Received 14 December 2018; revised 30 January 2019; accepted 13 February 2019. Date of publication 15 February 2019; date of current version 8 March 2019.
The review of this paper was arranged by Editor A. Nathan.

Digital Object Identifier 10.1109/JEDS.2019.2899646

Assessment and Optimization of the Circadian Performance of Smartphone-Based Virtual Reality Displays

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This work was supported in part by the Key Science and Technology Project of Fujian Province under Grant 2018H6022, in part by the Strait Post-Doctoral Foundation of Fujian Province, in part by the National Natural Science Foundation of China under Grant 61504112 and Grant 51605404, in part by the Technological Innovation Project of Economic and Information Commission of Fujian Province, and in part by the Natural Science Foundation of Fujian Province under Grant 2018J01103. *(Tingzhu Wu and Shijie Liang contributed equally to this work.)*

ABSTRACT The non-visual effects of blue light in displays mean that excessive use of smartphones can disturb the human circadian rhythm. Thus, the impact of virtual reality (VR) headsets, which are worn closer to the human eye, may be even more serious. In this paper, based on non-visual parameters, such as the circadian action factor (CAF) and circadian illuminance, the circadian performance of smartphone-based VR displays is quantitatively evaluated by an evaluation system we designed. Moreover, we investigate the improvements in the circadian performance of VR headsets resulting from three practical methods for reducing the blue light content. Finally, a theoretical method of shifting the green-light wavelength of the screen close to 555 nm to optimize the CAF of VR headsets is proposed. Overall, the results of this paper are of significant value in quantifying the effects of VR displays on circadian rhythms and improving the safety of VR headsets with regard to human health.

INDEX TERMS Displays, virtual reality, measurement, optimization methods, spectral analysis.

I. INTRODUCTION

In 2002, the intrinsically photosensitive retinal ganglion cells were discovered as the third type of photoreceptors in mammalian retinas [1], [2]. Shortly thereafter, these cells were found to be sensitive to blue light and associated with the secretion of melatonin, which controls the circadian rhythm of human beings [3]. Human eyes not only respond to visual aspects of light, such as color and brightness, but also non-visual aspects such as circadian rhythms [4]. Therefore, light is regarded as a central modulator of circadian rhythms, sleep, and related effects [5].

Light-emitting diodes (LEDs) are widely used in display and lighting applications [6]–[8]. Although the high definition and high brightness of emerging micro-LED displays make them a strong candidate for next-generation display technology [9]–[12], the LED-backlit liquid-crystal display (LCD) and the organic light-emitting diode (OLED) are currently the major display technologies used in the smartphone market [13]. Studies have already demonstrated that blue light from LED lighting and LED-backlit screens can disturb the human circadian rhythm [14]–[16]. In our previous work, we demonstrated that the influence on human circadian rhythms can be evaluated using the circadian action factor (CAF) and circadian illuminance (CIL), and we used multi-color LEDs to develop light sources that reduce both CAF and CIL without affecting visual characteristics [17], [18].

The physical world around us is three-dimensional (3D), yet traditional display devices can show only two-dimensional flat images [19]–[21]. Virtual reality (VR) is an interactive computer-generated experience that takes place within a simulated 3D environment. Smartphone-based

VR headsets display virtual images via the screen of the smartphone [22]. The average distance between the eyes and the screen is around 6 cm, much closer than the distance between the eyes and the screen during typical phone use. Additionally, the lenses embedded in VR headsets are convex. Therefore, it is obvious that a greater amount of light will be irradiated into the eyes under VR scenarios than in most typical mobile phone usage [23]. However, few studies have focused on the relation between human circadian rhythms and VR headsets, especially commercial VR headsets [22].

In this study, we develop an evaluation system to quantitatively assess the circadian performance of commercial VR headsets according to non-visual parameters such as CAF and CIL. This system can calculate the screen brightness threshold (SBT), which is the maximum screen brightness that does not disturb human circadian rhythms. Next, based on CAF, CIL, and SBT, we investigate the improvement of the circadian performance of VR headsets resulting from three practical methods that readily reduce the blue light content. Finally, we propose a theoretical method that shifts the green wavelength of the screen close to 555 nm to further reduce CAF and optimize the circadian performance of VR headsets. In summary, this study can be regarded as an important reference in the future spectral design of circadian-rhythm-friendly VR headsets.

II. THEORY AND OPTIMIZATION GOAL

In this paper, we employ the circadian spectral sensitivity function C(λ) according to Gall's model [17], [24], [25], as depicted in Fig. 1(a), to measure the circadian flux of smartphones and VR headsets. Also shown in this figure is the photopic sensitivity function V(λ), with the peak wavelength at 555 nm, which gauges the spectrally resolved sensitivities of human eyes in a bright environment.

There are several key parameters associated with vision and circadian performance. These are discussed below.

As the degree to which radiant light produces vision, the luminous efficacy of radiation (LER) is defined as the ratio of luminous flux to radiation flux [17], given by

$$LER = 683(lm/W)\frac{\int V(\lambda)S(\lambda)d\lambda}{\int S(\lambda)d\lambda}, \qquad (1)$$

where *S(λ)* denotes the spectral power distribution (SPD) measured by an illuminance meter. Similarly, we can write the circadian efficacy of radiation (CER) as the ratio of the circadian luminous flux to the radian flux [17], indicated as

$$CER = 683(lm/W)\frac{\int C(\lambda)S(\lambda)d\lambda}{\int S(\lambda)d\lambda}. \qquad (2)$$

The CAF, a key parameter of non-visual effects, is defined as the ratio of CER to LER [17], i.e.,

$$CAF = \frac{CER(blm/W)}{LER(lm/W)}. \qquad (3)$$

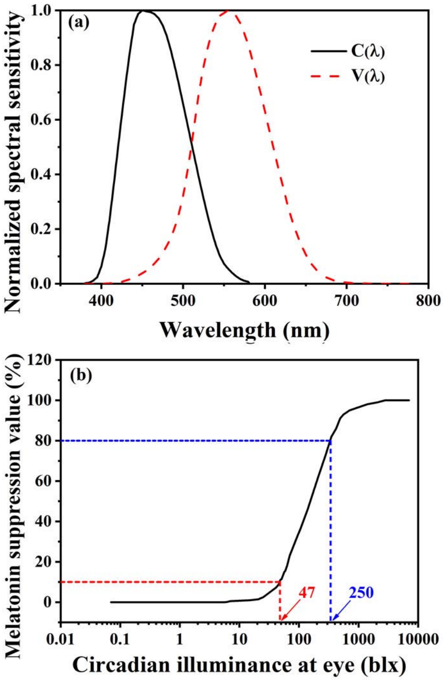

FIGURE 1. (a) Normalized spectra of C(λ) and V(λ), and (b) relation between melatonin suppression value and CIL [17].

Another key parameter of non-visual effects is the CIL, defined as the product of visual illuminance (VIL) and CAF [17]

$$CIL = VIL(lx) \times CAF(blm/lm). \qquad (4)$$

Because of their positive correlation with melatonin suppression, CAF and CIL are key parameters in optimizing the circadian performance of VR. Generally, under the same VIL conditions, higher values of CAF indicate more light energy concentrated on the blue spectral region. This is associated with higher CIL values, leading to melatonin suppression.

The relation between the melatonin suppression value (MSV) and CIL is illustrated in Fig. 1(b) [17], [23], [25]. Melatonin suppression rarely occurs below 47 blx (MSV $\leq$ 10%), whereas 80% of melatonin will be effectively suppressed when the CIL exceeds 250 blx.

To maintain the CIL below 47 blx and prevent VR from affecting the human circadian rhythm, we control the SPD of the screen to minimize CAF. As a result, we can obtain a maximum VIL (47 blx/CAF_{min}) that is positively correlated with screen brightness. Thus, we define the parameter SBT as the largest screen brightness at which CIL does not exceed 47 blx. In summary, the optimization goal of this study is to keep the CIL equal to the threshold of 47 blx and minimize the CAF to obtain improved SBT.

III. EVALUATION SYSTEM

It is vital to quantify the effects of smartphone and VR usage on human health via disrupting circadian rhythms. In this study, we propose an evaluation system for assessing the

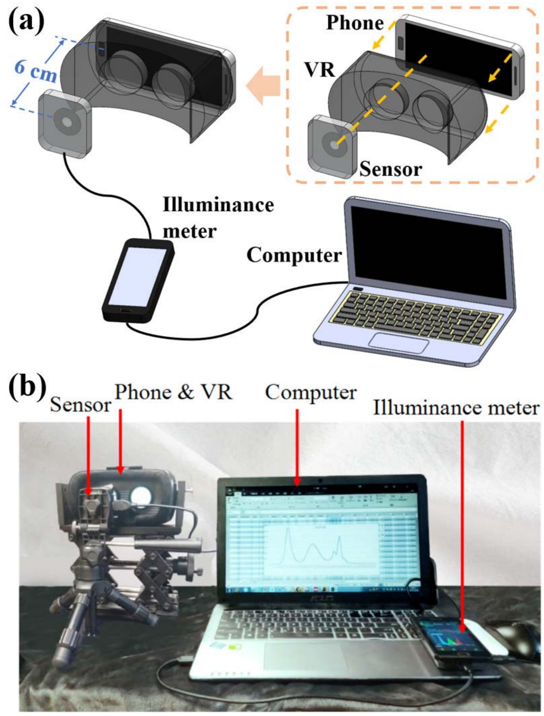

FIGURE 2. (a) Schematic diagram and (b) realistic picture of the evaluation system.

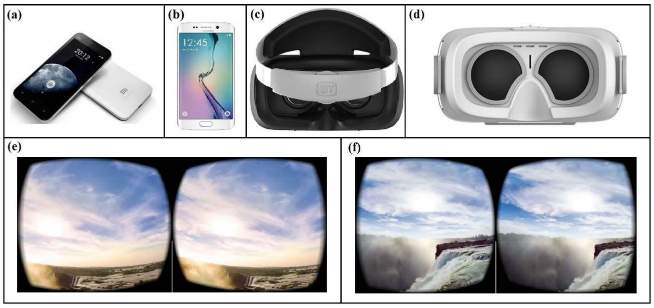

FIGURE 3. Smartphones and VR headsets used in our study (a) Xiaomi phone, (b) Samsung phone, (c) Iqiyi VR headset, (d) Baofeng VR headset. (e) and (f) are screenshots of the video played on the smartphones.

visual and non-visual effects of VR headsets, as illustrated in Fig. 2. A sensor for the illuminance meter (SPIC-200, EVERFINE Co. Ltd.) is on a tripod at a fixed distance of 6 cm from the smartphone screen. A computer is connected to the illuminance meter to control the measurements and receive the data automatically. To prevent noise effects from ambient light, the evaluation system is used in a darkroom.

We used a Xiaomi smartphone with an LCD screen and a Samsung smartphone with an OLED screen to quantitatively evaluate the non-visual effects of two VR headsets (Iqiyi VR and Baofeng VR). The smartphones and VR headsets used in our study are illustrated in Fig. 3. The vision and circadian performance parameters were measured while playing a National Geographic documentary on the smartphones for a total of 108 s, as depicted in Fig. 3(e), (f) [26].

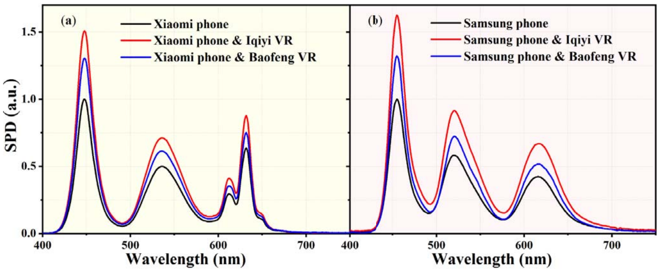

FIGURE 4. (a) SPD curves of Xiaomi phone with and without VR headsets. (b) SPD curves of Samsung phone with and without VR headsets.

The illuminance meter measured the VIL values and SPDs of the VR headsets at intervals of 9 s during the video playback. In this way, we obtained 11 sets of SPDs and VIL values. The data were averaged to calculate the CAF and CIL values, which are the key parameters for vision and circadian performance. Finally, we repeated the measurements by adjusting the screen brightness from 100% to 10% at intervals of 10% in the Android system of smartphones.

IV. RESULTS AND DISCUSSION

A. ASSESSMENT OF CIRCADIAN PARAMETERS OF VR HEADSETS

We investigated the spectroscopic non-visual effects of light from VR headsets by analyzing the SPDs. Fig. 4 depicts the normalized SPD curves of smartphones with and without the VR headsets at 100% screen brightness, with a fixed distance of 6 cm between the sensor and the smartphone screen.

The SPDs exhibit three peaks, located at 448 nm, 535 nm, and 632 nm in Fig. 4(a) and at 455 nm, 520 nm, and 615 nm in Fig. 4(b). In the red-light region, the SPD curves in Fig. 4(a) contain many small peaks and become unsmooth. This is because the LCD screen of the Xiaomi phone utilizes narrow-band red-emitting K_2SiF_6:Mn^{4+} (KSF) phosphors, which significantly improve the color gamut [8], [27].

In Fig. 4, smartphone SPDs are used as reference values, and their peak are normalized to 1. The intensities of the SPDs increase significantly when using the VR headsets. This is because the convex lenses in the VR headsets collect and focus the light emitted from the display onto the eyes. Additionally, every SPD exhibits high blue-light content, which will further affect human circadian rhythms. Therefore, it is necessary to take measures to reduce the intensity of the blue light and further reduce the influence of VR on circadian rhythms.

For each SPD in Fig. 4, we calculated the color performances through the correlated-color temperature (CCT) and chromaticity coordinates (CIE x, CIE y). The average CCT increases by 14.2% when the Xiaomi phone is used with a VR headset, whereas that of the Samsung phone decreases by an average of 1.7% when the VR headsets are applied. These data indicate that the addition of VR headsets has an impact on the shape of the spectrum, which will further affect the CAF value.

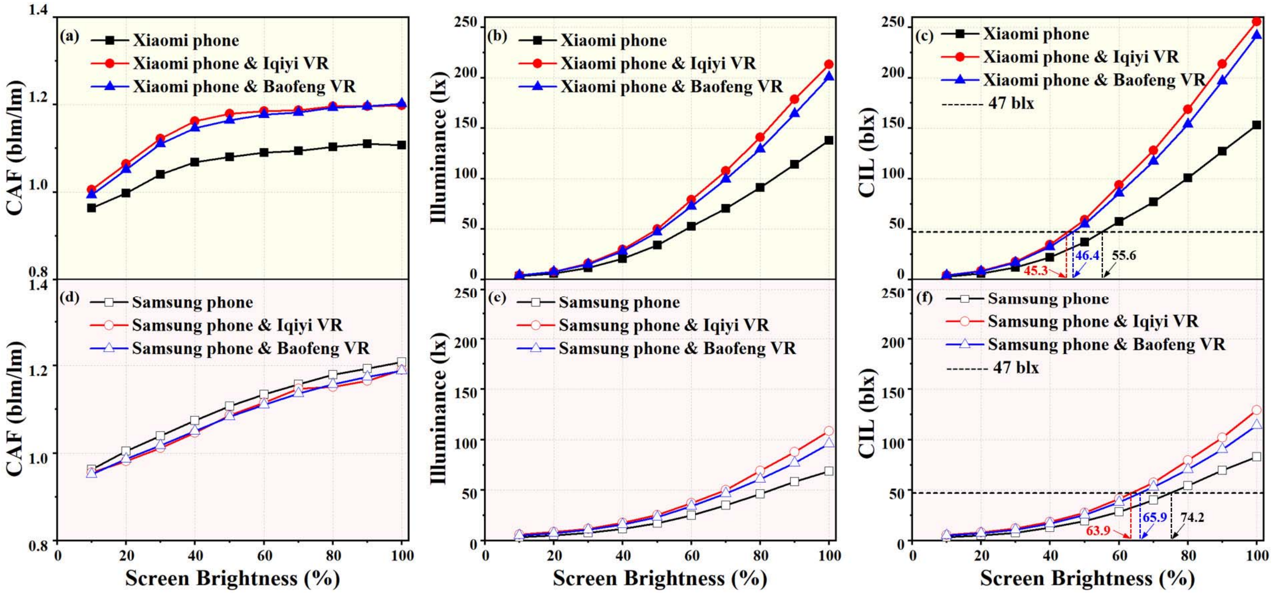

FIGURE 5. (a) CAF, (b) VIL, and (c) CIL for Xiaomi phone with and without VR headsets, (d) CAF, (e) VIL, and (f) CIL for Samsung phone with and without VR headsets.

TABLE 1. Changes in color performance with VR headsets.

Device	CCT (K)	CIE x	CIE y
Xiaomi phone	10163	0.2802	0.2864
Xiaomi phone & Iqiyi VR	11683	0.2739	0.2775
Xiaomi phone & Baofeng VR	11524	0.2744	0.2784
Samsung phone	9035	0.2853	0.2985
Samsung phone & Iqiyi VR	8799	0.2877	0.2990
Samsung phone & Baofeng VR	8968	0.2879	0.2941

According to Fig. 5(a), (d), at 100% screen brightness, using the VR headsets increases the CAF value by an average of 8.1% for the Xiaomi phone, but decreases the CAF value by an average of 1.7% in the Samsung phone. This phenomenon occurs because the blue-light content increases in the light transmitted through VR headsets from the Xiaomi smartphone, but decreases in the case of the Samsung smartphone, according to the different transmittance properties of convex lenses in VR headsets for different wavelengths of light. Moreover, the convex lenses embedded in VR headsets also gather light from the screen, which will greatly increase the VIL, as shown by Fig. 5(b), (e). For example, loading the VR headsets raises the VIL by an average of 67.4% for the Xiaomi phone and 57.8% for the Samsung phone. Based on the CAF and VIL values, we can calculate the CIL using (4) at different levels of screen brightness, as illustrated in Fig. 5(c), (f). In these two figures, our concern is whether the screen brightness affects human circadian rhythms. Therefore, the SBT parameter is the highest screen brightness for which CIL does not exceed 47 blx. If the brightness is below the SBT, the screen does not have a significant effect on melatonin suppression in the human body, and thus does not affect human circadian rhythms. Before loading the VR headsets, as long as the screen brightness of the Xiaomi and Samsung phones does not exceed 55.6% and 74.2%, respectively, human circadian rhythms will not be significantly affected. After loading the VR headsets, the SBTs decrease to an average of 45.9% (Xiaomi phone) and 64.9% (Samsung phone). The CIL curves rise because the VIL values increase more than the CAFs when using VR headsets, meaning that the use of VR headsets is more likely to affect human circadian rhythms under the same screen brightness.

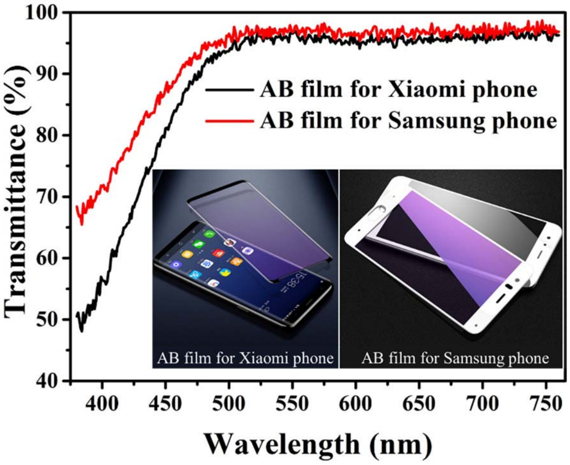

FIGURE 6. Transmittance curves and realistic pictures of two AB films.

B. PRACTICAL METHODS TO REDUCE CAF AND IMPROVE SBT

Because the use of VR headsets has more serious effects on human circadian rhythms than directly looking at smartphones, we propose three practical solutions that can readily reduce the blue-light content and thus the impact on human

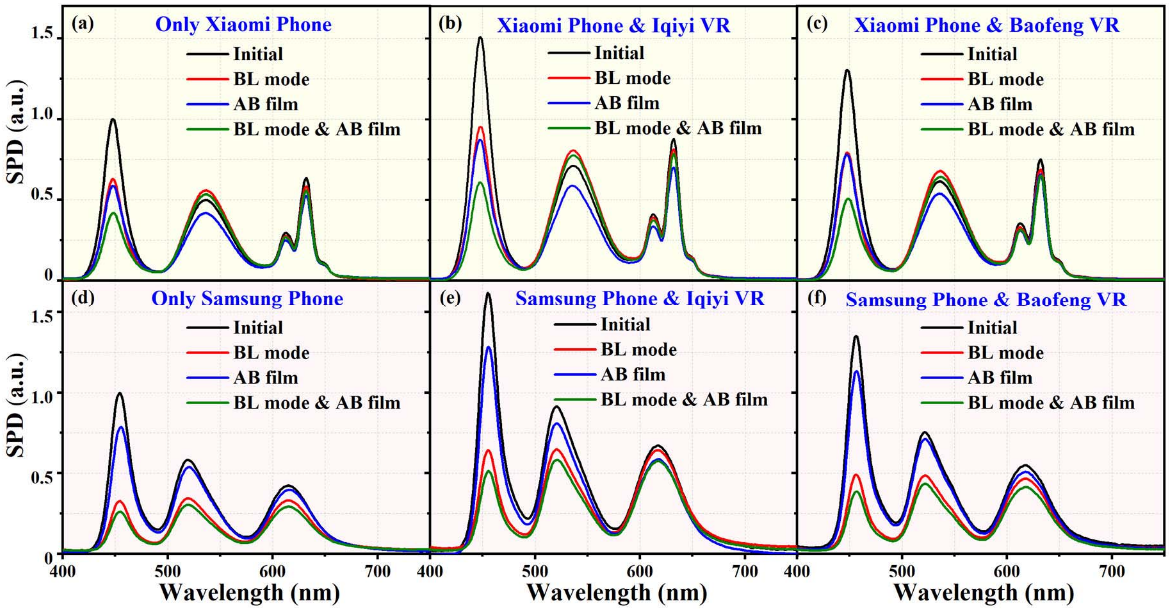

FIGURE 7. SPDs before and after applying the three practical methods for (a) Xiaomi phone, (b) Xiaomi phone & Iqiyi VR, (c) Xiaomi phone & Baofeng VR, (d) Samsung phone, (e) Samsung phone & Iqiyi VR, (f) Samsung phone & Baofeng VR.

circadian rhythms for smartphone-based VR headsets. These three methods involve turning on a blue-less (BL) mode, utilizing an anti-blue (AB) film, and using the BL mode plus the AB film.

First, the BL mode is a software function embedded in the operating system of the smartphone. When the BL mode is turned on, the blue-light content of screen is reduced. Second, as a hardware optimization, an AB film can be attached to the screen of smartphones to partially block blue light. The AB films used in this experiment are commercial products that are specially designed for the two smartphones. The transmittance curves of these AB films are displayed in Fig. 6. Third, using the BL mode plus the AB film combines the above two methods.

We measured the SPDs again under each of the three practical methods. Fig. 7(a), (d) shows that, for both the Xiaomi and Samsung phones, the BL mode significantly reduces the intensity of blue light and slightly reduces that of red light. However, the BL mode for the Samsung phone greatly reduces green light, whereas for the Xiaomi phone the green-light content is markedly enhanced. Applying the AB film to the smartphones greatly suppresses the blue light and slightly lowers the green-light content, although the red light is generally unchanged. Finally, the use of BL mode plus the AB film further reduces the blue-light content. After loading VR headsets, the SPDs increase in intensity while their shape remains unchanged (Fig. 7(b), (c), (e), (f) compared to Fig. 7(a), (d)). Therefore, the trend in the SPDs when using the three practical methods is similar to that displayed in Fig. 7(a), (d).

As depicted in Fig. 8(a), (d), turning on the BL mode produces a remarkable decrease in the initial CAF of the two smartphones. For example, the CAF values decrease by 26.2% and 26.7% at 100% screen brightness for the Xiaomi phone and Samsung phone, respectively. The reason can be found in Fig. 7(a), (d), where a decrease in the blue-light content leads to a significant drop in CAF. The reduction in CAF when using the AB film is not as great as for the BL mode, with CAF decreasing by 17.9% and 5.2% for the Xiaomi and Samsung phones at 100% brightness, respectively. The reason can again be found by observing the SPDs. In Fig. 7(a), the blue light attenuation of the two methods is similar, but the AB film also significantly reduces the green light of the Xiaomi phone. In Fig. 7(d), the AB film does not significantly attenuate the blue light of the Samsung phone compared to the effect of the BL mode. Therefore, the reduction in blue-light content via the AB film is not as good as that via the BL mode. Using both BL mode and AB film at the same time, the blue light can be suppressed simultaneously by the software and hardware, resulting in the lowest CAF value. For instance, the CAF decreases by 39.0% and 29.0% at 100% screen brightness for the Xiaomi and Samsung phones, respectively. Similarly, changes in the SPD shape caused by the VR headsets can be ignored when compared with those resulting from the three practical methods for attenuating the blue-light content. Therefore, the trend in the CAF curves in Fig. 8(b), (c), (e), (f) is similar to that in Fig. 8(a), (d).

Fig. 9 shows the VIL curves before and after applying the three practical blue-light reduction methods. In Fig. 9(a), BL mode enhances the initial VIL curve of the Xiaomi phone, because this method produces a marked improvement in the intensity of green light, and human eyes are most sensitive to green light in a bright environment. In contrast,

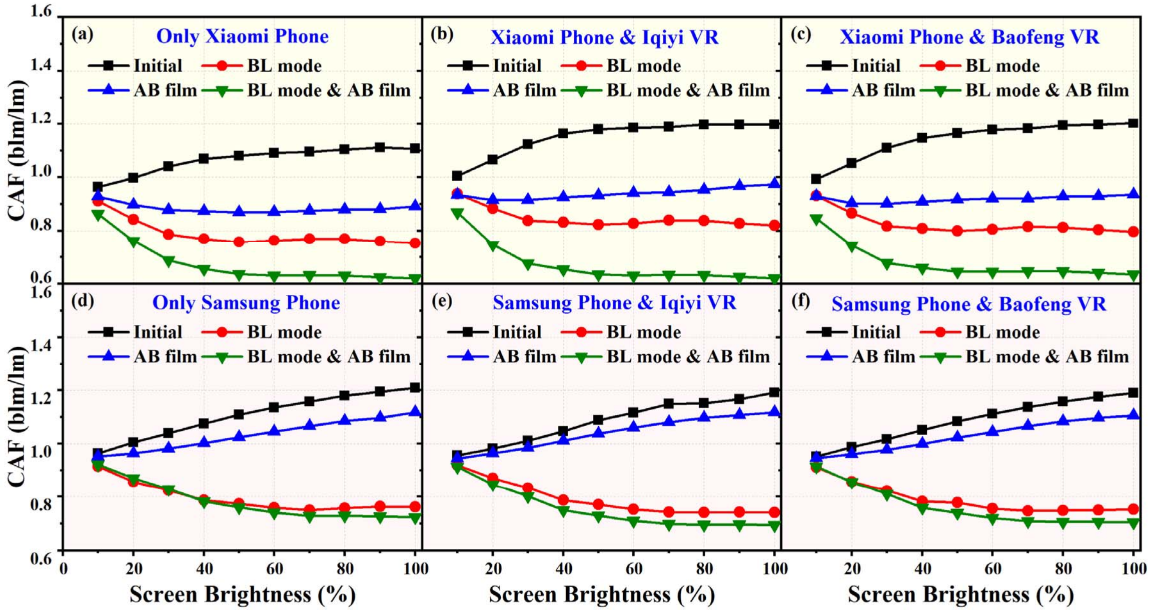

FIGURE 8. CAF curves before and after applying the three practical methods for (a) Xiaomi phone, (b) Xiaomi phone & Iqiyi VR, (c) Xiaomi phone & Baofeng VR, (d) Samsung phone, (e) Samsung phone & Iqiyi VR, (f) Samsung phone & Baofeng VR.

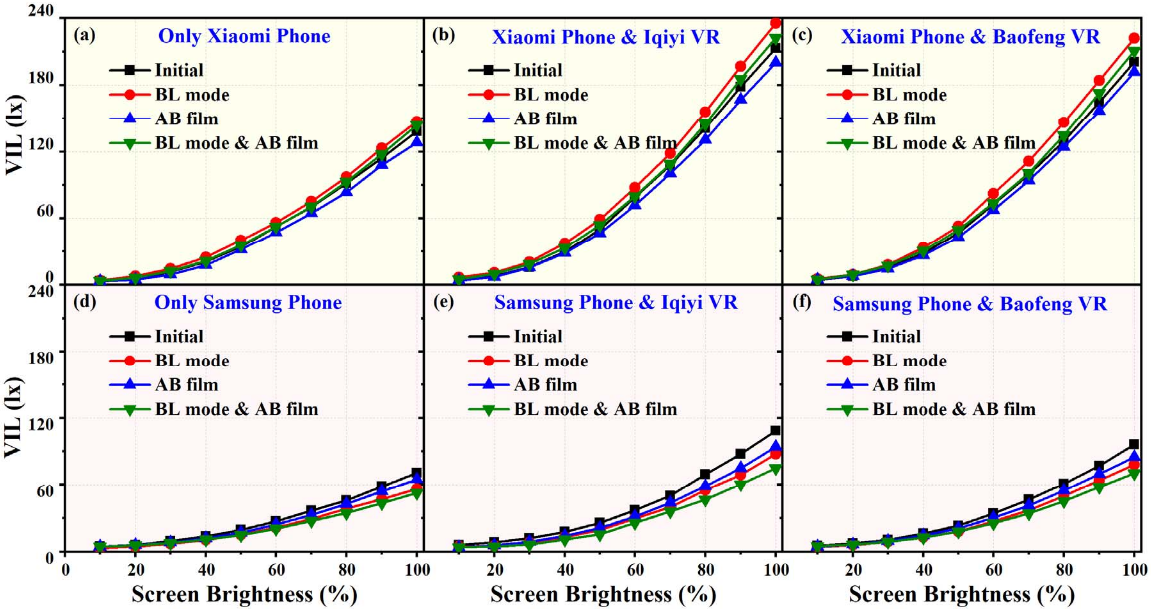

FIGURE 9. VIL curves before and after applying the three practical methods for (a) Xiaomi phone, (b) Xiaomi phone & Iqiyi VR, (c) Xiaomi phone & Baofeng VR, (d) Samsung phone, (e) Samsung phone & Iqiyi VR, (f) Samsung phone & Baofeng VR.

Fig. 9(d) shows that the BL mode in the Samsung phone attenuates all the RGB light, leading to a drop in VIL. The AB films reduce the VILs for both phones, because the entire SPD is attenuated by attaching AB film to the phone screens. Next, when the BL mode and AB film are used simultaneously, the total VIL increases in the Xiaomi mobile phone because the BL mode enhances the VIL more than the AB film. For the Samsung phone, the total VIL is further reduced by the superposition of the two methods. After adding the VR headsets, all VIL curves (Fig. 9(b), (c), (e), (f)) increase significantly because of the convex lenses. Moreover, the trend in VIL in Fig. 9(b), (c), (e), (f) is similar to that in Fig. 9(a), (d), because the addition of VR headsets does not change the shape of the SPD curves as significantly as the three practical methods.

According to (4), we can obtain CIL curves (Fig. 10) by multiplying CAF by VIL. It is obvious that the CIL curves drop significantly when using the three practical methods, with the third method (using BL mode plus AB film) being the most effective way to reduce CIL. Additionally, the

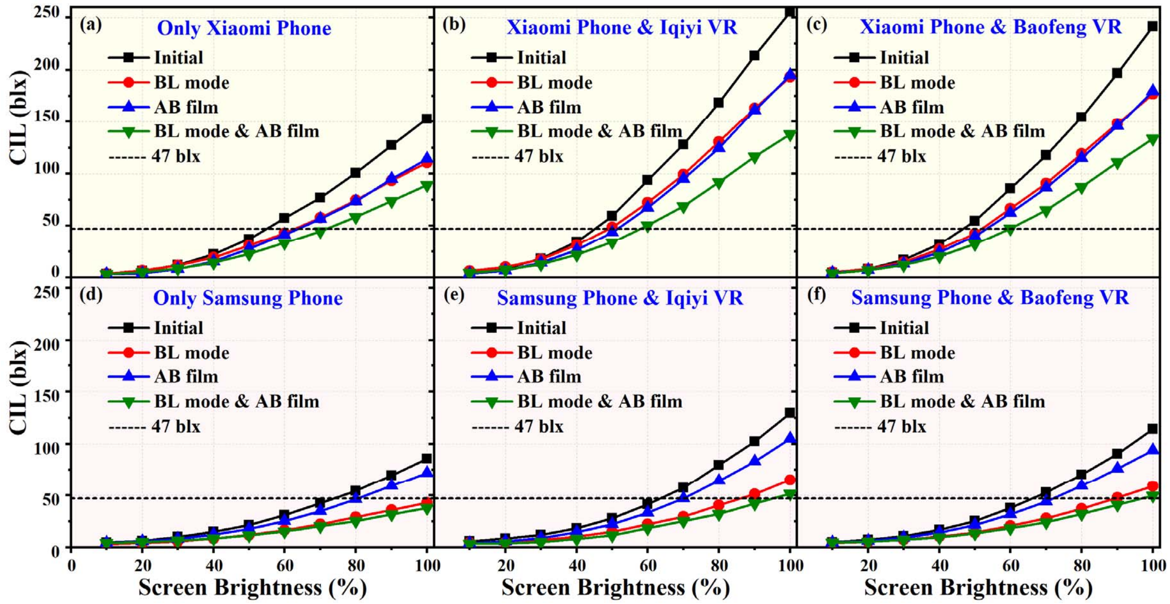

FIGURE 10. CIL curves before and after applying the three practical methods for (a) Xiaomi phone, (b) Xiaomi phone & Iqiyi VR, (c) Xiaomi phone & Baofeng VR, (d) Samsung phone, (e) Samsung phone & Iqiyi VR, (f) Samsung phone & Baofeng VR.

TABLE 2. SBT after using three practical methods to suppress blue light.

Device	SBT (%)			
	Initial	BL mode	AB film	BL mode & AB film
Xiaomi phone (Fig. 10(a))	55.6	62.9	62.9	72.1
With Iqiyi VR (Fig. 10(b))	45.3	49.5	51.5	58.7
With Baofeng VR (Fig. 10(c))	46.4	51.5	52.6	59.8
Samsung phone (Fig. 10(d))	74.2	100	80.4	100
With Iqiyi VR (Fig. 10(e))	63.9	86.6	70.1	95.8
With Baofeng VR (Fig. 10(f))	65.9	90.7	72.1	97.9

BL mode and the AB film have similar effects on CIL in the Xiaomi smartphone, whereas the BL mode has a better optimization effect than the AB film for the Samsung smartphone.

As mentioned before, as long as the CIL does not exceed 47 blx, the screen will not have a significant impact on human circadian rhythms. In Table 2, we summarize the SBT of each curve, that is, the abscissa of the intersection of each CIL curve and the threshold of 47 blx. As can be seen from Table 2, all three methods greatly improve the initial SBTs, especially the third method (combining the BL mode with the AB film). For the Xiaomi phone, after loading the Iqiyi headset and the Baofeng headset, the third method can increase the SBT from the original 45.3% and 46.4% to 58.7% and 59.8%, respectively. For the Samsung phone, after loading the two VR headsets, the third method can increase the SBT from the original 63.9% and 65.9% to 95.8% and 97.9%, respectively.

As all three methods effectively reduce the blue-light content, the color coordinates of the total output light inevitably shift, as depicted in Fig. 11. Generally, the greater the attenuation of blue light, the larger the SBT becomes, and the greater the shift in color coordinates. Therefore, considering the trade-off between reducing the effects on circadian rhythms and maintaining color stability, users need to select one of the three practical methods according to their application requirements.

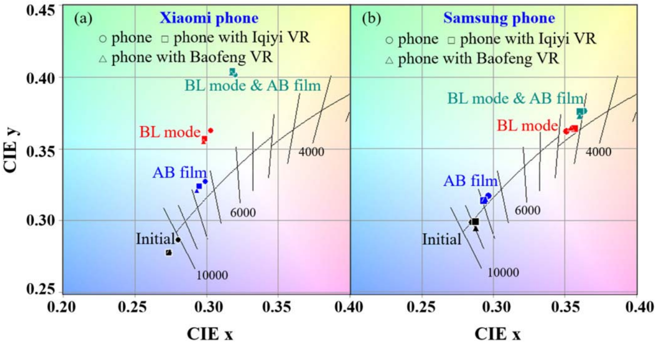

FIGURE 11. Color coordinates before and after applying the three practical methods for (a) Xiaomi phone and (b) Samsung phone.

C. THEORETICAL METHOD TO REDUCE CAF

The core optimization objective in this article is to reduce CAF. We have already discussed the effect of reducing CAF by using practical methods to attenuate the blue-light content. Next, we discuss another approach that would theoretically reduce CAF.

According to (3), CAF is defined as the ratio of CER to LER. Shortening the wavelength of blue light in a display backlight can efficiently decrease CER, thus reducing the value of CAF [23]. However, this method may lead to a blue light hazard because it enhances the energy of blue photons.

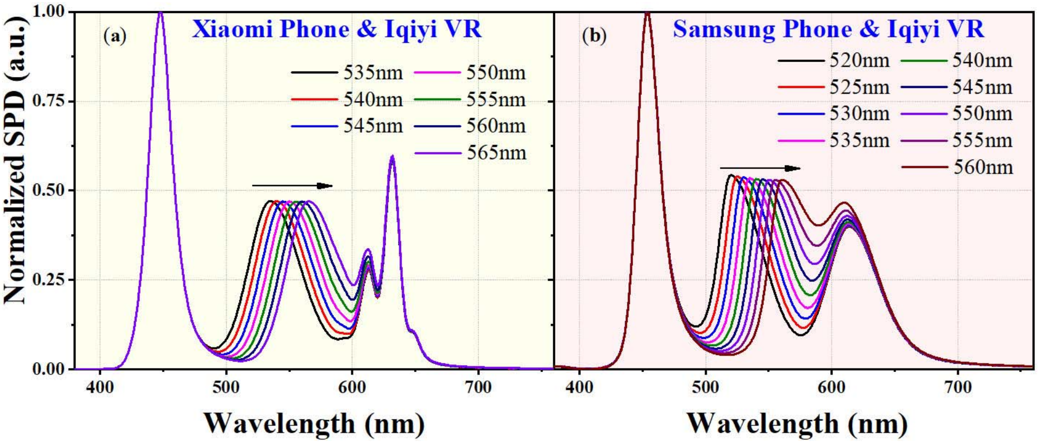

FIGURE 12. Simulated SPDs with respect to changes in green wavelength for (a) Xiaomi phone with Iqiyi VR and (b) Samsung phone with Iqiyi VR.

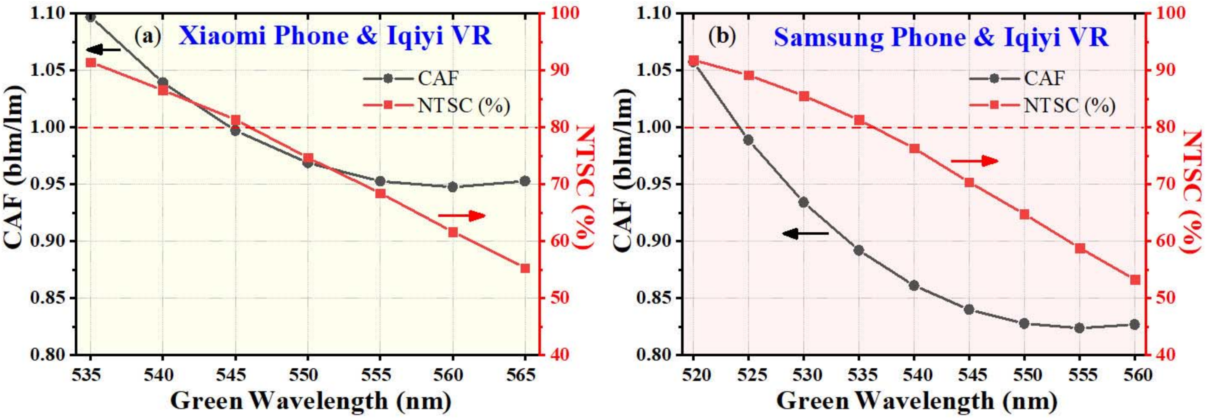

FIGURE 13. Changes in CAF and color gamut when green wavelength is shifted for both (a) Xiaomi phone with Iqiyi VR and (b) Samsung phone with Iqiyi VR.

In this study, we consider shifting the green wavelengths emitted by smartphone screens to close to 555 nm to increase LER. As a result, the CAF would be minimized.

We took the measured SPD from the Xiaomi phone with the Iqiyi headset (red curve in Fig. 4(a)) as the initial SPD, with a green wavelength of 535 nm, for the simulations. We then simulated shifting the green wavelength from 535 nm to 565 nm at 5 nm intervals. The results are shown in Fig. 12(a). In the same way, Fig. 12(b) shows the results of simulating a shift in the green wavelength from 520 nm to 560 nm for the Samsung phone with Iqiyi.

We then calculated the CAF and color gamut for each SPD. Fig. 13 displays the changes in CAF and color gamut with respect to the green wavelength for both the Xiaomi phone with Iqiyi VR and the Samsung phone with Iqiyi VR. As the green wavelength changes from the initial value to 555 nm, the CAF continues to decrease, which is beneficial to reducing the influence of VR equipment on human circadian rhythms. However, the color gamut shrinks at the same time. Therefore, we need to balance the trade-off between the CAF and the color gamut. If the minimum color gamut we can accept is 80% of the National Television System Committee (NTSC) standard, we can choose a green wavelength of 545 nm (Fig. 13(a)) or 535 nm (Fig. 13(b)). In these instances, the optimized CAFs will have decreased by 9.1% and 15.7% compared with the initial CAF values in Fig. 13(a), (b), respectively.

V. CONCLUSION

As VR technology continues to penetrate the smartphone market, it is increasingly important to develop health assessment criteria for VR headsets. Although VR headsets are small-sized display devices, they also emit light very close to the eyes, and can therefore seriously affect circadian rhythms. According to the relation between CIL and MSV, we derived an optimization goal for VR headsets of maintaining the CIL below a threshold of 47 blx and minimizing the CAF to obtain an improved SBT. Additionally, we developed an evaluation system to assess the visual and non-visual effects of commercial VR headsets. Moreover, we investigated three practical methods for decreasing the CAF by filtering out blue light and further reducing the impact on circadian rhythms caused by VR headsets. Finally, we discussed a theoretical approach for reducing CAF by increasing the

TABLE 3. Changes in color performance with VR headsets.

Acronym	Original Meaning
3D	Three-dimensional
AB film	Anti-blue film
BL mode	Blue-less mode
CAF	Circadian action factor
CCT	Correlated-color temperature
CER	Circadian efficacy of radiation
CIE x, CIE y	Chromaticity coordinates
CIL	Circadian illuminance
LCD	Liquid-crystal display
LED	Light-emitting diode
LER	Luminous efficacy of radiation
MSV	Melatonin suppression value
OLED	Organic light-emitting diode
SBT	Screen brightness threshold
SPDs	Spectral power distributions
VIL	Visual illuminance
VR	Virtual reality

green wavelength. For two phones, if we shift green wavelength from 535 nm and 520 nm to 545 nm and 535 nm, the optimized CAFs will have decreased by 9.1% and 15.7% compared with the initial values while the color gamut areas can still reach 80% of the NTSC. In summary, we hope that this research will go some way to allowing people to explore the 3D virtual worlds offered by VR technology without suffering health problems as a consequence.

APPENDIX

The acronyms and abbreviations used throughout this paper are listed in Table 3.

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