Evaluation of Two Strategies for Alleviating the Impact on the Circadian Cycle of Smartphone Screens

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ORIGINAL INVESTIGATION

Evaluation of Two Strategies for Alleviating the Impact on the Circadian Cycle of Smartphone Screens

Emiliano Teran, PhD,[1,2]* Cristo-Manuel Yee-Rendon, PhD,[1] Jesus Ortega-Salazar, BSc,[3] Pablo De Gracia, PhD, FAAO,[4] Efrain Garcia-Romo, MD,[5] and Russell L. Woods, PhD, FAAO[6]

SIGNIFICANCE: Electronic display devices used before bed may negatively affect sleep quality through the effects of short-wavelength (blue) light on melatonin production and the circadian cycle. We quantified the efficacy of night-mode functions and blue-light–reducing lenses in ameliorating this problem.

PURPOSE: The purpose of this study was to compare the radiation produced by smartphones that reaches the eye when using night-mode functions or blue-light–reducing spectacle lenses.

METHODS: Radiant flux of 64 smartphones was measured with an integrating sphere. The retinal illuminance was calculated from the radiant flux of the smartphones. For the night-mode functions, the spectra produced by the smartphones were measured. The transmittance of four blue-light–reducing spectacle lenses, which filter light with either antireflective coatings or tints, was measured using a spectrometer. To determine the impact of blue-light–reducing spectacles, the radiant flux of the smartphone was weighted by the transmission spectrum of these glasses. Visual and nonvisual (circadian) parameters were calculated to compute the melatonin suppression values (MSVs) through a logistic fitting of previously published data. The MSV was used as the figure of merit to evaluate the performance of blue-light spectacles and smartphone night-mode functions.

RESULTS: Night-mode functions in smartphones reduced MSVs by up to 93%. The warmest mode produced the least suppression. Blue-light–reducing spectacles reduced melatonin suppression by 33%, the coated lenses being more efficient than tinted lenses.

CONCLUSIONS: All smartphones in this study emit radiant power in the short-wavelength region of the visible spectrum. Such smartphones may impair the regulation of circadian cycles at nighttime. The activation of night-mode functions was more efficient than the commercially available blue-light–reducing spectacle lenses in reducing the amount of short-wavelength light (up to 2.25 times). These results can be extrapolated to most electronic devices because they share the same type of white radiant sources with smartphones.

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Author Affiliations:
[1]Faculty of Physical-Mathematical Sciences, Autonomous University of Sinaloa, Culiacan, Sinaloa, Mexico
[2]Department of Optometry, Center for Research and Teaching in Health Sciences, Autonomous University of Sinaloa, Culiacan, Sinaloa, Mexico
[3]División de Física Aplicada, Centro de Investigación Científica y de Educación Superior de Ensenada, Ensenada, Baja California, Mexico
[4]Chicago College of Optometry, Midwestern University, Downers Grove, Illinois
[5]Department of Ophthalmology, Center for Research and Teaching in Health Sciences, Autonomous University of Sinaloa, Culiacan, Sinaloa, Mexico
[6]Schepens Eye Research Institute, Boston, Massachusetts
*eteran@uas.edu.mx

In addition to the 2D representation of the external environment provided, initially, by cones and rods, there is another optical detector in the human retina that is thought to be insensitive to image structure: the intrinsically photosensitive retinal ganglion cells (ipRGCs). These cells detect the presence of light by using a melanopsin photopigment (peak sensitivity approximately 480 nm)[1] and from the input received from rods and cones[2] and drive various physiological and behavioral processes in human beings. One of the subtypes of ipRGCs that have been identified so far projects its axons to the suprachiasmatic nucleus, and this pathway ultimately leads to the pineal gland, which in turn controls melatonin release.[3–6] The hormone melatonin mediates the physiological control of sleep and is released into the body during dim light conditions.[7] The proper functioning of this system is critical to the circadian rhythm and emotional states.[8]

Exposure during the evening to short-wavelength (blue) light produced by the screen of smartphones could have deleterious effects on human health through the alteration of the circadian rhythm.[9] This negatively impacts sleep quality and duration, which in turn has widespread effects on human health, including increased mortality risk, weight gain and obesity, diabetes risk, cardiovascular disease, neurocognitive function, mental health, and traumatic accidents (such as car accidents).[10,11]

One hour of exposure to relatively low irradiances (10.3 log photons/cm^2 per second) has been reported to decrease melatonin secretion by 25%.[12] Therefore, even small behavioral changes that modify the exposure to blue light during the evening may be considered a health risk factor. For example, viewing smartphones at night has been shown to reduce melatonin secretion between 1.4 and 15% in dark rooms.[13,14] The latter reduction of the melatonin secretion can affect human health and the circadian rhythm.[6,15,16]

We studied two strategies to reduce blue light emitted by smartphones late at night: (1) night-mode functions and (2) spectacle lenses. These are illustrated in Fig. 1. It is not clear which strategy is better at reducing the possible circadian disruption due to blue-light exposure, and we are not aware of any previous direct comparisons of these two approaches. Manufacturers of some smartphones describe the night-mode functions as beneficial to sleep patterns, yet

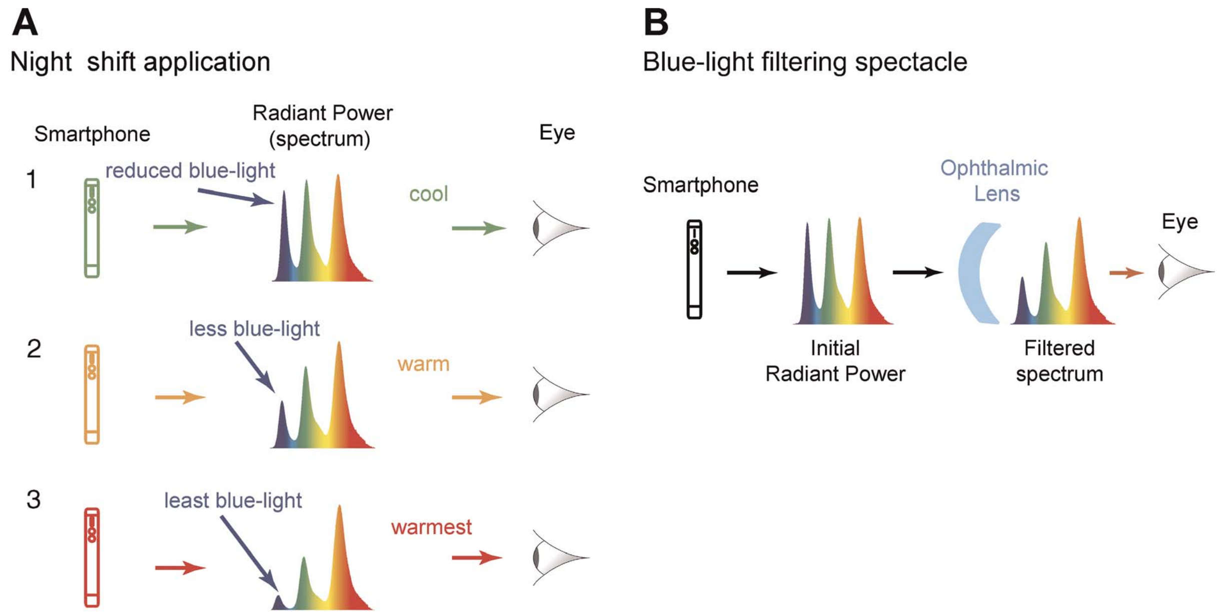

FIGURE 1. Hypothetical diagrams of the two blue-light reduction strategies explored here: (A) night-mode functions with (1) cool, (2) warm, and (3) warmest color temperatures and (B) blue-light–reducing spectacles.

little is known about how these night-mode functions modify the visible-light spectrum. A reduction in blue light corresponds to a “warmer” (browner) screen. There are different night-mode applications for Android (≥ version 7) and iPhones (≥ version 6). In some, the color temperature can be selected, such as *cool*, *warm*, and *warmest*, with warmest corresponding to a greater reduction in short-wavelength emission from the display (Fig. 1). Often, we can select the time during which the night mode is applied.

Manufacturers of commercial blue-light–reducing spectacle lenses also describe the hypothetical benefits of blocking short-wavelength light to protect the eye and to improve the effects on health, among them the sleep cycle.[17–19]

Leung et al.[16] reported the optical properties of five brands of blue-light–reducing lenses and found that these spectacle lenses reduced the transmittances of short (blue) wavelengths by between 75 and 90%, with melatonin suppression efficiency ranging from 6 to 15%.[6] This blue-light reduction and the corresponding increase in melatonin secretion are consistent with reports of blue-light–reducing lenses increasing the length or quality of sleep.[16,20] However, when considering randomized and controlled studies, the value and effectiveness of these lenses and their impact on visual performance and eye health are not clear.[20]

To determine the blue-light reduction of the night-mode functions and to compare those functions to the blue-light–reducing lenses, we used the smartphone figures of merit proposed by Oh et al.[14] to assess their “health” quality. These functions were used to determine the melatonin suppression values. Lower melatonin suppression values correspond to higher melatonin levels (secretion) and less impact on the circadian cycle and presume to improve sleep quality.

METHODS

Experimental Measurements

The spectral radiant power of 64 smartphones (49 models) was measured without filtering applied (Table 1): 17 from Samsung, 12 from Motorola, 10 from Huawei, nine from Apple (iPhones), eight from LG, two from Alcatel, two from Lenovo, and one each from Hisense, HTC, Lumia, Sony, and Xiaomi. We divided the smartphones into two groups as a function of the technology used for their screens: active-matrix organic light-emitting diode (AMOLED) and liquid-crystal display (LCD). Then, we calculated the median spectral radiant power for each of them. Each of these median spectral radiant powers underwent further testing, and their three night-mode settings (cool, warm, and warmest), each of which produces changes in color temperature, were weighted and categorized. We collected a total of 70 spectral radiant powers.

The schematic of the experimental setup used to measure the spectral radiant power of the smartphone screens is depicted in Fig. 2. An integrating sphere (Ocean Optics, Largo, FL, ISP-50-8-R-GT) was used to collect the emitted light. The surface of the sphere was covered with a white highly diffuse film. The sphere had a radius of 8 cm and four ports each with a radius of 1 cm. The one removable port was covered by a white surface with a diffuse reflectance of 98% to eliminate coherent components (specular reflection). This port and the entrance port formed an 8° angle relative to the sample surface. The sphere was connected to a spectrometer (AvaSpec, Haverhill, MA) by means of a fiber optic (Thorlabs, Newton, NJ, BFL200HS02).

For the study, the detection system (sphere, fiber optic, and spectrometer) was calibrated using a 1000 W Xenon lamp (Oriel, Newport, Irvine, CA, model 66924) with a Newport 1/8 m Cornerstone 130 monochromator and a thermal power sensor (Thorlabs S302C). In this setup, a collimated beam struck the sphere wall, and thus, the spectrometer acquired the corresponding photon count. Subsequently, the same beam illuminated the photodetector, from which the beam power was obtained. We varied the monochromator setting in steps of 10 nm from 350 to 700 nm for each measurement. A spline interpolation was applied (via MATLAB, Simulink, Natick, MA) to obtain a continuous visible-range spectrum (350 to 700 nm).

Each smartphone was positioned in front of the sample port of the sphere (Fig. 2A). The white region from a Google search webpage

TABLE 1. All the smartphone models considered in this study separated by the type of screen

Manufacturer	LCD	AMOLED
Alcatel	Shine, Idol	
Apple	iPhone 4, 4 s, 5c, 5 s, 6, 6 s, SE (2)	iPhone X
Hisense	C20	
HTC	530	
Huawei	G Elite, G Elite Plus (2), G Play Mini, P8 Lite (2), P9 Lite (2)	P20 Plus, P20*
Lenovo	K5, K6	
LG	X180 (2), 870, Leon, Pro Lite (2), H500f, G7 thinQ*	
Lumia	WP 340-XL	
Motorola	E, E4, G4+, G2, G4 (2), G5 (3), G6+, G8 (2)	
Samsung	Core2, Grand Neo, Galaxy A3, Grand Prime (2), Grand Prime Plus (2)	Galaxy A5 (2), J1 (2), J6, J7 (2), Note 8, S8 plus (2)
Sony	Xperia Z2*	
Xiaomi	Redmi4X	

In parentheses appear the times that the model is repeated. *Display has a fourth peak emission in the long-wavelength region (~630 nm). AMOLED = active-matrix organic light-emitting diode; LCD = liquid-crystal display.

as displayed on the phone was used to perform all measurements with 100% screen brightness. For the three night-mode settings, the same procedure was followed except with the appropriate night mode setting (cool, warm, and warmest) also applied.

The transmittances of four blue-light–reducing spectacle lenses were measured: two with an antireflective coating (Crizal Prevencia from Essilor, Dallas, TX, and Blue Protect from Zeiss, White Plains, NY) and two with tint (Anti Blu-Ray from Seto, Mexico City, Mexico, and 1.60 UV Blue Light from Vaccutek, Queretaro, Mexico) with no refractive power. These transmittances were measured using a 1000-W Xenon lamp (Oriel model 66924) as a light source connected to a 1/8 m Cornerstone 130 Monochromator (Newport). The monochromatic light was coupled to an optical fiber when measuring the spectacle lenses. The other side of the optical fiber was used to illuminate a cuvette holder (Ocean Optics CUV-ALL-UV) where an adapter was used to hold in place the lens under study. Light transmitted through the lens was captured by another optical fiber that was connected to a Silicon Switchable Gain Detector (Thorlabs PDA-100A). We varied the monochromator setting in steps of 5 nm from 350 to 700 nm for each measurement and then performed a spline interpolation to obtain a continuous spectrum for calculations.

Calculation of Figures of Merit

The computational part of this work included the following: (1) the calculation of the irradiance and illuminance of the smartphones across the models from the spectral radiant power measurements; (2)

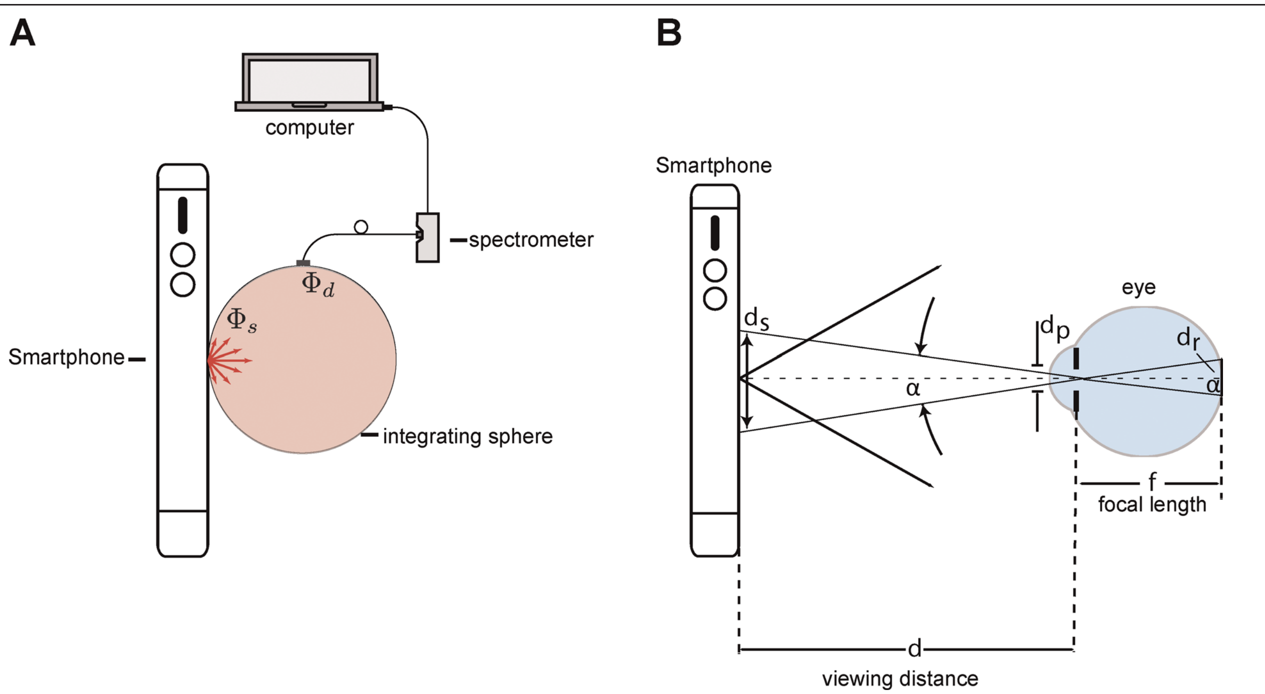

FIGURE 2. A, Experimental arrangement to measure spectral radiant power of smartphone screens using an integrating sphere. B, Schematic diagram used to calculate effective retinal irradiance.

the calculation of the melatonin suppression value in the night-mode functions, which was obtained from the spectral radiant power measurements; and (3) the calculation of the melatonin suppression value from the blue-light–reducing spectacle lenses, which was obtained from the median radiant power of the samples of AMOLED and LCD screens (as described later) and the transmittance of each of the four blue-light–reducing lenses.

Spectral Irradiance and Illuminance

The integrating sphere measures the spectral radiant power (termed only power henceforth), Φ_d (W/nm), emitted by the smartphone screen. The radiant power of the source can be readily converted to spectral radiance, as demonstrated in a later section. This detected power (Φ_d) can be related to the power source as follows:

$$\Phi_d = F\Phi_s, \text{(W)} \tag{1}$$

F denotes a constant that depends on the properties of the sphere, and Φ_s, the power of the source. F is a quantity that accounts for multiple reflections inside the sphere, which can be expressed as follows:

$$F = \frac{b_1/m}{1-b_2 R_{dd}}. \tag{2}$$

From Eq. (1), the radiant power of the source of light can be expressed as follows:

$$\Phi_s = \frac{m[1-b_1 R_{dd}]}{b_1}\Phi_d \tag{3}$$

where Φ_d denotes the radiant power of the smartphone as detected by the integrating sphere (Eq. (1)) and b_1, b_2, and m are the sphere constants defined previously. We assumed that the diffuse reflectance, R_{dd}, of the screen was the same across all models (10%).

The retinal irradiance, E_r (W/m^2), is directly related to radiant emittance, E_s (W/m^2); transmittance of the ocular media, τ; and pupil diameter, d_p (mm). For the Gullstrand eye model, f = 17 mm (Fig. 2B). Thus, E_r can be written as follows:

$$E_r = a\tau d_p^2 E_s T_L \text{(W/m}^2\text{)} \tag{4}$$

where $a = \pi/4f^2 = 2700/\text{m}^2$ (see Delori et al.[21]), and T_L denotes the transmittance of a spectacle lens, if any. Here, we assume that the smartphone is a Lambertian surface with area A_s. Thus, the source emittance can be expressed as follows:

$$E_s = \Phi_s/A_s \text{(W/m}^2\text{)} \tag{5}$$

The source area can be written as $A_s = \pi(d_s/2)^2$, where $d_s \approx \alpha d$ denotes the extent of the source (Fig. 2B). These quantities can be calculated considering an extended source with visual angle α = 0.1 steradians, separated by d = 30 cm from the eye and pupil. The diameter for longer exposures in the visible spectrum[21] is d_p = 3 mm.

Calculation of the Melatonin Suppression Value

The luminous efficacy of radiation (LER) and the circadian efficiency of radiation (CER) can be calculated by means of the following expressions[14]:

$$\text{LER} = 683\int_{380}^{780}\Phi_s V(\lambda)d\lambda/\int_{380}^{780}V(\lambda)d\lambda \text{(lumen/W)} \tag{6}$$

$$\text{CER} = 683\int_{380}^{780}\Phi_s C(\lambda)d\lambda/\int_{380}^{780}C(\lambda)d\lambda \text{(lumen/W)} \tag{7}$$

where the circadian spectral sensitivity is denoted by $C(\lambda)$, and the photopic spectral luminous efficiency function by $V(\lambda)$. These photometric quantities represent measurements of how well a light source produces visible (and nonvisible) light. Therefore, luminous efficacy of radiation and circadian efficiency of radiation are defined as parameters explaining how the average human eye responds to visual and nonvisual radiation from the emission spectrum.[14]

Upon converting irradiance (Eq. (4)) into illuminance, the photopic illuminance (PIL) can be obtained via the relationship:

$$\text{PIL} = 683\int_{380}^{780}E_r(\lambda)V(\lambda)d\lambda \text{(lumen/m}^2\text{)} \tag{8}$$

where the 683 (lumen/W) represents the maximum spectral luminous efficacy, and E_r is the retinal irradiance (W/m^2) from Eq. (4). Photopic illuminance measures how much visible light radiation illuminates a surface.

Parameter circadian action factor (CAF) was defined as the ratio of the circadian to scotopic efficacies of radiation, and it can be expressed as follows[21]:

$$\text{CAF} = \text{CER/LER}(-) \tag{9}$$

Circadian efficiency of radiation and luminous efficacy of radiation were obtained from Eq. (6), as well as circadian spectral sensitivity $C(\lambda)$ and photopic spectral luminous efficiency function $V(\lambda)$, respectively. The circadian action factor is an index that describes the circadian efficiency of the light's spectrum. For instance, a circadian action factor equal to 1 means that the luminous efficiency and the circadian efficiency of that source of light are equal.

The circadian illuminance parameter measures the potential effect on the human circadian system, because it weighs the radiant power of incident light by the circadian spectral luminous efficiency function ($C(\lambda)$). The circadian illuminance (CIL) is the product of the circadian action factor and photopic illuminance (Eq. (7)):

$$\text{CIL} = \text{CAF} \times \text{PIL}\text{(lumen/m}^2\text{)}. \tag{10}$$

In previous studies of the melatonin suppression value,[23–25] the melatonin suppression value for each lighting condition was defined as the difference between the melatonin concentration immediately after exposure to light and the concentration just before exposure. This is expressed as a percentage of the concentration before exposure. Exposures ranged from 30 to 90 minutes.[1,14,24,25] For our study, we did not measure melatonin levels, instead we used the relationship reported by Oh et al.[14] to obtain the (relative) melatonin suppression value as a function of the calculated circadian illuminance (Fig. 3). Previous studies have used a logistic function to fit this relationship.[1,14,23,25] To fit our data, we used a logistic function using a nonlinear least squares method. Data from Fig. 2B and Table 2 in the article by Oh et al.[14] were used (Fig. 3). The melatonin suppression value (MSV) can be written as:

$$\text{MSV} = \frac{1}{1+\exp[-k(\log(\text{CIL})-\log(\text{CIL}_0))]} \tag{11}$$

where, for the Oh et al.[14] data, k = 1.782 and CIL_0 = 103.5 were the fit parameters ($R^2_{adj} = 99.9\%$). The melatonin suppression values shown in Fig. 8 were calculated using Eq. (11), and the three melatonin suppression value–circadian illuminance relationships are shown in Fig. 3. From our reading of the three articles, we could not determine why the melatonin suppression value–circadian

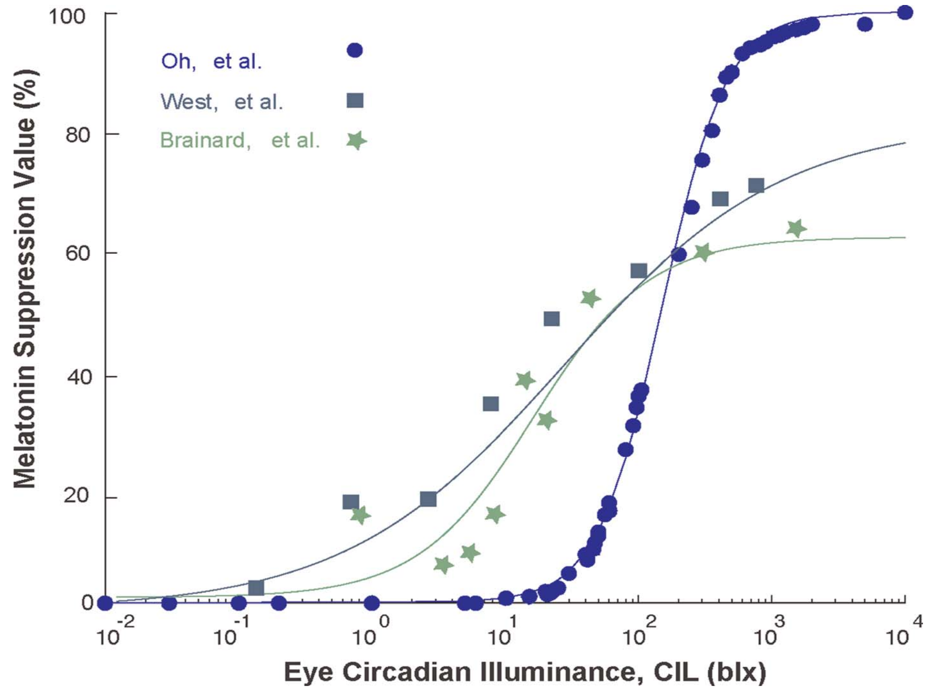

FIGURE 3. Eye circadian relationships between melatonin suppression values and circadian illuminance reported by Oh et al.,[14] West et al.,[25] and Brainard et al.[1] The continuous lines represent the fits to the data from each study using Eq. (11).

illuminance relationships differed between the studies apart from concluding that it probably was a result of differences between the study designs (e.g., exposure times, sources of light). For the data presented henceforth and shown in Tables 2 and 3 and Appendix Tables A1, A2, and A3 (available at http://links.lww.com/OPX/A441), we used the melatonin suppression value–circadian illuminance relationship reported by Oh et al.[14]

The melatonin suppression values presented in this study assume near-screen exposure times of between 30 and 90 minutes immediately before attempting to sleep, because the melatonin suppression value–circadian illuminance relationships (Fig. 3) were measured using data from studies with 30- to 90-minute exposures. This selected period is representative of viewing times that might occur in typical daily life. The effects of varying exposures have not been rigorously studied.

RESULTS

Radiant Powers

The spectral radiant powers of the smartphones considered in the study (Table 1) are shown in Fig. 4. The devices are shown separated into two groups as a function of the technology of the displays, LCD (Fig. 4A) and AMOLED (Fig. 4B).

TABLE 2. Melatonin suppression values (%) for generic LCD and AMOLED displays (Fig. 4C) when using three night-mode settings

	Reference	Cool	Warm	Warmest
LCD	9.9	7.3	2.9	0.68
AMOLED	13.6	11.3	4.8	1.25

These correspond to the spectral radiant powers presented in Fig. 5. AMOLED = active-matrix organic light-emitting diode; LCD = liquid-crystal display.

The spectral radiant power values of the LCD smartphone displays (Fig. 4A) were quite similar between models with three well-defined peaks at approximately 450-, 540-, and 620-nm wavelengths. The variations between models in absolute and relative amplitude of the peaks were small, except for the LG G7 thinQ and Sony Xperia2 LCDs, exhibited a fourth peak at approximately 640 nm (Fig. 4A). The magnitude (power) of the short-wavelength emission peak was higher than that of the medium- and long-wavelength emission peaks for all the models with LCD screens. The peaks varied in magnitude, ranging from approximately 20 to 400 μW. These spectra closely resemble the spectrum of many other trichromatic "white" LCD sources (e.g., electronic tablets, computer displays, many televisions).

The spectral radiant power of the AMOLED displays exhibited three peaks, around 450, 520, and 620 nm (Fig. 4B), except for Huawei P20 display, which had a fourth peak at approximately 635 nm (Fig. 4B). The three (main) peaks are more similar in amplitude (power) than the three peaks of the LCD phones (which had higher peaks for short than for medium and long wavelengths). The peak amplitudes varied between approximately 20 and 400 μW. Although the medium- and long-wavelength peaks were narrower than those of the LCDs (Fig. 4A), they carry similar total energy (as absorbed by the retinal cones) as the wider but lower (relative) peaks of the LCD phones. Otherwise, the color appearance would be substantially different between AMOLED and LCDs.

Thus, the radiant spectrums of AMOLED and LCDs differed mainly in the peak and the full width at half maximum of medium and long wavelengths, the AMOLED peaks being high and thin and the LCD being lower and wider, in general. The range of radiant powers was similar between the LCD and AMOLED displays in our sample.

TABLE 3. Melatonin suppression values (%) with a reference (no lens), an untinted lens, and the four blue-light–reducing lenses (whose transmittance is shown in Fig. 7) calculated using the spectral radiant powers of generic LCD and AMOLED displays (medians shown in Fig. 4C)

Display type	Reference (no lens)	Clear lens (uncoated)	1.6 UV Blue Light	Anti Blu-Ray	Crizal Prevencia	Blue Protect
LCD	9.87	8.49	8.41	7.95	6.44	7.56
AMOLED	13.6	11.8	12.0	11.3	9.25	10.8

AMOLED = active-matrix organic light-emitting diode; LCD = liquid-crystal display.

We used Eqs. (5) to (10) to calculate several figures of merit of the smartphones, using their spectral radiant powers (Fig. 4). To facilitate statistical analyses, we used the inverse of luminous efficacy of radiation and the logarithm of circadian efficiency of radiation, which approximately normalized those distributions. Median figures of merit and range are listed by display type in Appendix Table A1 (available at http://links.lww.com/OPX/A441). The range of values is consistent with those reported by Oh et al.[14] There were no differences between LCD and AMOLED for any of the figures of merit (linear regression; $z \leq 1.51$, $P > .13$), except that LCD devices had higher luminous efficacy of radiation than the AMOLED devices ($z = 2.19$, $P = .03$).

The circadian illuminance values varied widely. LCD displays had a median circadian illuminance of 44 biolumen (range, 5.8 to 81 biolumen). AMOLED displays had a median circadian illuminance of 56 biolumen (range, 14 to 93 biolumen). The melatonin suppression values of the smartphones with LCDs (median, 10.0%; range, 0.3 to 24.8%) was not different from that of the smartphones with AMOLED displays (median, 14.6%; range, 1.4 to 29.7%) in our sample of devices ($t = 0.55$, $P = .58$).

As noted, the short-wavelength peak of LCDs had the highest amplitude, whereas the short-wavelength peak of AMOLED displays was similar in amplitude to the other peaks (Fig. 4). The night-mode functions and blue-light filters were expected to have most impact on the short-wavelength peak. Our interest was in examining which of these two solutions, night-mode functions or blue-light–reducing spectacles, was better at reducing the exposure to short-wavelength radiation.

Night-mode Functions

The high-end smartphones, iPhone X, Samsung Galaxy Note8, LG G7 ThinQ, and Huawei P20 Plus, tended to have the brightest displays. The circadian illuminances of these devices were similar, varying from 62 to 93 biolumen. These circadian illuminance values can produce an increase in melatonin suppression value of approximately 17 to 30%, which can be harmful to the circadian rhythm.[14] However, these devices have installed applications that can selectively reduce the amount of blue light. The best application performance was achieved by the iPhone X, which had a reduction of approximately 90% of the circadian illuminance. We used the median of the LCD and AMOLED displays (shown in Fig. 4C) to perform the evaluation of night mode.

The median spectral radiant powers of the LCD and AMOLED displays (presented in Fig. 4C) weighted by the relative transmission of each of the three night-shift modes are presented in Fig. 5. The gray region represents the median power across smartphones (at maximum brightness), which was used as our reference. The night-shift modes were cool (green line), warm (orange line), and warmest (red line). Melatonin suppression values of the median LCD and AMOLED displays for the three night-shift modes are listed Table 2, and full factors of merit are reported in Appendix Table A2 (available at http://links.lww.com/OPX/A441).

As shown in Fig. 5, there was a considerable reduction in the blue-light emission of the LCD and AMOLED displays for the warmest color temperature (>90%). Moreover, there was also an intensity reduction in the medium-wavelength (green) peak; however, the long-wavelength (red) peak remained almost constant for all the night-mode settings. These changes in the spectral radiant power functions with the night modes produced (1) substantial reductions in the circadian efficiency of radiation and photopic illuminance peak magnitudes; (2) little change in luminous efficacy of radiation, apart from the warmest mode; and (3) a substantial reduction for the warmest night-shift setting in circadian illuminance (Appendix Table A2, available at http://links.lww.com/OPX/A441). Melatonin suppression value was reduced in magnitude, by approximately a factor of 10 with the warmest night-mode setting (Table 2). These results indicate that, although high-end smartphones, such as the iPhone X and Huawei P9 Lite, can cause considerable melatonin suppression, the warmest night-mode can mitigate this effect by more than 90%. Because the spectral-radiant powers of other smartphones were very similar (Fig. 4), similar reductions in melatonin suppression values would be expected in other smartphones that have night-mode functions. Thus, our calculations suggest that the night-mode function may be an effective strategy for reducing circadian-cycle disturbances caused by smartphones used for extended periods shortly before attempting to go to sleep. Although our measurements were made on smartphones, it should be noted that some electronic tablets and computers have night-mode functions and the night-mode function may have similar value.

Blue-light–reducing Spectacle Lenses

Now, we consider an alternative strategy for protection against circadian-cycle disruption, blue-light–reducing spectacle lenses. The relative transmittance of the four blue-light–reducing lenses is shown in Fig. 6; the two tinted are shown with red, and the two coated lenses in blue.

The two tinted lenses, Seto Anti Blu-Ray and Vaccutek 1.60 UV Blue Light, had similar spectral transmittance curves. These lenses almost completely blocked ultraviolet A, with maximum transmittance in the near ultraviolet (380 to 400 nm) of 0.26%. Blue light (400 to 490 nm) was also partially filtered by the tinted lenses with average transmittances of 64 and 60% for Anti Blu-Ray and 1.6 UV Blue light, respectively, whereas a relatively high mean transmission for visible light (400 to 700) was maintained (82 to 85%). The two coated lenses, Essilor Crizal Prevencia and Zeiss Blue Protect, had mean transmittances in the near-ultraviolet (380 to 400 nm) of 36 and 14%, respectively. For the short-wavelength range (400 to 490 nm), the transmittance was 80% for Crizal Prevencia and 82% for Blue Protect, whereas a high transmission for visible

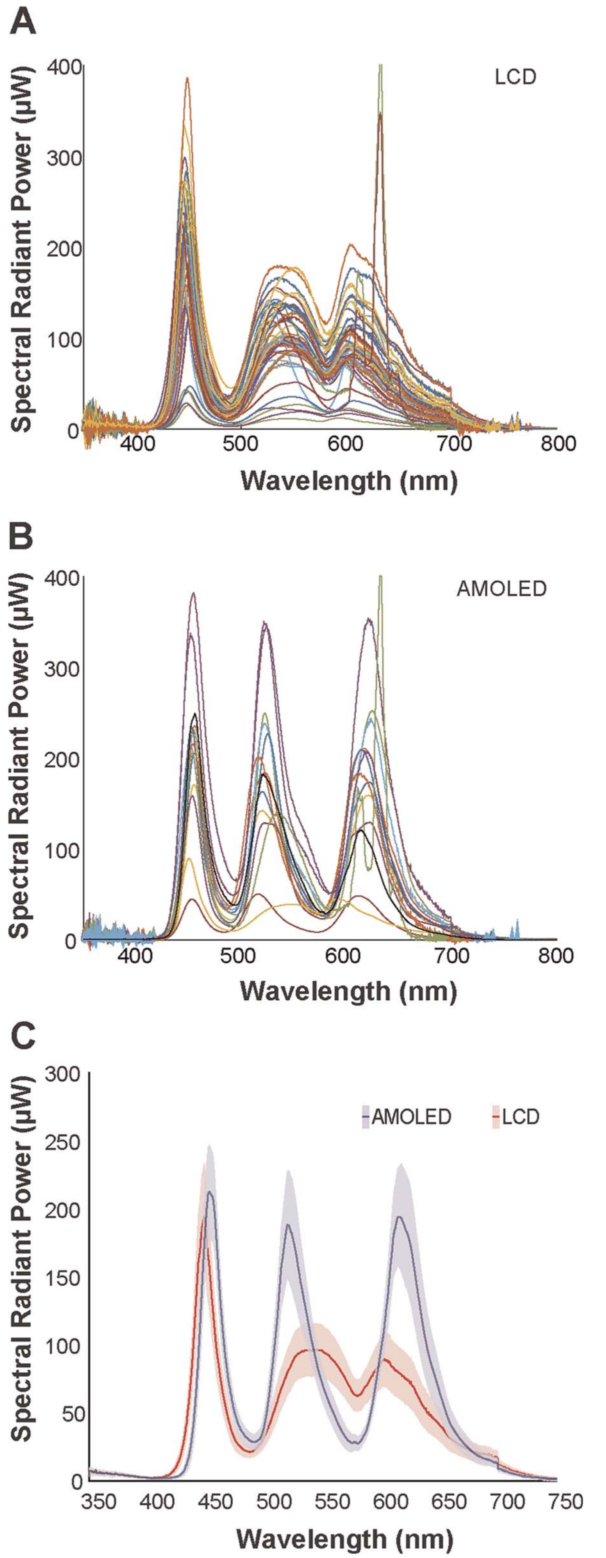

FIGURE 4. Spectral radiant powers of 64 smartphones with (A) LCD or (B) AMOLED displays. C, The solid lines show the medians of the LCD and AMOLED samples, the shaded region is ±standard deviation/2. These medians were used for calculations that are shown in Figs. 5, 7, and 8 and reported in Tables 2 and 3 and Appendix Tables A2 and A3 (available at http://links.lww.com/OPX/A441). AMOLED = active-matrix organic light-emitting diode; LCD = liquid-crystal display.

light was also achieved (mean, 91%). We hypothesized that a reduction in the spectacle lens transmittance around the peak of melatonin-suppression sensitivity (around 450 nm[24]) would strongly impact melatonin suppression more than reduction in the near-ultraviolet (380 to 400 nm) region, and this question directs the next aspect of the study.

The transmitted radiant powers (Fig. 7) of the blue-light–reducing spectacles were obtained as the product of the transmittances of the four blue-light–reducing lenses (Fig. 6) and the radiant power of a generic AMOLED phone or a generic LCD (from Fig. 4C). The gray region represents the power without a lens (labeled as Reference) and is the same as the gray zone in Fig. 6 (i.e., same baseline or reference).

The reduction in the blue-peak magnitude depended on the lens transmittance in the region 435 to 480 nm.[1] The two coated lenses (Crizal Prevencia and Blue Protect) reduced the magnitude of the short-wavelength peak by approximately 15%, whereas there was almost no reduction for the two tinted lenses (Anti Blu-Ray and 1.6 UV Blue light). The magnitudes of the medium- and long-wavelength peaks showed minor changes as the transmittances of the lenses at these wavelengths were in the range of 82 to 99%. The luminous efficacy of radiation and photopic illuminance were similar for all four lenses, and they were similar to the reference (Appendix Table A3, available at http://links.lww.com/OPX/A441). However, the circadian efficiency of radiation and circadian illuminance were lower for the Blue Protect and Crizal Prevencia (coated) lenses than for the Anti Blu-Ray and 1.6 UV Blue light (tinted) lenses, as compared with the no-lens reference (Appendix Table A3, available at http://links.lww.com/OPX/A441). The coated lenses (Blue Protect and Crizal Prevencia) had a calculated reduction in the melatonin suppression value of 21 to 35% relative to the no-lens reference, whereas the reduction provided by the tinted lenses (Anti Blu-Ray and 1.6 UV Blue light) was only 12 to 15% (Table 3). However, the clear uncoated (control) spectacle lens reduced melatonin suppression value by 13 to 14%. Thus, the tinted lenses provided no substantial improvement in melatonin suppression value reduction over a standard spectacle lens. A reduction of radiance at 390 to 405 nm will produce little reduction in the circadian illuminance, as there is little overlap with the melatonin action spectrum. These results are consistent with other studies.[6,13–15] Liquid-crystal displays are widely used in other electronic devices such as electronic tablets, computer displays, and many televisions. Hence, the impact on the circadian cycle of such devices with LCDs will be similar to that found with the generic LCD smartphone, and the effect of blue-light–reducing lenses is expected to be the same as shown in Fig. 7A.

Melatonin Suppression Values

Melatonin suppression values are reported in Tables 2 and 3 and Appendix Table A1 (available at http://links.lww.com/OPX/A441). In Fig. 8, we provide summary melatonin suppression values for generic or typical AMOLED and LCDs (Fig. 4C). Fig. 8 shows the melatonin suppression value calculated using Eq. (11). For Fig. 8, we determined a generic AMOLED and a generic LCD by taking the median power at each wavelength of the measured smartphones (excluding those with a fourth spectral peak) that are illustrated in Fig. 4C. Then, those median spectral powers were equated to have equal energy (area under curve), when weighted by the photopic spectral luminous efficiency function ($V(\lambda)$). For the night-mode settings, we took the proportional decrease in energy at each wavelength and then multiplied that proportional spectral

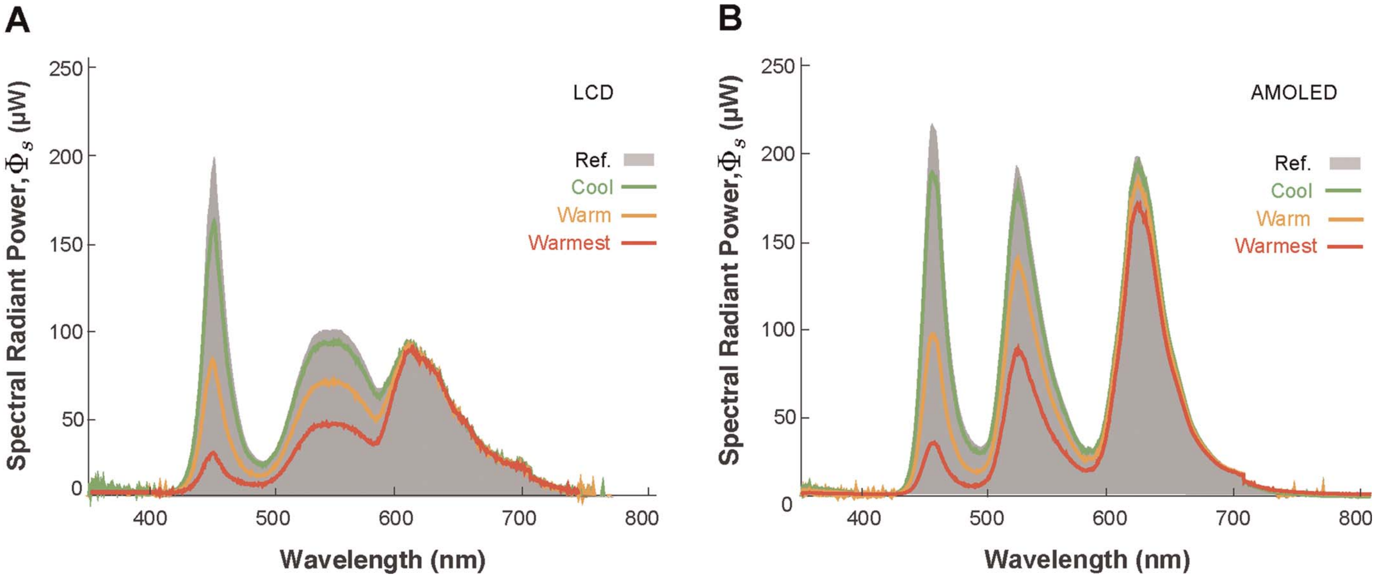

FIGURE 5. Spectral radiant power of generic (median from Fig. 4C) (A) LCD and (B) AMOLED displays before wavelength integration as a function of the night-mode settings (color temperatures): cool, warm, and warmest. AMOLED = active-matrix organic light-emitting diode; LCD = liquid-crystal display; Ref. = reference.

reduction (which is like a transmission function) by the normalized display spectral power.

Fig. 8 shows the melatonin suppression value when using the three night-mode functions (cool, warm, and warmest) and the two different types of blue-light–reducing spectacle lenses (tinted and coated) included on this study. The efficiency of melatonin suppression value reduction of these five strategies can be ordered as follows: Warmest Night Mode >> Warm Night Mode > Cold Night Mode ~ Coated Lenses > Tinted Lenses. When normalized, AMOLED had higher melatonin suppression values than the LCDs, suggesting that the AMOLED displays have more energy in the short wavelengths when weighted by the

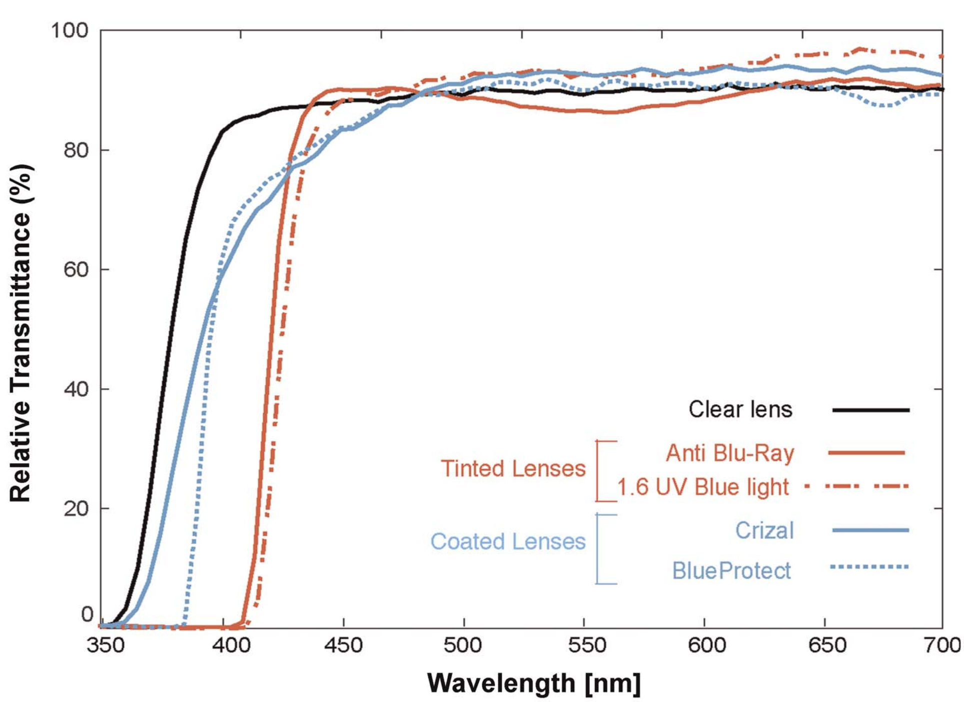

FIGURE 6. Transmittances of four blue-light–reducing spectacle lenses measured in this study: two with antireflective coatings (Crizal Prevencia from Essilor and Blue Protect from Zeiss) in light blue and two tinted lenses (Anti Blu-Ray from SETO and 1.60 UV Blue Light from Vaccutek) in red.

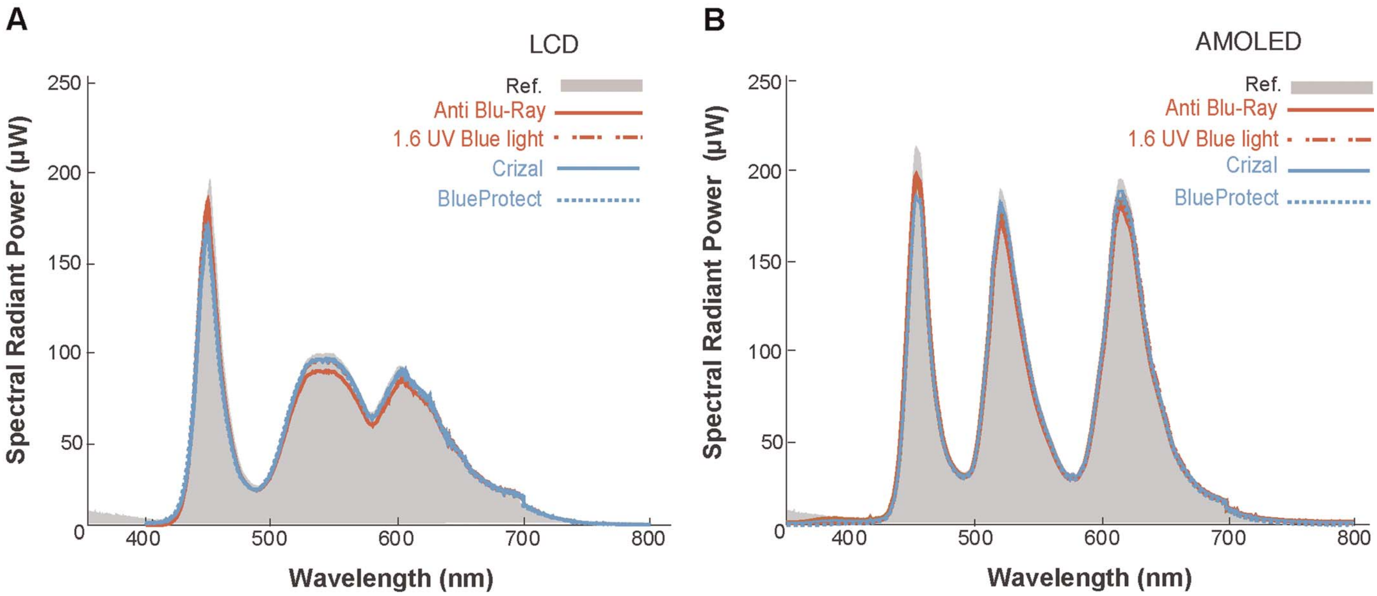

FIGURE 7. Transmitted radiant power of the four blue-light–reducing spectacle lenses considered in the study. The generic spectral radiant power of Fig. 4C: (A) LCD screen and (B) AMOLED screen without filtering lens are shown as the gray area and denoted as reference (Ref.). AMOLED = active-matrix organic light-emitting diode; LCD = liquid-crystal display.

circadian spectral luminous efficiency function ($C(\lambda)$). Thus, the effects of the blue-light–reducing strategies on LCDs, on average, were greater than for AMOLED displays.

DISCUSSION

The use of self-luminous screen devices such as smartphones can impact the circadian cycle, with the potential to reduce sleep duration.[10,11] In our study, we explored two different strategies to decrease the influence on the circadian cycle of the use of screen devices: night-mode functions (cold, warm, and warmest) and spectacle lenses (coated and tinted).

As expected, the warmer the night-mode function, the more efficient it was in reducing the circadian illuminance produced by smartphone screens (lower melatonin suppression value; Table 2, Fig. 8). The warmest mode was particularly effective, reducing the calculated melatonin suppression value by 90%. However, night mode is only effective if the device has a night-mode function, the user actively turns the night-mode function on (i.e., not a default setting), and the night-mode function in a display does not reduce short-wavelength light from other environmental sources such as room lighting.[14] The impact of other light sources was not considered in this study. It is not known whether there are differences in the effects of central versus peripheral retinal illumination on the circadian rhythm and sleep quality. For example, if you view the

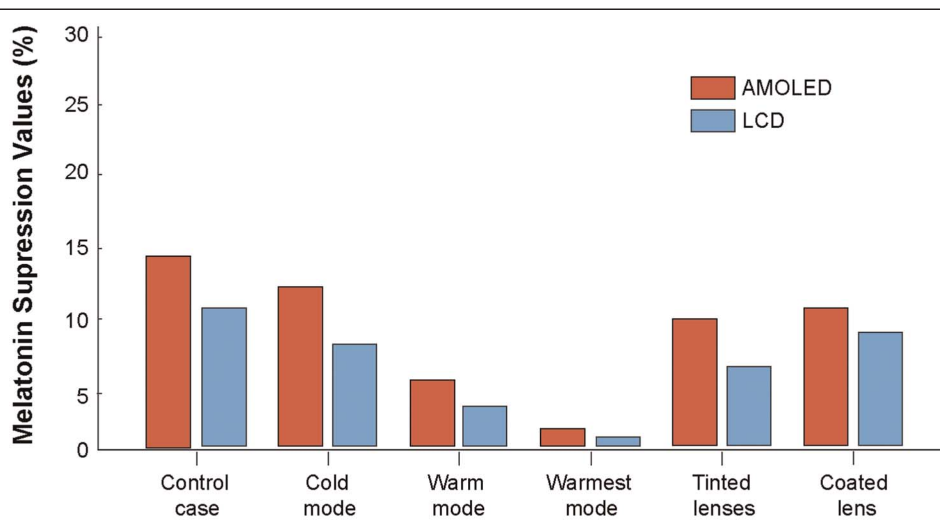

FIGURE 8. Melatonin suppression values as a function of the strategy used for reducing it separated for AMOLED and LCD displays and as a function of the melatonin suppression value–circadian illuminance relationships, as shown in Fig. 3: Oh et al. study.[14] AMOLED = active-matrix organic light-emitting diode; LCD = liquid-crystal display.

smartphone (central vision), does the room lighting matter? The room lighting would be providing peripheral retinal illumination.

Blue-light–reducing coated spectacle lenses were only moderately effective in decreasing circadian illuminance and therefore melatonin suppression value, whereas the tinted blue-light–reducing spectacle lenses were almost ineffective (Table 3). As shown in Fig. 6, the two tinted lenses had a sharp change in the transmission spectrum at around 420 nm, with transmission below approximately 420 nm being near 0% below and rising quickly above this point. The two coated lenses had a softer transition from 400 to 490 nm to near full transmission by approximately 500 nm (Fig. 6). This difference in the transmission spectra in the short-wavelength range makes coated lenses a better choice to reduce the circadian illuminance produced by electronic displays (Fig. 7). It seems that the reductions in the coated lenses transmittance were a better match to the spectral sensitivity of the melatonin-producing ipRGCs, which detect the presence of light using a melanopsin photopigment with a peak sensitivity at approximately 480 nm.[1]

We found that the transmission spectrum for one of the two coated spectacle lenses (Crizal Prevencia) differed from that reported by Leung et al.[16] In particular, we found more transmission in the 350- to 380-nm range and a mild reduction in its transmission for wavelengths from approximately 380 to 400 nm as compared with Leung et al.[16] Thus, this lens would provide more circadian illuminance than as measured by Leung et al.,[16] which would increase the calculated melatonin suppression value, but only slightly, as that range less than 400 nm would have minimal impact because of the melanopsin spectral sensitivity (peak, 480 nm).

For the clinician wishing to provide advice to patients, we can look at the relative benefit in prescribing the blue-light–reducing spectacle lenses measured in this study. Compared with a clear lens, which provided 13 to 14% reduction in the calculated melatonin suppression value, the two tinted lenses provided a further reduction of 7 to 21%. The two coated lenses reduced the fitted melatonin suppression value by 0 to 5% compared with the clear lens. Because the tinted lenses seem to provide a modest benefit over a clear lens, they might be worth recommending. For the patient who does not wear spectacles, we can ask whether the clinician might recommend wearing spectacles with blue-light–reducing lenses in the evening. Compared with no lens, the tinted lenses reduced the melatonin suppression value by 12 to 15%, whereas the coated lenses reduced the melatonin suppression value by 21 to 35%. Whether these levels of reduction will be sufficient to provide a benefit to the circadian cycle and thus sleep duration and quality is not known and needs further study.

A recent systematic review[20] found that there was insufficient evidence to warrant a recommendation of use of blue-light–reducing spectacle lenses in improving visual performance, macular health, or the sleep-wake cycle. The blue-light–reducing spectacle lenses that we measured provided very modest to minor reductions in the calculated melatonin suppression value. As such, it is not surprising perhaps that the studies reviewed by Lawrenson et al.[20] showed little effect. Our measurements and subsequent calculations suggest that there may be limited clinical value in many of such lenses. Given the variations in the expected benefit (i.e., reduction in melatonin suppression value) between lenses, as found in our study, further studies of lenses with higher circadian illuminances are warranted.

Different studies have found substantially different relationships between circadian illuminance and melatonin suppression value,[1,14,23–25] as shown in Fig. 3. Through most of our study, we used the melatonin suppression value–circadian illuminance found by one study.[14] Thus, the predicted effects on the circadian cycle can differ substantially, depending on which melatonin suppression value–circadian illuminance relationship is chosen. None of the studies[1,14,23–25] used a methodology that simulated smartphone use at bedtime. Such a study is warranted.

In conclusion, night-mode functions and blue-light–reducing spectacle lenses rely on different mechanisms for reducing the exposure to short-wavelength radiation. Blue-light–reducing lenses filter all light sources reaching the eye (e.g., overhead lights), whereas smartphone (and computer) functions only modulate light coming from the device. A combination of both spectacles and night-mode functions could further reduce eye exposure to blue light, and this might be the optimal approach.

Further studies are necessary to corroborate our calculations with actual measurements of melatonin concentration in blood and to quantify the sleep disturbances produced by the computed melatonin suppression value. Nonetheless, our findings can be used to support the development of more effective strategies to lower the exposure to short wavelength radiation from electronic display devices. Most importantly, it provides guidance to clinicians when advising their patients about the potential effectiveness of night-mode functions and blue-light–reducing lenses on improving the quality of sleep.

ARTICLE INFORMATION

Supplemental Digital Content: Appendix Table A1. Corresponding figures of merit (median and range) of the spectral radiant powers presented in Figs. 4A and 4B in the paper. Available at http://links.lww.com/OPX/A441.

Appendix Table A2. Figures of merit corresponding to the spectral radiant powers presented in Fig. 5 in the paper. Available at http://links.lww.com/OPX/A441.

Appendix Table A3. Figures of merit of the spectral radiant powers of generic LCD and AMOLED displays, the medians shown in Fig. 4C (full white; reference) in the paper and when viewed through a clear spectacle lens and each of the four blue-light-reducing lenses, whose transmittance is shown in Fig. 7 in the paper. Available at http://links.lww.com/OPX/A441.

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