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Article

Color Quality Versus Energy Efficiency: A Dual Perspective on LED Retrofits in Healthcare Examination Rooms

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Abstract: Selecting LED retrofits for examination rooms in healthcare buildings involves setting the right balance between lighting quality and energy efficiency. In the case of LEDs incorporated in luminaires used in medical examination rooms, it is essential to consider not only the correlated color temperature (CCT) and color rendering index (CRI Ra) in compliance with the lighting standards, but also the cyanosis observation index (COI) that meets the more demanding regulations of certain countries. In this work, the Color Preference Criteria (CPC) method is used to select LED retrofits for this application. The LEDs classified as P1 according to the CPC method were found to meet the required COI level.

Keywords: energy efficiency; LED; color quality; lighting; examination room; healthcare; hospital; luminaires



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1. Introduction

Examination rooms are frequently situated within the same premises as the physician's office, where patients may also receive treatment [1]. Electric lighting should create an optimal working environment [2,3] for physicians, physician assistants, and nurses, fostering a welcoming atmosphere for patients [4,5] while providing sufficient brightness and color rendering [6] to facilitate accurate examination and diagnosis [7,8]. Light combines two essential aspects in the examination and treatment rooms. It should positively influence the patient's perception of the environment, inducing a sense of calm, safety, and relaxation during the procedure [9–11]. The quality of lighting [12] in examination rooms has a significant impact on the clinical assessment of patients [13]. In addition to a warm and friendly atmosphere, physicians should see the finest color nuances on the patient's skin [14]. For this reason, adequate brightness and high-quality lighting are needed to perform these tasks effectively [15]. In European Union countries, the EN 12464-1 [16] standard specifies that an examination room's illuminance must be maintained at a level of 1000 lx. In the USA [17], Australia, and New Zealand, the same level of illuminance is also required [18]. Electric lighting must also meet additional requirements (Table 1) [16] in terms of Correlated Color Temperature (CCT) [19–21] and General Color Rendering Index (CRI Ra) [16,22]. In Australia and New Zealand, the allowed CCT range is broader than that in Europe, the United Kingdom, and the United States [18]. Additionally, Australia/New Zealand standards and regulations require sufficient detection of skin discoloration, which can indicate low oxygen levels in the blood. It specifically refers to a bluish tint appearing on the skin or mucous membranes, usually caused by inadequate blood circulation or

insufficient oxygen levels in the blood [18]. This requirement is quantified by an index called the Cyanosis Observation Index (COI). For any given light source, the numerical value of COI is calculated in relation to a 4000 K Planckian Radiator reference light source. It is defined as the magnitude of the change between the test light source and the reference light source in the color appearance of both fully oxygenated blood (100% oxygen saturation) and oxygen-reduced blood (50% oxygen saturation blue-purple blood). The COI calculations are described step-by-step in Appendix G of the AS/NZS 1680.2.5 document [18]. The calculations are based on spectral reflectance data for oxygenated and cyanated blood multiplied by spectral distribution data for the considered light sources (Figure 1). The lower the COI value, the smaller the change in color appearance under the evaluated light source. According to the guidelines in AS/NZS 1680.2.5:2018, any lighting to identify cyanosis should have a COI not exceeding 3.3. A lower COI value indicates that the light source is more suitable for the visual detection of specific color deviations associated with cyanosis.

Table 1. Standard requirements for light sources used in medical examination rooms.

Country and Region	Australia and New Zealand	European Union and United Kingdom	United States
CCT requirements	$3300\text{ K} \leq \text{CCT} \leq 5300\text{ K}$	Nominal CCT $4000\text{ K} \leq \text{CCT} \leq 5000\text{ K}$ Acceptance range $3710\text{ K} \leq \text{CCT} \leq 5312\text{ K}$	Nominal CCT $4000\text{ K} \leq \text{CCT} \leq 5000\text{ K}$ Acceptance range $3710\text{ K} \leq \text{CCT} \leq 5312\text{ K}$
general and ward areas General Color Rendering Index (CRI Ra)	≥ 80	≥ 80	No General Recommendation
examination and treatment areas General Color Rendering Index (CRI Ra)	≥ 85	≥ 90	≥ 80 (for exam areas) >90 (for surgery)
Special requirements	Cyanosis observation: $\text{COI} \leq 3.3$	CCT requirements for general lighting in the examination rooms $3710\text{ K} \leq \text{CCT} \leq 5312\text{ K}$	CCT requirements for lighting in the surgery and examination rooms $3710\text{ K} \leq \text{CCT} \leq 5312\text{ K}$

In addition to the parameters required by lighting standards [23], other parameters can be used to describe the color rendering qualities of lighting products [24–30]. For instance, the color rendering of human skin is assessed using the parameter $R_{f,skin}$ [26]. To evaluate how accurately a light source can reproduce saturated red colors (for objects whose reflectance spectra contain red wavelengths), the CRI R_9 parameter is used [31]. It is also possible to evaluate lighting quality based on user expectations by using the Color Preference Criteria method (CPC) defined in the ANSI/IES-TM-30 standard [26]. This method assesses the color quality of light on the basis of several parameters: general color fidelity index (R_f) [32–34] (currently is the most accurate measure of light color fidelity [26,35,36]), color gamut area index (R_g) (a metric that quantifies the average change in chroma across a color gamut), and local red chroma (saturation) shift ($R_{cs,h1}$) specified by hue angle bin. This classification system (see Table 2) defines four priority levels of color preference: P1, P2, and P3, and out-of-class, the latter corresponding to insufficient color rendering properties.

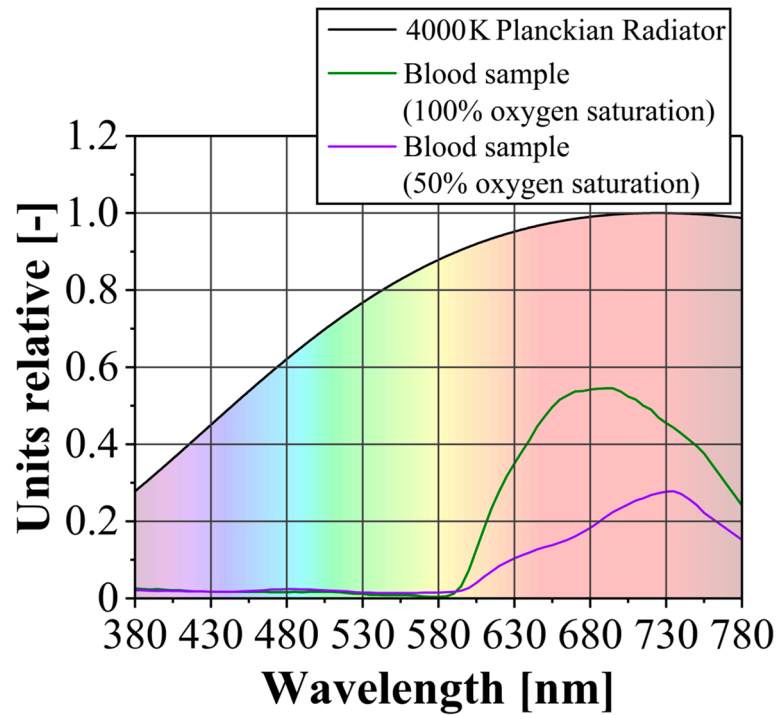


Figure 1. The spectral properties of fully oxygenated blood (100% oxygen saturation is represented by the green line) and oxygen-reduced blood (50% oxygen saturation blue-purple blood is represented by the violet line), and the spectral power distribution (SPD) of the 4000 K Planckian Radiator reference light is represented by the black line.

Table 2. The boundaries of categorization parameters according to the color preference criteria ANSI/IES TM 30-20 method priority levels (class) [26].

Class P1 “Best”	Class P2 “Good”	Class P3 “Acceptable”
$R_f \geq 78$	$R_f \geq 74$	$R_f \geq 70$
$R_g \geq 95$	$R_g \geq 92$	$R_g \geq 89$
$-1\% \leq R_{cs,h1} \leq 15\%$	$-7\% \leq R_{cs,h1} \leq 19\%$	$-12\% \leq R_{cs,h1} \leq 23\%$

Until now, fluorescent lamps (FLs) have been widely used for interior lighting, particularly in public building spaces. The spectral power distribution (SPD) of commercially available FLs exhibits narrow peaks resulting from mercury (Hg) emission lines and phosphor-based emissions (refer to Figure 2a).

The chromaticities of these FLs (Figure 2b) meet the ANSI chromaticity tolerance requirements for nominal CCT [39,40] given by MacAdam standardized ellipses (the range in which all colors around a reference point in a chromaticity diagram are indistinguishable by the average human eye MacAdam called as “1-step ellipse”). Any point on the boundary of a “1-step” ellipse drawn around a target represents one standard deviation from the target. Due to this, these ellipses are also known as the “Standard Deviation of Color Matching” (SDCM). By more restricted categorization, the document [39] establishes a “4-step” SDCM ellipses categorization (the boundary represents four standard deviations from the target chromaticities) and a “5-step” SDCM ellipses categorization (the boundary represents five standard deviations from the target chromaticities) with less restricted categorization requirements [40]. Their chromaticities are presented in Figure 2 by the magenta and yellowish (lime yellow) stars for lamps applicable in Australia/New Zealand and by magenta stars for lamps used in Europe, the United Kingdom, and the United States in medical examination rooms.

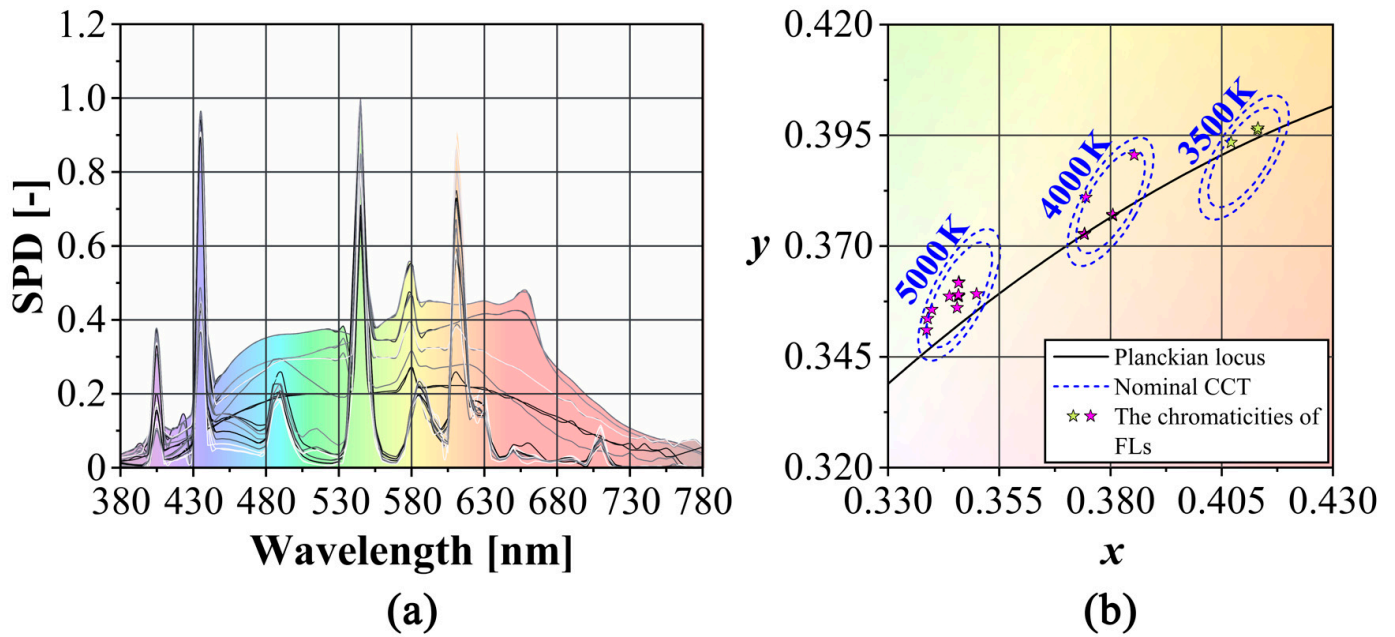


Figure 2. (a) spectral power distributions (SPDs) of typical fluorescent lamps [26,37,38] and (b) chromaticity coordinates of these lamps. The ellipses (4 steps and 5 steps) for the three nominal CCT values are indicated by blue dashed lines. The magenta and yellowish (lime yellow) stars are for lamps applicable in Australia/New Zealand, where CCT is in the range $3300\text{ K} \leq \text{CCT} \leq 5300\text{ K}$, and the magenta stars are for lamps with nominal CCT in the range $4000\text{ K} \leq \text{CCT} \leq 5000\text{ K}$.

In Figure 3, the parameters (R_f , R_g , $R_{cs,h1}$) of the FLs that are compliant with the ANSI chromaticity requirements are presented. These lamps satisfy the criteria for being categorized into one of the CPC classes.

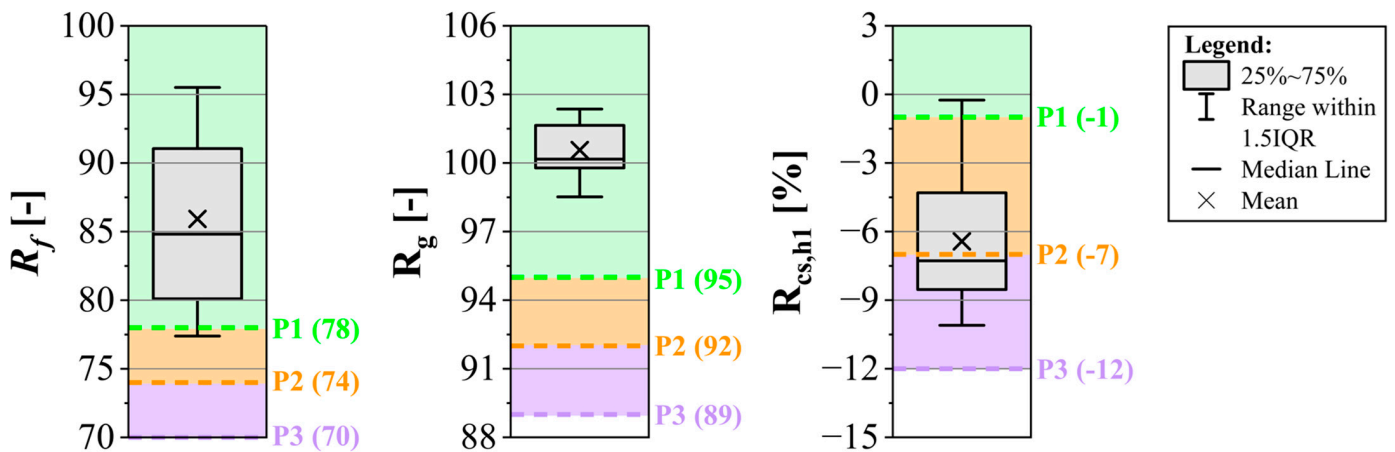


Figure 3. The values of R_f , R_g , and $R_{cs,h1}$ parameters of FL sources.

The graphs in Figure 3 show that the R_f and R_g indices always correspond to the requirements of the highest CPC class (P1). In contrast, the $R_{cs,h1}$ parameter can be associated with any of the three CPC classes. This parameter, therefore, plays a pivotal role in determining the CPC classification (Table 3) of FL lamps.

Table 3. TM-30-2020 color rendering indices of fluorescent lamps according to their CPC class.

Parameter		Class P1	Class P2	Class P3
R_f	-	95~96	89~94	77~86
R_g	-	102	99~101	99~102
$R_{cs,h1}$	[%]	-0.28~-0.25	-5.73~-4.25	-10.10~-7.25

Table 4 provides the luminous efficiency of radiation (LER), together with the values of CCT, CRI Ra, CRI R₉, $R_{f,skin}$, and COI, according to the CPC class (P1, P2, and P3). Considering the requirements concerning the COI parameter, all fluorescent lamps belonging to P1 class are suitable for use in medical examination rooms. However, their LER values are the lowest in comparison to other CPC classes. Table 4 also shows that not all FLs belonging to P2 or P3 classes meet the COI requirement.

Table 4. Other parameters of fluorescent lamps according to their CPC class.

Parameter		Class P1	Class P2	Class P3
Correlated Color Temperature (CCT)	[K]	4995~4997	4149~5250	3381~5072
General Color Rendering Index (CRI Ra)	-	96	88~93	80~88
Luminous efficiency of radiation (LER)	[lm/W]	254	261~273	316~349
R ₉	-	98	58~70	15~46
$R_{f,skin}$	-	97	90~93	88~96
COI	-	2.70	2.47~4.42	1.17~5.33

In the European Union (EU), a regulation is being enacted to eliminate environmentally hazardous materials, including mercury [1]. The EU has prohibited the largest category of mercury-containing light sources for both new and renovated lighting installations as of September 2023 [12]. This ban aligns with the EU's Restriction of Hazardous Substances (RoHS) Directive [9], which aims to accelerate the global shift to sustainable and energy-efficient LED lighting [41], in harmony with the United Nations Minamata Convention on Mercury [13]. This shift has also led to the integration of LEDs into healthcare facilities. Consequently, there is currently a massive transition from traditional light sources, such as fluorescent lamps, to solid-state lighting (LED-based lighting products). The transition to LEDs is additionally driven by legislation on product energy efficiency [42–46], emphasizing the importance of adopting high-efficiency lighting solutions across various applications. Depending on the application of LEDs, parameters other than energy efficiency need to be examined [47].

The following sections examine commercially available LEDs and investigate the relationship between their color quality and their energy efficiency when they are used in healthcare examination rooms. The latest recommended method (CPC classification) to describe the color quality of LED lights, which was also introduced by ANSI as the TM30-20 standard, is used in this investigation. This method is new but internationally recognized and applied in research by many lighting professionals [34,48–53]. In addition, the results given by the CPC methods are compared with the LED classification given by classically used in those types of application CRI Ra, R₉, and $R_{f,skin}$ parameters.

2. Materials and Results

Some publicly available databases of LED spectral power distributions (SPDs) are used to provide a representative dataset of commercially available LED products. The following databases were used: the “Real Light Source SPDs and Color Data for Use in Research” database [38] provided by the Pacific Northwest National Laboratory (PNNL), USA, and the “EMPIR 15SIB07 PhotoLED” database [54] collected by the partners and collaborators of the European metrology project EURAMET EMPIR 15SIB07 PhotoLED consisting of more than 3000 SPDs of commercially available LEDs. These databases include LEDs of different technologies: phosphor-converted LEDs (pc-LEDs) and color-mixing LEDs (cm-LEDs). In general lighting applications, the pc-LEDs are the most widely used technology [55]. The pc-LEDs with nominal CCT of 3500 K (91 pcs), 4000 K (256 pcs), 4500 K (33 pcs), and 5000 K (36 pcs), and CRI Ra values consistent with the requirement of medical examination rooms (Table 1) were selected, representing a total number of 416 different LEDs. The SPDs and chromaticity coordinates (represented by colored dots) are shown in Figure 4. The magenta and yellowish dots are for LEDs that are compliant with the Australia/New Zealand requirements, where CCT is in the range of 3300 K~5300 K. Magenta dots are used to represent LEDs with nominal CCT in the range of 4000 K~5000 K. The $(R_f, R_g, \text{ and } R_{cs,H1})$ parameters of these LEDs are shown in Figure 5. The number of LEDs belonging to each CPC class is presented in Figure 6.

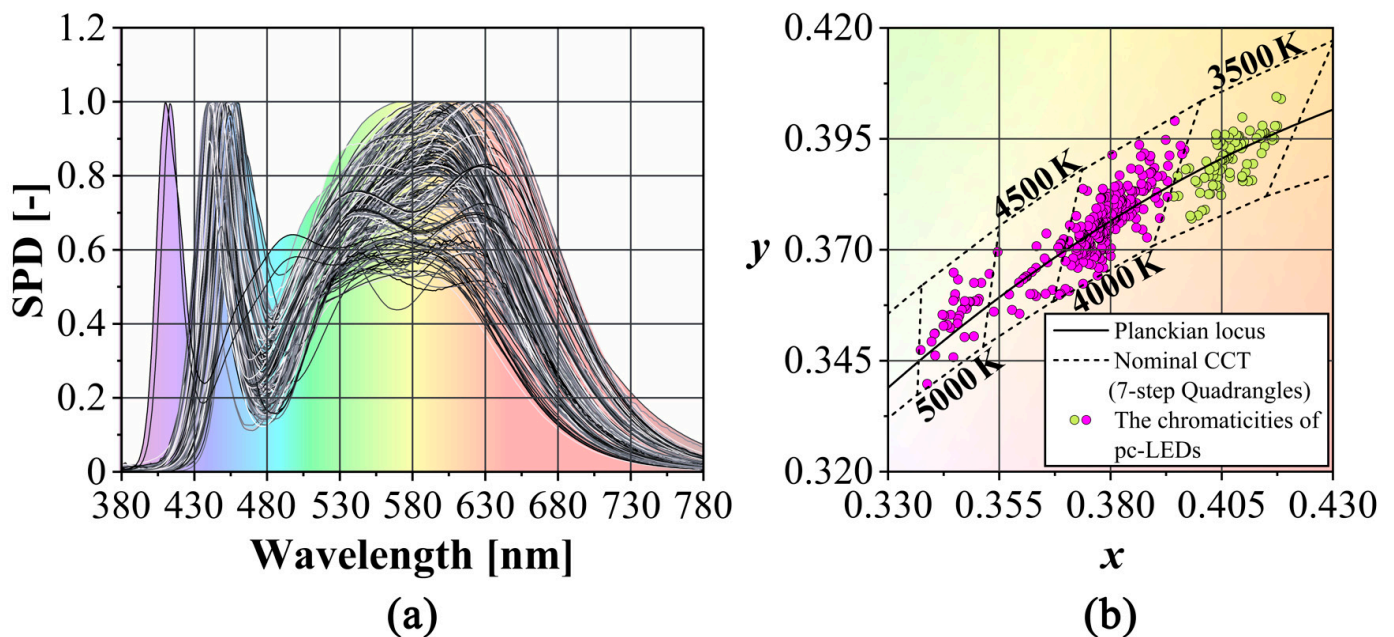


Figure 4. (a) SPDs of commercially available LED light sources and (b) chromaticity coordinates of these LEDs. The area with nominal CCT values according to 7-step quadrangles is delimited by black dashed lines. The magenta and yellowish dots correspond to LEDs applicable in Australia/New Zealand, for which CCT is in the range of 3300 K~5300 K. Magenta dots correspond to LEDs in a nominal CCT range of 4000 K~5000 K.

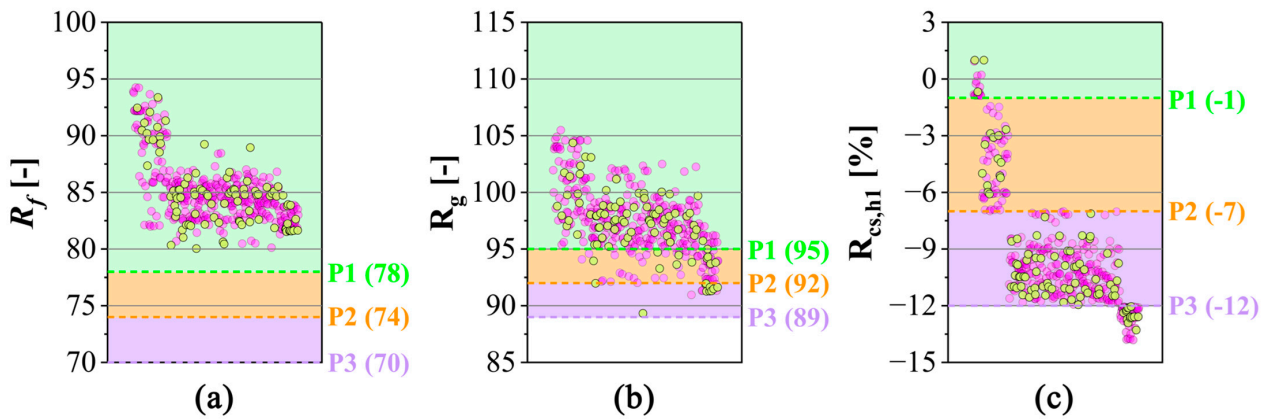


Figure 5. (a) R_f , (b) R_g , and (c) $R_{cs,h1}$ values of the LEDs under consideration. The magenta and yellowish dots are for LEDs, which are applicable in Australia/New Zealand, where CCT is in the range of 3300 K~5300 K. The magenta dots are used for the LEDs with a nominal CCT in the range of 4000 K~5000 K, which are applicable in the European Union, United Kingdom, and United States.

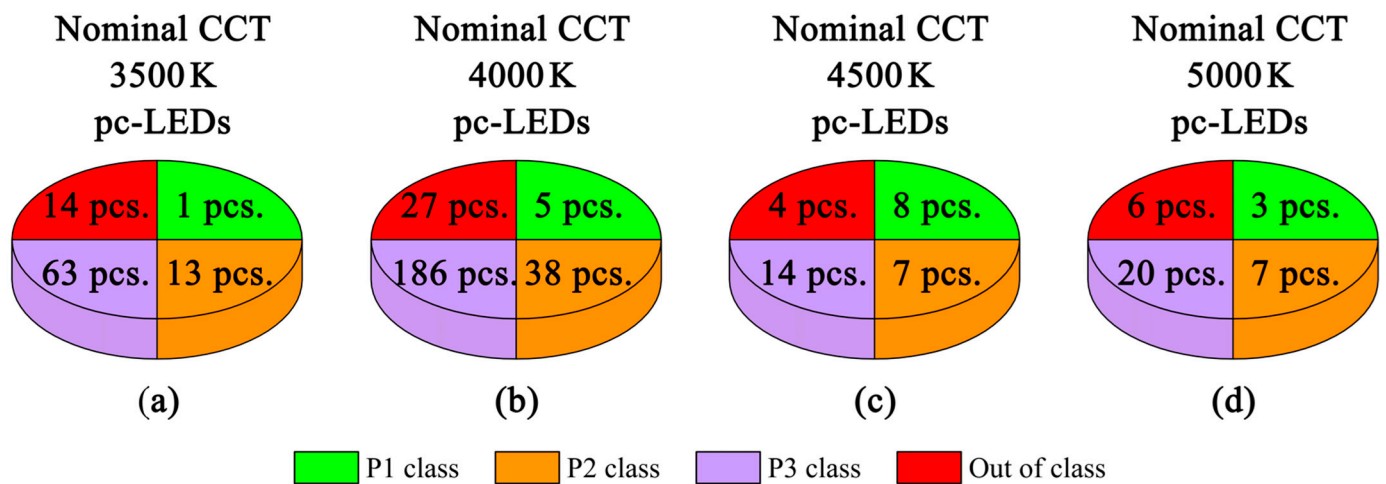


Figure 6. The number of selected LEDs according to their nominal CCT value and CPC class, where (a) is for 3500 K nominal CCT, (b) is for 4000 K nominal CCT, (c) is for 4500 K nominal CCT, (d) is for 5000 K nominal CCT.

The CRI R_a values of the tested LEDs are plotted as a function of the CPC class in Figure 7. Figure 8 shows the CCT values. Figures 7–11 represent the values of a specific parameter for all the tested LEDs according to the corresponding CPC class. In Figures 7 and 8, the magenta and yellowish dots represent LEDs applicable in Australia/New Zealand ($3300\text{ K} \leq \text{CCT} \leq 5300\text{ K}$). Magenta dots are only for LEDs satisfying $4000\text{ K} \leq \text{CCT} \leq 5000\text{ K}$, such as those required for healthcare lighting in Europe, the United Kingdom, and the United States. The COI values of the LEDs under consideration are presented in Figure 9. Figure 10 shows the LER values. The values of CRI R_9 for these pc-LEDs are presented in Figure 11, while Figure 12 shows the $R_{f,skin}$.

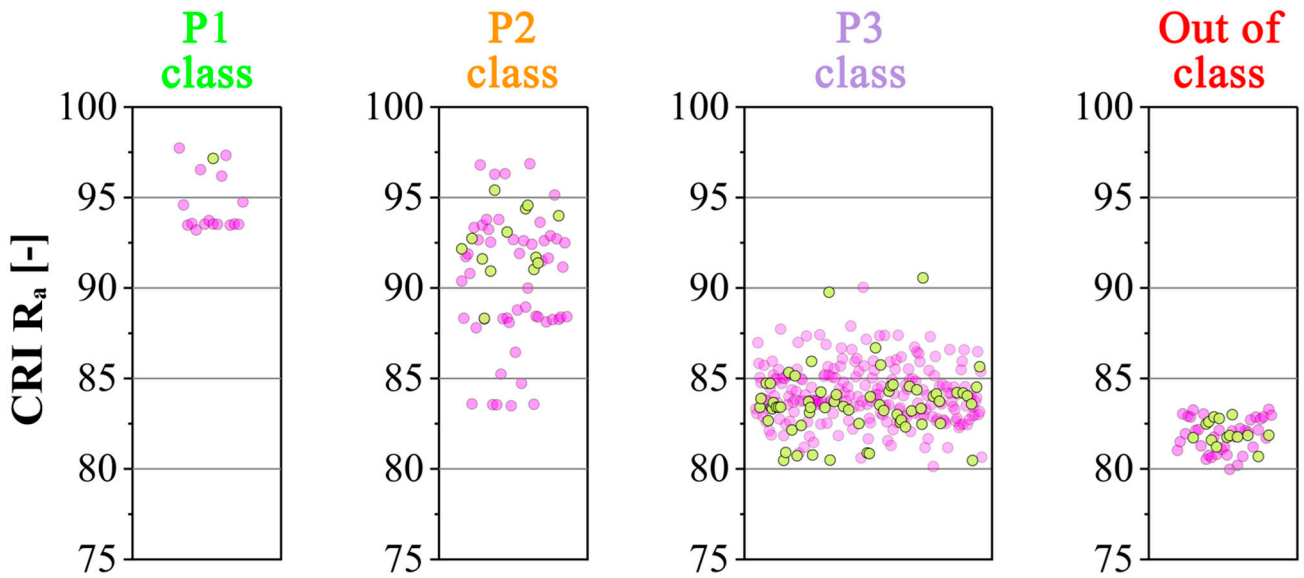


Figure 7. The CRI Ra values of the LEDs under consideration according to their CPC classification. The magenta and yellowish dots represent the LEDs, which are applicable in Australia/New Zealand, where CCT is in the range of 3300 K~5300 K. The magenta dots are for the LEDs with a nominal CCT in the range of 4000 K~5000 K, which are applicable in the European Union, United Kingdom, and United States.

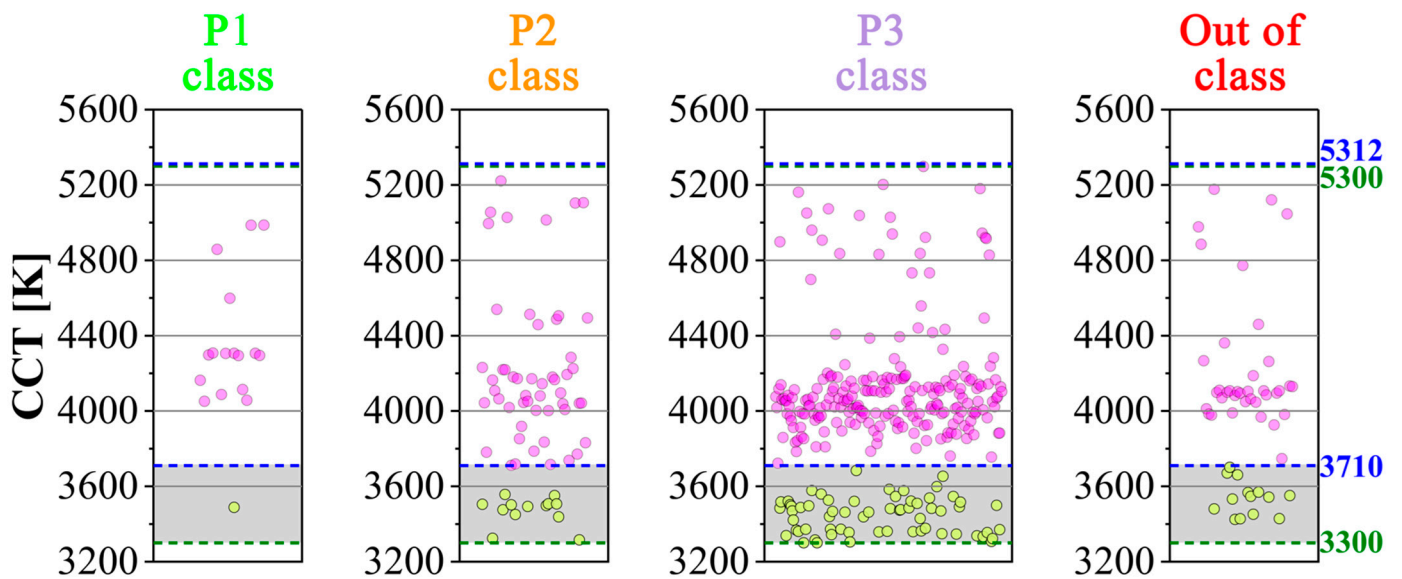


Figure 8. The CCT values of the LEDs under consideration, according to their CPC classification. The magenta and yellowish dots represent the LEDs, which are applicable in Australia/New Zealand, where CCT is in the range of 3300 K~5300 K. The magenta dots are for LEDs with a nominal CCT in the range of 4000 K~5000 K, which are applicable in the European Union, United Kingdom, and United States.

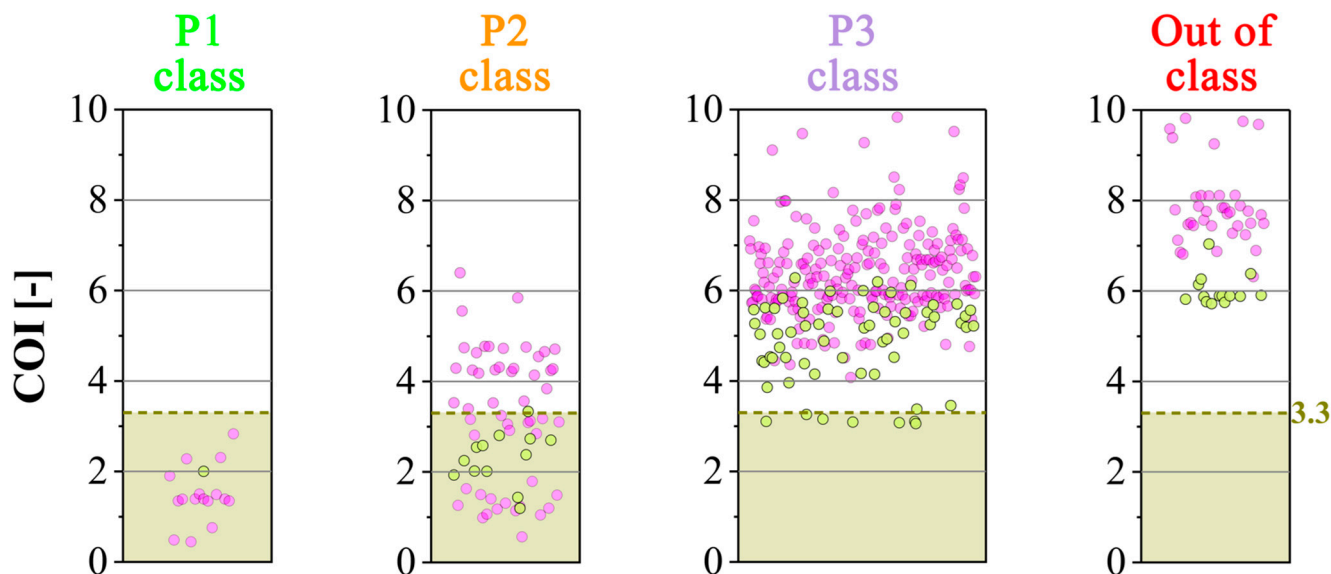


Figure 9. The COI values of the LEDs under consideration, according to their CPC classification. The magenta and yellowish dots represent the LEDs, which are applicable in Australia/New Zealand, where CCT is in the range of 3300 K~5300 K. The magenta dots are for the LEDs with a nominal CCT in the range of 4000 K~5000 K, which are applicable in the European Union, United Kingdom, and United States. The brown zone corresponds to compliance with the requirement of a COI of less than 3.3.

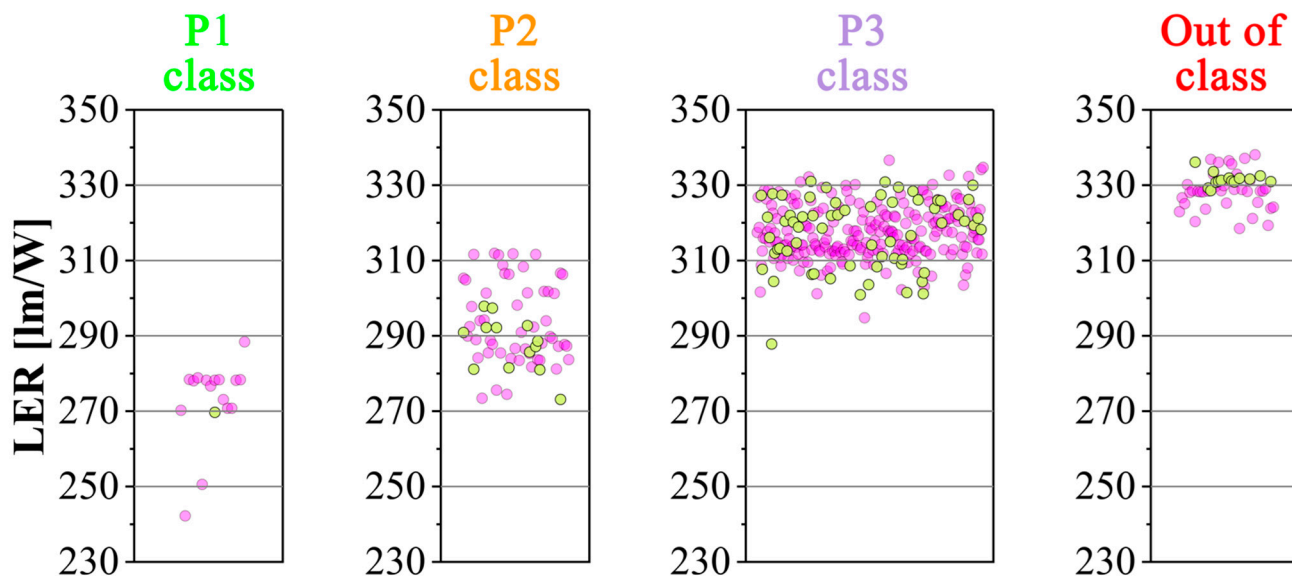


Figure 10. The LER values of the LEDs under consideration, according to their CPC classification. The magenta and yellowish dots represent the LEDs, which are applicable in Australia/New Zealand, where CCT is in the range of 3300 K~5300 K. The magenta dots are for the LEDs with a nominal CCT in the range of 4000 K~5000 K, which are applicable in the European Union, United Kingdom, and United States.

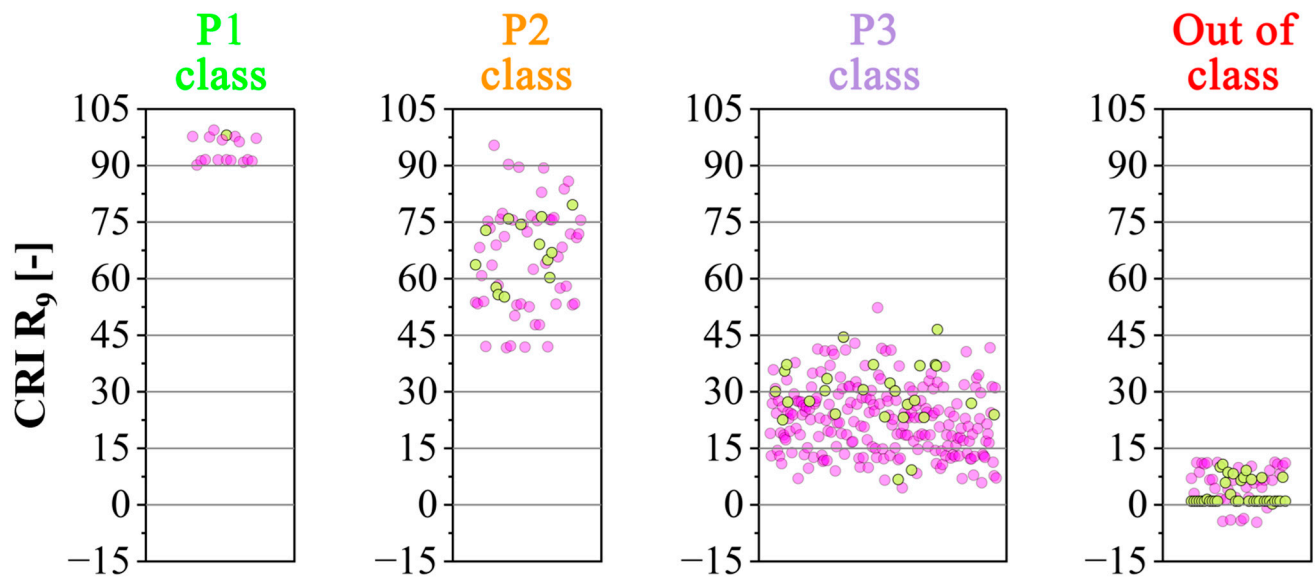


Figure 11. The $CRI R_9$ values of the LEDs under consideration according to their CPC classification. The magenta and yellowish dots represent the LEDs, which are applicable in Australia/New Zealand, where CCT is in the range of 3300 K~5300 K. The magenta dots are for the LEDs with a nominal CCT in the range of 4000 K~5000 K, which are applicable in the European Union, United Kingdom, and United States.

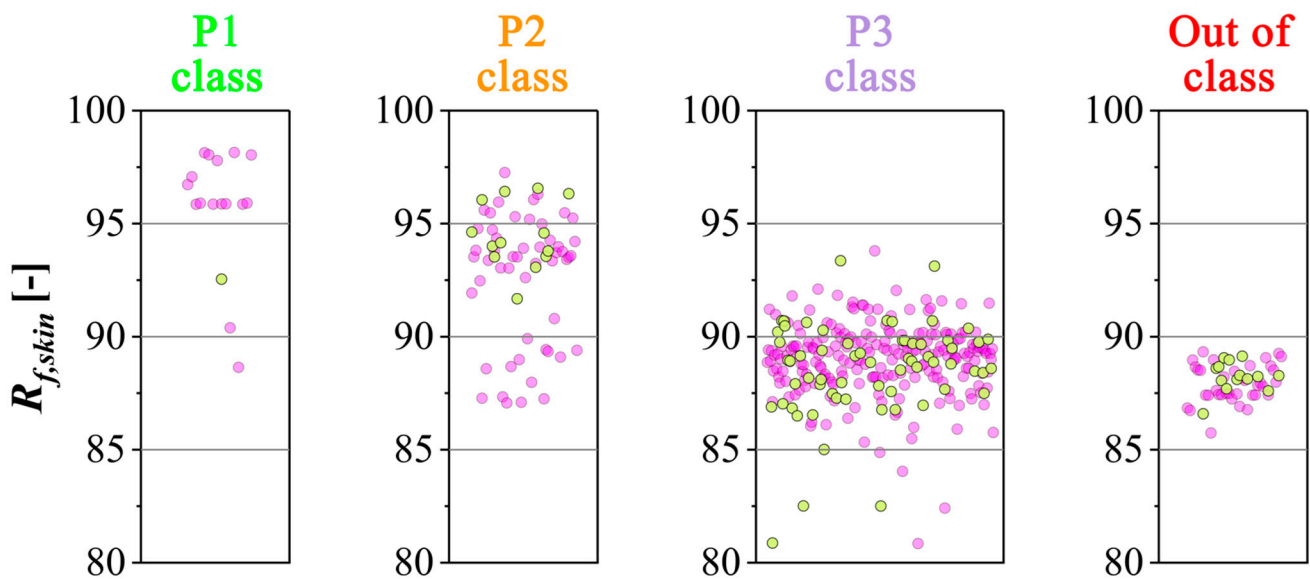


Figure 12. The $R_{f,skin}$ values of the LEDs under consideration, according to their CPC classification. The magenta and yellowish dots represent the LEDs, which are applicable in Australia/New Zealand, where CCT is in the range of 3300 K~5300 K. The magenta dots are for the LEDs with a nominal CCT in the range of 4000 K~5000 K, which are applicable in the European Union, United Kingdom, and United States.

3. Discussion

Figure 8 shows that, regardless of their nominal CCT, the vast majority (88% for Australia/New Zealand evaluated LEDs and 89% for European Union, United Kingdom, and United States evaluated LEDs) of the tested commercially available LED sources can be classified as P1 (best color rendering quality), P2 (good color rendering quality), or P3 (acceptable color rendering quality) class in the CPC classification. As expected, Figure 8 also shows that CCT is not correlated with the color rendering quality assessed using the

CPC method. Figure 7 shows that the CRI Ra values can reach values exceeding 95 for some LEDs in class P1 and other LEDs in class P2. Therefore, this parameter is not sufficient to express the differences between the P1 and P2 classes. The LEDs classified as P3 class have CRI Ra in the range (80~90), and their $R_{f,skin}$ parameter is mostly within a similar range of values, but their CRI R₉ parameter has unacceptable values for proper rendering of the red color (Figure 11). All LEDs classified as out-of-class due to CPC classification have their CRI Ra in the range (80~85) and $R_{f,skin}$ in the range (85~90), but their COI parameter is out of the acceptable range, exceeding the maximum allowed value by a factor of about 2 (Figure 9).

According to Figure 10, LEDs classified as P3 have higher LER (light efficiency of radiation) values than LEDs of the P2 and P1 classes, thereby offering the possibility of reaching the best energy efficiency for luminaires incorporating this type of LEDs.

As illustrated in Figure 11, the CRI R₉ values (measuring red color rendering) correlate well with the CPC class. The best CRI R₉ values (equal to or greater than 90) are obtained with LEDs of the P1 class. Lower CRI R₉ values, but still positive, are found for LEDs of class P2 or P3.

Figure 9 shows that all LEDs belonging to the P1 class and some LEDs in the P2 class comply with the Australia/New Zealand COI requirements for medical examination room lighting (COI value not exceeding 3.3).

The COI parameter is related to the LER value. It has been demonstrated that LEDs with low LER values (230~290) are capable of fulfilling the standard requirements for the COI value (not exceeding the value of 3.3). Furthermore, these LEDs are classified as P1 (Figure 9). The LEDs classified as P2 meet the COI requirements only when their LER is less than 300 lm/W. The LEDs classified as P3, according to CPC classification, have a higher LER (mostly with the value in the range 310~330 lm/W) compared with the LER of P1 and P2 LEDs. Only a few of these meet the COI requirements. The most energy-efficient LEDs with an LER beyond 330 lm/W do not meet the COI requirements. Furthermore, their $R_{f,skin}$ parameter is less than 90, and the CRI R₉ parameter is too low to ensure good rendering of red colors (Figure 11).

In Figure 12, the data show that $R_{f,skin}$ parameter is not a good predictor of the COI parameter. It is interesting to note that many LEDs with a high $R_{f,skin}$ value (good color rendering of the skin) are unable to comply with the COI requirement of less than 3.3. The values of $R_{f,skin}$ parameter range from 85 to 100 for classes P1 and P2, 80 to 95 for class P3, and 85 to 90 for the out-of-class LED products (Figure 12). In each of these classes, the $R_{f,skin}$ values are high, but the COI required is met only for class P1 and partially for class P2 (Figure 9). It is worth mentioning that in the same range of $R_{f,skin}$ parameters, LEDs can have (Figure 12) non-compliant COI values (Figure 9). Therefore, $R_{f,skin}$ cannot be considered a reliable predictor of medical examination room lighting quality.

4. Conclusions

This article demonstrates that the CPC method can provide very precise discrimination in the color rendering properties of a large number of available LEDs for lighting applications. This method is especially useful for choosing the best LEDs to equip luminaires designed for medical examinations in healthcare facilities. These results show that the specific requirements used in Australia and New Zealand to help the observation and diagnosis of cyanosis can be met with LEDs classified in the P1 class of the CPC (best preferred color rendering qualities). This class also provides the best color rendering of saturated red colors, as measured by the CRI R₉ index. However, the CPC class is not a good predictor of the color rendering of the skin, as measured by the $R_{f,skin}$ index. The $R_{f,skin}$ values are between 85 and 100 for LEDs of the P1 and P2 classes and between 80 and 95 for

class P3 LEDs. However, LEDs with an $R_{f,skin}$ index between 85 and 90 can be classified as out-of-class with respect to the CPC requirements. As a consequence, the CPC classification is not applicable to choosing LEDs with respect to their color rendering of the skin.

This work confirms that the standard color rendering index CRI Ra is not adapted to guarantee good observation of cyanosis during medical examination. The use of light sources with a CRI Ra in the range that classifies them as suitable for general lighting applications (between 80 and 100) does not always ensure that the COI parameter is in the required range of values. The issue is that different light sources with the same CRI Ra may or may not meet the COI requirement. The CRI Ra is not a predictor of the COI index.

This paper presents a tool that allows users to evaluate the quality of light sources in medical examination rooms. This article emphasizes the validity of using the CPC methodology to evaluate the qualitative parameters of LED sources. The article also points out that this type of classification is essential to ensure complete and reliable knowledge of lighting, and that looking only at the energy efficiency of LEDs that meet CRI Ra requirements is not enough to have high-quality lighting in medical examination room applications.

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

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