Reduction of the blue light hazard by adding a cyan light LED

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Abstract. The Liquid Crystal Display (LCD) system has permeated every aspect of our daily lives. However, few people are aware of the blue light hazard of a Light Emitting Diode (LED), which is widely used as a light source in the backlight system of display devices. Presently, many manufacturers take a series of countermeasures, and most of them focus on reducing blue light through software technology, as this technique is easy to conduct and cost-friendly. However, there are still two manufacturers that insist on hardware methods to reduce the blue light hazard, as they seek to maintain the color performance. In this paper, we have proposed a new method of reducing blue light via hardware and have evaluated both the software method and the hardware method by means of numerical analysis. The new design is based on a backlight system in which the original white LED is modified so that the blue-band energy is reduced by 50% and cyan light LEDs are added among the white light LEDs. In addition, we have optimized and adjusted the distribution of the LEDs’ energy to reduce the harm of the blue light, and we have simultaneously maintained good color performance. According to the simulation results, the newly designed backlight unit could effectively cut down over 50% of the blue light and maintain the correlated color temperature (CCT) at 6081K, which approaches the standard value of 6500K. In addition, the color rendering index (CRI) can also be maintained at 74.818, which is almost the same as an ordinary white LED without blue light filtering.

Keywords: Blue light hazard, Cyan light, LED, Correlated color temperature, Color rendering index, Photobiological safety

1. Introduction

The liquid crystal display (LCD) device has become the most commercially successful panel
display device. This device is widely used in mobile display terminals, home entertainment systems and commercial exhibitions. However, the liquid crystal is non-luminous, and an LCD backlight system is required to flash an LCD panel. Moreover, the Light Emitting Diode (LED) has become the best choice of backlight system for several reasons. First, solid light sources have a long life, high brightness, and low power consumption. In addition, LEDs have become as inexpensive as traditional light sources due to the popularity of LED technology and mass production.

However, the blue light hazard has been identified as one of the most serious problems of LEDs in many published papers such as Understanding Radiation Safety of High-Intensity LEDs [1]. These studies show that through human vision, which is the most important sense to humans, over 80% of the total information is obtained. Therefore, the potential danger of blue LEDs has been one of the focus points in the field of biological safety in recent years.

To remove the blue light hazard, software technologies have been developed to modify an original image that includes a blue light component. In addition to the software technologies, hardware technologies that employ a specialized attachment on the screen have been developed. These technologies can remove the blue light hazard to some extent. However, the correlated color temperature (CCT) is still significantly below normal levels. The color renditions of images are still restricted by the spectrum of traditional white LEDs. To solve the problem, we have proposed a new method based on the adjustment of the spectrum by adding cyan LEDs. Cyan LEDs play a vital role in both increasing the CCT and improving the color rendering index (CRI).

An important research work has been presented that human melanopsin forms a pigment that is maximally sensitive to blue light ($\lambda_{\text{max}}=479$ nm) and supports the activation of Gq/11 and Gi/o signaling cascades [2]. The wavelength of cyan is 479 nm. In addition, as another research work, the sleep pattern and circadian rhythms have been shown to be regulated via the retinohypothalamic tract in response to the stimulation of a subset of retinal ganglion cells, which is predominantly caused by blue light (450-490 nm) [3]; this band of the visual spectrum is also blue and cyan. Therefore, reducing all of the components of blue light is not wise.

The current paper is divided into 6 chapters. The first chapter introduces the severity of the blue light hazard in LEDs, and it is followed and supported by background research on the effect of blue light in LEDs on people’s daily lives. Chapter 3 examines the favored methods adopted by some leading manufacturers of display devices. Chapter 4 analyzes the feasibility of the existing methods of blue light reduction, and the next chapter proposes a more advanced hardware method to combat the blue light hazard in LEDs. Then, Chapter 6 compares the newly proposed methods with the existing two hardware methods and demonstrates the superiority of the former method. The last chapter completes the main findings of the paper.

2. Background
As early as 1966, Nell and other studies found that exposure to blue light can cause retinal cell damage, resulting in an ocular deterioration or even a loss of vision. The wavelength of 400-480 nm between the short-wave blue light causes the greatest harm to the retina. In 2010, in the annual meeting of the International Optical Association, the world's top optical experts unanimously noted the following: short-wave blue light with high energy can penetrate the lens and land directly on the retina. Blue light irradiation of the retina will produce free radicals, which will lead to the death of retinal pigment epithelium cells. Furthermore, epithelial cell decay can lead to the malnutrition of photosensitivity cells, which will cause visual impairment; these injuries are irreversible.

However, some researchers challenged the correlation between blue light and human retinal impairment and proposed contrary opinions in regard to the blue light hazard. Among many such scholars, Ian Ashdown, who is the leading scientist with Lighting Analysts, noted that the light intensities as well as the times of exposure adopted in most of the research work far exceeded those in daily life. Thus, the blue light hazards those authors proposed were not in line with real-life health risks.

However, there are many mainstream studies confirming the correlation of the blue light hazard and health risks to mankind. Researchers have conducted many physiological experiments to clarify the mechanism of the blue light hazard, such as the paper published in 2015 by Harvard University [4]. As examples cited in the research, the effects of blue light LEDs on melatonin suppression have been described, and display manufacturers can determine how their products will affect melatonin levels [5]. In another research study, the blue light from LEDs was found to elicit a dose-dependent suppression of melatonin in humans [6]. One of the most important issues of concern is the effect of the blue light hazard on our vision. One study clearly showed the relationship between blue light and Age-related Macular Degeneration (AMD) [7]. Similarly, other papers have conducted experiments to explore the effect of blue blocker techniques on mankind, such as the effect of blue blocker glasses on male teenagers [8]. This paper will focus on the techniques of blocking the blue light hazard.

3. Related work

LCDs are widely used in three fields: mobile phones, computer monitors and LCD TVs. In addition, it is easy to install and use third-party software to mitigate the blue light hazard. Currently, the most popular software to cut down blue light on a computer are f. Lux and Redshift. There are more applications on mobile phones, and the effect is almost the same on both platforms. These programs’ main principle is adjusting the color palette of blue pixel values through software to reduce the blue light. Other methods exist such as controlling the display characteristics through changes in the luminance and CCT to reduce blue light [9].

In terms of blocking the blue light by hardware, there are two main methods according to the latest study. These methods were developed by professional production companies of displays and have been successfully launched to market. Both methods first defined specific spectral bands of the blue light hazard, and then, they process the light through hardware. The two companies are the professional monitor manufacturers BenQ and AOC.

Specifically, AOC changed the backlight module of the white LED phosphor powder composition so that the entire spectral band shifts in the long-wave direction. Similar to the method of changing phosphor powder, there is some research on this idea [10]. The identified blue
spectral peaks are moved from the original bands of 444 nm to 460 nm; thus, these monitors avoid the most harmful band of 400 nm-450 nm and filter the blue light. There is evidence that 420–453 nm blue light will do harm to human skin [11]. Another study even extends the band of the wavelength to 480 nm, which is the cyan color, to analyze the blue light irradiation on human dermal fibroblasts [12]. In contrast, the method used in BenQ is to directly cut part of the blue light below 455 nm by means of hardware and retain the energy of blue light over 455 nm to achieve the desired filtering of blue light.

The two methods of reducing the blue light hazard developed by BenQ and AOC will be evaluated through numerical analysis in the next chapter.

4. Feasibility of the existing methods of blue light reduction

The two methods of blocking blue light have been mentioned in related works, namely, the software method and the hardware method. Whereas a software method changes the standard of the RGB color space to decrease the blue light, a hardware method adjusts the hardware of the black light panel by using a filter in the LED or changing the phosphor of the LED to decrease the blue light. However, average customers hardly have sufficient knowledge to choose an ideal product to avoid the blue light hazard. More importantly, it is still unclear how the blue light blocking effect changes the color performance. In this paper, we provide the basis to facilitate the decision-making of average consumers by evaluating these methods with visual analytics.

4.1 Establishing the standard model of the common LCD backlight system

To evaluate the effect of the two methods of blocking blue light, we have developed a standard model without processing. This model has some parameters that can be adjusted and modified to obtain the Total Illuminance Map and Total CIE Color Map.

The CCT is a physical quantity used to define the color of the light source in illumination optics. The color of the light source is often represented by the CCT. Currently, the vast majority of ordinary liquid crystal displays on the market have CCTs between 6000-6500K white LED, and 6500K is the standard light source for D65 CCT. Therefore, this CCT occurs in the vast majority of current displays.

Figure 1 shows simulation results with the Monte Carlo method by using a large number of ray tracings on the backlight LED. This method has proved to be very useful in the precise optical modeling of a blue LED [13].

Figure 2 shows the Total CIE Color Map of the calculation results by ray tracing. The left portion of Fig. 2 shows the light source of the backlight after the light is presented by the spectral color. The color is almost cold white, and the light field distribution is basically uniform. The coordinates of the right graph are the standard CIE 1931 color coordinates in that the light field distribution is basically uniform but not completely uniform. Therefore, there will be a slight deviation in the simulation of the color coordinates. The backlight spectral CCT is approximately 7000K and is marked in Fig. 2. This figure shows the average value of the entire light field.

In the progress of the backlight LED parameter settings, we use the spectral distribution data of Samsung 5630 lamp beads under 6500K, but the actual simulation results are slightly
higher than 6500K. Taking various factors into account such as the arrangement density of the LEDs in the modeling and the stray light produced by the Monte Carlo process, the simulation results are within the error range.

Fig. 1 Simulation of ordinary LCD backlight LEDs by ray tracing

Fig. 2 The total CIE Color Map of the general LCD display backlight LED after simulation

4.2 A verification of the proposed method by software

At present, the blue screen of software manufacturers enables users to filter 30%, 50% or 70% of the blue light. As the proportion of blue light filtered through the software increases, the color cast of the display will become more serious. Thus, the user will commonly choose the 30% or 50% blue-light-filter mode. Here, we analyze the effects of three types of filtering blue light through the simulation results of the model.

Figures 3-5 show the color performance of the LED backlight module after the light source has filtered 30%, 50% and 70% of the blue light. From these results, we found that the higher the proportion of filtered blue light is, the more the original white backlight color will shift to green. High filtering also results in a severe distortion of the final display color.
Fig. 3 Total CIE Color Map of an ordinary liquid crystal display obtained after filtering 30% of the blue light.

Fig. 4 Total CIE Color Map of an ordinary liquid crystal display obtained after filtering 50% of the blue light.

Fig. 5 Total CIE Color Map of an ordinary liquid crystal display obtained after filtering 70% of the blue light.
By comparing the parameters in Table 1, we have clarified that the more the blue light is filtered, the more the CCT will decrease, and both the CRI and the luminous flux of the whole output will decrease at the same time.

Table 1 Comparison of the optical characteristics of different ratios of blue filters

| Blue light filtering | CIExy       | CCT (K) | RGB         | CRI | Total Flux (lm) |
|----------------------|-------------|---------|-------------|-----|-----------------|
| 30%                  | (0.371, 0.456) | 5618    | (227, 255, 169) | 69.6 | 1034.2          |
| 50%                  | (0.329, 0.371) | 5029    | (222, 255, 111) | 67.6 | 973.79          |
| 70%                  | (0.349, 0.456) | 4623    | (221, 255, 55) | 63.8 | 953.45          |

The color performance of backlight mainly refers to the color rendering index (CRI). When the spectrum of the light source has little or no reflected main wave from the reference light sources of objects, the color will have a significant color shift. The greater the degree of the color shift is, the worse the color performance of the light source will be. Another important index to evaluate the color performance of backlight is the CCT. The CCT of every display is set to be approximately 6500K, which is the same figure as solar light. Therefore, the color performance of backlight is worsening whenever the color temperature falls below 6500K. Based on the simulation result of Table 1, few people can accept this color performance of a display device even though it is healthy for human eyes. In addition to the free software that enables blue light filtering and the accessory functions that are provided by manufacturers, new blue-light-filtering methods in software, such as using the colorimetric characterization of the display [14], have been developed. However, these new methods are still insufficient, especially in terms of the CRI.

Although two hardware methods by AOC and BenQ have been proposed to improve upon the software methods, they cost much more and make the backlight system more complicated. However, we must examine whether the performances of these two methods are better than the software methods with respect to mitigating the blue light hazard. If the current hardware methods are inferior, we need a better method for filtering blue light.

Fig. 6 The backlight models of AOC and BenQ
4.3 A verification of the proposed method by hardware

According to the analysis and description of the related work, we have developed the model of the backlight panels of AOC and BenQ, as shown in Fig. 6. The model is given the corresponding material properties and optical parameters of the backlight model. According to the technical information published by BenQ, the blue-light-filtering method is to cut the wavelength below 455 nm. However, the specific percentage to cut has not been revealed. In terms of the bad effect of blue light on health, we use blue light completely below 455 nm as the basis of the simulation, and we evaluate and compare the simulated results of the different methods.

Fig. 7 shows the backlight LED spectral distribution of the common liquid crystal display and displays by AOC and BenQ. Fig. 7 (a) shows the spectral distribution curve of an ordinary white LED, which is the most widely used blue light LED. The abscissa is the wavelength of visible light from 380 nm to 780 nm, and the ordinate is the normalized energy distribution. It is clear from (a) that although the wavelength broadening of blue light is only 100 nm from 380 nm to approximately 480 nm, the proportion of the energy of the blue part is quite high. This finding is especially true in the wavelength of 440-450 nm, though the entire range of visible light is from 380 nm to 780 nm. Therefore, many studies have shown that this part of the high-energy blue light spectrum is harmful to physical health, and especially to human eyes.

(a) Ordinary white LED spectrum distribution  
(b) Backlighting LED spectrum distribution of the AOC display  
(c) Backlighting LED spectrum distribution of the BenQ display

Fig. 7 Backlighting LEDs spectrum distribution for common LCD displays, and for the displays of AOC and BenQ
The spectral distribution curve of the backlight LED in Fig. 7 (b) and (c) is obtained from the products of AOC and BenQ after adjusting the ordinary white LED based on the above principle. From the comparison of (a), (b) and (c), we have clarified that (b) showed little difference from (a), as the whole spectrum only shifted 10 nm in the right direction. The two firms’ products moved the most harmful peak wavelength of blue light. However, the spectrum in Fig. 7 (c) changed quite substantially. The spectrum distribution of BenQ cut the blue light below 455 nm completely, as this firm believes that the wavelength under 455 nm is the band of the blue light hazard. Because of these different improvements and changes, the products we examined change the optical properties and parameters such as the CCT and CRI.

4.4 Simulation results and analysis of two types of blue-light-filtering display backlights

Figures 8 and 9 show the backlight color simulation results of the two companies AOC and BenQ applying their hardware methods to filter the blue light of an LCD. The simulation results of AOC (Fig. 8) show that the CCT of the backlight source is warmer than the CCT of normal white light because it shifts the blue wavelength band and reduces the blue light. Therefore, the CCT is reduced from approximately 6500K to approximately 5800K, which is not a serious degradation. The simulation result of BenQ’s blue-light-display backlight shows that the backlight color has a severe deviation from the normal cold white light because it completely filters out the blue light below a wavelength of 455 nm. As a result, the color cast is also more serious, and the CCT decreases from the ordinary backlight of approximately 6500K to approximately 4900K.

Fig. 8 Total CIE Color Map of an AOC liquid-crystal-display backlight LED after simulation
Fig. 9 Total CIE Color Map of a BenQ liquid-crystal-display backlight LED after simulation

With the decrease of the CCT, the white color light tends to be warmer. The performance of the color changes gradually from pure white to pink to pale orange, and finally, it changes to deep orange. The left picture in Figs. 8 and 9 shows that the backlight is the specific color. The color of the AOC display appears pink, which is normal. However, the color of the AOC display turns green at the normal CCT of approximately 4900K. We can see from the spectral characteristics of the ordinary white LED in Fig. 7 (a) that in addition to blue light, green light also takes a high proportion in the energy of the light, while the red color has the lowest proportion. Obviously, after reducing the blue light directly, green light becomes the highest light of greatest energy, which leads to the result of the simulation.

5. New method for filtering blue light through hardware

5.1 New proposal of combining two types of LEDs in backlighting to filter blue light

The above two companies have successfully applied hardware methods to filter blue light in their products, and they have made a great breakthrough compared to the traditional software methods. However, there will still be a certain degree of color cast, and the CCT will also be significantly reduced.

Therefore, we propose a new method to filter blue light through hardware to maintain the basic CCT and prevent the color cast phenomenon of LCD devices. Currently, there are two types of white LEDs: one is the single-core light-emitting device, which uses blue LEDs as a substrate and stimulates red and green light with blue phosphor to obtain white light. The other LED is the three-core light-emitting device that uses three independent RGB LED chips and obtains white light by mixing them. At present, the former white LED is widely used because it is more energy efficient and much cheaper than the latter. Additionally, the former LED can be made in an ultra-thin size that is suitable for LCD backlighting.

However, the emission of white light by a single core has some natural features because of its light-emitting principle. Our study will give a new proposal associated with these features. In the traditional blue-light-excited white LED spectral distribution, the energy concentrates in
the area of blue light, namely, the wavelength band of 440-450 nm. This band is considered to be the most harmful band according to other research. Due to the excitation characteristics of the phosphor, there is a depression at approximately 490-520 nm in the band of cyan light. Therefore, we have proposed a new method that reduces the blue light at the wavelength of 440-450 nm; adding the specific 490 nm cyan light led us to compensate for this spectral depression. It is possible to adjust the spectrum distribution to achieve compensation for the CCT.

Figure 10 shows the function curves for the "retinal thermal" (R(λ)) and "retinal photochemical" (B(λ)) hazard types of relevance for LEDs. According to the current International Electrotechnical Commission (IEC) standard for blue light hazards, the band approximately 490 nm is far away from this dangerous area. In accordance with IEC 62471 published data, the hazard value of the band of 435 nm and 440 nm is 1, whereas the hazard value of the 490 nm band has been reduced to 0.22.

Fig. 10 Spectral weighting functions for the B(λ) and R(λ) retinal hazard from IEC 62471

Fig. 11 shows the proposal backlight panel model with our method of filtering blue light towards problems in other methods through hardware. We have added a new cyan LED at a wavelength of approximately 490 nm in the traditional white LED between intervals. A cyan LED is indicated by the green color in Fig. 11. The energies of these LEDs do not need to be high because their function is the color complement after applying blue-light-filtering technology, which minimizes the color shift and CCT reduction.

Fig. 11 Backlight panel model of our method of filtering blue light

5.2 Analysis and calculation of the CRI and CCT
The CCT and CRI are the most important indicators of the spectral color. Whereas the CCT is the most common indicator of the spectral quality of a light source, the CRI is used to measure the degree of color reduction. The D65 light source as a standard light source often has a CCT of 6500K, and the CCT reference is the noon CCT of sunlight. The CRI of the solar spectrum is defined to have a maximum of 100. The closer to 100 the CRI is, the more effectively the light source will restore the color. Incidentally, the CRI of the incandescent lamp is also defined as 100, but the CCT of the incandescent lamp is approximately 3000K. However, such a CCT is not suitable for the backlight of a display. Therefore, we have mainly calculated by comparing the solar spectrum’s CCT and CRI for simulation and analysis.

The spectral curve in (a) of Fig. 12 is the portion of the harmful blue light spectrum to be filtered out in this article; in (b), cyan light is added to balance the spectrum. Moreover, (c) is the spectrum of the red and green bands that remain after the original white LED has been filtered. Because the decreased proportion of blue light energy and the increased proportion of cyan energy need to be analyzed, we split the original spectrum into three separate spectrums for our analysis and discussion of the final synthetic spectrum.

We use the spectral fitting method to address this problem, and we utilize the target spectrum (solar spectrum) to carry out resolution and principal component analysis of the LED spectral distribution. By using least squares to fit the simulation target’s spectrum, we obtain the corresponding energy comparison coefficient. Although the main method of spectral fitting is the iterative algorithm, which encompasses the fastest gradient method published by NIST [15], the least squares method has the advantages of high efficiency and convenient operation with respect to the matrix. We have applied the least squares method.

First, according to the principles of the spectral superposition LED and spectral synthesis model [16],

\[ L(\lambda) = \sum k_i S_i(\lambda) \]  

Lambda refers to the wavelength, \( i \) is the number of spectrum units of the fitted curves, and \( S \) is the spectral matrix that refers to the number of discretized wave bands.

Using spectral discrete sampling, we construct the target spectral matrix:
\[ S(t) = [y_1, y_2, y_3, \ldots, y_t]^T \]  
(2)

Where \( t \) is the number of discrete sampling points of the target spectrum and \( y \) refers to the normalized energy value under different wavelengths.

We construct the LED spectral matrix \( S_{\text{LED}}(i) \) and LED unit \( N_i(t) \) as follows:

\[ S_{\text{LED}}(i) = [N_i(t), N_i(t), \ldots, N_i(t)]^T \]  
(3)

Where \( t \) is the number of discrete sampling points of the LED unit and \( i \) is the number of fitting units to determine the size of the fitting matrix and simulation accuracy. The more LEDs there are, the more accurate the simulation will be.

We construct the coefficient matrix \( K = [k_1, k_2, \ldots, k_i]^T \) and obtain the fitting formula

\[ S_{\text{LED}}(i)K = S(t) \]  
(4)

The coefficients are calculated by formula (4). Because \( i \ll t \), the calculation is the solving process of the overdetermined equation. Although the overdetermined system has no classical solution, its generalized solution can be obtained, namely, the least squares solution \( K^* \):

\[ \|S(t) - S_{\text{LED}}(i)K^*\|_2 = \min_{K \in \mathbb{R}} \|S(t) - S_{\text{LED}}K\|_2 \]

\[ K^* = \arg \min_{K \in \mathbb{R}} \|S(t) - S_{\text{LED}}K\|_2 \]  
(5)

Here, we will take the three-independent spectral matrix into the LED spectral synthesis model:

\[ S_{\text{LED}}(i) = [S_{\text{blue}}, S_{\text{cyan}}, S_{\text{GR}}] \]  
(6)

Then, the solar spectrum is used as the fitting target spectrum; let

\[ S(t) = S_{\text{sol}}(t) \]  
(7)

By solving the overdetermined equation of this structure, we obtain three coefficient solutions.

\[
\begin{bmatrix}
k_{\text{blue}} \\
k_{\text{cyan}} \\
k_{\text{GR}}
\end{bmatrix}
= \begin{bmatrix}
1.3832 \\
1.1046 \\
2.4783
\end{bmatrix}
\]  
(8)

From the coefficients in (8), we have clarified that the energy of the blue part is about half of the energy of the red-green part. We assume that the energy of the red-green light is the same as the energy of the original white LED, which implies that the blue part of the energy is filtered out at an approximate proportion of 50%. Furthermore, the proportion of the cyan light increase is less than 50%. The increased cyan did not bring new blue light hazards.

Because the fitting target of this simulation is the solar spectrum, we can see from this ratio of the coefficients \( K \) that the damage from the blue light in the real solar spectrum is very minimal. This damage is approximately equal to half of the damage of a white LED in the case of the same transmission power, as shown in Fig. 13.
Then, we have calculated the correlated CCT and color-rendering index by programming, and the spectral curve of the fitting result is shown in Fig. 14. From the calculated results in Fig. 14, we have obtained that the CCT value is 5774.8K after fitting and the CRI is 73.8647. This result is close to the AOC hardware method. We hope that the CCT can reach more than 6000K. Still, the CRI can be further improved. Although taking into account the fitting of the solar spectrum is a valid method to improve the CRI, it did not increase the CCT. Therefore, under the premise that 50% of the blue light is filtered, we need to modify the proportion of the
green light’s energy. Here, the energy proportion coefficient of cyan light was adjusted to increase it by factors of 1.5 and 2. Then, a new spectral synthetic curve was obtained and the corresponding results were calculated.

From Table 2, when the proportion of cyan light energy increased by a factor of 1.5, the CCT continued to increase but the CRI decreased. We believe that increasing the cyan light energy by a proportion of 1.5 of the original spectral fitting of the cyan coefficient is the most appropriate.

Table 2 The effect of the proportion of cyan energy on the CCTs and CRIs of the synthetic spectra

| Percentage of cyan light energy | CIExy          | CCT(K)    | CRI      | Color appearance |
|--------------------------------|----------------|-----------|----------|------------------|
| 1                              | (0.324816, 0.384283) | 5774.81   | 73.8647  |                   |
| 1.5                            | (0.316706, 0.378753) | 6081.23   | 74.817   |                   |
| 2                              | (0.295255, 0.364126) | 7061.52   | 73.1668  |                   |

6. Results

After applying the hardware methods, the three designs of the blue backlight panel have several key optical parameters that need to be discussed. First, we consider the color performance measured by factors such as the CCT, which is followed by an LMS color analysis for the human eye. Moreover, we conduct related calculations and analysis of the blue light hazards to the human eye.

Table 3 Ordinary white LED and three types of hardware filters’ blue optical parameters: a comparison

| Different types of LED backlight | CIExy          | CCT(K)    | CRI      | Color appearance |
|--------------------------------|----------------|-----------|----------|------------------|
| Ordinary white LED             | (0.305836, 0.326304) | 6914.24   | 74.5182  |                   |
| AOC                            | (0.325552, 0.338874) | 5813.66   | 77.4582  |                   |
| BenQ                           | (0.370761, 0.462893) | 4658.89   | 63.6568  |                   |
| Our proposal                   | (0.316706, 0.378753) | 6081.23   | 74.817   |                   |

6.1 A comparison of the optical parameters between our proposal and the two existing ones.

Using the program shown in Fig. 14, we have calculated the optical parameters and obtained the color performance of the other two hardware blue-light-filtering methods. Table 3 shows the calculation results of the light-color performance for four LED backlight systems. From
these results, the LED of AOC has the best performance in terms of the CRI. However, compared to the standard 6500K sunlight CCT, there is a sharp decrease; 6500K is the most suitable and standard CCT for the vision of humankind. The mechanism of filtering blue light of BenQ indicates that it will have the worst performance both on the CCT and CRI, and the numbers are given in Table 3. Our proposed method is the closest to the standard CCT, and it also has good performance in terms of the CRI that is almost as same as an ordinary white LED.

6.2 The calculation of LMS cone cell responses in human eyes

We have conducted simulations on the objective evaluation of the display parameters. Then, we made calculations associated with the subjective evaluation of the human visual system. The visual process of the human eye is to perceive things by means of visible light. Visible light with its spectral distribution goes through the cornea, pupil, and lens and reaches the retina of the human eye. Then, the light is absorbed by the three types of cone cells on the retina, forming a visual response to the color of the three-dimensional world. The human eye has three types of cone cells. Each cone cell absorbs light and fuses the spectra of all of the wavelengths incident on it into three signals L, M and S, as shown in equation (9). This process has also become the design principle for all color measurements and radiation detectors [17].

\[
\begin{align*}
L &= \int L(\lambda)E(\lambda)d\lambda \\
M &= \int M(\lambda)E(\lambda)d\lambda \\
S &= \int S(\lambda)E(\lambda)d\lambda
\end{align*}
\]

(9)

\(E(\lambda)\) is the incident spectrum, and \(L(\lambda), M(\lambda), S(\lambda)\) are the spectral responses of L, M and S cone cells, respectively.

The spectral response functions corresponding to L, M, and S cone cells are shown in Fig. 15.

![Fig. 15 Spectral response functions corresponding to L, M, and S cone cells](image)

Fig. 15 clearly shows that both the L and M bands have a broad spectrum of cone responses. Although the response peak wavelengths are slightly different, the response spectrum covers...
three RGB color bands, while the S-band pyramidal cell response is too narrow to cover more bands. Table 4 clearly show the effects of three types of blue filters on the backlight panel with respect to the response values of LMS human cone cells. Compared with the ordinary white LEDs without blue light filters, the response values of the L and M bands in our proposal are almost the same, which means that the response of red and green is the same as ordinary white LEDs. However, due to the proposal of filtering the harmful blue band at 450 nm, which was mentioned in related works [7][11], along with the addition of the cyan band at 490 nm, which was mentioned in the introduction [3], there has been a certain average in the effect. The response of the S-band is reduced to some extent based on the adjustment of the spectrum of blue light.

Table 4 L, M, and S cone cell signal responses for different types of LED backlights

| LED backlight          | L  | M  | S   |
|------------------------|----|----|-----|
| Ordinary white LED     | 8.6037 | 7.3459 | 4.5740 |
| AOC                    | 8.7283 | 7.2036 | 3.8057 |
| BenQ                   | 8.4410 | 7.0427 | 1.2591 |
| Our proposal           | 8.9587 | 7.8298 | 3.2832 |

Because the spectrum resulting from AOC’s method only has a 10 nm shift from the original white LED spectrum, the original white LED spectral change is minimal. Therefore, the responses of the L and M cone wave cells in the two bands are very close to the response to an ordinary white LED in the same position. However, because the blue-light band shift is the overall movement of the high-energy peak wavelength, the S-band cone cell’s response will be reduced compared to the original white LED at the same position.

Finally, BenQ's method is to directly filter out the entire band of blue light below 455 nm and not change the other band. According to Fig.15 and its L and M-band cone response curves, we have shown that the response below 455 nm has been significantly reduced. Therefore, the BenQ calculation results of the L and M response values are slightly decreased compared to the ordinary white LED at the same position. BenQ only filters out the entire band of blue light below 455 nm, resulting in the sharp drop of the S-band response results from 4.5740 to 1.2591 compared to ordinary white LEDs. This system naturally causes serious color cast effects, which means we can hardly distinguish colors on the display system.

6.3 The Calculation of the Weight of the Blue Light Hazard

IEC 62471-2006 [18] was the common standard of Photobiological Safety of Lamps and Lamp Systems, and the most detailed definition of the Blue light hazard is currently the ICE 62778-2014 standard [19], ICE 62778-2014 is the supplement of IEC 62471 for the assessment of the blue light hazard to light sources and luminaires; it mainly evaluates the light biosafety of light sources and light source systems and gives the evaluation criteria and calculation methods of the response. Our research on reducing the blue light hazard is based on IEC 62778-2014. Other
research has conducted many experiments to evaluate the risk assessment from exposure to LEDs [20]. Because the purpose of this research is to focus on the evaluation of the blue light hazard, the authors do not need to compare types of blue light filtering panels. Therefore, under the same standard of ICE 62471 but in contrast to our research, the time and power were addressed in their research. Thus, our research is just a comparison of the blue light hazard and does not address the time and power of light sources.

In order to protect the retina from long-term exposure and cause harm, the relationship between spectral radiance of the optical radiation source \( L(\lambda) \), the blue light hazard function \( B(\lambda) \) and blue light weighted brightness is as follows:

\[
L_B = \sum_{\lambda=300}^{700} L(\lambda, t) \cdot B(\lambda) \cdot \Delta\lambda \leq 100W \cdot m^{-2} \cdot sr^{-1} \quad (t > 10^4s)
\]

\( L_B \) is the retinal light damage, \( L(\lambda, t) \) is the spectral radiance, and the unit is \( W \cdot m^{-2} \cdot sr^{-1} \). Furthermore, \( B(\lambda) \) is the blue-light-hazard weighted index, \( \Delta\lambda \) is the

Based on the formula of blue light hazard, we calculate the different types of LED backlight blue light damage.

From Table 5, observe that before the blue light is filtered out, the ordinary white LED light spectrum makes the greatest contribution to the blue light hazard. Based on the above result, BenQ’s blue-light-filter solution best minimized the harm of the blue light hazard but had the worst color performance. In contrast, the method of AOC had the best color performance but did not effectively reduce the blue light hazard. Our proposal obtained a balance between reducing the blue light hazard and maintaining high color performance, which we showed in Table 3.

### Table 5 Different types of LED backlight blue-light damage

| Different types of LED backlight | CIExy                  | CCT(K)   | CRI     | Color appearance | \( L_B \) |
|---------------------------------|------------------------|----------|---------|------------------|----------|
| Ordinary white LED              | (0.305836, 0.326304)   | 6914.24  | 74.5182 |                  | 4.8149   |
| AOC                             | (0.325552, 0.338874)   | 5813.66  | 77.4582 |                  | 4.0448   |
| BenQ                            | (0.370761, 0.462893)   | 4658.89  | 63.6568 |                  | 1.3950   |
| Our proposal                    | (0.316706, 0.378753)   | 6081.23  | 74.817  |                  | 3.5853   |

### 7. Conclusion

Recently, many manufacturers have begun to focus on blue light filtering to reduce the harm of blue light on humans. Software modeling and numerical analysis are employed to prove that hardware methods are better than software methods. In this paper, we proposed a new type of hardware method of filtering blue light, and we compared our method to BenQ and AOC’s
methods. From these analyses, we have shown the advantages and disadvantages of these three types of hardware methods.

Achieving complete safety of blue light filtering or minimizing the blue light hazard must be performed at the expense of high-quality color. According to all of the simulation results and parameters of the comparison, our proposal enables one to balance the reduction of the blue light hazard and maintain good color performance.

As future work, we can see that the multi-spectral inversion algorithm is still incomplete. In this paper, we have tried to adjust the coefficients to obtain the best effect, but this adjustment is still very rough. In addition, we may consider setting a number of narrowband LEDs near the cyan light instead of a single cyan light LED or using a wider spectrum of cyan light LEDs. We may obtain better results in the resulting fitting spectrum by using this broadband cyan light LED combined with a multispectral inversion algorithm.

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