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Does the smartphone's eye protection mode work?

WENQIAN XU,[1,2,3] PEIYU WU,[1] QI YAO,[1,2,3,*] RONGJUN ZHANG,[1,4] PENGFEI LI,[5] LEIMIN BAO,[6] CHENG WANG,[4] SHENFEI CHEN,[7] YUHUI ZHANG,[1] AND YEDONG SHEN[1]

[1] *Academy for Engineering and Technology, Fudan University, Shanghai 200433, China*
[2] *State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Ji Lin, China*
[3] *Research and Development Department, Zhongshan Fudan Joint Innovation Center, Guangdong, China*
[4] *Department of Optical Science and Engineering, Fudan University, Shanghai 200433, China*
[5] *Shanghai Tailong Haoguan Lighting Technology Co., Ltd., Shanghai 200062, China*
[6] *CQC Standard (Shanghai) Testing Technology Co., Ltd., Shanghai 200061, China*
[7] *College of Architecture and Urban Planning, Tongji University, Shanghai, 200092, China*
[*] *yaoqi@fudan.edu.cn*

Abstract: People spend about 5-8 hours per day on phones, causing circadian disruption and eye fatigue, thus raising a great need for comfort and health. Most phones have eye protection modes, claiming a potential eye protection effect. To examine the effectiveness, we investigated the color quality, namely gamut area and just noticeable color difference (JNCD), and circadian effect, namely equivalent melanopic lux (EML) and melanopic daylight efficacy ratio (MDER), characteristics of two smartphones: iPhone 13 and HUAWEI P30, in normal and eye protection mode. The results show that the circadian effect is inversely proportional to color quality when the iPhone 13 and HUAWEI P30 changed from normal to eye protection mode. The gamut area changed from 102.51% to 82.5% sRGB and 100.36% to 84.55% sRGB, respectively. The EML and MDER decreased by 13 and 15, and, 0.50 and 0.38, respectively, affected by the eye protection mode and screen luminance. The EML and JNCD results in different modes show that the eye protection mode benefits the nighttime circadian effect at the cost of the image quality. This study provides a way to precisely assess the image quality and circadian effect of displays and elucidates the tradeoff relationship between them.

1. Introduction

Computers, smartphones, and tablets play an irreplaceable role in our work and life [1]. Statistics show that by 2018, the Chinese daily smartphone usage time reached 115 mins. By 2019 and 2020, they spent 198 mins and 210 mins per day on their phones. In modern life, people are used to looking at the electronic screen for a long time after turning off the light. Recently investigators [2] have examined 844 subjects' smartphone usage time before going to bed. Almost 56.3% of subjects used smartphones within 1 hour after lights out, 9.8% used smartphones after midnight, and 31.2% did this between these two points of time. It might cause visual and circadian issues by using these devices for a long time. About 78% of the 2,012 people surveyed by Slep Junkie admitted to 'revenge sleep procrastination', with the average time taken to fall asleep after playing with their phones before bed averaging one hour. The use of optoelectronic devices at night reduced the proportion of rapid eye movement [3] sleep from 23% to 14%.

At present, display technologies are used in electronic devices including liquid crystal display (LCD) and organic light emitting diode (OLED) [4]. LCD is a liquid crystal display technology using a light-emitting diode (LED) as the backlight source. While most mobile displays are still LCD-based, OLEDs have been capturing a rapidly increasing share of the market [5]. Compared

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with LCD, OLED displays images based on the mixed principle of R, G, and B primary colors in different proportions. It is a self-luminous screen with advantages such as high flexibility, wide viewing angle, bright color, high contrast, and wide gamut [6]. It has become a hot choice for mainstream high-end smartphones. OLED can be classified as passive matrix organic light-emitting diode (PMOLED) and active-matrix organic light-emitting diode (AMOLED) [7]. AMOLED originated from the Samsung company. Each pixel is equipped with a thin film transistor with a switch. Such panels are widely used in consumer electronic products [8]. PMOLED, which has low manufacturing costs and fast response speed, is of great potential in displaying simple microdevices. However, its disadvantages are high power consumption, reduced life, and a limitation of product size of 5 inches [9].

Light can regulate a variety of physiological functions, such as biological rhythms, sleep, arousal, cognition, and emotion [10], which changes with the duration, wavelength, and intensity of light [11]. These non-visual responses originate via a specialized class of retinal neurons, the intrinsically photosensitive retinal ganglion cells (ipRGCs) [12]. These cells have their intrinsic sensitivity to light and combine this intrinsic melanopic input with rod and cone inputs [13]. Since the discovery of ipRGCs, different action spectra and metrics have been proposed to estimate the potential melanopic contribution of lighting. Lucas et al. quantified the input from the different photoreceptor classes to non-visual systems via the α-opic metric in 2017 [14]. The metric can be used to calculate illuminance integrated within the intrinsic spectral sensitivity functions of rods, cones, and ipRGCs from any light spectra [15]. The frequency and duration of using light-emitting devices after lights out will suppress the hormone of melatonin and affect circadian health, leading to poor sleep quality, daytime sleepiness, insomnia, and other symptoms [16]. Long-term diurnal rhythm disorder will increase the risk of chronic diseases. Therefore, health display has a great application value for the rhythm health of the whole age population.

Manufacturers began to provide eye protection modes to filter blue light through hardware and software techniques. The software technique reduces the blue light component by reducing the correlated color temperature (CCT) and luminance of the screen manually [17]. This might degrade users' viewing experience. The hardware technique is more inclined to hardware adjustment, by fine-tuning the LED backlight to change the peak wavelength of blue light from 450 nm to 460 nm. This method is more thorough and can filter out about 85% blue light without causing the screen yellowing effect, but it is difficult to popularize due to its high cost [18].

So far, there have been few discussions about the effects of eye protection mode. Surveys such as the American Lighting Research Center studied the inhibitory effect of iPad night shift mode on melatonin in 2017 [19]. Based on the circadian stimulus model proposed by Mark Rea et al. [20], changing the spectral composition of self-luminous displays, without changing their luminance settings, may be insufficient for preventing impacts on melatonin suppression. Another research conducted by Duraccio showed that the eye protection mode of the iPhone might not improve sleep quality [21].

Although there has been some progress in eye protection research, the influence of eye protection mode on circadian effect and image quality relation had not been studied. Does the eye protection mode work? We made investigations of the optics characteristics of two smartphones, the iPhone 13 and HUAWEI P30, in normal and eye protection mode. There are two primary aims. Firstly, to investigate the non-visual effects on human rhythm and potential damage reduction in eye protection mode. Secondly, to examine the tradeoff between the circadian rhythm effect and image quality based on the color gamut area and JNCD approach.

2. Performance of smartphone screens

To verify whether the eye protection modes of smartphones work or not, we focus on efficiency, blue light damage, circadian effect, and color quality performance. These performances correspond to some parameters, luminous efficacy of radiation (LER), luminous efficacy (LE), blue light hazard (BLH), equivalent melanopic lux (EML), melanopic daylight efficacy ratio (MDER), gamut, and just noticeable color difference (JNCD).

The efficiency performance is mainly determined by two parameters, LER and LE. The LER is used to describe the efficiency characteristic of the screen on human eyes and is determined by the spectral power distributions of the screen [22], defined as Eq. (1), where V(λ) is the photopic vision sensitivity curve as shown in Fig. 1 and the constant $K_m = 683$ lm/W represents the maximum spectral luminous efficacy regarding the visual system, and the P(λ) refers to the spectral power distributions of light emitted from a smartphone screen. The LE is normally used as the conversion efficiency from electrical power to optical power (called radiant efficiency) [23] and the formula is shown as Eq. (2), where Φ_v is luminous flux and P is the power consumed by the light source.

$$LER = \frac{K_m \int_{380}^{780} P(\lambda)V(\lambda)d\lambda}{\int_{380}^{780} P(\lambda)d\lambda} \tag{1}$$

$$LE = \frac{\Phi_V}{P} \tag{2}$$

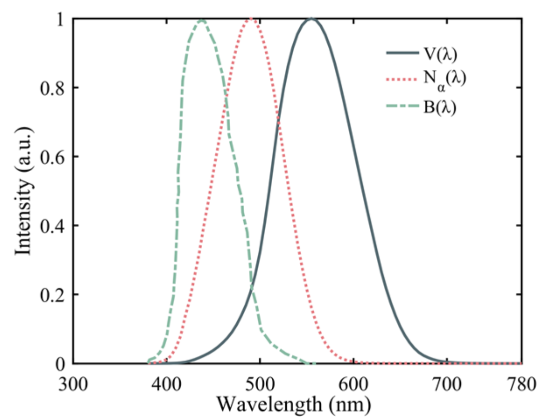

Fig. 1. Response functions of human eyes to visible light. V(λ), B(λ), and N_α (λ) are the action spectra of photopic vision, blue light hazard, and melanopic effect peaked at 555, 437, and 490 nm, respectively.

Blue light has a relatively short wavelength and may cause potential retina damage when reaching the exposure limit value [24]. The BLH refers to the damage to the retina caused by 400-500 nm short-wave blue light and we use the proportion of blue light R_B in the range of wavelength 400-500 nm to characterize the intensity of the BLH [25]. The calculation formula is shown in Eq. (3). The B(λ) refers to the weighting factor function of BLH as shown in Fig. 1, and the light in the 400 to 500 nm range takes about $\int_{400}^{500} B(\lambda)d\lambda / \int_{380}^{780} B(\lambda)d\lambda = 0.956$. Therefore, B(λ) can be approximated as 1 in the range of wavelength 400-500 nm and as 0 in the other range. The proportion of blue light R_B in the range of wavelength 400-500 nm might indicate the impact of BLH.

$$R_B = \frac{\int_{400}^{500} P(\lambda)d\lambda}{\int_{380}^{780} P(\lambda)d\lambda} \tag{3}$$

Circadian effect of light is a hot topic in the past decades, and several indexes have been proposed, of which EML and MDER are more recognized. The EML is calculated by multiplying the photopic illuminance by the melanopic ratio as shown in Eq. (4) [26], where $E_{e,\lambda}(\lambda)$ refers to the photopic illuminance that can be perceived by the human eye, and N_α (λ) in Fig. 1 is the melanopic action spectrum representing the normalized relative spectral sensitivity of the ipRGC photoreceptor to optical radiation incident at the cornea developed by Lucas et al. [14]. The MDER is proposed by CIE S 026 to determine the biological potential for a light spectrum to activate melanopsin relative to visual illuminance [27]. As shown in Eq. (5) and Eq. (6), the MDER is the ratio of the melanopic efficacy of luminous radiation (MELR) for a test source, $K_{mel,v}$, to the MELR for D65 daylight, $K_{mel,v}^{D65}$. The $K_{mel,v}$ defines the melanopic irradiance of a test light, E_{mel}, divided by its illuminance, E_v. Superscript indicates the illuminant, being either the source (empty superscript) or D65. Although EML and MDER describe similar effects, EML is more likely to be an absolute value, and MDER is a relative value in terms of spectrum. BLH, EML, and MDER are all related to the short wavelength part and may be highly correlated to each other under specific conditions.

$$EML = 72983.25 \int_{380}^{780} E_{e,\lambda}(\lambda) N_{\alpha}(\lambda) d\lambda \tag{4}$$

$$MDER = \frac{K_{mel,v}}{K_{mel,v}^{D65}} \tag{5}$$

$$K_{\mathrm{mel},v} = \frac{E_{mel}}{E_v} = \frac{\int E_{e,\lambda}(\lambda) N_{\alpha}(\lambda) d\lambda}{K_m \int P(\lambda) V(\lambda) d\lambda} \tag{6}$$

Color quality directly affects the visual perception of users, which can be measured by gamut and JNCD. Gamut is defined as a chromaticity area surrounded by triangles, and its area represents the color reproduction ability of display technology [28]. The standard sRGB gamut is one of the early gamut standards based on the CIE 1931 chromaticity diagram and was used as a reference for the variation of gamut coverage [29]. The JNCD is the smallest unit of color variance that the human eye can distinguish [30]. JNCD offers an accurate and objective way to evaluate the color accuracy of a display in terms of the eye's sensitivity to color [31]. The calculation formulas are Eq. (7) and Eq. (8), and the calculated angular color shift (Δu'v') values are easily transformed into JNCD [32]. When viewing the screen during the day or at night, a color shift in the case of less than 3-4 JNCDs is not visually noticeable on a display by the human eye [33]. The gamut area is an overall description of a display's color quality and has been widely used, while JNCD could measure the color quality of a given image at the pixel level.

$$\Delta u'v' = \sqrt{(u_2' - u_1')^2 + (v_2' - v_1')^2} \tag{7}$$

$$\mathrm{JNCD} = \frac{\Delta u'v'}{0.004} \tag{8}$$

3. Method

3.1. Test samples

In this study, we analyzed the data collected from iPhone 13 and HUAWEI P30. Table 1 lists the specifications and attributes of the two smartphones. Both phones adopt the AMOLED screen produced by Samsung or LG company, which supports a DCI-P3 gamut with ultra-high contrast and luminance.

3.2. Measurement of spectral power distributions, corneal illuminance, luminous flux, and power consumption of smartphone screens

Experiments were carried out in a dark room (< 5 lx at eye level) to avoid interference from stray light. Smartphone screen is set at normal and eye protection modes and eye protection modes embody cold, moderate, and warm mode, respectively. As shown in Table 2, the display luminance is kept at 100% level, four graphs white (255, 255, 255), red (255, 0, 0), green (0, 255, 0), and blue (0, 0, 255) are displayed in sequence. A hyperspectral imaging camera (SR-5000, TOPCON) and an illuminometer (IM-1000, TOPCON) optical measuring device were vertically positioned at the center of the screen, 40 cm away from the screen as shown in Fig. 2. By adjusting the integration time, the spectral data (380-780 nm, 1 nm interval) of each pixel of the two smartphone screens were collected to form a cube image of 1.4 million resolution (1376 × 1024). These data were used to calculate the LER, BLH, CCT, and JNCD. The corneal illuminance and spectrum at 40 cm from an observer's view using an illuminometer were also obtained. These data were used to calculate the EML and MDER.

There are few ways to measure the luminous flux of a smartphone screen. In this work, we projected the screen's light on the area with mesh segmentation and measured the illuminance at the joint of mesh segmentation. We roughly obtain the luminous flux by integrating the illuminance and area. A POWER-Z power detector is used to obtain the power consumption of smartphones. Generally, the power consumption of the OLED display accounts for about 26.33% of the smartphone's [34]. We used these data for an estimation of the smartphone screens' LE.

Table 1. Specifications and properties

	iPhone 13	HUAWEI P30
Display technology	AMOLED	AMOLED
Display manufacturer	Samsung /LG	Samsung /LG
Screen diagonal (in.)	6.1	6.1
Frequency (Hz)	90	60
Gamut	DCI-P3	DCI-P3
Display resolution	2532 × 1170	2340 × 1080
Pixels per inch (PPI)	460	422

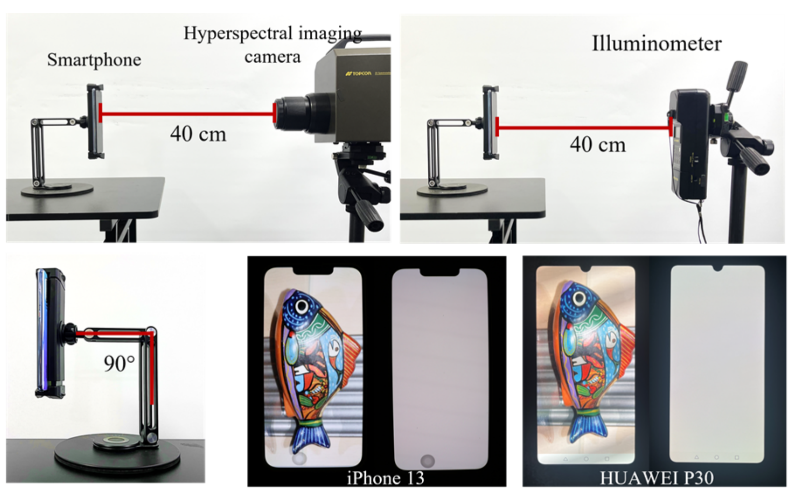

Fig. 2. Measurement of spectral power distributions and corneal illuminance of smartphone screens.

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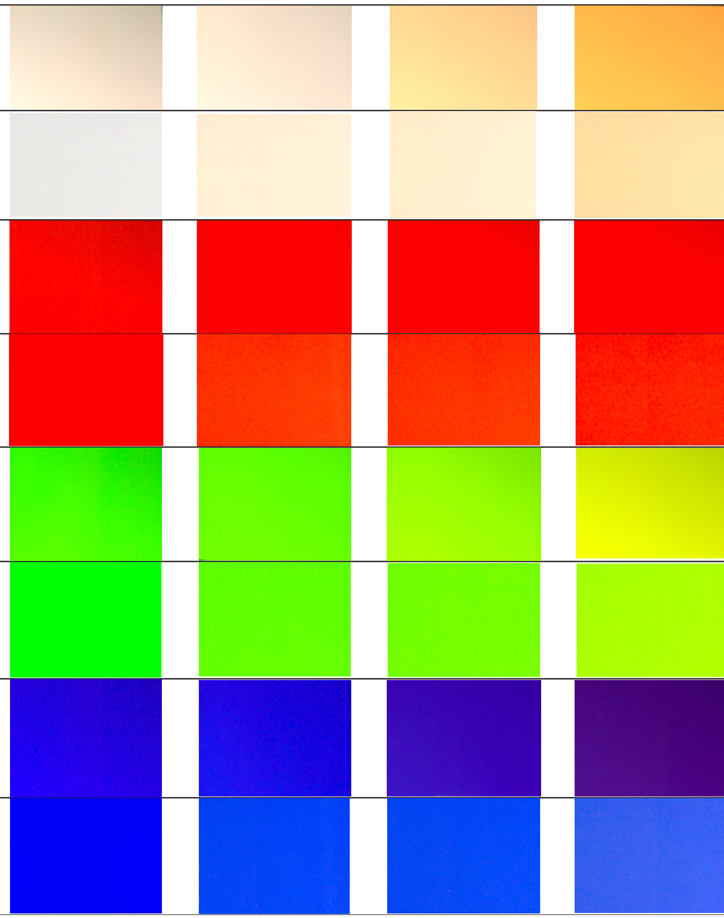
Table 2. Real-time screen in different modes

		Normal	Cold	Moderate	Warm
White	iPhone 13				
	HUAWEI P30				
Red	iPhone 13				
	HUAWEI P30				
Green	iPhone 13				
	HUAWEI P30				
Blue	iPhone 13				
	HUAWEI P30				



4. Results and discussion

4.1. *Spectral power distributions of smartphone screens*

The spectral power distributions of the two smartphone screens in normal and eye protection modes are shown in Fig. 3. All analyses and calculations are performed using Matlab 2019a.

According to the white light spectrum analysis, the peak wavelengths and full-width at half-maximums are 623/15, 531/13, 464/15 nm for iPhone 13 and 621/35, 525/35, 456/21 nm for HUAWEI P30. The peak wavelength of the blue light is about 460 nm, avoiding the blue light wavelength region of 415-455 nm which may cause the atrophy of the retinal pigment epithelium cells [22]. When changing from normal to warm eye protection mode, the blue light component decreases from 43.69% to 14.20%, the green light component increases from 26.94% to 28.86%, and the red light component increases from 29.37% to 56.94% for iPhone 13. The blue light component decreases from 39.73% to 20.54%, the green light component increases from 32.65% to 34.70%, and the red light component increases from 27.62% to 44.75% for HUAWEI P30.

4.2. *Gamma correction*

The gamma corrections of R, G, and B channels for iPhone 13 and HUAWEI P30 are shown in Fig. 4. We use $y = a \cdot x^{\gamma}$ for the R, G, and B channels to complete gamma corrections. The

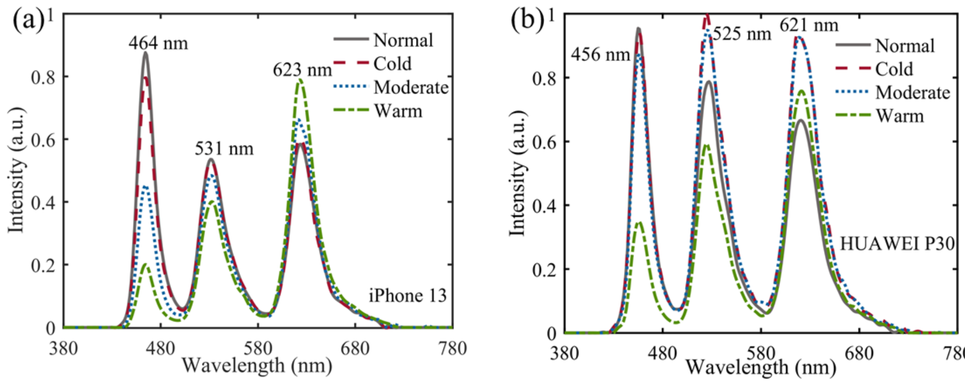


Fig. 3. Measured spectral power distributions of iPhone 13 and HUAWEI P30 in normal and eye protection modes. The green light of HUAWEI P30 is normalized to a maximum of 1, and taken as a reference for other spectral power distributions.

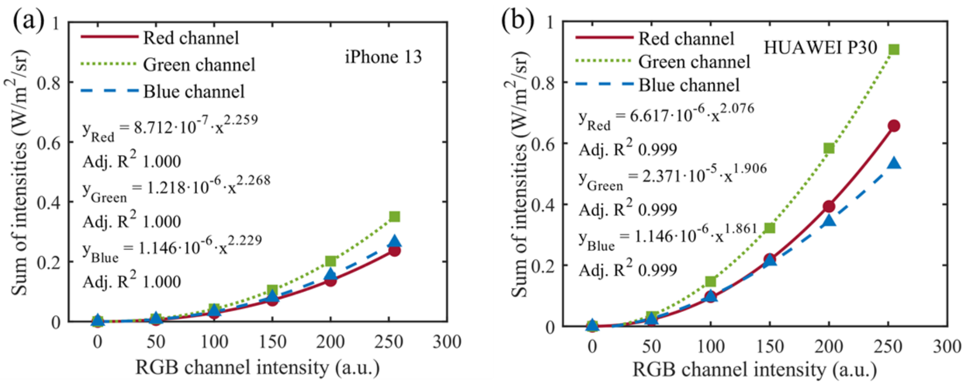


Fig. 4. Sum of spectral radiances as function of gray intensity of red, green, and blue channels. (a) iPhone 13; (b) HUAWEI P30.

y-axis represents the sum of the spectral intensities for each channel, the x-axis represents the gray intensity from 0 to 255, parameter a is the coefficient, and γ is the gamma correction coefficient. Typically, a display device has a gamma greater than 1.0, and the standard of the National Television System Committee recommends a gamma of 2.2 [35]. The gamma values of three channels for the two phones are around 2.2 with a high goodness of fit of adjusted R^2 value closing to 1.

4.3. Assessment of LER, BLH, EML, MDER, and CCT performances

The screen spectra and luminance parameters were measured using a hyperspectral imaging camera. We calculate the LER, BLH, EML, MDER, and CCT of the two smartphones in different modes, the data are presented in Fig. 5. It is clear that the highest luminance and blue light spectral irradiance occur from a white screen. Any other colors are generated by removing part of the emission from the device. The following discussion takes the white screen as an example when the two smartphones change from normal to warm eye protection mode. The LER increases from 279 to 300 lm/W and 282 to 309 lm/W, and the luminance decreases from 240 to 146 cd/m^2 and 515 to 452 cd/m^2, for iPhone 13 and HUAWEI P30, respectively. The LE increases from

15.8 lm/W to 30.5 lm/W and from 12.4 lm/W to 21.2 lm/W for iPhone 13 and HUAWEI P30. The LE is affected by the luminance, quantum efficiency of the chip, and light composition.

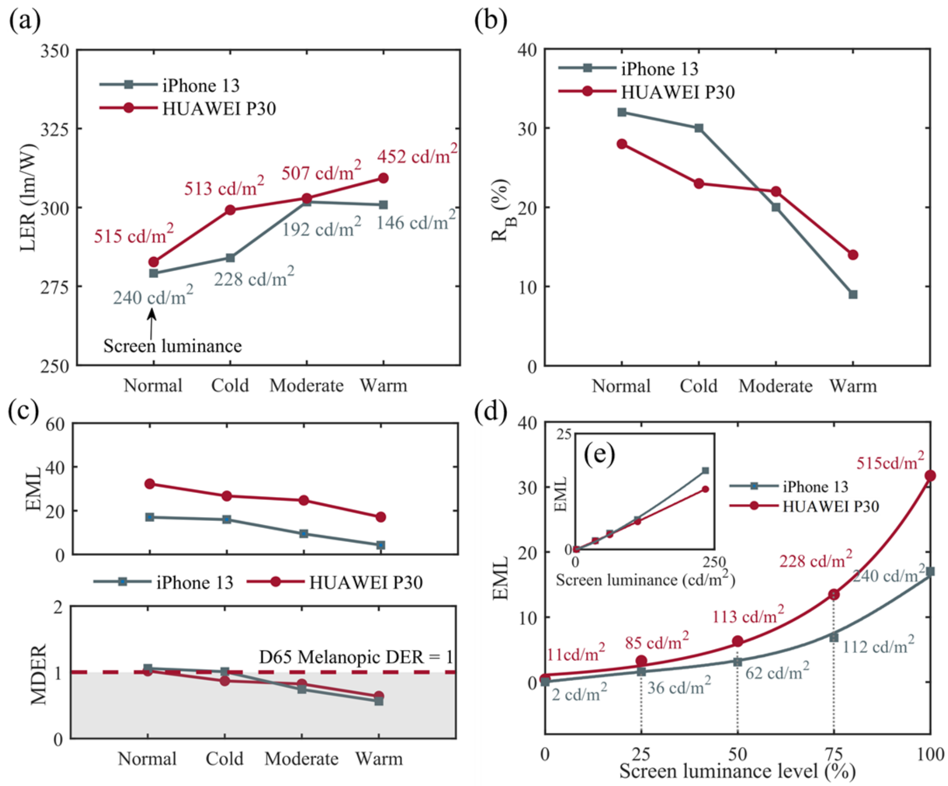


Fig. 5. Change of performances for iPhone 13 and HUAWEI P30: (a) LER; (b) R_B; (c) EML and MDER; (d) screen luminance level and EML; (e) screen luminance and EML.

As to BLH, the R_B changes from 33% to 10% and 29% to 14% for iPhone 13 and HUAWEI P30. The R_B decreases by 23% and 15% for the two smartphones, respectively. As is suggested, the lower the R_B the safer for the human eye. From the above analysis, eye protection mode can reduce the amount of blue light to some extent.

In this section, the EML is calculated from the corneal spectrum. The EML decreases from 17 to 4 and 32 to 17 for iPhone 13 and HUAWEI P30, respectively. Schlangen et al. proposed and modeled a sigmoidal relation between melatonin suppression and melanopic illuminance [36]. They revealed that melatonin suppression is predicted to be 10%, 50%, and 90% melatonin suppression occurring at 1.5 EML, 21 EML, and 305 EML, respectively. According to this model, melatonin suppression drops from about 46% to 21% and 57% to 46% for iPhone 13 and HUAWEI P30, namely a 25% and 11% decrease, respectively. Activating the eye protection mode reduces melanopic illuminance may benefit the secretion of melatonin. The EML content in smartphone displays has been shown not only to suppress melatonin but also to induce circadian phase-shifting and impact sleep and alertness. The EML of displays should be lowered as much as possible from the perspective of reliving the circadian rhythm effect at nighttime.

We use CIE S 026 α-opic toolbox [37] to calculate the MDER. When changing from normal to eye protection mode, the MDER decreases from 1.06 to 0.56 and 1.02 to 0.64 for iPhone 13 and HUAWEI P30, respectively. This result is attributed to the spectral sensitivity of melatonin which is more sensitive to short wavelengths (in the region of blue). Light emission with spectral content which is rich in short wavelength radiation inhibits the secretion of melatonin, thus boosting alertness. By definition, MDER is normalized to 1 for the reference illuminant D65 [38] and the MDER of both two smartphones dropped below 1, which reflected the difference between the observed smartphone's screen light and D65. A higher MDER value indicates the light source's higher capability to stimulate the ipRGC [39]. The eye protection modes have a beneficial effect on the nighttime human circadian rhythm.

Screen luminance has a great impact on EML and we analyze the relationship between EML and screen luminance in normal mode as shown in Fig. 5(d). Section 4.2 have verified that gamma values for both two smartphones are close to 2.2. When the screen luminance changes from 0% to 100% level, the EML increases from 0.04 to 17 and 0.5 to 32, and, melatonin suppression increases from about 1% to 46% and 5% to 57%, for iPhone 13 and HUAWEI P30, respectively. A low screen luminance may be better for avoiding adverse impacts on melatonin secretion and circadian system. However, it is expected that low luminance settings are more likely to cause eye fatigue [40]. Zhou et al. proposed that screen luminance levels should be in 20.63-75.15 cd/m^2 to obtain optimal subjective feelings of visual fatigue and visual comfort during the evening [41]. Thus, the suitable screen luminance range at night is 15%-60% level and 5%-30% level, and, the melatonin suppression changes [36] from 6% to 18% and 8% to 22% for iPhone 13 and HUAWEI P30, respectively.

When the screen luminance changes from 0% to 100% level as shown in Fig. 5(d), the luminance of HUAWEI P30 (11-515 cd/m^2) is much higher than that of iPhone 13 (2-234 cd/m^2) and the EML of HUAWEI P30 is generally high. Taking the screen luminance range of iPhone 13 as a reference, we compare the EML of the two phones in the same luminance range as shown in Fig. 5(e). When the screen luminance changes from 2 to 234 cd/m^2, the EML increased from 0.04 to 17 and 0.5 to 13, and, the melatonin suppression [36] increases from about 1% to 46% and 5% to 42%, for iPhone 13 and HUAWEI P30, respectively. The iPhone 13's low EML is mainly attributed to low screen luminance.

From the normal to warm eye protection mode, the decrease of blue light component leads to a decrease of CCT. The CCT changes from 6534 to 2762 K for iPhone 13, and from 6389 to 3500 K for HUAWEI P30, respectively, as shown in Fig. 6. Shamsul et al. proposed that the 3000-5500 K range is the intermediate CCT with a soft light line. If it is too high or low, it will be bluish or yellowish [42]. People prefer warm colors and bright lighting and the most comfortable and relaxed light situation was at 3000 K with warm color [43]. Thus, the warm eye protection mode may bring comfort.

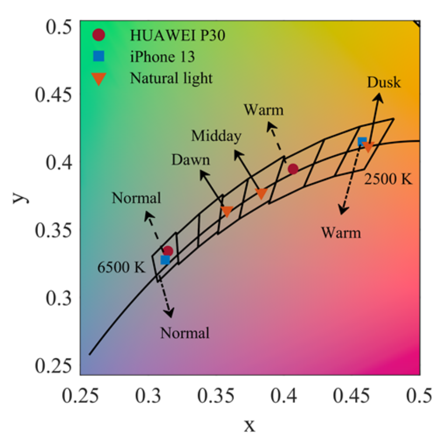


Fig. 6. CCT representation in CIE 1931 XYZ chromaticity diagram.

4.4. Properties of gamut and color drift

The color gamut of the two smartphones in the CIE 1931 chromaticity diagram is shown in Fig. 7(a)-(b). As described in Fig. 7(c), in different modes, the gamut area changes are 102.51%, 102.41%, 99.46%, and 82.50% sRGB for iPhone 13, and 100.36%, 94.02%, 91.79%, and 84.55% sRGB for HUAWEI P30. The gamut decreases with the increase of eye protection mode level.

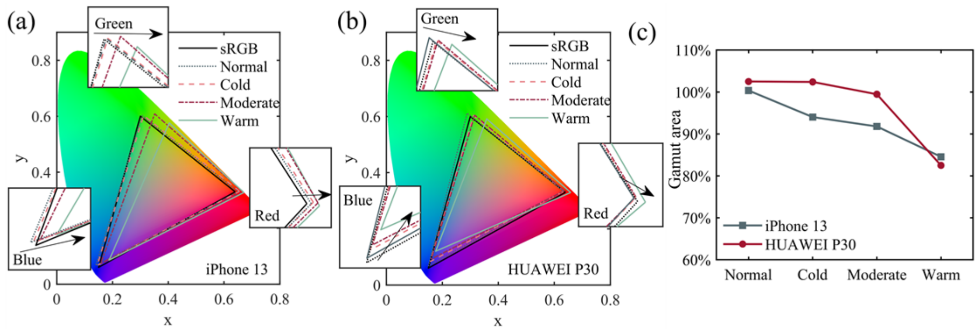


Fig. 7. Variation of color gamut and drift of red, green, and blue chromaticity points in CIE 1931 chromaticity diagram in normal and eye protection modes of (a) iPhone 13, and (b) HUAWEI P30; (c) the change of gamut area of two smartphones in different modes.

When the two smartphones change from normal to warm eye protection mode, the red, green, and blue chromaticity points all drifted in the CIE 1931 chromaticity diagram. There is a great deviation in green, and blue color, and a small deviation in red color. The degree of deviation directly affects the color accuracy.

4.5. Evaluation of image quality and EML/MDER

Compared with the original test image, we analyze the color changes of each pixel in the test image and EML/MDER under different display settings. Test images are from a public image database that has been used in over 100 studies [44].

The real-time images displayed in normal and warm eye protection mode for iPhone 13 and HUAWEI P30 are shown in Fig. 8(a)-(b). Taking the original image (Fig. 8(c)) as a reference, we calculate the JNCD of displayed at each pixel in both normal and warm eye protection modes, as shown in Fig. 8(d)-(e). It can be seen that the average JNCD of these two smartphones in normal mode is less than 4. However, in the warm eye protection mode, the average JNCD reaches about 22 for iPhone 13 and 13 for HUAWEI P30. Figure 9(a)-(b) shows the chromaticity change of each pixel in the test image of the two smartphones in different modes in the more uniform color CIE 1976 u'v' chromaticity diagram. The original image gamut is used as a reference for the variation of gamut coverage. In normal and warm eye protection modes, the gamut area changes from 80.59% to 39.31% for iPhone 13, and from 83.05% to 52.33% for HUAWEI P30. The JNCD is positively correlated with the level of eye protection mode, and the larger the JNCD is, the greater the deviation of the chromaticity value of each pixel, and the worse the image quality is. This suggests that JNCD can be used as a good index for evaluating the real-time image quality reduction when viewing phones.

We also analyze the relationship between EML/MDER and test image quality (average JNCD) of two smartphones, as shown in Fig. 9(c). As the eye protection mode level rises, the average JNCD increases from 3.8 to 22 and 3 to 13 for iPhone 13 and HUAWEI P30. The EML decreases from 4.7 to 1.3 and 14 to 8, and, the MDER drops from 0.9926 to 0.4402 and 0.9507 to 0.6438, respectively. The higher the level of eye protection mode, the lower the EML and MDER, the larger the JNCD, and the worse the image quality.

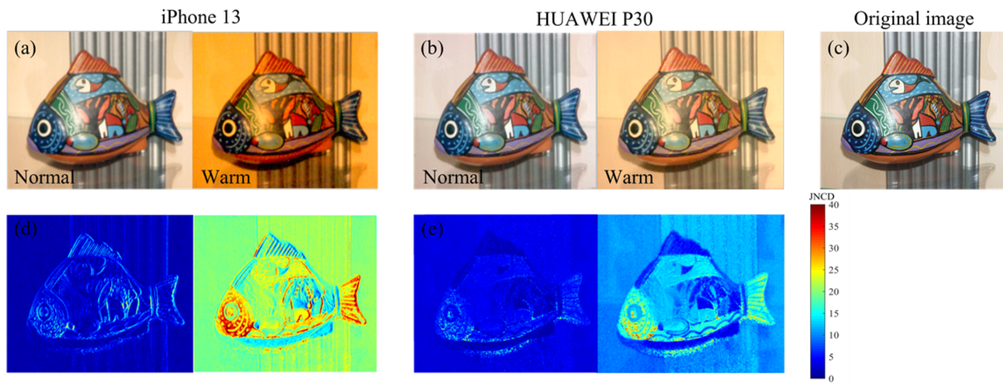


Fig. 8. Image display in normal and warm eye protection mode for (a) iPhone 13, and (b) HUAWEI P30; (c) original image of 384×512 px; JNCD in normal and eye protection mode for (d) iPhone 13, and (e) HUAWEI P30.

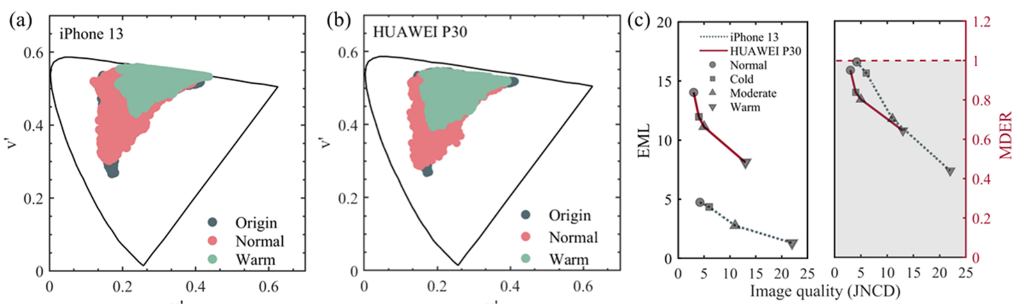


Fig. 9. The chromaticity distribution of each pixel changes in original, normal, and warm eye protection mode for (a) iPhone 13, and (b) HUAWEI P30; (c) the relationship between EML/MDER and image quality.

In general, the eye protection modes of the iPhone 13 and HUAWEI P30 have positive effects at nighttime in terms of blue light damage, circadian effect, and energy consumption as shown in Table 3. However, the color quality decreases with the eye protection level. The results show that the percentage of short wavelength reduces and luminous efficacy improves in the eye protection modes. As to the circadian effect, because EML is proportional to luminance level, we choose the relative value MDER which is not affected by luminance for comparison. The MDER decreases, but JNCD increases with the increase of the eye protection level. This shows that the eye protection mode benefits the nighttime circadian effect at the cost of the color quality performance. The iPhone 13 may perform better in luminous efficacy, while the HUAWEI P30 can reach a higher luminance level. In the warm eye protection mode, iPhone 13 performs better at blue light damage and circadian rhythm performance but worse at color quality than HUAWEI P30. A good eye protection mode requires a comprehensive optimization on both the circadian effect and color quality. There are still a lot of work to reach a better effect for these phones.

Table 3. LER, LE, luminance, R_B, MDER, and JNCD in different modes for iPhone 13 and HUAWEI P30.

	iPhone 13				HUAWEI P30			
	Normal	Cold	Moderate	Warm	Normal	Cold	Moderate	Warm
LER (lm/W)	279	284	301	300	282	299	303	**309**
LE (lm/W)	15.8	16.2	24.2	**30.5**	12.4	13.9	16.3	21.2
Luminance (cd/m^2)	240	228	192	146	**515**	513	507	452
R_B (%)	33	30	20	**10**	29	23	22	14
MDER	1.06	1.01	0.74	**0.56**	1.02	0.87	0.82	0.64
JNCD	3.8	4.5	10.2	**22**	3	5.1	8.1	13

5. Conclusions

In this study, we evaluate the efficacy, blue light damage, circadian effect, and color quality of two smartphones, iPhone 13 and HUAWEI P30, in normal and eye protection mode. We can reach the following conclusions.

Firstly, the eye protection mode of the two smartphones is realized by changing the screen spectra and luminance. Screen luminance and the blue light components in the spectra gradually decrease with the increase of eye protection mode level, which reduces the damage of blue light radiation to eye health to a certain extent. Secondly, the BLH, EML, MDER, and CCT characteristics all decrease when changing from normal to eye protection mode of two smartphones. The eye protection mode mainly minimizes the light impact on melatonin suppression by reducing melanopic illuminance. Lastly, both the gamut and JNCD are good indicators to evaluate the effect of eye protection mode on image quality. The color gamut could indicate the color of a phone that could present in a given mode, while the JNCD could indicate the color quality of a given image. The higher the level of eye protection mode, the larger the JNCD, the more significant the color difference, and the worse the image quality.

The red, green, and blue light components of the spectrum and the change of luminance are related to the phone model. When changing from normal to eye protection mode, the blue light ratio decreased to 23% for the iPhone13, and 15% for the HUAWEI P30. The luminance decreased by 94 cd/m^2 for iPhone 13, and 63 cd/m^2 for HUAWEI P30. Differences in the adjustment mechanism might affect the effectiveness of the eye protection mode. In summary, the eye protection mode benefits circadian rhythm at night and reduces blue light damage to a certain degree, but at the cost of image quality. Our work for the first time quantifies the light impact on the circadian rhythm and image quality reduction. The work elucidates the tradeoff between the circadian effect and image quality and may greatly improve the display in a healthier and more eye-friendly way. From this study, although the eye protection modes of these two phones work, they lack of a better optimization strategy. None of these phones have intuitive and friendly user interfaces for adjustments and presentation of optics characteristics. Optimizations are required regarding color quality and circadian effect, and optimization strategy should be adapted to a change of the displayed images.

There are still some limitations in this work. Firstly, the experiment is carried out in a completely dark room, and the ambient light is not involved. Secondly, users viewing time and dose are not included in this work.

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Data availability. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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References

1. L. Exelmans and J. V. D. Buick, "Bedtime mobile phone use and sleep in adults," Soc. Sci. Med. **148**(24), 93–101 (2016).
2. T. Munezawa, Y. Kaneita, Y. Osaki, H. Kanda, M. Minowa, K. Suzuki, S. Higuchi, J. Mori, R. Yamamoto, and T. Ohida, "The association between use of mobile phones after lights out and sleep disturbances among Japanese adolescents: a nationwide cross-sectional survey," Sleep **34**(8), 1013–1020 (2011).
3. J. F. Gagnon, R. B. Postuma, S. Mazza, J. Doyon, and J. Montplaisir, "Rapid-eye-movement sleep behavior disorder and neurodegenerative diseases," Lancet Neurol. **5**(5), 424–432 (2006).
4. Y. Huang, E. L. Hsiang, M. Y. Deng, and S. T. Wu, "Mini-LED, Micro-LED, and OLED displays: present status and future perspectives," Light: Sci. Appl. **9**(1), 1–16 (2020).
5. W. Y. Choi, "A highly power-efficient LED back-light power supply for LCD display," J. Disp. Technol. **9**(5), 382–387 (2013).
6. J. Wu, M. Wei, Y. Fu, and C. Cui, "Color mismatch and observer metamerism between Liquid Crystal Displays and Organic Light Emitting Diode Displays," Opt. Express **29**(8), 12292–12306 (2021).
7. N. Sain, D. Sharma, and P. Choudhary, "A review paper on: organic light-emitting diode (oled) technology and applications," Int. J. Eng. Appl. Sci. Technol **4**(11), 587–591 (2020).
8. H. Ma, Z. Liu, S. Heo, J. Lee, K. Na, B. J. Han, S. Jung, K. Park, J. J. Kim, and F. Bien, "On-display transparent half-diamond pattern capacitive fingerprint sensor compatible with AMOLED display," IEEE Sens. J. **16**(22), 8124–8131 (2016).
9. T. Umeda, Y. Tsukamoto, B. Zhang, T. Jo, H. Imada, S. Kawato, and S. Mitsui, "Late-News Paper: Low-Power-Consumption Flexible AMOLED Display with Highly Efficient TE-Type Blue OLED," Dig. Tech. Pap. - Soc. Inf. Disp. Int. Symp. **50**(1), 54–57 (2019).
10. A. S. Fisk, S. K. E. Tam, L. A. Brown, V. V. Vyazovskiy, D. M. Bannerman, and S. N. Peirson, "Light and cognition: roles for circadian rhythms, sleep, and arousal," Front. Neurol. **9**(9), 1–18 (2018).
11. M. S. Rea, M. G. Figueiro, A. Bierman, and J. D. Bullough, "Circadian light," J. Circadian Rhythms **8**(1), 1–10 (2010).
12. T. Brown, G. Brainard, C. Cajochen, C. Czeisler, J. Hanifin, S. Lockley, R. Lucas, M. Munch, J. O'Hagan, and S. Peirson, "Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults," PLoS Biol. **20**(3), e3001571 (2022).
13. F. H. Zaidi, J. T. Hull, S. N. Peirson, K. Wulff, D. Aeschbach, J. J. Gooley, G. C. Brainard, K. G. Evans, J. F. Rizzo, C. A. Czeisler, R. G. Foster, M. J. Moseley, and S. W. Lockley, "Short-wavelength light sensitivity of circadian, pupillary, and visual awareness in humans lacking an outer retina," Curr. Biol. **17**(24), 2122–2128 (2007).
14. R. J. Lucas, S. N. Peirson, D. M. Berson, T. M. Brown, H. M. Cooper, C. A. Czeisler, M. G. Figueiro, P. D. Gamlin, S. W. Lockley, J. B. O'Hagan, L. L. A. Price, I. Provencio, D. J. Skene, and G. C. Brainard, "Measuring and using light in the melanopsin age," Trends Neurosci. **37**(1), 1–9 (2014).
15. R. Soler and E. Voss, "Biologically relevant lighting: An industry perspective," Front. Neurosci. **15**, 637221 (2021).
16. K. Wulff, S. Gatti, J. G. Wettstein, and R. G. Foster, "Sleep and circadian rhythm disruption in psychiatric and neurodegenerative disease," Nat. Rev. Neurosci. **11**(8), 589–599 (2010).
17. W. Dawson, T. Nakanishi-Ueda, D. Armstrong, D. Reitze, D. Samuelson, M. Hope, S. Fukuda, M. Matsuishi, T. Ozawa, and T. Ueda, "Local fundus response to blue (LED and Laser) and infrared (LED and laser) sources," Exp. Eye Res. **73**(1), 137–147 (2001).
18. K. A. Solhaug, L. Xie, and Y. Gauslaa, "Unequal allocation of excitation energy between photosystem II and I reduces cyanolichen photosynthesis in blue light," Plant Cell Physiol. **55**(8), 1404–1414 (2014).
19. R. Nagare, B. Plitnick, and M. G. Figueiro, "Does the iPad Night Shift mode reduce melatonin suppression?" Ligh: Res. Technol. **51**(3), 373–383 (2019).
20. M. S. Rea, M. G. Figueiro, J. D. Bullough, and A. Bierman, "A model of phototransduction by the human circadian system," Brain Res. Rev. **50**(2), 213–228 (2005).
21. K. M. Duraccio, K. K. Zaugg, R. C. Blackburn, and C. D. Jensen, "Does iPhone night shift mitigate negative effects of smartphone use on sleep outcomes in emerging adults?" Sleep Health **7**(4), 478–484 (2021).
22. Q. Yao, L. Zhang, Q. Dai, Y. Wang, and P. Wu, "Chromaticity-based real-time assessment of melanopic and luminous efficiency of smartphone displays," Opt. Express **28**(4), 4898–4910 (2020).
23. Y. Ohno, "Color rendering and luminous efficacy of white LED spectra," Fourth International Conference on Solid State Lighting **5530**, 88–98 (2014).
24. I. Jaadane, G. V. Rodriguez, P. Boulenguez, S. Carré, I. Dassieni, C. Lebon, S. Chahory, F. Behar-Cohen, C. Martinsons, and A. Torriglia, "Retinal phototoxicity and the evaluation of the blue light hazard of a new solid-state lighting technology," Sci. Rep. **10**(1), 1–13 (2020).
25. C. Yang, W. Fang, J. Tang, Y. Fan, and C. Li, "Change of blue light hazard and circadian effect of LED backlight displayer with color temperature and age," Opt. Express **26**(21), 27021–27032 (2018).
26. Circadian Lighting Design|WELL Standard. Available online: https://standard.wellcertified.com/light/circadian-lighting-design (accessed on 2 August 2020).
27. CIE S 026/E:2018., *CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light*. CIE Central Bureau, Vienna, (2018).

Optics EXPRESS

28. Q. Yao, W. Zhang, L. Zhang, and Y. Bian, "Establishing functional model of photometric performance of trichromatic light sources in chromaticity diagrams," IEEE Photonics J. **10**(4), 1–12 (2018).
29. K. Masaoka and Y Nishida, "Metric of color-space coverage for wide-gamut displays," Opt. Express **23**(6), 7802–7808 (2015).
30. S. Park, T. H. Kim, and Y. Yun, "75-4: Low Luminance JND and JNCD," Dig. Tech. Pap. - Soc. Inf. Disp. Int. Symp. **53**(1), 1021–1023 (2022).
31. J. S. Steckel, J. Ho, C. Hamilton, J. Xi, C. Breen, W. Liu, P. Allen, and S. C. Sullivan, "Quantum dots: The ultimate down-conversion material for LCD displays," J. Soc. Inf. Disp. **23**(7), 294–305 (2015).
32. S. Park, J. T. Lim, W. Y. Jin, H. Lee, B. H. Kwon, N. S. Cho, J. H. Han, J. W. Kang, S. Yoo, and J. I. Lee, "Efficient large-area transparent OLEDs based on a laminated top electrode with an embedded auxiliary mesh," ACS Photonics **4**(5), 1114–1122 (2017).
33. M. H. U. Rashid, M. M. Ahmed, S. Chowdhury, and S. Ahmed, "Effectiveness of visual inspection with acetic acid as a test for cervical cancer screening," J. Intern. Med. **2**(1), 3–7 (2017).
34. L. Corral, A. B. Georgiev, A. Sillitti, and G. Succi, "A method for characterizing energy consumption in Android smartphones," in *2nd International Workshop on Green and Sustainable Software (GREENS), San Francisco, CA, USA* (2013).
35. H. Guo, H. He, and M. Chen, "Gamma correction for digital fringe projection profilometry," Appl. Opt. **43**(14), 2906–2914 (2004).
36. A. S. Prayag, R. P. Najjar, and C. Gronfier, "Melatonin suppression is exquisitely sensitive to light and primarily driven by melanopsin in humans," J. Pineal Res. **66**(4), e12562 (2019).
37. CIE. S 026 a-opic toolbox. Vienna: CIE Central Bureau, 2020. https://doi.org/10.25039/S026.2018.
38. L. J. M. Schlangen and L. L. A. Price, "The lighting environment, its metrology, and non-visual responses," Front. Neurol. **12**, 624861 (2021).
39. M. A. Siraji, V. Kalavally, A. Schaefer, and S. Haque, "Effects of daytime electric light exposure on human alertness and higher cognitive functions: A systematic review," Front. Psychol. **12**, 6079 (2022).
40. P. Kalra and V. Karar, "Effect of brightness on visual fatigue during video viewing," Productivity with Health, Safety, and Environment **1**, 357–363 (2022).
41. Y. Zhou, H. Shi, Q. W. Chen, T. Ru, and G. Zhou, "Investigation of the Optimum Display Luminance of an LCD Screen under Different Ambient Illuminances in the Evening," Appl. Sci. **11**(9), 4108 (2021).
42. B. M. T. Shamsul, C. C. Sia, Y. G. Ng, and K. Karmegan, "Effects of light's color temperatures on visual comfort level, task performances, and alertness among students," Am. J. Public. Health **1**(7), 159–165 (2013).
43. R. Chen, M. C. Tsai, and Y. S. Tsay, "Effect of Color Temperature and Illuminance on Psychology, Physiology, and Productivity: An Experimental Study," Energies **15**(12), 1–23 (2022).
44. G. Schaefer and M. Stich, "UCID: An uncompressed color image database," SPIE **5307**(18), 472–480 (2004).