioimmunoassay kit from Labor Diagnostika Nord, (Nordhorn, Germany). The limit of detection for the assay was 0.9 pg/ml, and the intra and inter-assay coefficients of variability were 11.4% and 12.7% respectively.

4.2.1.2 Melatonin Suppression

As described in section 4.1.1.2 (Equation 6), an adjusted dark value was calculated using the orange goggle night as the dark control night. Suppression was calculated using Equation 7.

4.2.1.3 Dimesimeter Measurements

Refer to section 4.1.1.3 (page 54)

The Dimesimeter was programmed to record data every 30 seconds. Lux, CL_A, and CS values were provided for every 30-second data collection interval, and were averaged to provide a value corresponding to one-hour of exposure.

4.2.1.4 Statistical Analysis

A 2 x 3 x 4 (two light levels, three data collection times, and four light conditions) repeated measures ANOVA was performed on the raw melatonin concentrations, and subjective questionnaire items relating to picture quality, picture color, whether or not the subject would purchase the TV, and KSS. For the question about whether or not the picture was white, the percentage of subjects indicating yes or no was determined for each spectral condition and time. The Bonferroni correction was used to adjust for multiple post-hoc comparisons. Of the subjects that responded no, the percentage of subjects responding that the color appeared blue, green, or orange, was also determined for each spectral condition and time. The responses for the question regarding how much blue, green, or orange the display appeared were averaged together to form one value for each time for each spectral condition.

4.2.2 Results

4.2.2.1 Model Predictions

CS predictions for each lighting condition were made using the CL_A data obtained from the Dimesimeter. An adjusted CS was also calclulated assuming a 4 mm pupil diameter (Table 11). The mean [median] ± SEM CS values when a 2.3 mm pupil was assumed were 0.01[0.01] ± 0.001, 0.01[0.01] ± 0.001, and 0.004[0.004] ± 0.0002 for the 12,000 K, 6500 K, and 2700 K conditions respectively when viewed from 6 ft. It was assumed, however, that the pupil diameters during the experimental sessions were larger than 2.3mm. For this reason, predictions were also made assuming a 4 mm pupil. When pupil diameter was assumed to be 4 mm, CS values increased to 0.04[0.04] ±

0.002, 0.04[0.04] ± 0.004, and 0.01[0.01] ± 0.001 for the 12,000 K, 6500 K, and 2700 K conditions respectively at a 6 ft viewing distance. In the same order, the values at 9 ft were 0.008[0.008] ± 0.0001, 0.007[0.007] ± 0.0003, and 0.002[0.002] ± 0.00002 for 2.3 mm and 0.03[0.03] ± 0.001, 0.02[0.02] ± 0.01, and 0.006[0.006] ± 0.0001 for 4 mm. The 12,000 K plus orange-tinted goggle condition was used as the dark control condition for the experiment. It was assumed that suppression would not occur when exposed to this condition because the wavelength of light that has the greatest affect on the circadian system is removed when wearing the goggles. Mean[median] ± SEM CS values for this condition were 0.0004[0.0004] ± 0.00002 and 0.001[0.001] ± 0.0001 for a 2.3 and 4 mm pupil respectively at a 6 ft distance, and 0.0002[0.0002] ± 0.00001 and 0.001[0.001] ± 0.00002 for a 2.3 and 4 mm pupil at 9ft. Illuminance, CL_A, and CS were all greater for the 6ft (high) light level group than the 9 ft (low) light level group. These predictions are for a 60 minute exposure.

				CS (%)		Measured Suppression (%)	
		Illuminance (lux)	**CL_A**	**2.3mm pupil**	**4mm pupil**	**45 min.**	**90 min.**
High (6 ft)	12,000K + orange-tinted goggles*	3.17 [3.00] ± 0.19	0.39 [0.37] ± 0.02	< 0.01 [< 0.01] ± < 0.01	< 0.01 [< 0.01] ± < 0.01	NA	NA
	12,000K	9.01 [8.94] ± 0.44	10.40 [9.94] ± 0.46	0.01 [0.01] ± < 0.01	0.04 [0.04] ± < 0.01	-1.7 [0.1] ± 4.3	4.3 [10.0] ± 10.8
	6500K	9.65 [9.04] ± 0.76	9.34 [8.71] ± 0.82	0.01 [0.01] ± 0.001	0.04 [0.04] ± < 0.01	-9.8 [-2.8] ± 9.5	-4.4 [-4.6] ± 13.0
	2700K	5.02 [4.71] ± 0.31	3.43 [3.32] ± 0.15	< 0.01 [< 0.01] ± < 0.01	0.01 [0.01] ± 0.001	-2.5 [-6.1] ± 9.1	4.0 [2.5] ± 8.1
Low (9 ft)	12,000K + orange-tinted goggles*	1.88 [1.83] ± 0.06	0.24 [0.23] ± 0.008	< 0.01 [< 0.01] ± < 0.01	< 0.01 [< 0.01] ± < 0.01	NA	NA
	12,000K	5.20 [5.14] ± 0.13	6.26 [9.94] ± 0.10	< 0.01 [< 0.01] ± < 0.01	0.03 [0.03] ± < 0.01	-0.02 [0.7] ± 11.0	-10.8 [-2.4] ± 14.9
	6500K	5.53 [5.58] ± 0.20	5.35 [5.18] ± 0.25	< 0.01 [< 0.01] ± < 0.01	0.02 [0.02] ± < 0.01	6.6 [7.7] ± 8.4	-5.3 [0.1] ± 12.3
	2700K	2.71 [2.70] ± 0.09	1.59 [1.58] ± 0.02	< 0.01 [< 0.01] ± < 0.01	< 0.01 [< 0.01] ± < 0.01	11.1 [14.1] ± 8.2	0.20 [11.0] ± 15.5

Table 11: **Mean[median] ± SEM Dimesimeter light measurements, CS values, and measured suppression for the TV study. * This condition was used as the adjusted dark.**

4.2.2.2 Melatonin

Figures 19 and 20 show the mean ± SEM suppression values after 45 and 90 minutes of exposure. Mean[median] ± SEM percent melatonin suppression values after 45 minutes of exposure were -1.7[0.1] ± 4.3, -9.8[-2.8] ± 9.5, and -2.5[-6.1] ± 9.1 for the 12,000 K, 6500 K and 2700 K conditions respectively at 6 ft. In the same order, after 90 minutes these values increased to 4.3[10.0] ± 10.8, -4.4[-4.6] ± 13.0, and 4.0[2.5] ± 8.1. The percent suppression values at 9 ft were -0.02[0.7] ± 11.0, 6.6[7.7] ± 8.4, and 11.1[14.1] ± 8.2 after 45 minutes of exposure to 12,000 K, 6500 K, and 2700 K respectively. After 90 minutes, these values were -10.8[-2.4] ± 14.9, -5.3[0.1] ± 12.3, and 0.20[11.0] ± 15.5 for the 12,000 K, 6500 K, and 2700 K conditions respectively. Results of a three factor (2 light levels x 3 collection time x 4 light conditions) repeated measures ANOVA showed a significant main effect of time ($(F_{2.28}) = 33.471$, $p < 0.001$), and lighting condition($(F_{3, 42}) = 5.408$, $p = 0.003$) on the raw melatonin concentrations. Melatonin concentrations were significantly higher after exposure to the 12,000 K than after exposure to the 2700 K setting ($p = 0.007$). Melatonin concentrations were significantly higher at collection time two ($p < 0.001$) and time three ($p < 0.001$) compared to time one, and significantly higher at time three compared to time two ($p = 0.002$). No interactions between light level, lighting condition, or time were observed to have a significant effect.

Two-tailed, one-sample t-tests revealed that the results of viewing the TV for 45 minutes at a 6 ft distance for the 2700 K ($t(7) = -0.275$, $p = 0.792$), 6500 K ($t(7) = -1.036$, $p = 0.335$), and 12,000 K ($t(7) = -0.204$, $p = 0.844$) conditions were not statistically reliable. Statistically reliable results were also not observed after 45 minutes of exposure at 9 ft to the 2700 K ($t(7) = 0.486$, $p = 0.642$), 6500 K ($t(7) = -0.340$, $p = 0.744$), and 12,000 K ($t(7) = 0.397$, $p = 0.703$) conditions.

Reliable results were also not observed after 90 minutes of exposure at 6 feet for the 2700 K ($t(7) = 1.359$, $p = 0.216$), 6500K ($t(7) = 0.789$, $p = 0.456$), and 12,000 K ($t(7) = -0.022$, $p = 0.983$) conditions. When the three CCT settings were viewed from 9 ft, the results obtained were also not statistically reliable for the 2700 K ($t(7) = 0.013$, $p = 0.990$), 6500 K ($t(7) = -0.434$, $p = 0.677$), or 12000 K ($t(7) = -0.742$, $p = 0.492$) conditions.

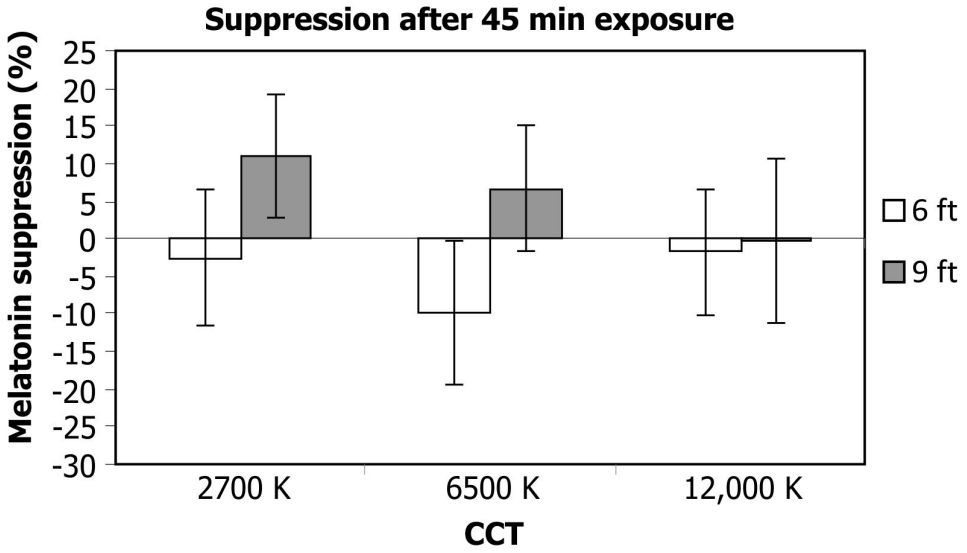

Figure 19: Mean ± SEM suppression after 45 minutes exposure.

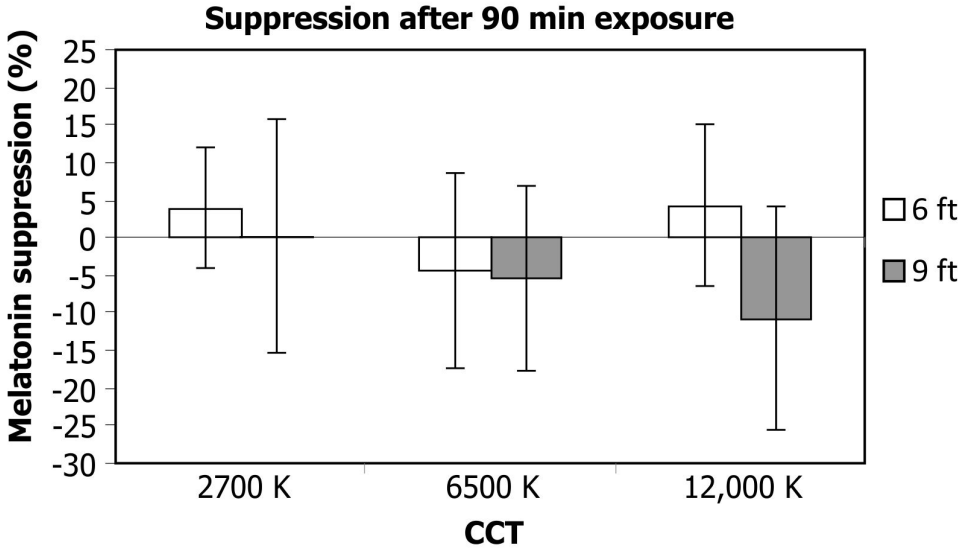

Figure 20: Mean ± SEM suppression after 90 minutes exposure.

4.2.2.3 Subjective Ratings

A repeated measures ANOVA revealed no effect of time (($F_{2,28}$) = 0.099, p = 0.854) nor any interactions between light level, time, or light condition on the subjective ratings of picture quality, but there was, however, a main effect of light condition (($F_{3,42}$)

= 3.759, p = 0.018). Subjective ratings of picture quality were significantly higher when the 2700 K was viewed compared to the 12,000 K plus orange-tinted glasses condition (p = 0.011). Significantly higher ratings were also provided when the 6500 K condition was viewed compared to the 12,000 K plus orange-tinted glasses condition (p = 0.038).

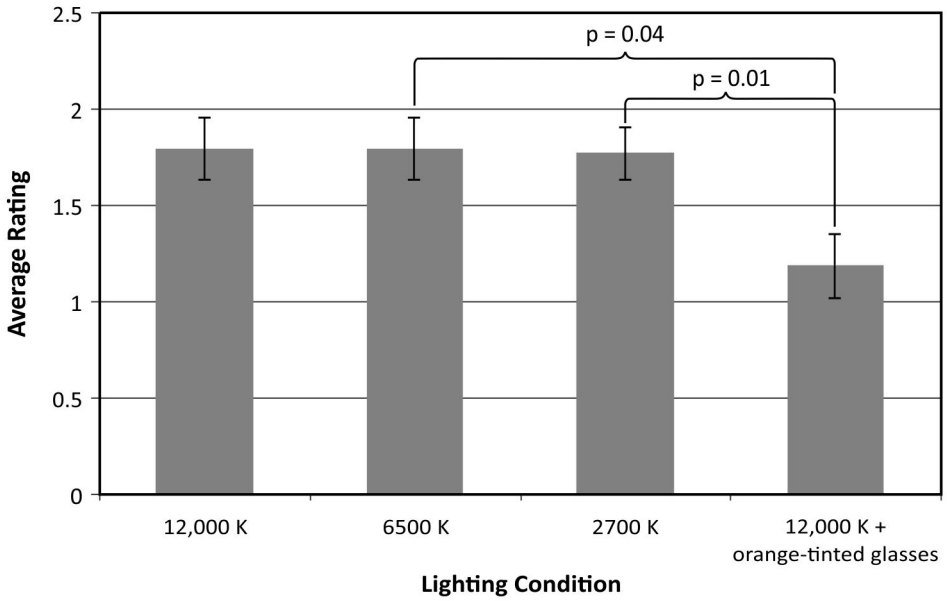

Figure 21: **Average ± SEM subjective ratings when asked "how do you like the overall picture quality?".**

No significant main effect of time (($F_{2,28}$) = 1.478, p = 0.245), nor any interactions between light level, light condition, or time were observed on the subjective ratings for color of the picture. There was, however, a significant effect of light condition (($F_{3,42}$) = 26.781, p < 0.001). Ratings when the TV was viewed at 12,000 K through orange-tinted glasses were significantly lower than those for the 12,000 K (p < 0.001), 6500 K (p < 0.001), and 2700 K (p < 0.001) conditions.

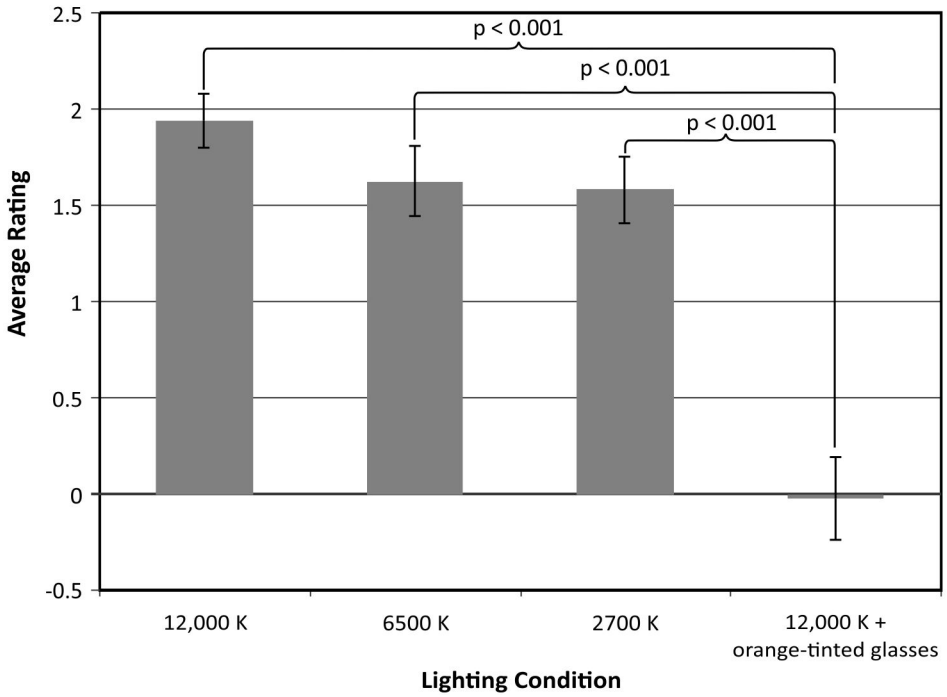

Figure 22: **Average ± SEM subjective ratings when asked "how do you like the color of the picture?".**

No effect of time ($(F_{2,28}) = 0.654$, $p = 0.528$), nor light condition ($(F_{3,42}) = 2.732$, $p = 0.056$) was observed regarding whether or not the participant would purchase the TV, but there was a significant interaction between light level and light condition ($(F_{3,42}) = 3.079$, $p = 0.038$). Subjective ratings were significantly lower when the TV was viewed through orange-tinted glasses compared to the 12,000 K ($p = 0.001$), 6500 K ($p = 0.001$), and 2700 K ($p = 0.001$) conditions at 9 ft.

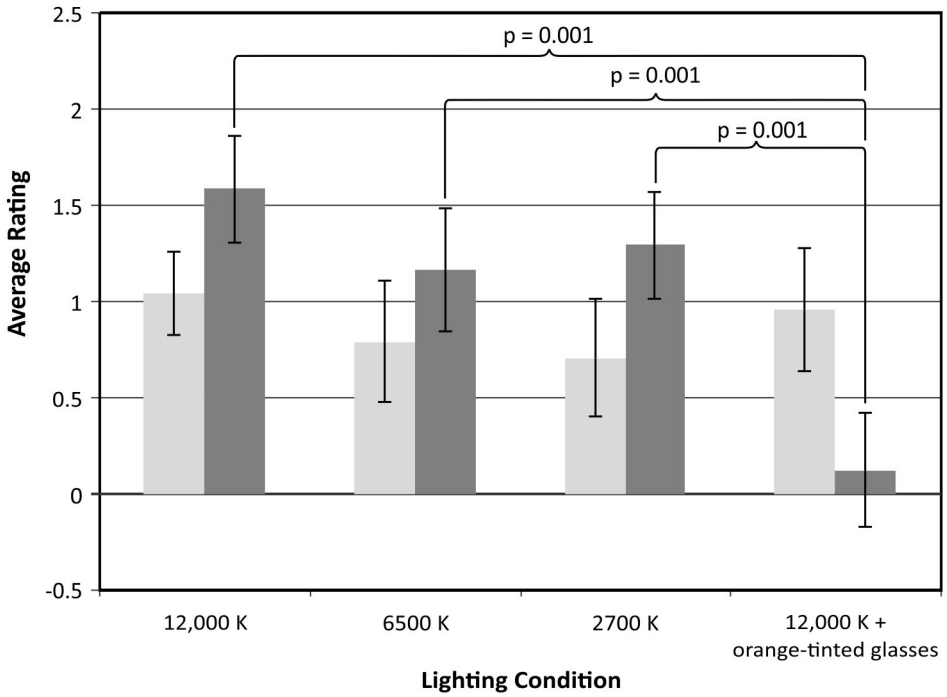

Figure 23: **Average ± SEM subjective ratings when asked "would you buy this television?" The darker bars correspond to the 9 ft group and the lighter bars correspond to the 6 ft group.**

The last item on the questionnaire was the KSS. Significant main effects of light condition (($F_{3,42}$) = 4.046, p = 0.013) and time ($F_{(2,28)}$ = 11.867, p < 0.001) were observed. No interactions were observed between light level, light condition, and/or time. KSS ratings were significantly lower at time one compared to time two (p = 0.026), and time one was also significantly lower than time three (p = 0.008). Ratings of sleepiness were also lower at time two compared to time three (p = 0.014). When the TV was viewed at the 6500 K setting, KSS responses were significantly lower than when viewed at the 12,000 K setting (p = 0.002).

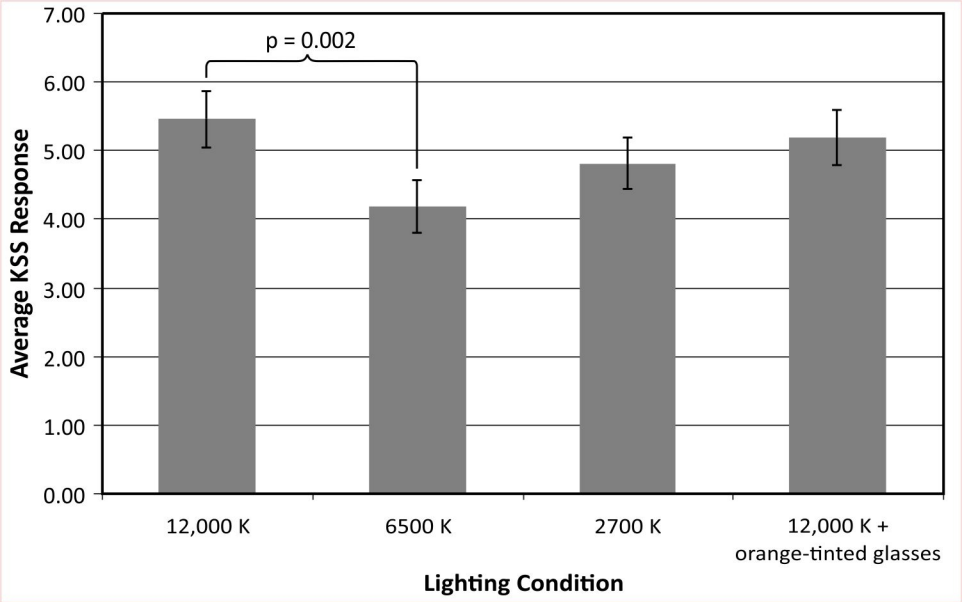

Figure 24: **Average ± SEM KSS values for the four light conditions.**

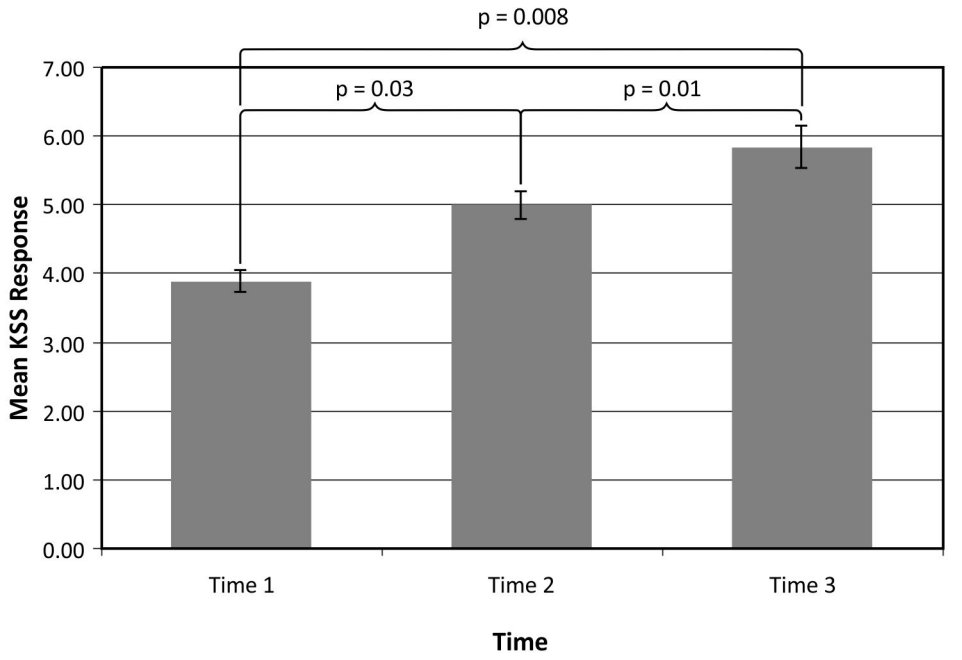

Figure 25: **Mean ± SEM KSS values for time 1, time 2, and time 3.**

The subjects were asked to indicate whether or not the picture on the TV appeared white. The percentage of subjects answering YES or NO is provided in Table 12. For the 12,000 K plus orange-tinted glasses condition, 100% of the subjects in each group answered that the picture was not white. Seventy-five percent of the subjects in

the 6 ft group answered that the picture was white, as did 87.5% of the subjects in the 9 ft group when viewing the 12,000 K condition. No change was observed in these responses from time one to time three. When the 6500 K condition was viewed from 6 ft, 12.5% more subjects reported a white picture at time one than at time three. At 9 ft, however, 12.5% more subjects reported a white picture at time three than time one. For the 2700 K condition, 12.5% more subjects reported a white picture at time three than time one at 6 ft, and the percentage remained the same for the 9 ft group.

CCT		12,000K plus orange-tinted glasses			12,000K			6500K			2700K		
Time		**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
6 ft	% Yes	0	0	0	75	75	75	50	37.5	37.5	50	75	62.5
9 ft	% Yes	0	0	0	87.5	87.5	87.5	62.5	75	75	75	62.5	75

Table 12: **Subjects responses to "is the picture white?".**

The subjects that indicated that the picture did not appear white were also asked to indicate whether the picture looked blue, green, or orange. The percentage of responses for each color are provided in Table 13. For the 12,000 K plus orange-tinted glasses condition, the responses were either green or orange for both the 6 ft and 9 ft group. Only three responded with green, a subject during time one at 6 ft, time two at 9 ft, and time three at 9 ft. Although some subjects indicated that the picture viewed during the 12,000 K condition was not white, they did not specify what color they perceived. No responses were given for the 9 ft group, and the only color reported for the 6 ft group was blue. Green was not a response for the 6500 K condition when viewed from 6 ft. At time one, the responses were split 50-50 between blue and orange.

At time three, the responses were 60% blue and 40% orange. For the 9 ft group, 100% of the responses were blue at time one. By time three, this value decreased to 33.33% for blue, and increased to 33.33% for green and orange. Green was also not a response for the 2700 K condition for the 6 ft group.

CCT		12,000K plus orange-tinted glasses			12,000K			6500K			2700K		
Time		**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
6 ft	% Blue	0	0	0	50	100	50	50	60	60	75	100	67.5
	% Green	12.5	0	0	0	0	0	0	0	0	0	0	0
	% Orange	87.5	100	100	0	0	0	50	40	40	25	0	33.33
9 ft	% Blue	0	0	0	NA			100	50	33.33	50	100	100
	% Green	0	12.5	12.5				0	50	33.33	50	0	0
	% Orange	100	87.5	87.5				0	0	33.33	0	0	0

Table 13: Subject responses to "does the color appear blue, green or orange?".

5. Discussion

Melatonin suppression was assessed following exposure to two types of self-luminous devices, a tablet and a TV. The mean ± SEM light exposure experienced by the subjects during the tablet-only condition was 16.0 ± 2.67 lux for one hour. The CS value determined from the Dimesimeter data recorded during the tablet-only condition was 0.03. When viewing the tablet while wearing 470 nm-light goggles, the illuminance value increased to 57.48 ± 3.75 lux and the CS value increased to 0.46. Illuminance levels while viewing the TV were lower than those provided by the tablet. Mean ± SEM illuminance values at the 6 ft viewing distance were 9.01 ± 0.44, 9.65 ± 0.76, and 5.02 ± 0.31 lux for the 12,000 K, 6500 K, and 2700 K conditions respectively. In the same order, the corresponding CS values for these light levels were 0.01, 0.01, and 0.004. Both illuminance and CS values were lower among the group viewing the TV from 9 ft. The mean ± SEM illuminance values for the 12,000 K, 6500 K, and 2700 K conditions at 9 ft were 5.20 ± 0.13, 5.53 ± 0.20, and 2.71 ± 0.09 lux respectively. Listed in the same order as the illuminance values, the CS values corresponding to these light levels were 0.008, 0.007, and 0.002.

As hypothesized greater suppression was observed after exposure to the tablet plus 470 nm-light goggles. Statistically significant suppression was observed after both one-hour and two-hour exposures to the tablet plus 470 nm-light goggles. The tablet-only condition resulted in statistically significant suppression after two hours of exposure, but not after one. A significant effect of time was observed for the reaction test, with reaction time being longer after one hour than after thirty-minutes of exposure. Significance was not observed between any other trials. Although it was not a significant difference, reaction time after two-hours of exposure was longer than at the start of the experimental session. During the week prior to the experimental session, each participant was asked to maintain a 23:00 to 7:00 sleep schedule. On the night of the experiment, the participants were required to stay awake until the end of the exposure period at 1:00. Increased reaction times towards the end of the experimental session may just be the result of fatigue, and the light from the tablet did not counteract this effect. A significant interaction between lighting condition and time was not observed; reaction times increased for all three lighting conditions.

Like the tablet experiment, the orange-tinted safety glasses were worn while viewing the TV; thus making the 12,000 K setting plus orange-tinted safety glasses the dark control condition. Melatonin suppression was expected to be greater after exposure to the 12,000 K and 6500 K conditions compared to the 2700 K condition. The 6500 K condition never resulted in suppression greater than the 2700 K condition, and the 12,000 K condition only resulted in suppression greater than the 2700 K condition when viewed at 6 ft. Significant melatonin suppression was not observed for any lighting condition at either viewing distance. It was also thought that the 12,000 K and 6500 K conditions would result in lower responses on the KSS, which would indicate that the subjects felt less tired. Although not significant, average responses on the KSS for the 6500 K condition were lower than the orange-glasses condition. Responses for the 12,000 and 12,000 K plus orange-tinted glasses condition were not significantly different. Unexpectedly, however, responses on the KSS were significantly lower for the 6500 K condition compared to the 12,000 K condition. Although the exact reason for this result is unknown, it may be due to the order in which the movies were presented. All the subjects viewed Toy Story during the first and final experimental sessions, once during the 12,000 K condition and once while viewing the 12,000 K condition while wearing orange-tinted glasses. Higher responses for the KSS may be the result of boredom due to watching the movie for the second time. KSS did not improve during the experimental session after exposure to any lighting condition. Significantly lower responses were given at time one compared to time two and time three, and responses at time two were significantly lower than time three. Similar to the tablet study, subjects were asked to keep a 23:00 to 07:00 sleep schedule the week prior to the experimental session. Since they were required to stay awake until 00:30 the night of the study, it is likely that the light exposure provided by the TV was not enough to counteract fatigue. No significant interaction between lighting condition and time was observed among the responses to the KSS.

A significant effect of light condition was observed for the subjective ratings regarding whether or not the subjects liked the color of the picture on the TV and whether or not they liked the quality of the picture. Ratings were significantly lower for the dark control than any other condition. A significant interaction between light level

and lighting condition was observed for the question that asked whether or not the subjects would buy the TV. For the low light level (9 ft) group, significantly lower ratings were provided for the dark control (12,000 K plus orange-tinted glasses) than for all other conditions experienced by that group. The reason for this result from the 9 ft group and not the 6 ft group is unknown, but may just reflect the individual preference differences between the subjects in the two groups. There was no significant difference, however, between the responses given for the different CCT settings of the TV on any of these questions. These results suggest that lowering the CCT of a display may be an option to decrease the amount of short-wavelength light one is exposed to at night. However, since suppression was not observed for any condition, including the 12,000 K setting, lowering the CCT of a display may not be necessary. Light exposure from a TV may not be as much cause for concern as light from other self-luminous devices.

Several studies, including the tablet study, have been conducted using 470 nm-light goggles as a "true positive" condition and orange-tinted glasses as a "true control". Unlike the tablet study, the TV study did not have a "true positive" and the light conditions were not properly counterbalanced. The results, however, still matched the predictions made using the model, which was that melatonin suppression after exposure to the TV would be low. An interesting similarity between the two studies was the measured melatonin suppression among the teenage female participants. Melatonin suppression values for these subjects after exposure to the tablet-only condition for two hours were 35, 59, and 47%. These subjects that illustrated a potential increased sensitivity to light from the tablet study also showed an increased sensitivity to light from the TV, even though the light levels experienced during the TV study were lower than those experienced during the tablet experiment. Suppression values corresponding to the TV study were 40, 17, and 31%. While the suppression values for these subjects were greater than the other subjects, based on the Dimesimeter data they did not experience a greater light exposure. Although the results from the TV study itself may not be too surprising, they become more interesting when the other research in the literature is considered.

In order to understand the effects of self-luminous electronic devices, several aspects should be considered. Of most importance is the spectral irradiance distribution

incident on the cornea weighted by the circadian system's response. When self-luminous displays are used, the spectral irradiance is dependent upon the application for which the display is being used. Of the studies in Table 14, only the iPad study, TV study, and the study conducted by Figueiro et al. (2011b) measured the actual light exposures experienced by the subjects throughout the experimental sessions. Higuchi et al. (2003) and Cajochen et al. (2011) each report a single photopic illuminance measurement taken prior to the experimental session. Actual light exposures experienced by the subjects of these two experiments may have varied from the calibrated value during the various tasks that were performed. Understanding the effects of the devices in real-life situations involves being able to account for the changes in spectral irradiance that can occur with changes in application. For example, spectral irradiance may be different when reading e-mail than when watching a movie or playing a game.

Quantity of light is one factor that impacts the spectral irradiance distribution on the cornea. Illuminance values for the thirteen subjects participating in the tablet experiment ranged from 5 to 51 lux for the tablet-only condition. Since the subjects were allowed to choose the task they performed during the experiment, some subjects were exposed to higher illuminance levels than others. The tablets of users who were reading an eBook or browsing Facebook, tasks with a white background, provided higher illuminance levels (51 lux) than those of users who were watching a movie (5 lux).

The relative spectrum of the light provided by the display may have also impacted the results. In addition to varying illuminance by task, the relative spectrum of the light provided by the tablet may have also varied depending upon the task being performed. Illuminance at the eye and relative spectrum are used to determine the CL_A provided by a light source. Data from the Dimesimeter revealed that the CL_A for the subject watching a movie on his iPad was 5.81 compared to 64.02 for the subject who was reading an eBook during the experiment. This difference may be due to the greater short-wavelength component of the white background compared to the darker, colored background of the movie. Although relative spectrum was not measured during the experimental sessions, the displays measured during pilot data collection revealed a

greater amount of short-wavelength light with a white background compared to a colored background. Quantity of light at the eye and the relative spectrum of the source both influence the effect the light exposure will have on the circadian system.

Another characteristic of the stimulus that may have affected melatonin suppression was the spatial distribution of the light. During the tablet study, the subjects were able to view the tablet from a position that was comfortable for them. The display was not fixed to a specific viewing angle or distance during the experiment. When viewing the TV, illuminance at the eye decreased as one moved away from the center of the display. Differences in the spatial distribution of the light from the display can affect the quantity of light reaching they eye, thus also affecting the variation between estimated and actual melatonin suppression. For example, if an individual tilts their display away from them while using it, less light may reach the eye than if it was perpendicular. If it was assumed perpendicular when the prediction was made, then the estimated suppression may be greater than the actual suppression because of the different ways for which the display was viewed.

The duration for which a display is used will also impact the effect the light exposure will have on the circadian system. As was previously mentioned, the tablet device did not result in significant suppression after one hour, but did reach significance after two hours of exposure. The suppression observed after two hours of exposure to the tablet resulted in greater suppression than that which occurred after exposure to the CRT screen used during the experiment conducted by Figueiro et al. (2011b) for the same duration. Significant suppression was not observed for any condition of the TV experiment that involved a ninety-minute exposure to the display, the shortest of all the durations listed in Table 14. Conversely, the five-hour duration experienced during the experiment conducted by Cajochen et al. (2011) was the greatest of all the experiments listed in Table 14. Although the duration of exposure was the longest, the suppression measured was not the greatest. These results suggest that duration alone does not determine the impact a display will have on melatonin suppression.

The timing of a light exposure may also affect the impact the exposure will have on the circadian system. The five-hour duration of the Cajochen et al. (2011) experiment began at 20:00. A stimulus provided early in the night, when melatonin is on

the upslope of production, may have less of a measurable effect than light provided later in the evening. With the exception of the experiment conducted by Cajochen et al. (2011), all the experiments listed in Table 14 began at 23:00.

In summary, there are several characteristics of the light emitted from a self-luminous display that may influence melatonin suppression. With measurement of the stimulus provided, predictions can be made that are proportional to the measured amount of melatonin suppression. The quantity of light provided for a given amount of time determines the light exposure. CS is a prediction made assuming a one-hour duration, at the midpoint of melatonin production, with 2.3 mm pupil diameter. For exposures beyond one hour, predictions are made with uncertainty. CS*duration is a simple estimate of exposure for durations longer than two hours. This value is solely an estimate, and is not based on any scientific reasoning. Figure 26 illustrates a positive correlation between measured melatonin suppression and the product of CS and duration. A 2.3 mm pupil diameter was assumed for all values of CS. In general, as CS*duration increased, the measured melatonin suppression also increased.

During the tablet and TV experiments, the displays were set to full brightness and were used in a dark room. Many devices today, however, have an automatic brightness adjustment feature. Depending upon the ambient lighting in the space where the tablet is being used, the brightness of the display either increases or decreases. If the automatic adjustment were used in a dark room, the display would decrease in brightness. The CS value for the tablet in a dark room with a white background is 0.004 using the automatic brightness adjustment compared to 0.03 for the same background at full brightness. These CS values were obtained assuming a 2.3 mm pupil. If the tablet were used in a room where ambient lighting was available, the brightness of the display would increase. Thus, the stimulus provided by the tablet itself would be greater in an ambient-lit room than in total darkness. The ambient lighting would also provide a stimulus, however, the effect of light from a tablet-device while in an ambient-lit room has not been measured.

Study		Diagonal Size (inches)	Viewing Distance (inches)	Solid Angle (steradians)	Duration	Illuminance (lux)	CS	Measured Suppression (%)
iPad		9.7	12	0.26	1 hour	16.0	0.03	7[1]
					2 hours			23[2]
TV (6 ft)	12,000 K	70	72	0.36	90 min	9.01	0.01	4.3[3]
	6500 K					9.65	0.01	-4.4[4]
	2700 K					5.02	0.004	4.0[5]
TV (9 ft)	12,000 K		108	0.17		5.20	0.008	-10.8[6]
	6500 K					5.53	0.007	-5.3[7]
	2700 K					2.71	0.002	0.20[8]
Figueiro et al. (2011b)		17	20.1	0.28	2 hours	28	0.19	11[9]
Higuchi et al. (2003)		17	17.7	0.35	3 hours	45	0.05*	8[10]**
						45		0[11]***
						15	0.02	-19.54[12]**
Cajochen et al. (2011)		24	23.6	0.39	5 hours	94.5	0.15	28[13]

Table 14: **Diagonal size, viewing distance, solid angle, duration, illuminance, CS, and suppression for five studies involving self-luminous displays. * Since the SPD of the display used by Higuchi et al. (2003) was not provided, CS for this experiment was calculated using an SPD that matched a description of the display. ** These values correspond to the measured suppression values when an exciting task was viewed at 15 and 45 lux. *** This value corresponds to the measured suppression when a boring task was viewed at 45 lux. The boring task when viewed at 15 lux was used at the dark control when calculated suppression.**

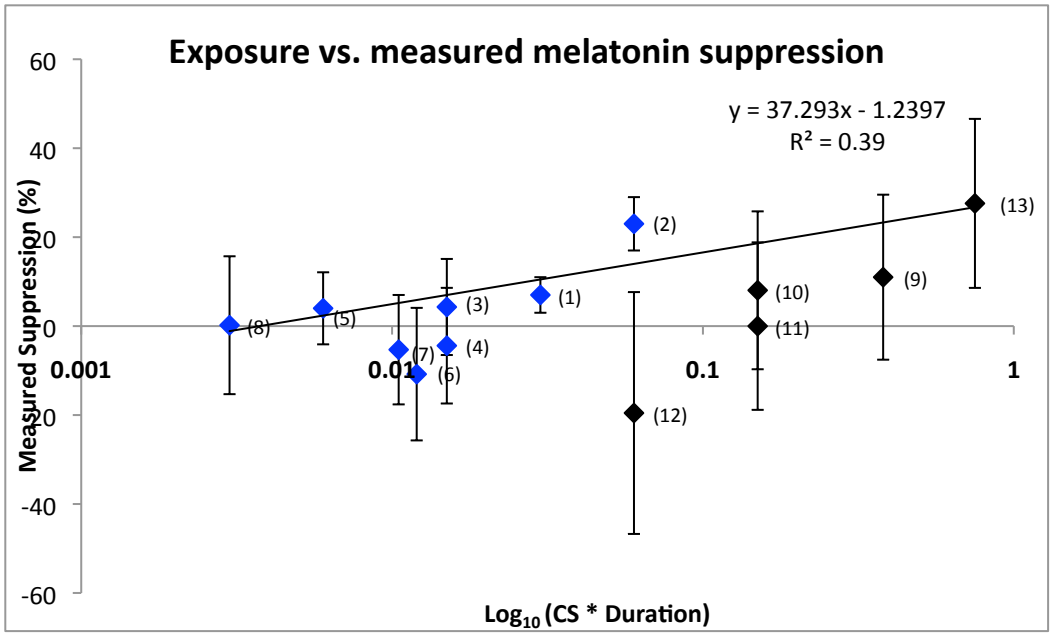

Figure 26: **Exposure vs. measured melatonin suppression for the experiments listed in Table 14. The numbers next to the data points correspond to the values provided in the table.**

In modern society, exposure to light at night is not often avoided. Mean ± SD photopic illuminance levels for a sample of female school teachers were 28 ± 24 lux between civil twilight and bedtime. Mean ± SD CS levels corresponding to this illuminance was 0.07 ± 0.05 (Rea et al., 2011b). As has been previously stated, melatonin appears to have oncostatic benefits (Brzezinski et al., 1997). Night-shift workers, individuals forced to be awake at times when melatonin concentration would typically be at its highest, are at an increased risk for developing breast cancer. Exposure to certain cancer causing agents at a young age can also increase the incidence of breast cancer in women (Russo & Russo, 1996), thus raising concern about exposure to light at night among today's youth. While exposure to light at night may not always be avoided, there are precautions an individual can take to minimize the negative effect the light may have. The threshold for reaching a statistically significant amount of melatonin suppression after exposure to 470 nm-light is 1.2 lux (2 $\mu W/cm^2$) for a 90-minute duration (Figueiro et al., 2011a). For this illuminance with a 2.3 mm pupil, the CS value is 0.04. In order to obtain the same CS for the tablet display with a white background, 24 lux is required to reach a statistically reliable difference from zero. Dimming the brightness of the display below this value may reduce the chance of melatonin suppression as a result of the light exposure. When using a self-luminous display at night, dimming the display may be beneficial to reduce the amount of light at the eye. If the display is an iPad, perhaps changing the display to the 'white on black' option is more appropriate during the nighttime hours if the user would like to avoid melatonin suppression. While the trend for many manufacturers may be to create larger and brighter displays, it may be beneficial to create more "circadian friendly" alternatives for the individual who desires to use their display at night.

Until this point, displays have been discussed in terms of lowering the amount of light from them to avoid melatonin suppression at night. However there may be applications for which the light provided by a self-luminous display may be beneficial. For example, these displays can potentially be used as a device to deliver light treatment to individuals that often experience disrupted sleep patterns, such as elderly individuals in senior homes. Having them use their display while performing a task that provides

the appropriate circadian stimulus in the morning may be beneficial to this population of individuals. This same idea could apply to students in schools during the winter months. A self-luminous display could potentially be used to provide the stimulus the circadian system needs in the morning hours.

It is undoubtedly important to quantify what stimulus is being provided to the circadian system, but other factors remain that may also affect melatonin suppression. While most subjects suppressed melatonin after exposure to their tablet device, there were some subjects for which suppression did not occur. Individual differences, such as photic history and various unknown genetic factors, may explain the difference in results obtained between subjects. For example, individuals who were exposed to higher light levels during the day prior to the experimental session may have been less sensitive to light than the subjects exposed to lower light levels. Photic history was not a factor controlled during the tablet or TV studies. Research conducted by Higuchi, Motohashi, Ishibashi, and Maeda (2007) suggests a decreased sensitivity to light among "dark-eyed" Asians, as evidenced by lower melatonin suppression. Although the results obtained by Higuchi et al. (2007) may not have solely been the result of differences in eye color, it does support the idea of unknown genetic factors causing individual differences in melatonin suppression.

6. Conclusions and Future Work

Two experiments were conducted to investigate the impact of self-luminous displays on melatonin. Statistically significant suppression of melatonin was observed after just two hours of nighttime exposure to light from an Apple iPad tablet. Light provided from a TV, however, was not observed to have an effect on melatonin. The results of the experiment were obtained while the displays were set to full brightness. Since most devices come equipped with light sensors, the brightness of the display automatically decreases as ambient light level decreases. If displays do not have the automatic dimming option, they should be manually dimmed at night to decrease the amount of light one is exposed to. While these results are important, they only illustrate the effect of self-luminous displays after one short exposure period.

Future work should include investigating the effects of newer displays that are often becoming larger and brighter, and are also utilizing new technologies, such as organic-LEDs (OLED). Displays that are typically used while holding them closer to the eye, such as cell phones, should also be investigated. Display settings that reduce the amount of light reaching the eye, such as automatic dimming and the 'white on black' option the iPad and iPhone, should be studied to determine the impact they may have on the circadian system. Work involving these displays should be done in more real-life settings, not just in the laboratory environment. Future work should also include examining the differences between different populations of subjects. While it appears from the results that the three Asian subjects have a reduced sensitivity light, it is not clear if this is true of all Asians. If there are populations that have a reduced sensitivity to light, do populations exist that have an increased sensitivity to light? While the suppression values of the Asian subjects were among the lowest obtained during the experiment, the suppression values of the teenage female subjects were among the highest obtained. Exposure to cancer causing agents early in life, such as during the teenage years, may result in increased cancer risk when one becomes an adult (Russo & Russo, 1996). Thus, light at night exposure among teenage girls may be more of a concern than light at night exposure for other individuals. Exposure to light at night may be more hazardous for individuals who are more sensitive to light, so it is important to determine the differences that may exist between individuals.

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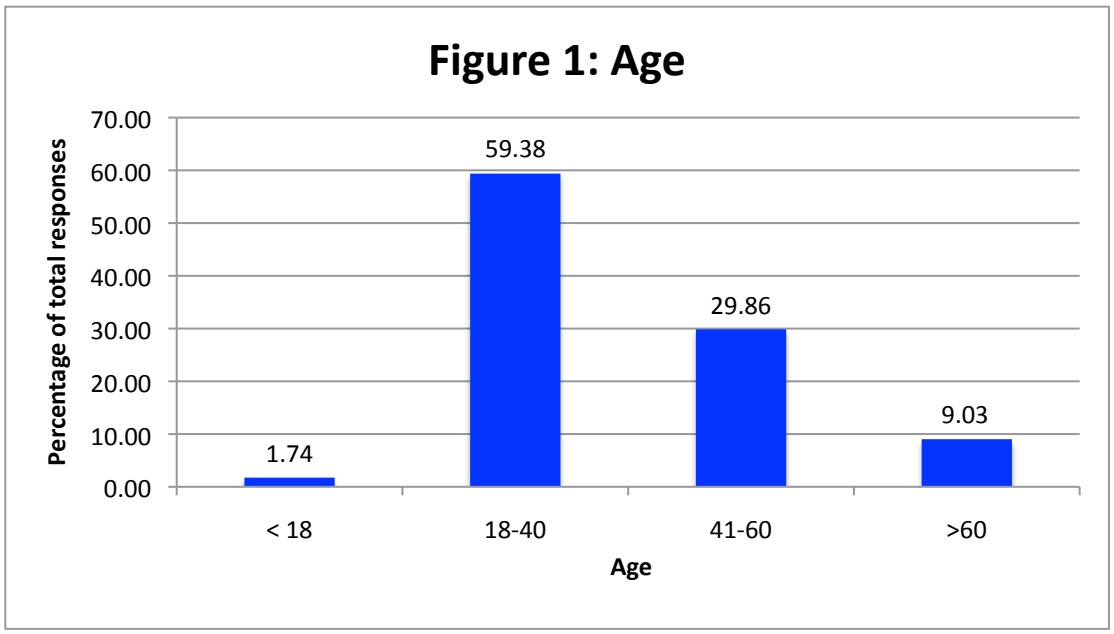
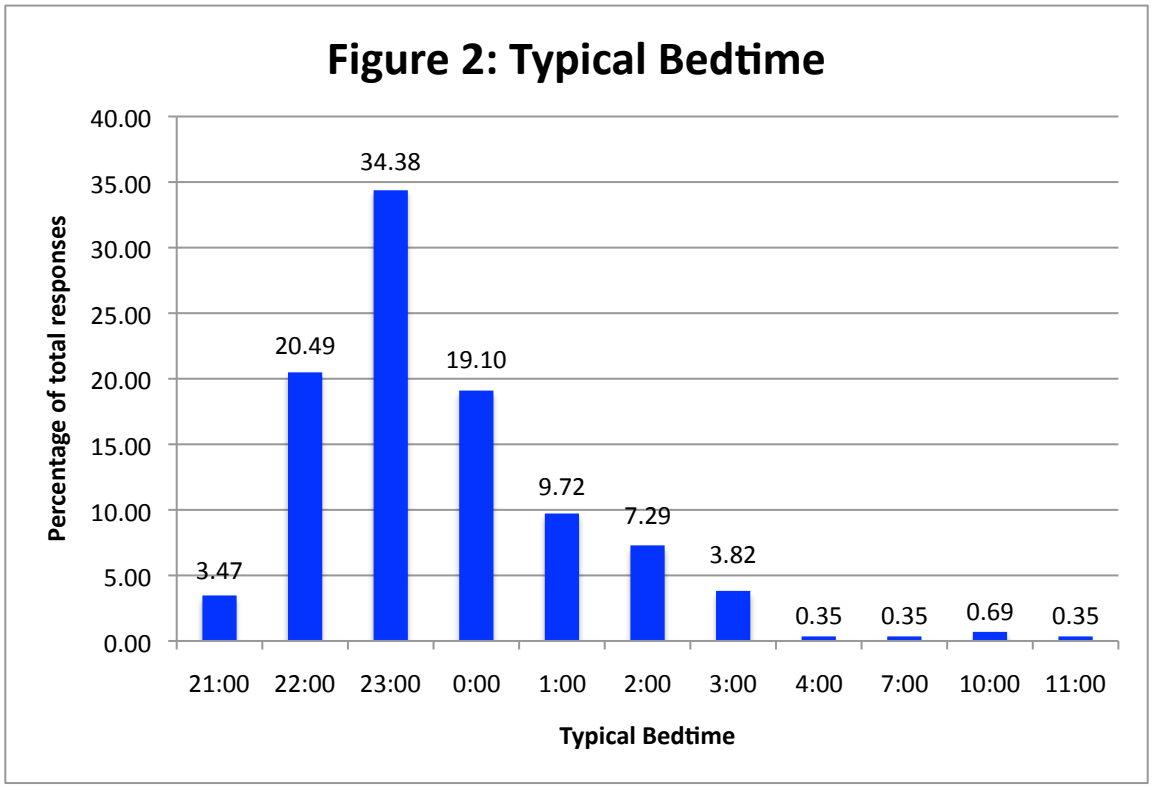
8. Appendices

8.1 Appendix A – Display Survey Results





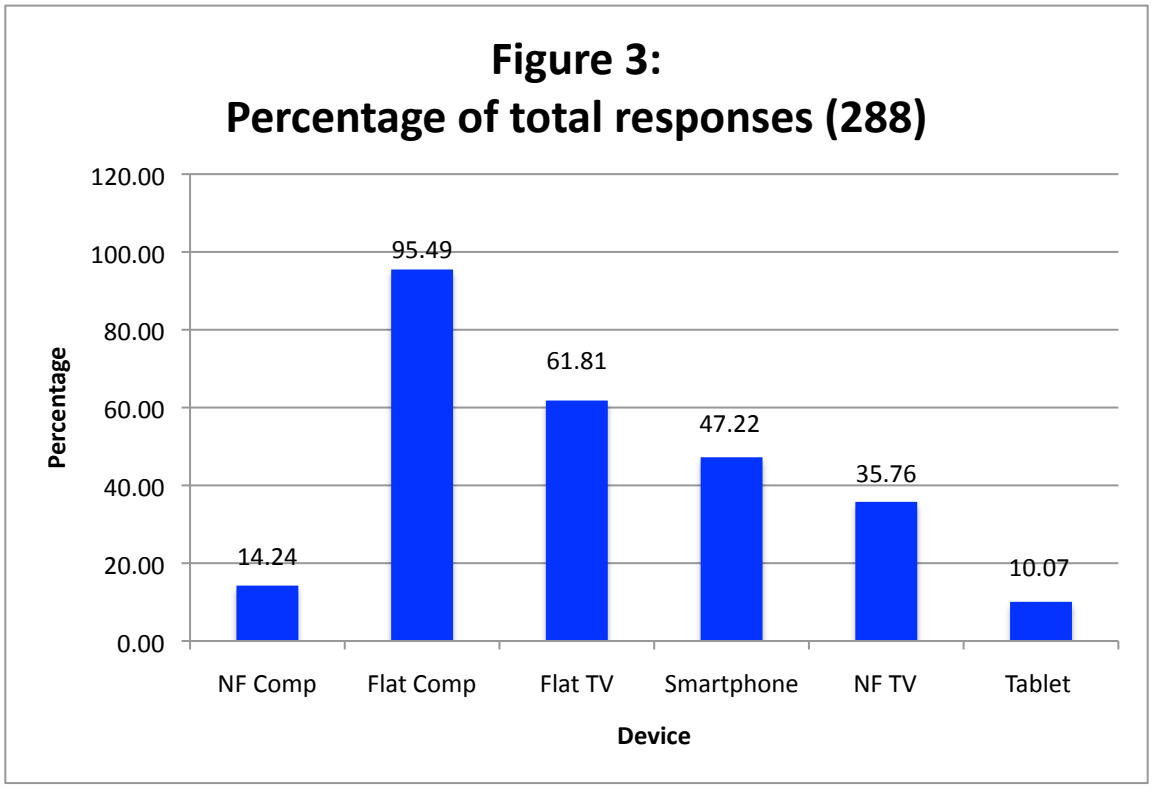


Figure 3:
Percentage of total responses (288)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Percentage
95.49
61.81
47.22
35.76
14.24
10.07
NF Comp
Flat Comp
Flat TV
Smartphone
NF TV
Tablet
Device

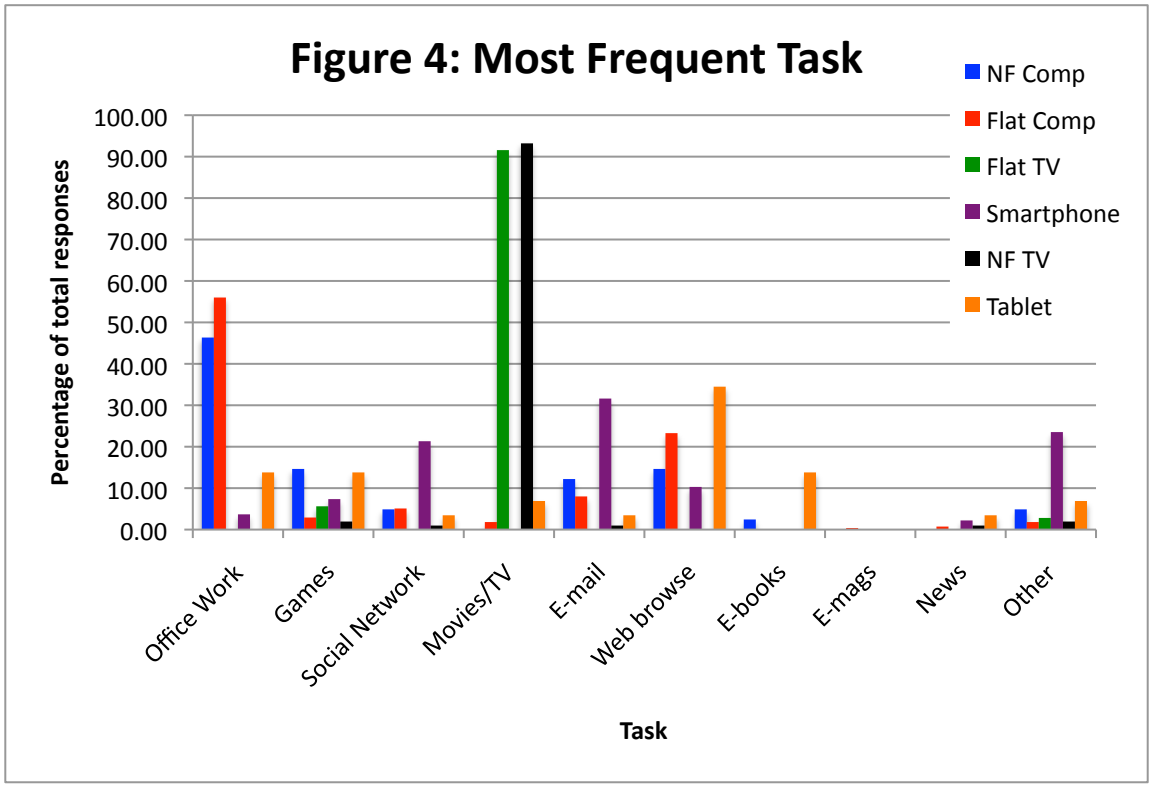


Figure 4: Most Frequent Task
NF Comp
Flat Comp
Flat TV
Smartphone
NF TV
Tablet
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Percentage of total responses
Office Work
Games
Social Network
Movies/TV
E-mail
Web browse
E-books
E-mags
News
Other
Task

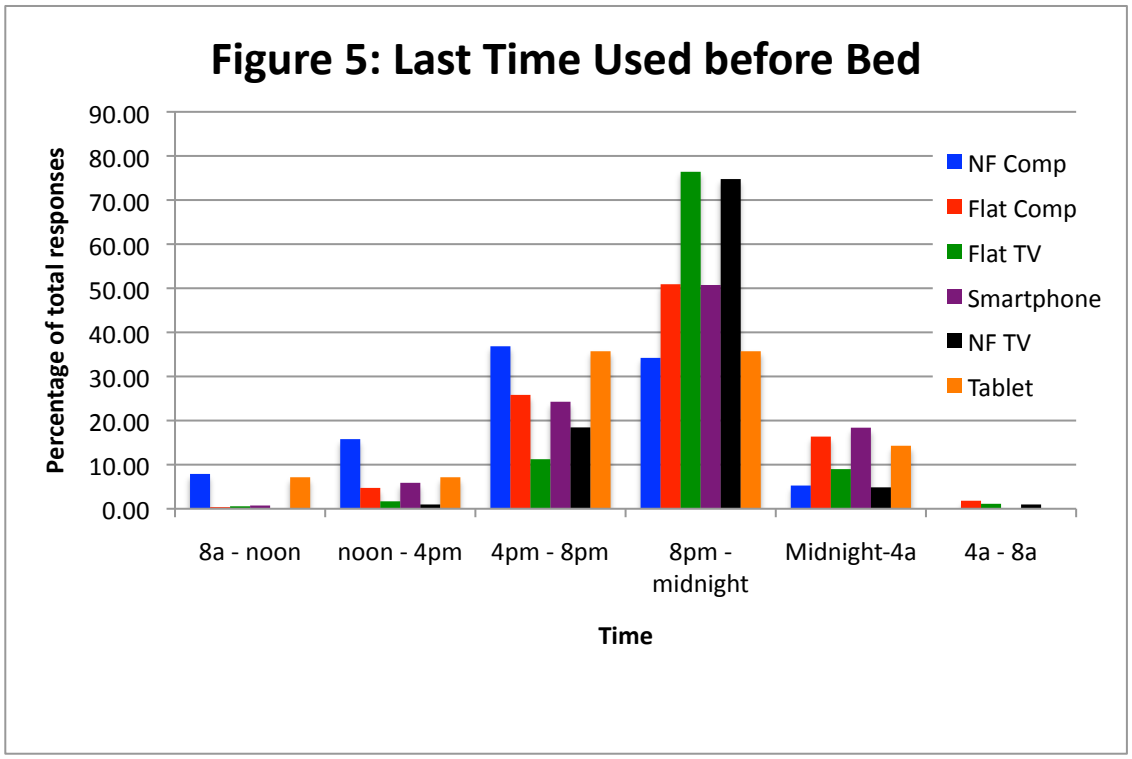


Figure 5: Last Time Used before Bed
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Percentage of total responses
NF Comp
Flat Comp
Flat TV
Smartphone
NF TV
Tablet
8a - noon
noon - 4pm
4pm - 8pm
8pm - midnight
Midnight-4a
4a - 8a
Time

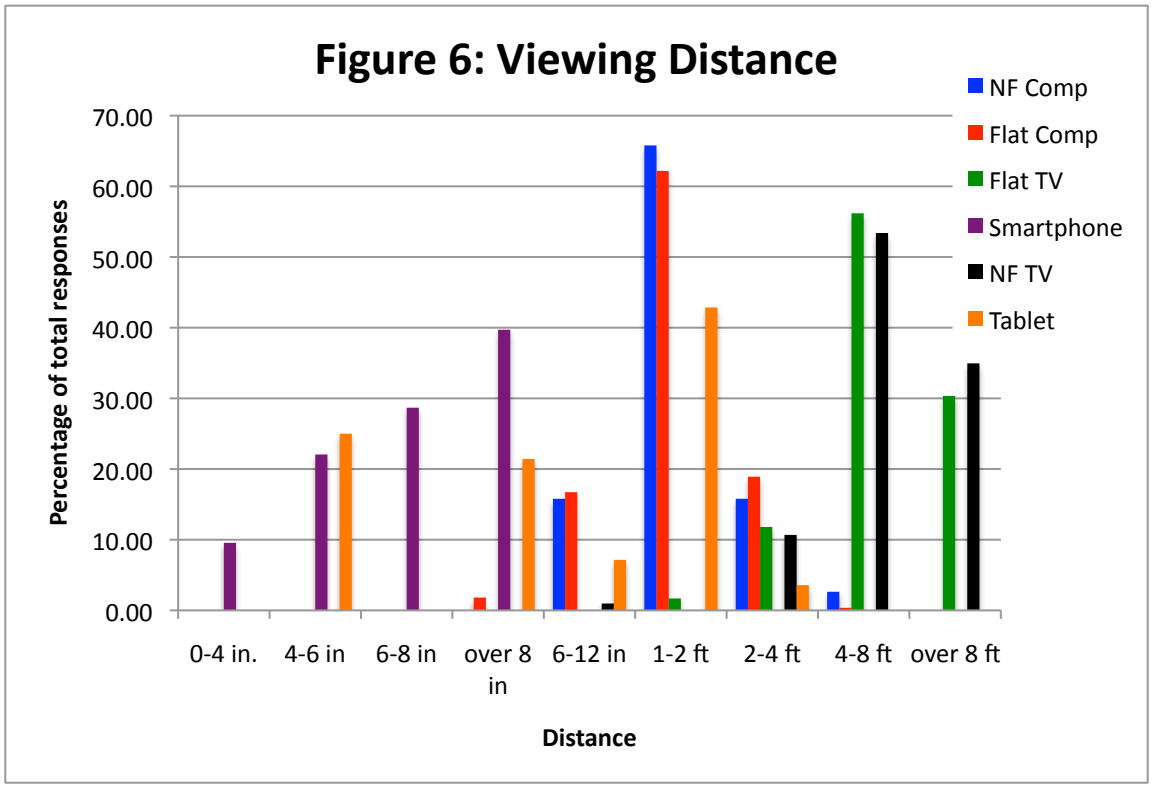
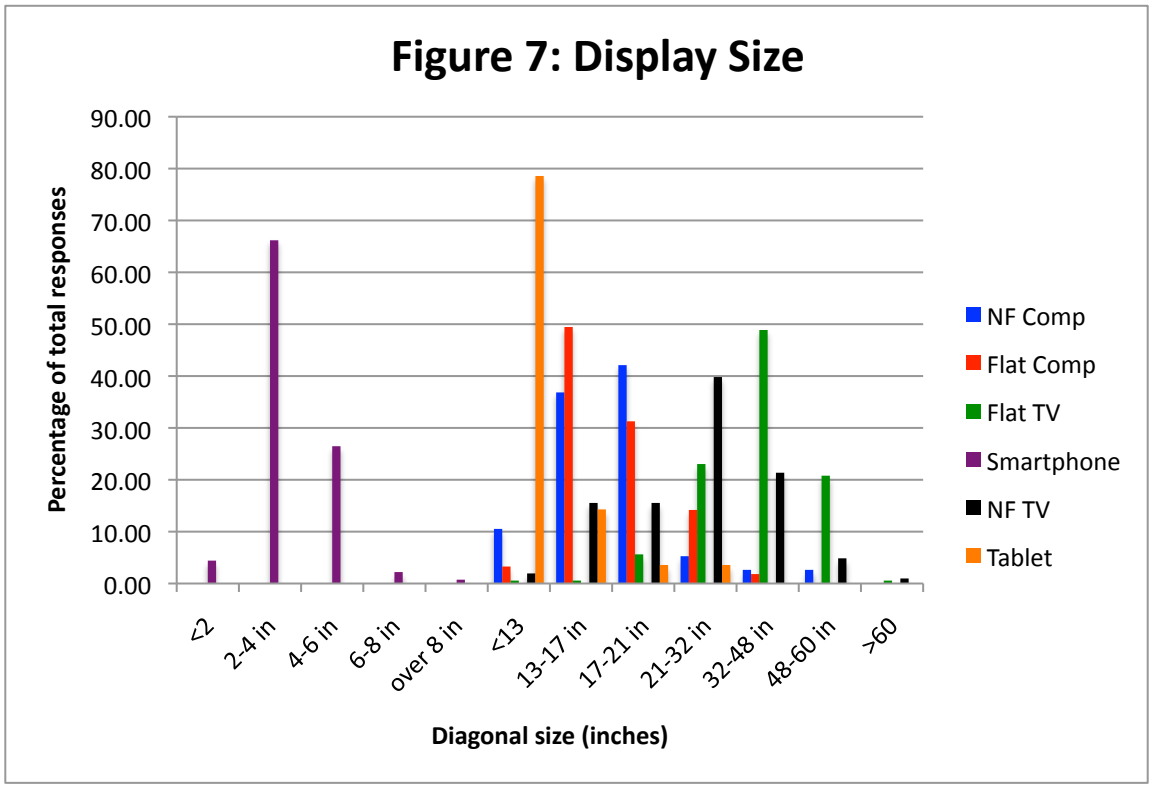


Figure 6: Viewing Distance
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Percentage of total responses
NF Comp
Flat Comp
Flat TV
Smartphone
NF TV
Tablet
0-4 in.
4-6 in
6-8 in
over 8 in
6-12 in
1-2 ft
2-4 ft
4-8 ft
over 8 ft
Distance



8.2 Appendix B – Self-luminous Display Measurements

Table 1: **Device settings for measurement.**

Brightness	RGB
Standard	Standard
Full brightness	Standard
Full brightness	Full blue
Full brightness	No blue

Table 2: **Viewing distance for various device types.**

Device type	Distance (inches)
Television	72
Computer	16
Tablet	10
Cell phone	6

Table 3: **Summary of the devices measured.**

Manufacturer	Device type	Diagonal size (inches)
Sanyo	Television	50
Sharp-42	Television	42
Vizio	Television	32
Apple iMac	Computer	21.50
Dell	Computer	15.38
Toshiba	Computer	15.63
Gateway	Computer	15.63
Archos	Tablet	10.10
Asus	Tablet	10.10
Apple iPad	Tablet	10.10
iPhone 4 w/screen protector	Cell phone	3.50
LG	Cell phone	3.25
iPhone 3GS	Cell phone	3.50

Table 4: **Display luminance measurements (cd/m^2).**

Manufacturer	Standard		Full brightness	
	Black	**White**	**Black**	**White**
Sanyo	0.07	21.18	3.30	21.69
Sharp-42	0.03	85.02	0.44	147.20
Vizio	0.04	10.7	0.43	52.65
Apple iMac	0.35	334.1	0.35	334.10
Dell	12.03	125.9	12.03	125.90
Toshiba	3.18	22.74	3.18	22.74
Gateway	2.64	38.83	2.64	38.83
Archos	1.32	27.19	2.55	77.32
Asus	0.07	10.02	1.06	74.59
iPad	0.07	19.27	0.55	112.60
iPhone 4 (w/screen protector)	0.01	11.24	1.00	90.22
LG	0.31	59.41	0.65	118.00
iPhone 3GS	0.06	0.89	3.40	61.34

Table 5: Sharp 70-inch television data when set to full brightness

Distance	Color Temperature (K)	Illuminance (lux)		CLa		CS	
		Black	White	Black	White	Black	White
6 ft	12000	0.107	82.6	0	196.63	0	0.24
	6500	0.098	81.5	0.33	119.84	0.0003	0.16
	2700	0.048	32.07	0.18	42.93	0.0001	0.06
9 ft	12000	0.051	44.4	0	112.75	0	0.15
	6500	0.048	41.4	0.18	72.86	0.0001	0.10
	2700	0.021	16.28	0.06	25.77	0.00005	0.04
11.5 ft	12000	0.034	28.93	0	73.36	0	0.10
	6500	0.032	26.95	0.17	47.34	0.0001	0.07
	2700	0.014	10.64	0.06	16.84	0.00004	0.02

Table 6: iPad data when set to full brightness

Distance	Illuminance (lux)		CLa		CS	
	Black	White	Black	White	Black	White
10 inches	0.32	40.3	1.61	60.95	0.0018	0.09
16 inches	0.08	16.67	0.42	31.06	0.0004	0.04
24 inches	0.04	7.65	0.28	21.95	0.0002	0.03