Article

Approach for Designing Human-Centered and Energy Saving Lighting Luminaires

Jwo-Huei Jou *, Zhe-Kai He, Deepak Kumar Dubey, Yi-Fang Tsai, Snehasis Sahoo, Yu-Ting Su and Chun-Hua Wu

Department of Materials Science and Engineering, National Tsing Hua University, No. 101, Section 2, Guangfu Road, East District, Hsinchu City 30013, Taiwan
* Correspondence: jou@mx.nthu.edu.tw

Abstract: Electric light has been widely adopted in numerous applications, including signage, display, and illumination. Enhancing its efficiency and quality has been the focal point until now. Long exposure to intensive blue-light-enriched white light is, however, likely to cause health concerns, such as retina damage and melatonin suppression. A good light should hence be redefined as, at least, human-friendly, besides energy-saving and high-quality. Here, we demonstrate a novel design approach toward a good light based on the state-of-the-art solid-state lighting technologies. Taking the typical phosphor converted white-light-emitting diode (LED) for lighting, for example, a 2000 K orange-white emission with a black-body-radiation chromaticity can be 5 times safer than the 5000 K pure-white counterpart from a retina-protection perspective and 3.9 times safer from an MLT-secretion perspective. Further tuning its chromaticity from black-body-radiation- to sunlight-style, the 2000 K LED can be made 303% safer in terms of maximum retina permissible exposure limit or 100% better in terms of melatonin suppression sensitivity. Moreover, its corresponding efficacy limit can be increased from 270 to 285 lm/W, while keeping light quality constant at 91, in terms of natural light spectrum resemblance index. The same approach can be extended to organic LED as well as the design of a good light for display, wherein pure-white emission with a color temperature around 6000 K is suggested to replace the bluish-white backlight to safeguard human health.

Keywords: eco-friendly light sources; light design; organic light-emitting diodes; energy saving; high-quality light; spectrum-tuning; light-at-night

1. Introduction

Sunlight is crucial for health and well-being. It is amazing that we wake to a reddish sunrise, spend the day in blueish light, with the peak intensity at noon, and fall asleep to the reddish sunset or the warm red glow of firelight. Diurnally varying color and brightness of the sun exhibit a significant effect on the circadian rhythm of living organisms, and it is a basic component required to sustain all plants, animals, and people on Earth [1]. It produces the highest quality light with true and natural colors of objects, but regrettably it cannot be used for illumination at night. Artificial lighting sources that simulate light components ranging from near ultraviolet to infrared typically can be classified into two categories: (i) burning hydrocarbons and (b) electrical sources. However, they only fulfill fundamental lighting needs and hardly satisfy our need for natural lighting. The burning hydrocarbons luminaires consist of oil lamps, gas lamps, candles, and charcoal lamps. These lighting sources are friendly to the ecosystem and the human body due to their blue light-less emission but they are always criticized for energy wasting, burning, catching fire, flickering, carbon blacking, oxygen consuming, and release of greenhouse gas, etc. [1,2].
The introduction of artificial light sources was a pivotal moment in history, allowing a human being greater flexibility in controlling the environment. It led to safe, comfortable, and more artistic civilizations and has become one of the most essential parts of our life. Now, we cannot imagine our life without it. According to the International Energy Agency, lighting accounts for almost 20% of total global energy consumption [3]. Extensive use of lighting consumes a huge amount of energy, which can be controlled by realizing high-efficiency lighting devices. Lately, light-emitting diodes (LEDs) are being extensively adopted for general lighting purposes. In the last 10 years, luminous efficacy of LED lights has increased by a factor of three or greater, i.e., from less than 50 lm/W to approximately 150 lm/W [4]. As of 2015, 137 lm/W and 168 lm/W have been achieved for warm and cold white LEDs, respectively, and a goal of 255 lm/W has been set for both [4]. Meanwhile, another solid-state lighting technology, namely organic light emitting diode (OLED), has evolved and many high-efficiency lighting devices are reported. Since Kido et al. developed the first ever white OLED in 1995 [5], numerous high-efficiency devices have been developed. In the display market, OLEDs are also receiving enormous attention. Some of the OLED-based display products are already on the market, and have achieved significant efficacy of 168 cd/m² [6].

Light quality of a light source becomes a major concern when appearance of an object is considered. To obtain a true and natural impression of an illuminated object, high-quality light sources are required. A high-quality light can differentiate colors between objects of similar appearance. To quantify this parameter, there are two light quality indices available so far, namely, the color-rendering index (CRI) and the spectrum resemblance index (SRI) [7]. The SRI defines light quality from a 0 to 100 scale, where zero represents a light with the poorest quality and 100 the best quality. Whereas the CRI will give a negative value for some lighting sources with relatively poor quality [8]. Incandescent bulbs have already achieved a 100 CRI or a 97 SRI, but with a comparatively poor power efficacy of 10–15 lm/W [9,10]. In addition, they have a fixed color temperature, not matching that of natural light like sunlight, which gives varying colors (color temperatures, CT, Figure S1) at different daytimes. However, new-generation solid-state lighting such as LEDs and OLEDs also achieved new heights. For white LEDs and OLEDs, a CRI of 98 has been achieved so far [11,12]. When SRI is concerned, both white LEDs and OLEDs have achieved a value of 96 [11].

A lighting source should also be human-friendly in nature to be well accepted, especially by noting the increasing hazards from short wavelength emission [13–15]. Long exposure to blue- and/or violet-light-enriched white lights might cause health issues, such as damage to the light-sensitive tissues of eyes, circadian disruption [13–15], sleep disorders [16], and breast cancer resulting from the suppression of the oncostatic hormone, melatonin [17–19]. While chasing higher luminaire efficiency is always a must, it is not less urgent or less important at all to develop blue- or violet-emission-free light sources to resolve these health issues. Blue-emission-free, low color temperature LEDs and OLEDs with high energy efficiency are still under development, although quite a few middle color temperature, warm-white lighting technologies are already on the market. According to the study by Kozaki et al., a light source with a color temperature much below 2300 K could be thought to be blue-hazard-free from a melatonin secretion perspective [20].

Energy-saving has been a crucial issue for a relatively long period of time, especially since the first global energy crisis appeared [21–23]. High-efficiency lighting has hence been a major concern, and energy-saving solid-state lighting technologies have become the mainstream in modern lighting [24,25]. Naturally, a light source with high energy efficiency as well as high light quality may be thought to be a good light. This was true until the appearance of “phototoxicity” [26,27] or “blue hazard” [28] when humankind started to realize that the increasing intensive blue-light-enriched lighting imposed an increasing threat to human eyes [28], human health [14], ecosystems [29,30], artifacts [31], and night skies [28,30]. Therefore, a “good light” should, at least, also be friendly to all the
factors mentioned above. At the moment, the threats of light for retina damage [32] and melatonin generation suppression [33,34] can be quantified. As a result, a “good light” should be redefined as a light that is, but is not limited to, being friendly to human eyes and melatonin secretion, besides being energy-saving and high in light quality.

Ever since the first development of white LED (WLED) with luminous efficiency of just 5 lm/W, numerous research groups have developed very high-efficiency white LEDs. Nichia and Cree announced laboratory-result efficacy of 169 lm/W and 208 lm/W, respectively, for WLEDs [35,36]. As to white OLEDs (WOLEDs), Reineke et al. reported approaching fluorescent tube efficacy of 90 lm/W [37]. Zhou et al. realized white flexible OLED of 106 lm/W [38]. Kato et al. developed an all-phosphorescent white OLED with a power efficiency of 139 lm/W [39]. Many researchers also reported high-quality lighting devices. Lin and Song et al. reported a white LED with 90 CRI [40,41]. Srivastava et al. designed WLEDs with a CRI of 87 [42]. Zhnag et al. and Sun et al. reported white OLEDs with a CRI of 92 and 94, respectively [43,44]. Recently, Dubey et al. reported a low-cost solution-processed 2083 K OLED device with maximum PE of 51.4 lm/W and luminance of 44,548 cd/m² with a turn-on voltage of 2.1 V. The resultant light source is also 42 and 104 times safer in terms of retinal protection and ~4 and ~11 times safer in terms of melatonin generation when compared with those of a real candle and incandescent bulb, respectively [45].

The motivation of this study is to devise a novel approach for the design of a good light that is friendly to retina and melatonin secretion from the standpoints of display and lighting, besides being energy-saving and with high light quality. For displays such as TVs, PC monitors, and cell phones, etc., a pure-white light with a color temperature of 6000 K would be more human-friendly as compared with the bluish white light with a color temperature higher than 7000 K. For lighting applications, the white LED with 2000 K orange-white emission with black-body-radiation-style chromaticity can be 5 and 3.9 times better from the perspective of retina protection and MLT secretion when compared with its counterpart 5000 K pure-white LED in that order. It is notable that a sunlight-style LED with 2000 K CT can be 303 and 100% safer in terms of the maximum retina permissible exposure limit and melatonin suppression sensitivity, respectively. Moreover, its corresponding efficacy limit can be increased from 270 to 285 lm/W, while keeping the light quality (SRI) constant at 91. The same approach can be extended to OLEDs as well for the design of a good light for both lighting and display applications.

2. Theoretical Analysis

2.1. Maximum Retina Admissible Exposure Limit (t)

The maximum retina admissible exposure limit (t) was first described by the International Electrotechnical Commission (IEC) [46]. The parameter is denoted with a unit sec. The value of “t” can be evaluated according to a formula:

\[ t = \frac{100}{E_B} \]  

(1)

where \( E_B \) is known as blue-light weighted irradiance and can be calculated by a formula:

\[ E_B = \sum_{\lambda} E_\lambda \times B(\lambda) \]  

(2)

where \( B(\lambda) \) is known as blue-light hazard function (Figure 1a) [47] and \( E_\lambda \) as the spectral irradiance.

The resultant “t” can be used to classify the given light source into one of the four risk groups, i.e., risk group 0, risk group 1, risk group 2, and risk group 3. If “t” is greater than 10,000 s, then the light source could be assigned to the risk group 0, which presumably has “no risk” to retina. The light source could otherwise be assigned to the risk group 1, risk group 2, or risk group 3 if “t” is between 100 and 10,000 s, between 0.25
and 100 s, or less than 0.25 s, respectively. In this study, “t” is calculated with an illumination of 100 or 500 lx, for home lighting or office lighting, respectively.

2.2. Action Spectrum of MLT Suppression

Action spectrum of MLT suppression, SPQ, was first reported by Prof. Jou in a US patent [47]. The parameter can be expressed as follows.

\[ S_{pq} = 10^{(\lambda_{r} - \lambda_{c})/C} \]

Specifically, SPQ denotes suppression power per photon quanta of a given monochromatic light, \( \lambda \), relative to that of the reference light, \( \lambda_{r} \), and “C” is a fitting constant. Most frequently studied blue light with wavelength 460 or 480 nm can be utilized as reference light. Here in this study, we have chosen the 480 nm blue light, unless otherwise specified.

2.3. Light Quality Index—SRI & CRI

SRI: The light quality of a given light can be quantified by its light spectrum resemblance index, SRI, as ported by Jou et al. for the first time ever [10]. The SRI is a direct comparison of the luminance spectrum of a given light source with the black-body-radiation counterpart at the same color temperature and can be defined as follows.

\[ SRI = \frac{\int L(\lambda, T) d\lambda}{\int L_{BB}(\lambda, T) d\lambda} \]

where \( L_{BB}(\lambda, T) \) is the luminance spectrum of the black-body-radiation, and \( L(\lambda, T) \) is the overlapping area between the luminance spectra of the studied light source and its corresponding black-body-radiation.

CRI:
1. Measure the chromaticity coordinates of the given light source on the CIE-1960 color space.
2. From the color coordinates, find the closest point on the black-body’s radiation path to determine its correlated color temperature (CCT).
3. Selection of reference light source: If the correlated color temperature is less than 5000 K, then assume black-body-radiation as the reference light source. If the correlated color temperature is greater than 5000 K, then CIE standard light source (daylight) can act as a reference light source.
4. To irradiate the standard test pieces: The first eight specimens of the reference light source and the given light source are irradiated to find the light color coordinates of the test pieces on CIE-1960.
5. Calculate CRI: Calculate the average light color difference according to the eight light color coordinates measured above. If eight light color coordinates reflected from the given light source are reflected with the eight lights from the reference light source, the light color coordinates are the same, and the average light color difference is zero, then the CRI would be 100 [48-49].

2.4. Theoretical Efficiency Limit

The theoretical efficiency limit can be calculated as follows according to Jiang et al. [50]. It is defined as:

\[ E_{max} = K_{m} \frac{\int S_{r}(\lambda)V(\lambda) d\lambda}{\int S_{r}(\lambda) d\lambda} \]
where SI(\(\lambda\)) is the power spectrum of the studied light, V(\(\lambda\)) the photopic luminosity function, and Km 683 lm/W, the maximum spectral light efficacy at 555 nm.

3. Definition—Pseudo-Sunlight and Anti-Pseudo-Sunlight

Here, we define pseudo-sunlight as the light with a chromaticity closely matching that of sunlight. As seen in Figure 1b, the color of the sun varies with the variation of daytime. Its emission track falls slightly above the locus of black-body-radiation. For those falling below the black-body-radiation track, we define them as anti-pseudo-sunlight.

![Figure 1](image-url)

**Figure 1.** (a) The action spectrum of blue-light hazard function. (b) The chromaticity of the sunset hue. The data were adopted from the literature by Jou et al. [51]. Bandwidth effect on the exposure limit of retina at (c) 500 lx and (d) 100 lx, where the LED light source is composed of three white light complementary emissions with bandwidths comparatively narrower than those of the OLED counterpart.

4. Results and Discussion

4.1. Design of Human-Friendly Light Sources

4.1.1. From the Perspective of Retina Protection

Bandwidth Effect

Figure 1c,d show the effect of color temperature on the exposure limit of retina from different lighting sources including black-body-radiation (in black), LED (in green), and OLED (in pink) at two typical illuminances, 500 lx for office lighting and 100 lx for residential lighting. From the plots, we can say that the admissible exposure limit would increase with the decrease of color temperature regardless of the lighting source. In particular, the applied illuminance has a profound effect on the admissible exposure limit. By reducing the brightness from 500 to 100 lx, the entire exposure limit curve shifts from the RG2 to the RG1 zone, especially for those with a greater than 4000 K color temperature.
Considering the black-body-radiation at 500 lx, for example, the retina can sustain 407 s at 2000 K (orange-white), 146 s at 3000 K (warm white), 63 s at 5000 K (white), and 40 s at 8000 K (cold white). Alternatively, the light at 2000 K is 3, 6, and 10 times safer than those at 3000 K, 5000 K, and 8000 K, respectively. By reducing the illumination to 100 lx (Figure 1c), the exposure limit increases by 4 times over the entire color temperature studied. By switching to LED, the admissible times are found to be 370, 155, 74, and 50 s at 2000, 3000, 5000, and 8000 K, respectively. As OLED light is considered, the admissible times are 369, 153, 70, and 47 s at 2000, 3000, 5000, and 8000 K, respectively. Although the bandwidths are quite different for LED, OLED, and black-body-radiation (Figure 2a–c), the difference in admissible exposure limit between LED and OLED is tiny, i.e., the largest difference is only 6%. However, no matter whether LED or OLED, the light at 2000 K is 2, 5, and 7 times safer than those at 3000, 5000, and 8000 K, respectively.

Figure 2. The spectra of the natural light style: (a) LED, (b) OLED, and (c) black-body-radiation [52]. (d) The effects of black-body-radiation spectrum ranges on the exposure limit.

To shift the curves from RG1 to RG0 for LED lights, for example, the applied illuminance should further be reduced to or below 20, 7, 3, and 2 lx at 2000, 3000, 5000, and 8000 K, respectively. It should be noted that even a light with RG0 classification is harmful to retina as the exposure time exceeds 10,000 s.

Spectrum Range Effects on Exposure Limit

Figure 2d shows the effect of spectrum range of the black-body-radiation on the maximum permissible exposure limit before causing permanent retina damage. Four different spectrum ranges are investigated; they are black-body-radiation I (B-I), with a full spectrum from 380 to 780 nm, B-II (420–740 nm), B-III (460–700 nm), and B-IV (500–660 nm), whose spectrum is shown in Figure 3a. As seen, the permissible exposure limit can be greatly increased, as more than 80 nm of the deep blue and deep red ranges are truncated from the full-spectrum black-body-radiation regardless of its color temperature. In contrast, the change is very little if the truncated range is 40 nm or smaller.
At 3000 K, for example, the exposure limits are 732, 788, 1633, and 9486 s for B-I to B-IV, respectively. The light would become 1.2 and 12 times safer, respectively, as the spectrum is truncated by 80 and 120 nm from both ends. If truncated by 40 nm, the light is only 8% safer.

It is noteworthy that truncating the spectrum not only improves the safety factor for retina but also changes the resulting color and/or color temperature of the light. Taking the 8000 K black-body-radiation, for example, its color temperature will change to 7638, 4949, and 3799 K as 40, 80, and 120 nm are truncated, respectively. Color-wise, its original blue white will correspondingly change to light-blue white, nearly pure white, and warm white. However, the color would barely change if the black-body-radiation is at all around 2000 K initially. At 2000 K, for example, the color temperature is 2007, 2010, and 2038 K as the origin is truncated by 40, 80, and 120 nm, respectively.

The color temperature is changing with the different spectrum range, instead of remaining uniform. It becomes much closer to the lower color temperature as the full spectrum is truncated by an increasing quantity of light from both ends. The truncation shows much more color temperature effect on the spectrum at high color temperature.

Natural Light Style Effect

Figure 3b shows the maximum permissible exposure limits for different natural light style LEDs and OLEDs studied. Here, we have studied three different natural light style lights; they are pseudo-sunlight (in green), black-body-radiation style (in black), and anti-pseudo-sunlight (in purple). No matter whether LED or OLED, the pseudo-sunlight is always the safest, based on the same color temperature. Taking 2000 K, for example, the exposure limits of the three different natural light style LEDs are 7457, 1848, and 1069 s, respectively. The pseudo-sunlight LED is 303% and 600% safer than the black-body-radiation- and anti-pseudo-sunlight-style counterparts, respectively. In contrast, the anti-pseudo-sunlight LED is 70% more hazardous than the black-body-radiation-style counterpart.
As to OLED, the pseudo-sunlight OLED is 100% safer than the black-body-radiation-style counterpart. In contrary, the anti-pseudo-sunlight OLED is 60% more hazardous than the black-body-radiation-style counterpart.

4.1.2. From the Perspective of Melatonin Generation

Effect of Lighting Technology

Figure 3c shows the effects of different lighting sources, namely the full-spectrum black-body-radiation, black-body-radiation-style LED, and black-body-radiation-style OLED on MLT suppression sensitivity, relative to that of the 480 nm blue light. It is found that a light source with a lower color temperature is friendlier to the generation of melatonin. Notably, different lighting sources show different suppression effects, especially at or above 3000 K. At low color temperature such as 2000 K, for example, the difference in suppression sensitivity is relatively minor. Specifically, the sensitivities are 4%, 5%, and 6% for LED, OLED, and black-body-radiation, respectively. At 5000 K, the difference is rather high, 16%, 22%, and 61% for LED, OLED, and black-body-radiation, respectively. At 8000 K, the corresponding suppression sensitivities are 23%, 33%, and 118%.

Spectrum Range Effects on MLT Suppression

Figure 3d shows the effects of the spectrum range of black-body-radiation on the MLT suppression sensitivity. As seen, the MLT suppression sensitivity will become much less, as more of the deep blue and deep red emissions are excluded. Taking the full spectrum at 5000 K, for example, the sensitivity will drop from 61% to 23%, 8%, and 3%, respectively, as it is truncated by 40, 80, and 120 nm from both ends. The light would become 6.6 and 19 times safer, respectively, as the spectrum is truncated by 80 and 120 nm from both ends.

Color Effects of Lighting Technology

Figure 4 shows the effects of the color of natural light style LEDs and OLEDs on MLT suppression sensitivity based on the same color temperature. Here, we have studied three different kinds of natural light style LEDs and OLEDs, namely, pseudo-sunlight, black-body-radiation, and anti-pseudo-sunlight-style. At low color temperature such as 2000 K, for example, the suppression sensitivities of the pseudo-sunlight LED and OLED are 2% and 3%, respectively. With increasing color temperature, the difference in sensitivities between both the lights increases gradually. At 5000 K, the pseudo-sunlight LED and OLED showed sensitivities of 14% and 18%, respectively. Moreover, at 8000 K, they exhibited suppression sensitivities of 20% and 28%.
Figure 4. The effects of the color of natural light style LEDs and OLEDs on the MLT suppression sensitivity.

When the black-body-radiation-style LED and OLED are studied, for example at 2000 K, they showed MLT suppression sensitivities of 4% and 5%, respectively. The corresponding values at 8000 K are 23% and 33%. Accordingly, for anti-pseudo-sunlight-style LED and OLED, at 2000 K, they exhibited sensitivities of 6% and 7%, respectively, and at 8000 K, the corresponding values are 26% and 38%. Throughout the study, the pseudo-sunlight-style LED performed as the safest light by showing the lowest MLT suppression sensitivities amongst all the different color temperatures.

4.2. Design of Quality Light Sources
4.2.1. From the Perspective of SRI

Effect of Lighting Technology

Figure 5a shows the light quality, in terms of SRI, of the two different lighting technologies, LED and OLED. The SRI values are measured for black-body-radiation-style LED and OLED by assuming the black-body-radiation, as a standard, having an SRI of 100, at the same color temperature. With the color temperature varying from 2000 to 8000 K, for example, the LED shows an SRI varying from 91 to 88, peaking at 94 at 3000 K, while it varies from 84 to 91 for the OLED counterparts. Both the LED and OLED show different trends in SRI with increasing color temperature. From 2000 to 6000 K, the LED shows an SRI higher than the OLED. Beyond 6000 K, the trend is reversed. Two of them exhibit the same SRI of 90 at 6000 K. Speaking overall, both lighting technologies exhibit high light quality throughout the studied color temperature range.
Figure 5. (a) The SRI of the black-body-radiation-style LED and OLED. (b) The SRI of the black-body-radiations with different spectrum ranges. (c) The SRI of the three types of natural light style LED and natural light style OLED. (d) The CRI of the black-body radiation style LED and OLED. (e) The CRIs of the black-body-radiations with four different spectrum ranges. (f) The CRI of the three types of natural light style LED and natural light style OLED.

Spectrum Range Effects on the SRI of Black-Body-Radiation

Figure 5b shows the SRI of the black-body-radiations with different spectrum ranges. As seen, all the lights fall into the very high SRI bin, although it would be the same decrease as a significant portion of the deep blue and deep red emissions are truncated. At 2000 K for example, the SRI drops from 100 to 96 as 120 nm is truncated from both ends, while dropping to 90 at 8000 K.

Color Effects of Lighting Technology on SRI

Figure 5c shows the SRI of the three different natural light style LEDs and OLEDs. Overall, the pseudo-sunlight LED shows the comparatively highest SRI over the entire color temperature range studied, except at 2000 K. At 2000 K, all the three different types of natural light style LEDs show an identical SRI of 91. If at 5000 K, the SRIs are 93, 92, and 86, respectively, for the pseudo-sunlight, black-body-radiation style, and anti-pseudo-sunlight LEDs. At high color temperature such as 8000 K, the pseudo-sunlight and black-body-radiation-style LEDs show a slight decrease in SRI to 90 and 88, respectively, while it drops to 78 for the anti-pseudo-sunlight-style counterpart.

However, all the three different types of natural light styles OLEDs show nearly the same light quality over the entire studied color temperature range. As the color temperature increases from 2000 to 8000 K, the resulting SRI also increases from 84 to 90 ± 1.

4.2.2. From the Perspective of CRI

Effect of Lighting Technology on CRI

Figure 5d shows the light quality, in terms of CRI of the two different natural light style lighting sources. Compared with that in SRI, the difference in CRI between the black-body-radiation-style LED and OLED is larger. Specifically, the maximum difference is 7 in SRI and 24 in CRI. The black-body-radiation-style LED falls into the high CRI bin but enters into the middle CRI bin as the color temperature is higher than 5000 K.
Spectrum Range Effect on the CRI of Black-Body-Radiation

Figure 5e shows the CRIs of the black-body-radiations with four different spectrum ranges. The black-body-radiation still shows very high CRI as 40 nm of the deep blue and deep red emissions are truncated from both ends. However, unlike the SRI, the lights would fall from the very high to high CRI bin, and even to the middle CRI bin, as 80 or 120 nm are truncated. Taking 8000 K, for example, the CRI slightly decreases from 100 to 98 as the original full spectrum is truncated by 40 nm, while it drops to 69 and 50, respectively, as 80 and 120 nm are truncated.

Color Effects of Lighting Technology on CRI

Figure 5f shows the CRI of the three different types of natural light style LEDs and OLEDs. The pseudo-sunlight LED shows a CRI higher than that of the other two types from 3000 to 8000 K. Below 3000 K, the black-body-radiation-style LED exhibits a CRI higher than that of the other two types. Taking 5000 K, for example, the CRIs are 81, 76, and 65, respectively, for the pseudo-sunlight, black-body-radiation-style, and antipseudo-sunlight LEDs. If at 2000 K, the corresponding CRIs are 72, 80, and 76.

Similar to LED, the pseudo-sunlight OLED shows the comparatively highest CRI over the entire studied color temperature, except for 8000 K. Taking 5000 K, for example, the CRIs of pseudo-sunlight, black-body-radiation-style, and anti-pseudo-sunlight OLEDs are 90, 84, and 65, respectively, when at 2000 K, the corresponding CRIs are 79, 79, and 74. However, the respective CRIs are 87, 88, and 66 when the color temperature is 8000 K.

4.3. Design of Energy-Efficient Light Sources

4.3.1. Effect of Lighting Technology on Efficacy Limit

Figure 6a shows the efficacy limit of the three different natural light style lighting sources. For LED, its efficacy increases from 276 to 286 lm/W as its color temperature is increased from 2000 to 3700 K. It starts to decrease gradually from 286 to 267 lm/W as the color temperature is further increased from 3700 to 8000 K. The maximum efficacy difference is 7%.

For OLED, a similar trend is observed. Its efficacy increases from 245 to 269 lm/W as its color temp is increased from 2000 to 4000 K. It starts to decrease gradually from 269 to 253 lm/W as the color temp is further increased from 4000 to 8000 K. The maximum efficacy difference is 10%. Entirely speaking, the efficacy limit of the natural light style LED is higher than that of the OLED counterpart over the entire color temperature range studied. Taking 3000 K, for example, the efficacy limits are 284 and 267 lm/W for LED and OLED, respectively. At 5000 K, the corresponding efficacy limits are 278 and 264 lm/W. Thus speaking, the black-body-radiation shows a much lower efficacy limit because it contains the full spectrum of very low luminance efficiency deep blue and deep red emissions.

4.3.2. Spectrum Range Effect on the Efficacy Limit of Black-Body-Radiation

Figure 6b shows the truncation of the deep blue and deep red to favor the efficacy limit. The efficacy limit would increase from 94 to 135, 210, and 328 lm/W at around 2000 K as the full spectrum is truncated by 40, 80, and 120 nm from both ends. At 5000 K, the corresponding efficacy limit can be increased from 195 to 235, 300, and 415 lm/W.

4.3.3. Color Effects of Lighting Technology on Efficacy Limit

Figure 6c shows the efficacy limit of the three types of natural light style LEDs and OLEDs. Regardless of the color temperature, the efficacy limit of the pseudo-sunlight LED is significantly higher than the black-body-radiation-style counterpart, which in turn is higher than the anti-pseudo-sunlight counterpart. At 2000 K, the efficacy limits are 285, 270, and 255 lm/W, respectively, for the pseudo-sunlight, black-body-radiation-style, and
anti-pseudo-sunlight LEDs. At 3000 K, the corresponding efficacy limits are 285, 265, and 250 lm/W, and they are 260, 240, and 210 lm/W at 5000 K.

![Figure 6](image)

**Figure 6.** (a) The efficacy limit of the three different natural light style lighting sources. (b) The efficacy limit of the black-body-radiations with four different spectrum ranges. (c) The efficacy limit of the three types of natural light style LED and natural light style OLED.

When natural light style OLEDs are considered, the pseudo-sunlight counterpart shows a higher efficacy limit than that of the other two types over the entire color temperature range studied. Taking 3000 K, for example, the efficacy limits for the pseudo-sunlight, black-body-radiation-style, and anti-pseudo-sunlight OLEDs are 280, 267, and
253 lm/W, respectively. The corresponding efficacy limits are 290, 264, and 238 lm/W at color temperature 5000 K.

5. Conclusions

To conclude, we demonstrate here an original and simple approach to design human-centered and energy saving lighting luminaires. From a lighting perspective, an ideal lighting source should be capable of generating a sunlight-style illumination with various daylight chromaticity values, whose CT fully covers the full daylight at different times and regions. It produces high CT light in daytime to promote the secretion of cortisol, causing people to awake and be more concentrative and productive at work. During evening and night, the light should be made with a color temperature as low as that of candles to reduce the suppression of MLT that disrupts the human circadian clock seriously and causes the growth of cancer cells in the body. From a display perspective, high light quality and energy-efficient backlights can also be made accordingly. However, it is suggested that their color temperature be kept below 6000 K or at around that of pure-white light to minimize the unnecessary blue hazards from the excessive blue emission.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/photonics9100726/s1, Figure S1: Relationship between the color temperature and different visible color.


Funding: The authors would like to acknowledge the support from the Energy Fund of the Ministry of Eco-nomic Affairs and Ministry of Science and Technology, Taiwan. This work was financially sup-ported in part by Grants MEA 104-EC-17-A-07-S3-012, MOST 105-2119-M-007-012.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References
3. IEA “Topics”. Available online: https://www.iea.org/topics/energyefficiency/subtopics/lighting/ (accessed on 15 January 2022.).
4. Solid state lighting R&D plan June 2016, Department of energy.


52. Available online: Welcome to the Montana Space Grant Consortium http://spacegrant.montana.edu/MSIPreproject/Light.html (accessed on 18 December 2021).