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Smartphone Use at Night Affects Melatonin Secretion, Body Temperature, and Heart Rate

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Abstract

In the present study, we investigated the physiological effects of smartphone use at night when the display luminance and white balance were differently manipulated. Two levels of luminance and two types of white balance were combined to form four types of displays. Subjects were instructed to use smartphones between 23:00 to 01:00 twice a week for two weeks, and for each trial, subjects were given one of the four display types. Melatonin concentration in the saliva, body temperature and heart rate were measured before and after each experiment. The experimental result showed that the low luminance display supported melatonin secretion and thermoregulation compared to the high luminance display. With regard to the white balance, higher melatonin level was observed when using the display that filtered blue light. The low luminance display together with yellowish tint best supported restful sleep at night in terms of every physiological response. This study collectively demonstrates that bright and blue light emitted from smartphone displays adversely affect melatonin secretion, body temperature, and heart rate, and therefore, suggests the use of a display with low luminance or a display that filters blue light for a restful sleep at night.

Key words: Optimal Display, Smartphone, Display Luminance, White Balance

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1. Introduction

Advances in display technology have increased the development of diverse kinds of visual display terminals (VDTs) such as televisions, computers, tablet PCs, and eBooks. Above all, smartphones have been particularly widespread in recent years due to portability and multi-functionality. The average amount of time that people spend using their smartphones is more than three hours a day, and that time is concentrated at nighttime before sleeping (Bulck, 2007; Sale et al., 2014). However, the light emitted from smartphone displays has been shown to give rise to an adverse health effect on users, and this problem becomes far more serious at nighttime (Lanaj et al., 2014; Benedetto et al., 2014; Chen et al., 2012). Exposure to bright light at night might cause visual discomfort but also hinder people's ability to fall asleep easily or comfortably because of the suppression of nocturnal melatonin secretion (LeMwy et al., 1980; Figueiro, 2013; Ou et al., 2015; Lambooij et al., 2009).

Melatonin is a hormone secreted by darkness, thus usually at night, by the pineal gland in the brain (Garfinkel et al., 1995; Dubocovich, 1983). The light-dark perception is transmitted from the eyes via the retinohypothalamic tract (RHT) to the suprachiasmatic nuclei (SCN). A neural pathway extends from the SCN to the pineal gland for the regulation of melatonin secretion (Brainard et al., 2001). In virtually all species, melatonin secretion is high during the night and low during the daytime. Hence, light exposure is known to be the primary suppressor of melatonin, as well as an entrainment cue for circadian rhythms.

Melatonin secretion is affected by several dimensions of light, such as timing, intensity, and duration of light exposure (Wright & Lack, 2001). Ferracioli-Oda's research team (2013) demonstrated that melatonin decreases sleep onset latency, increases total sleep time and improves overall sleep quality. Consequently, great attention has been given to uncovering the effect of smartphone use on the user's physiological responses. A recent study revealed that evening use of a light-emitting device negatively affects sleep and the circadian clock (Chang et al., 2015). Higuchi's research team (2003) examined how bright displays and exciting tasks induce suppression of nocturnal melatonin secretion. Na and her colleagues (2014) investigated the optimal display luminance for comfortable use of the smartphone in dark environment.

However, recent studies have indicated that the melatonin regulation system does not simply count or average photons, but rather is dependent on exposure to particular wavelengths of visible light (Cajochen et al., 2005; Lockley et al., 2003). As one of the earliest studies of the effect of light wavelength, Brainard (2001) revealed that 505 nm light is significantly stronger than an equal photon does at 555 nm for suppressing melatonin secretion. In support of this notion, Thapan and his colleagues (2001) observed that the spectral sensitivity of melatonin suppression was maximum in short wavelengths that are very different from the classical photopic and scotopic visual systems. Hatori and Panda (2010) have shown the 460-500 nm portion of the spectrum, which lies in the blue/cyan range of the visible light, as the most potent wavelengths regulating melatonin secretion. Such blue-shift in sensitivity to the visible light provided strong evidence that the rod and cone cells are not the primary photoreceptor system for melatonin regulation, suggesting that there is a novel melanopsin-containing retinal ganglion cells in the human retina (Berson et al., 2002). Consistent with these findings, Oh (2015) recently reported the harmful effect of blue light from smartphones on circadian rhythm and health. Also, Wood's team (2013) investigated the impact of white balance of self-luminous tablet displays on nocturnal melatonin suppression.

Earlier studies achieved great discoveries on the physiological effect of smartphone displays on the human body; however, the interactive effect of display luminance and white balance has not been studied yet. In the current study, we investigated the physiological effect of

smartphone use at night in human when the display luminance and white balance are differently articulated. We attempted to propose an appropriate display setting for maintaining a regular circadian rhythm. Salivary melatonin concentration and body temperature were measured before and after each experiment, since they have been used as a marker of circadian rhythm regulation in other studies (Czeisler et al., 1980; Leichtfried et al., 2015). Heart rate was also recorded to observe the activity levels of the central nervous system (Higuchi et al., 2003; Waldeck & Lambert, 2003). We hypothesized that use of the display with low luminance and yellowish nuanced white supports higher melatonin concentration, decreases in body temperature and heart rate.

2. Method

2.1. Subjects

A group of sixteen people comprised of eight males and eight females was recruited for the experiment. The average age of the subjects was 22.1 years with a standard deviation of 3.0 years, and all of them had normal vision or corrected-to-normal vision. Individuals with any major health problems, sleep disorders, or those taking medicine regularly were excluded from the study. All subjects signed an informed consent form prior to the experiment, and the protocol was approved by the Institutional Review Board, KAIST (approval number: KH2014-34). All experiments were performed in accordance with relevant guidelines and regulations of Institutional Review Board of KAIST.

2.2. Stimuli

Two levels of display luminance and two types of white balance were employed. Firstly, for the display-luminance variations, the high luminance was set at 400 cd/m^2, as this is the maximum luminance of most smartphones. For low luminance, 40 cd/m^2 was applied, since it was the most preferred luminance for nighttime smartphone use based on the previous study (Na and Suk, 2014). With regard to the display white balance, it varied between a pure white and yellowish nuanced white. A pure white was reproduced when all R, G, and B channels were set at maximum (i.e., 255, 255, and 255). The alternative white tinged with yellow was set with the RGB values of 255, 255, and 200, which filtered blue light while not distorting the perceived quality of display color (Na & Suk, 2016). In total, four types of display stimuli (two levels of luminance and two types of white balance) were created and labeled as follows: high luminance and pure white (HW), high luminance and white tinged with yellow (HY), low luminance and pure white (LW), and low luminance and white tinged with yellow (LY). All the stimuli were displayed on a smartphone with a 5.1-inch Super AMOLED display (Samsung Galaxy S6, Seoul, Korea).

2.3. Procedure

The subjects were instructed to maintain regular sleep-wake cycles for a week before the experiment. They were required to go to bed between 23:00 and 00:00 and to wake up between 07:00 and 08:00. Subjects sent text messages at both bedtime and wake time every day in order for the examiner to monitor their sleep schedule. Moreover, the subjects were asked to avoid consuming medicine, alcohol, nicotine, and any foods or drinks containing caffeine during this period.

Each experimental session was carried out from 23:00 to 01:00 at their own home, and the subjects were asked to refrain from using personal VDTs for two hours before the experiment and to sleep immediately after the end of the experiment. From the subject's position, the measured illuminance was less than 1 lx if the smartphone was completely off. During the experiment, they were required to engage in the tasks during two

hours in order of watching videos for 20 minutes, reading books for 40 minutes, and Web browsing for an hour on the smartphone. The given tasks were same for every subject. The American show 'Modern Family', 'Nudge' written by Richard H. Thaler and Cass R. Sunstein, and Korean website 'Naver new' were provided as videos, books and website stimuli, respectively. Viewing position was not strictly controlled, but they were advised to view the smartphone from about 30 cm away, a typical viewing distance of a smartphone display (Li et al., 2015). As there were four types of display stimuli, a total of four experimental sessions were arranged for each subject. The experiment lasted for two weeks, and the interval between sessions was at least three days. All sixteen subjects participated in whole sessions, and the four types of display stimuli were provided in random order.

2.4. Measurement of melatonin in the saliva

Saliva samples were collected by using cotton wool and a plastic tube at 23:00 (before the experiment), 01:00 (after the experiment), and 09:00 the next day. The melatonin concentration was analyzed by enzyme immunoassay using a commercially available ELISA kit (Salimetrics, State College, PA, USA). The inter- and intra-assay coefficients of variation were 7.4 % and 2.6 %, respectively, and the kit sensitivity was 1.37 pg/ml. Body temperature and heart rate were also measured by infrared ear thermometer and sphygmomanometer, respectively.

3. Results

For analysis, the melatonin concentrations, body temperatures, and heart rates were averaged at 23:00, 01:00, and 09:00 the next day. Three subjects with insufficient saliva sample were excluded from the analysis. For the remaining thirteen subjects, the Shapiro-Wilk test was used to test for normality. Among 36 sets of data (3 measurements × 4 display stimuli × 3 time points), 24 sets of data were normally distributed ($p > .05$). Hence, a paired sample t-test (two-tailed) was performed to examine the effect of display luminance and white balance on melatonin concentration between 23:00 and 01:00. The results indicated that the melatonin concentration at 01:00 increased in HY ($t(12) = -2.226$, $p = 0.046$, Cohen's $d = 0.618$), LW ($t(12) = -2.648$, $p = 0.021$, Cohen's $d = 0.734$), and LY condition ($t(12) = -2.907$, $p = 0.013$, Cohen's $d = 0.806$). However, there was no significant difference observed in HW condition ($t(12) = -2.130$, $p = 0.055$, Cohen's $d = 0.591$), indicating that the high luminance and pure white display stimulus suppresses nocturnal melatonin secretion compared to the low luminance or yellow-tinged display stimuli. There was no difference in melatonin concentration between 23:00 and 09:00 the next day except for LW condition ($t(12) = -2.344$, $p = 0.037$, Cohen's $d = 0.650$).

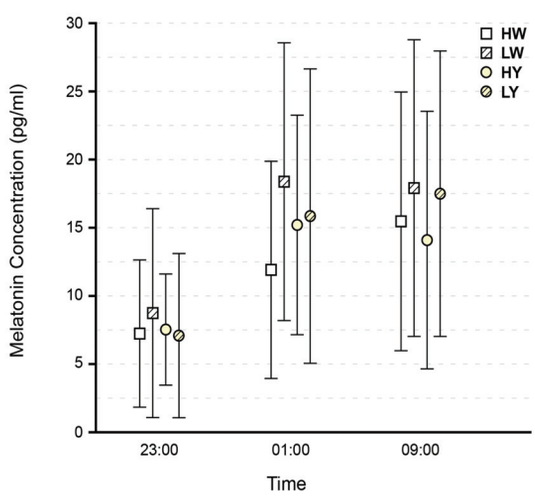

Fig. 1. The mean melatonin concentration at 23:00, 01:00, and 09:00 the next day for the four display stimuli with 95% confidence intervals

The mean body temperatures measured at 23:00, 01:00, and 09:00 the next day are shown in Fig. 2. A paired samples t-test confirmed the statistically significant decrease in body temperature at 01:00 compared to 23:00 in low luminance conditions (LW: $t(12) = 3.742$, $p = 0.003$, Cohen's $d = 1.038$; LY: $t(12) = 2.891$, $p = 0.014$,

Cohen's $d = 0.802$). In high luminance conditions, however, the body temperature did not decrease (HW: $t(12) = 1.802$, $p = 0.097$, Cohen's $d = 0.500$; HY: $t(12) = 1.336$, $p = 0.206$, Cohen's $d = 0.371$). The body temperature decreased at 09:00 the next day in all conditions ($p < .05$). The results indicated that the high luminance displays adversely affect thermoregulation at night.

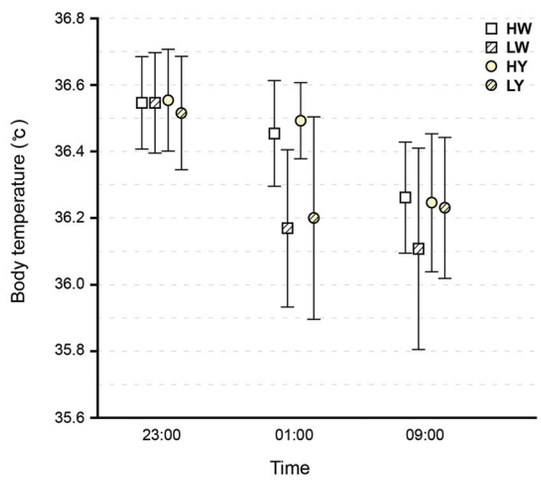

Fig. 2. The mean body temperature at 23:00, 01:00, and 09:00 the next day for the four display stimuli with 95% confidence intervals

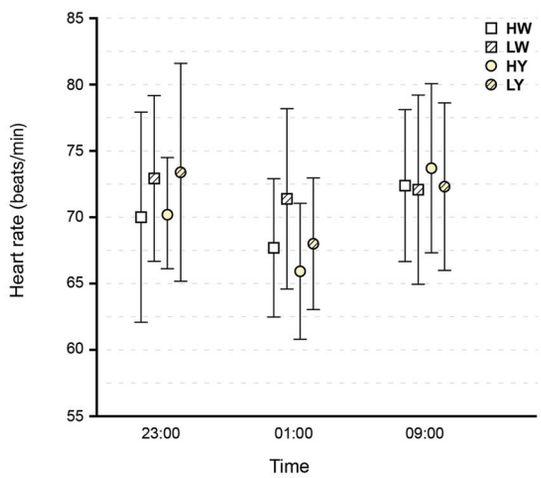

Fig. 3. The mean body temperature at 23:00, 01:00, and 09:00 the next day for the four display stimuli with 95% confidence intervals

Regarding the heart rate, a paired samples t-test indicated that the heart rate decreased at 01:00 compared to 23:00 in LY condition ($t(12) = 2.266$, $p = 0.043$, Cohen's $d = 0.628$), whereas no significant difference was observed in high luminance or pure white displays (HW: $t(12) = 0.981$, $p = 0.346$, Cohen's $d = 0.272$; HY: $t(12) = 2.143$, $p = 0.053$, Cohen's $d = 0.594$; LW: $t(12) = 0.710$, $p = 0.491$, Cohen's $d = 0.197$). In all conditions, the heart rate returned to normal after waking up (09:00 the next day), as shown in Fig. 3. The results of the heart rate measurement indicated that the high luminance or pure white displays adversely affect the activity levels of the central nervous system.

4. Discussion

The bright display had an adverse influence on nocturnal melatonin secretion, body temperature, and heart rate. When using displays with low luminance, we observed relatively higher melatonin concentrations and decreases in body temperature, which reflects the regular circadian rhythm at night (Colquhoun, 1971; Monk et al., 1997; Lack et al., 2008). The heart rate did not decrease after using the high luminance display, resulting in trouble falling asleep. The result was consistent with the previous studies in that the task performance with a bright display suppresses the nocturnal melatonin concentration and other physiological indicators of human circadian rhythm (Higuchi et al., 2003; Wood et al., 2013). In other words, the displays with low luminance are less expected to interfere with one's nighttime sleep and not to evoke a harmful effect on circadian rhythm.

The influence of display white balance was observed in nocturnal melatonin secretion and heart rate. Comparatively higher melatonin concentration was reported when using the display tinged with yellow, which filtered more blue light than the pure white display. The pure white displays with blue light adversely affected heart rate. The blue-shifted melatonin suppression response correlates with the peak spectral sensitivity of melanopsin photopigment at 480 nm, which lies in the blue range

of the visible light (Hatori & Panda, 2010). However, it should be noted that such blue-shift was observed only in the melatonin suppression and heart rate response. The effect of white balance on body temperature was not statistically significant, which is contradictory to the findings of Cajochen (2005). Hence, besides regulating human circadian rhythms, it remains to be determined if the novel melanopsin-containing retinal ganglion cells are also involved in the autonomic thermoregulation. A definite answer to this would be to investigate people having a melanopsin deficiency.

Although this study discovers physiological effect on smartphone use at night, there are some limitations in the study. First, the experimental environment could not be completely controlled, because the experiments were conducted in each subject's private room in order to increase a sense of reality. If they did not follow the provided guideline for taking food and medicine, using the smartphone, and sleep-wake cycle, the collected data might have been less accurate. Second, we missed collecting data when the subjects did not use any smartphone display. The data might have increased accuracy of the results.

5. Conclusion

The bright and blue light emitted from smartphone displays adversely affect users' melatonin secretion, body temperature, and heart rate. Hence, the use of a display with low luminance or a display that filters blue light is suggested for maintaining a regular circadian rhythm at night. The yellow-tinged display together with low luminance best supports restful sleep at night in terms of melatonin secretion, body temperature, and heart rate. However, people might not prefer the display due to the lower aesthetic quality. In that case, viewing a white display with low luminance or a yellow-tinged display that filters blue light with high luminance can be the second-best plan for getting a restful sleep. Last but not least, it should be noted that although the low luminance or yellowish white balance could help in reducing the sleep disturbance compared to the original display setting, the ideal solution would still be to stop using a smartphone before we go to bed.

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