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Light level and duration of exposure determine the impact of self-luminous tablets on melatonin suppression

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ABSTRACT

Exposure to light from self-luminous displays may be linked to increased risk for sleep disorders because these devices emit optical radiation at short wavelengths, close to the peak sensitivity of melatonin suppression. Thirteen participants experienced three experimental conditions in a within-subjects design to investigate the impact of self-luminous tablet displays on nocturnal melatonin suppression: 1) tablets-only set to the highest brightness, 2) tablets viewed through clear-lens goggles equipped with blue light-emitting diodes that provided 40 lux of 470-nm light at the cornea, and 3) tablets viewed through orange-tinted glasses (dark control; optical radiation <525 nm ≈ 0). Melatonin suppressions after 1-h and 2-h exposures to tablets viewed with the blue light were significantly greater than zero. Suppression levels after 1-h exposure to the tablets-only were not statistically different than zero; however, this difference reached significance after 2 h. Based on these results, display manufacturers can determine how their products will affect melatonin levels and use model predictions to tune the spectral power distribution of self-luminous devices to increase or to decrease stimulation to the circadian system.

1. Background

Melatonin is a hormone produced by the pineal gland at night and under conditions of darkness in both diurnal and nocturnal species. It is a timing messenger, signaling nighttime information throughout the body. Exposure to light at night can retard or even cease nocturnal melatonin production. Short-wavelength light is maximally effective at suppressing melatonin (peak sensitivity ≈ 460 nm). Suppression of melatonin by light at night has been implicated in disruption of sleep, increased risk for obesity, as well as increased risk for more serious diseases, such as breast cancer (Blask et al., 1999).

Technological developments have led to bigger and brighter self-luminous electronic devices, such as televisions, computer screens, and cell phones. Some have suggested that light at night from electronic devices can suppress nocturnal melatonin (Figueiro et al., 2011; Cajochen et al., 2011), which may disrupt sleep or pose a health risk. To produce white light, these electronic devices must emit light at short wavelengths, which makes them potential sources for suppressing melatonin at night or for delaying the onset of melatonin in the evening, thereby possibly reducing sleep duration and disrupting sleep. This is particularly worrisome in populations such a young adults and adolescents, who already tend to be more “night owls”.

For example, Cajochen et al. (2011) showed that a 5-h exposure to a (white) light-emitting diode (LED) backlit computer screen significantly suppressed melatonin and enhanced performance compared to a non-LED backlit screen. Their results showed that although melatonin levels were still rising over the course of the night, they did not rise as steeply as when subjects remained in darkness.

Using a similar protocol as the one employed in the present study, Figueiro et al. (2011) showed that a 2-h exposure to light from cathode ray tube computer screens induced a slight, but not statistically significant reduction in melatonin concentrations in college students. The present study extends the findings from this previous study by investigating the impact of self-luminous tablets on melatonin suppression. In order to simulate typical usage of these devices (Apple iPads), participants were allowed to choose their preferred tasks on the tablets (e.g., games, on-line shopping, reading, etc.). The Dimesimeter (Figueiro et al., in press), a circadian light meter developed to measure photopic and circadian light, was used to record personal light exposures during the experiment. These data were used in conjunction with the model of human circadian phototransduction proposed by Rea and colleagues to calculate photopic illuminance (lux), circadian light (CL_A), and circadian stimulus (CS) levels (Rea et al., 2005, 2010, 2011). Comparisons of actual and predicted melatonin suppression were performed.

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2. Methods

2.1. Subjects

Thirteen subjects were recruited to participate in the study by e-mail, web posting, and word-of-mouth. The mean ± standard deviation (SD) age of the subjects was 18.9 ± 5.2 years. Individuals were excluded from participation if they smoked or had a major health problem such as heart disease, diabetes, and high blood pressure. Individuals were also excluded if they were taking over-the-counter melatonin or prescription medication such as blood pressure medication, antidepressants, beta-blockers, or sleep medicine. Women taking oral contraception 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 et al., 2003). This screening method helped ensure that the subjects would produce melatonin between the hours of 23:00 and 01:00, the period of data collection. The mean ± SD MCTQ score of the subjects was 3.5 ± 1.3.

2.2. Lighting conditions

During the experiment, the three lighting conditions were provided in the same test room. In one condition, subjects viewed their tablets through a pair of clear goggles fitted with short-wavelength (blue) LEDs. The goggles were calibrated to deliver 40 lux (40 μW/cm^2) of blue light ($\lambda_{max} \approx$ 470-nm) at the cornea of each participant (Fig. 1). Two LEDs were mounted to each lens; one was located above and one was located below a line of sight through the center of each goggle lens. To minimize discomfort glare and blue-light hazard (Bullough, 2000), polycarbonate translucent tape diffused the light emitted by the LEDs. Before each experimental session, the goggles were calibrated using an optical fiber with a Lambertian diffuser on one end. The irradiances of the left and right lens were measured independently and, if necessary, the voltage from a 9 V battery was adjusted so that a mean illuminance of 40 lux at the corneas was achieved. This light level was selected because in previous studies, it has been shown to deliver a light stimulus that is predicted to be above threshold and below saturation (Rea et al., 2005). Based upon these previous findings, the tablet with the blue LEDs condition served as a "true-positive" condition for the present experiment.

The second experimental condition involved viewing the tablets through orange-tinted glasses. These glasses (SAF-T-CURE® Orange UV Filter, Chicago IL) filtered out optical radiation below 525 nm (Fig. 1). The tablet with the orange-tinted glasses served as the "dark" control condition because the short-wavelength radiation capable of suppressing melatonin was filtered out (Rea et al., 2005, 2011).

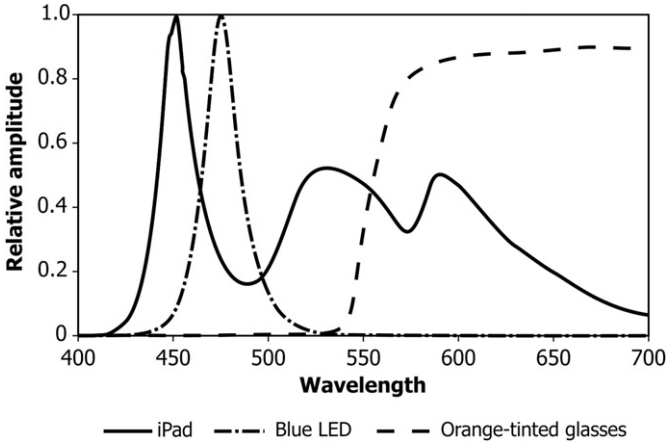

Fig. 1. Spectral transmittance of the orange-tinted glasses, the relative spectral power distribution (SPD) of a 470-nm (blue) LED, and the relative SPD of an iPad 1 (white screen, full brightness) used in the experiment.

The third condition was the tablet-only experimental condition; the relative spectral power distribution (SPD) of an exemplar tablet is shown in Fig. 1 as measured with an Ocean Optic USB 650 spectroradiometer (Dunedin FL). During all three conditions, the tablets were set to full brightness. The only additional lighting in the room was from two red lights located behind the subjects (<1 lux at the cornea). No measurable stray light from the blue-light goggles reached the other subjects' eyes. All the participants were seated facing the same direction and the subjects wearing the goggles with the blue LEDs sat in front of all the other participants.

2.2.1. Tablet displays

Each participant used an Apple iPad; two subjects used the first generation (iPad 1) and the others used the second generation (iPad 2). The display of the iPad is approximately 9.7 inches diagonally and is backlit with LEDs. The screen resolution is 1024 × 728 pixels at 132 pixels per inch (Apple Inc., 2012). Each iPad was viewed while set to full brightness. Measurements from a calibrated illuminance meter (Gigahertz-Optik, X91, Turkenfeld, Germany) obtained prior to the experiment revealed that, with an all-white background at a 10-inch viewing distance, the iPads could deliver 40 lux at the corneas.

2.2.2. Dimesimeter measurements

In order to accurately record personal light exposures during the experiment, each subject wore a Dimesimeter close to the plane of the cornea. The Dimesimeter is a small (~ 2 cm diameter) measurement instrument that continuously records light [via red (R), green (G), and blue (B) sensors] and activity levels (Figueiro et al., in press). A Dimesimeter was worn on a headband by subjects during the tablet-only condition. Similarly, it was clipped to the temple of the goggles for the condition where the blue LEDs were energized. The Dimesimeter was mounted behind the bridge of the orange-tinted glasses, just above the nosepiece, for the third, control condition. During the experiment, data were logged every 30 s from 23:00 to 01:00. The RGB light data from the Dimesimeters were downloaded and stored on a computer following each experimental session. After downloading, the raw measurements from the RGB sensors were converted into photopic illuminance (lux), circadian light (CLA), and circadian stimulus (CS) levels. (Rea et al., 2005, 2010, 2011). Concisely, photopic illuminance is irradiance transformed by the photopic luminous efficiency function (V(λ)), providing an orthodox measure of the spectral sensitivity of the human fovea. CLA, based on nocturnal melatonin suppression, is irradiance weighted by the spectral sensitivity of the retinal phototransduction mechanisms stimulating the biological clock. CS is a transform of CLA into relative units from 0, the threshold for circadian system activation, to 0.7, response saturation, and corresponds to relative suppression of nocturnal melatonin after one hour of light exposure for a 2.3 mm diameter pupil during the midpoint of melatonin production.

2.2.3. Protocol

All thirteen participants experienced the three experimental sessions, each one week apart. They were asked to maintain a regular sleep schedule for the week prior to each session, requiring them to go to bed no later than 23:00 and wake up no later than 07:30. In order to verify compliance with the sleep schedule, all thirteen subjects were asked to keep sleep logs the week of the experiment. Seven of the subjects were also asked to call into the lab at 07:30 and 08:30 each day to ensure they were awake. Six of the subjects attend high school at the same time each day, 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. In order to counterbalance the lighting conditions, subjects were randomly assigned to one of three groups. During the experiment, all three groups were seated in the same room and by the end of the three weeks all subjects had been exposed to all three lighting conditions.

On the day of the experiment (Friday nights), subjects arrived at the laboratory at 22:30 and spent the first 30 min in dim red light (less than 1 lux at the cornea from two red LED traffic lights, $\lambda_{max} = 630$ nm). At 23:00, the first saliva sample was collected while the subjects remained in the dim light. Saliva samples were collected using the salivette system (SciMart, Saint Louis MO). To provide a saliva sample, subjects were asked 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 without touching it with their hands. The experimenter then collected the sample and centrifuged it for 5 min at 3000 g to remove the saliva from the cotton. The cotton was discarded and saliva immediately frozen (−20 °C).

After the subjects were done with their first saliva sample collection, they were asked to turn on their tablets and start using them. From 23:00 to 01:00 the subjects were allowed to engage in whatever task they chose on their tablets; viewing position and distance were not controlled. Saliva samples were collected after 1 h (at 00:00) and 2 h (at 01:00) of tablet use.

3. Data Analyses

Saliva samples were later assayed by radioimmunoassay using a commercially available kit from Labor Diagnostika Nord (Nordhorn, Germany). The limit of detection was 0.9 pg/mL and the intra- and inter-assay coefficients of variability were determined to be 11.4 and 12.7%, respectively.

Adjusted dark values (A) were calculated for each subject to account for their natural rise in melatonin level concentrations (C) while in the dark and for differences in the initial melatonin concentrations week-to-week. Melatonin concentrations obtained from each subject during the tablet with the orange-tinted glasses condition (D) were used for the adjusted dark values. Melatonin suppression was calculated for both lighting conditions (L_1 = tablet-only and L_2 = tablet with blue LEDs) using the adjusted dark value at the same sampling time (T_n). The adjusted dark value (A) for a given lighting condition (L_m) and sampling time (T_n) is given by:

$$A = (C_{T1,Lm}/C_{T1,D})C_{Tn,D} \quad (1)$$

Where: C = melatonin concentration (pg/ml)

T = sampling time, n = 1,2,3
1 = 23:00; 2 = 00:00 and 3 = 01:00
L = lighting condition, m = 1,2
1 = tablet-only; 2 = tablet with blue LEDs
D = tablet with orange-tinted glasses

$$\text{Melatonin suppression}(S) = 1 - [C_{Tn,Lm}/A] \quad (2)$$

4. Results

4.1. Light measurements

Table 1 shows the mean ± standard error of the means (SEM) light measurement, CL_A, and CS values from the Dimesimeter. In addition, luminance measurements were made during the experiment. Luminance values from the subjects' devices ranged from 1.4 to 184 cd/m^2. Mean [median] ± SEM luminance values were 77 [73] ± 66 cd/m^2.

Table 1
Lighting conditions (photopic illuminance in lux and CL_A measured with the Dimesimeter), predicted melatonin suppression (CS) and measured melatonin suppression after 1-h and 2-h exposures. Mean ± standard error of the mean (SEM) values are shown.

		Photopic illuminance (lux)	CL_A	CS[b]	Measured suppression (%)
1 h	Tablet + blue LEDs	59 ± 5.0	648 ± 4.9	0.46 ± 0.0013	48 ± 4
	Tablet + orange-tinted glasses[a]	9.8 ± 1.9	1.5 ± 0.31	0.0017 ± 0.0004	NA
	Tablet-only	18 ± 3. 8	19 ± 4.6	0.03 ± 0.0066	7.0 ± 4
2 h	Tablet + blue LEDs	57 ± 3.8	645 ± 3.4	NA	66 ± 4
	Tablet + orange-tinted glasses[a]	9.9 ± 1.6	1.5 ± 0.29	NA	NA
	Tablet-only	16 ± 2.7	17 ± 3.51	NA	23 ± 6

NA: not applicable.
[a] The tablet with the orange-tinted glasses condition was used as the dark control.
[b] Based upon a 1-hr duration of light exposure and a 2.3 mm pupil diameter.

Based on the CL_A measurements with the Dimesimeter and assuming a reference pupil diameter of 2.3 mm, the calculated mean ± SEM CS values after 1-h exposures were 0.46 ± 0.0013 for the tablet with blue LEDs condition and 0.03 ± 0.0066 for the tablet-only condition. These CS values translate into a predicted suppression of approximately 46 and 3% for the tablet with the blue LEDs and the tablet only conditions, respectively. No predictions were made for the 2-h exposures data because the model by Rea and colleagues assumes a 1-h exposure (Rea et al., 2005). It had been assumed that the tablet with the orange-tinted glasses would not produce exposures necessary for suppression. Indeed, using the measured CL_A values and a 2.3 mm diameter pupil, the calculated mean ± SEM CS value was 0.0017 ± 0.0004.

4.2. Melatonin

Although thirteen subjects completed the experiment, two subjects did not provide a sufficient quantity of saliva for assay at the 00:00 sampling time and one subject did not provide a sample at 01:00. Thus, two subjects were omitted from the 1-h analysis ($n = 11$) and one subject was omitted from the 2-h analysis ($n = 12$).

Table 1 and Fig. 2 show the mean ± SEM suppression values for the tablet-only and for the tablet with blue LEDs conditions at 00:00 and at 01:00. Two-tailed, One-Sample t-tests were used to determine statistical reliability. For the tablet with blue LEDs condition, suppression values were significantly different than zero at 00:00 ($t(10) = 15.0$, $p < 0.001$) and at 01:00 ($t(11) = 16.1$, $p < 0.001$). The mean ± SEM suppression after 1-hr exposure to the tablet with blue LEDs condition was 48% ± 4%, very close to the predicted values, which was 46%. For the tablet-only condition, suppression was not significantly different than zero after 1-h exposure ($t(10) = 1.80$, $p = 0.103$) to the tablet, but was significantly greater than zero after 2 h of exposure ($t(11) = 3.39$, $p = 0.006$). Suppression after 1-h exposure to the tablet only condition was 7% ± 4%, again, very close to the model predictions, which was 3%.

5. Discussions

The present study extends results from Figueiro et al. (2011) showing that a 2-h exposure to self-luminous tablets can result in a measurable, statistically reliable suppression of melatonin in

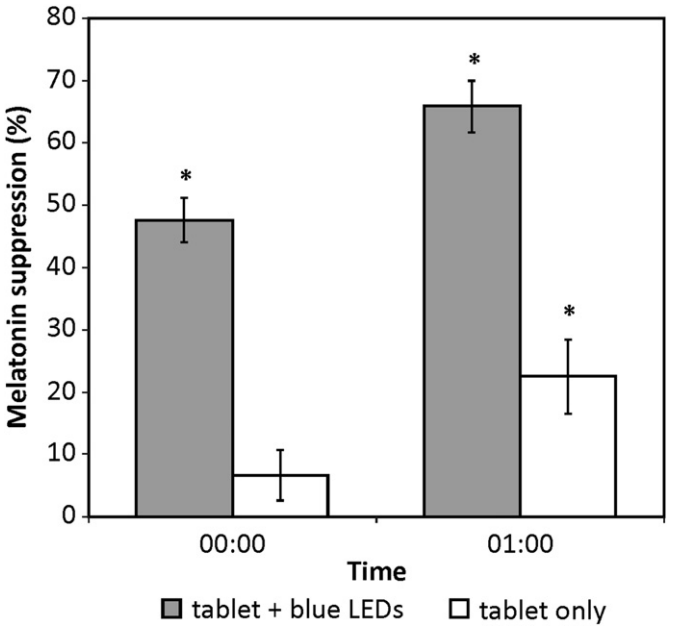

Fig. 2. Mean ± SEM suppression values for the tablet-only and for the tablet with blue LEDs at 00:00 and at 01:00. Suppression after 1-h exposure to the tablet-only condition was not significantly different than zero; all other suppression values (marked with asterisks) were significantly greater than zero ($p < 0.05$). The orange-tinted glasses condition served as the "dark" control condition.

a population of young adults. It should be pointed out that, as predicted by the model of human circadian phototransduction, 1-h exposures to the tablet-only condition at full brightness resulted in a level of melatonin suppression close to that which was predicted (i.e., the CS values); however, this level of suppression was not statistically different than zero. After 2 h of exposure to the tablet-only condition, melatonin suppression was statistically different than zero. Therefore, it is important to have quantitative estimates of both the SPD (level and spectrum) and the duration of exposure before drawing reliable inferences about the ability of self-luminous tablets to induce nocturnal melatonin suppression. Moreover, the type of task being performed on the tablets will also determine how much light the self-luminous devices are delivering at the cornea and, therefore, its impact on evening melatonin levels. As shown by our Dimesimeter measurements, the range of photopic illuminance levels at the cornea from the tablets alone varied from 5 lux, which is likely not affecting melatonin levels, to over 50 lux, which as shown in the present study, will result in measurable melatonin suppression after a 2-h exposure.

Since the predictions of acute melatonin suppression based upon the measured circadian light levels and the model by Rea and colleagues (Rea et al., 2005, 2010, 2011) were very close to the observed suppression levels after 1 h, manufacturers may now be able to design self-luminous display screens that can either increase (e.g., desirable during morning hours) or decrease (e.g., desirable during evening hours) circadian stimulation. Further, it might be possible to develop software to control circadian light exposures based upon the SPD of the display together with the time and the hours of operation, with the purpose of limiting melatonin suppression in the evening. The present results may be a positive step toward the development of more "circadian-friendly" electronic devices. Even if new technologies (e.g., organic light emitting diodes, OLEDs) are used in the development of self-luminous electronic devices, these results are still relevant because we showed that the model is useful in predicting the effectiveness of these devices on melatonin suppression after 1-h exposure. In other words, as long as the spectral irradiance distribution at the cornea from a self-luminous technology is known, one can predict its impact on melatonin suppression after 1 h of viewing (Rea et al., 2010). Since a large portion of the population spends most of their waking hours in front of a self-luminous display, it is important that manufactures and users have a tool to increase or to decrease circadian stimulation delivered by their self-luminous displays.

However, it is also important to consider how and how long these devices are used. Large self-luminous displays (e.g., flat-screen televisions) or ones that are operated close to the eyes (e.g., cell phones) would be expected to provide relatively high circadian stimulation. For example, Shieh and Lee (2007) showed that the preferred viewing distance for E-paper was 500 mm, which is similar to the preferred viewing distance for visual display terminals. These distances are certainly much closer than those of television viewing. Currently, the model of human circadian phototransduction by Rea and colleagues only takes into account the absolute SPD of the light source. Variables such as duration of exposure and spatial distribution also need to be added to the model to improve its ability to predict the impact of self-luminous displays on acute melatonin suppression.

Finally, it is important to acknowledge that usage of self-luminous electronic devices before sleep may disrupt sleep even if melatonin is not suppressed. Clearly, the tasks themselves may be alerting or stressful stimuli that can lead to sleep disruption. For now, however, it is recommended that these devices be dimmed at night as much as possible in order to minimize melatonin suppression, and that the duration of use be limited prior to bedtimes.

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