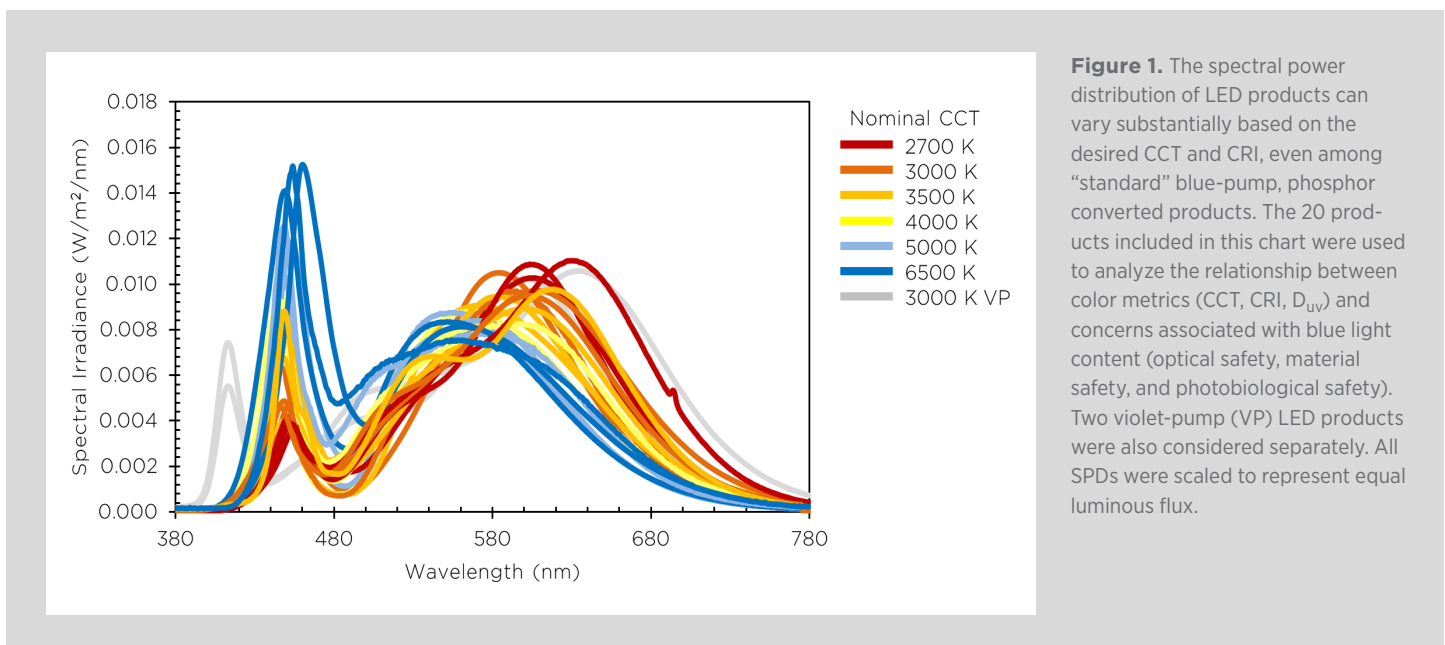# TRUE COLORS

LEDs and the relationship between CCT, CRI, optical safety, material degradation, and photobiological stimulation

The spectral emission of LEDs is a frequent topic of conversation among lighting professionals and the public. There is no shortage of published material—some of it myth, some of it fact, and some of it a combination—addressing the spectral power distribution (SPD) of LED products used for general illumination. This document addresses some of the common concerns, using an example dataset of 20 CALiPER-tested products with correlated color temperatures (CCTs) between 2700 K and 6500 K, and color rendering indices (CRIs) between 62 and 98—essentially the full range of what is commonly available (see Figure 1).[1] The specific concerns addressed include the potential for light-induced retinal damage (optical safety), light-induced changes to artwork or other media (material degradation), and light-induced stimulation of human circadian functions (photobiological safety).

Although the main analysis is based on standard blue-pump, phosphor converted LEDs, the analysis anecdotally considers violet-pump LEDs as well. Commercially available color-mixed LED systems were not analyzed, but analysis of a theoretical four-component model is subsequently provided. While several correlations are addressed, it is acknowledged that carefully tuning the spectrum of LEDs—or any other type of light source—may distort the correlation to some degree. All lighting products should be evaluated on their own merits.

Figure 1. The spectral power distribution of LED products can vary substantially based on the desired CCT and CRI, even among "standard" blue-pump, phosphor converted products. The 20 products included in this chart were used to analyze the relationship between color metrics (CCT, CRI, D_{uv}) and concerns associated with blue light content (optical safety, material safety, and photobiological safety). Two violet-pump (VP) LED products were also considered separately. All SPDs were scaled to represent equal luminous flux.

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1 Products were selected to fill bins for CCT (2700 K, 3000 K, 3500 K, 4000 K, 5000 K, and 6500 K) and CRI (60+, 70+, 80+, 90+). If available, one product was included for each cell of the matrix. Only standard, blue-pump, phosphor converted LEDs were considered for the main analysis.

Is light from LED products the same as light from other types of light sources?

Although it may seem obvious, it is important to state explicitly that LEDs emit the same type of radiant energy—within the visible range of the electromagnetic spectrum—as every other light source. They do, however, have their own unique signature visible in their spectral power distribution: a peak in the short-wavelength "blue" region,[2] around 450 nm, and a broader peak somewhere between 550 and 650 nm.[3] This archetypal attribute is shown in Figure 1—to allow for appropriate comparison, all the SPDs have been scaled to represent equal lumen output.

In general, higher CCT LED products have a more prominent blue peak, which is dictated by the need to have proportionally more blue radiation—a fact that is common to all high CCT sources. Additionally, most LED products achieving a higher CRI have a broader range of phosphor emission, which tends to provide more long wavelength (red) radiation. There are notable alternatives to the de facto standard approach, such as color mixed systems, which would not necessarily have the same characteristics.

Understanding SPD Plots

SPDs describe the amount of radiant energy across a range of wavelengths (colors), but one contributing factor to the confusion about spectrum-related effects of LEDs is the way data is often presented. Many times, data will be plotted as a *relative* SPD, where the maximum value of the distribution is set to be one, with the remaining values scaled accordingly. Comparisons of such data can be misleading, because the different SPDs represent different quantities of light—for example, one might be comparing a 50-lumen source to a 500-lumen source. This may lead to erroneous conclusions, since quantity of light is a key factor for any type of optical radiation risk.

When examining effects inherently related to the quantity of light, a better way to examine spectral data is to compare the *absolute* SPD of two or more sources, where each value is appropriately scaled based on the radiometric measurement, and may be normalized (based on luminous flux, for example) to allow for appropriate comparisons. In practice, it may be important to consider the variable lumen output of two sources being considered; in this document, which is focused on generalized comparisons, the absolute SPDs have been normalized so that they represent equivalent luminous

flux.[4] The lumen is a basic unit of lighting specification and is physiologically relevant, whereas other potential normalization metrics, such as total radiant flux, would still result in comparing two sources that provide different quantities of light.

Figure 2 shows a comparison of charts displaying absolute and relative SPDs for a typical LED, a CIE F Series illuminant (fluorescent lamp model), and either a CIE D Series illuminant (phase of daylight model) or blackbody radiation.[5] When looking at relative SPDs (bottom), the LED looks like it produces much more blue light than the incandescent source, for example. Conversely, when comparing the absolute SPDs normalized for equal lumen output, the minimal difference in total blue light is apparent—as described in the next section, peak emission does not correlate to the total amount of blue light, which must be considered over a range of wavelengths.

Of course, numerical values provide the most technically accurate comparisons, although they are rarely provided in specification literature. The numerical values analyzed in this report are calculated, and are intended to represent a realistic range of commonly available LED products. It is possible that there are products that fall outside this range or otherwise are not represented; if blue light risks are an important concern, analyses of specific products are warranted.

Examining Spectral Data

Some of the confusion about spectrum-related effects of LEDs is caused by the way SPDs are presented.

Relative SPD—The maximum value of the distribution is set to be one, with the remaining values scaled accordingly. The resulting distribution is unitless. Comparisons of such data can be misleading because the different SPDs represent different quantities of lumens.

Absolute SPD—The values represent radiant energy (e.g., W/nm). The distribution may be scaled to represent a given amount of luminous flux, for example, which is necessary for making appropriate comparisons between sources when examining optical, material, or photobiological risks. That is, it is important to compare SPDs representing sources that provide an equivalent visual experience, based on lumen output.

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2   Technically, light and objects are not inherently colored; rather, they emit radiation (spectral power distribution) or reflect radiation (spectral reflectance distribution). The sensation of color is a result of the brain's interpretation of the interaction of radiant energy (light) and the reflectance of an object. Nonetheless, blue light has become a ubiquitous term, so it is used in this report.

3   For more information, including a description of the less common LED product types, see the DOE SSL fact sheet, LED Color Characteristics.

4   Normalization is accomplished by applying a single scale to the entire distribution so that the area under the visual efficiency function (V_λ) is the same across all sources being compared. The same procedure could be used to normalize for luminous intensity or illuminance.

5   CIE standard illuminants, like the D Series and F Series, are mathematical models of common sources, such as daylight and fluorescent lamps. Blackbody radiation is a mathematical model of radiant energy generated from a heated, opaque, non-reflective, theoretical mass. Emission from incandescent and halogen lamps is similar to blackbody radiation, but in some cases may include less ultraviolet or very-short-wavelength radiation due to the filtering properties of glass lenses.
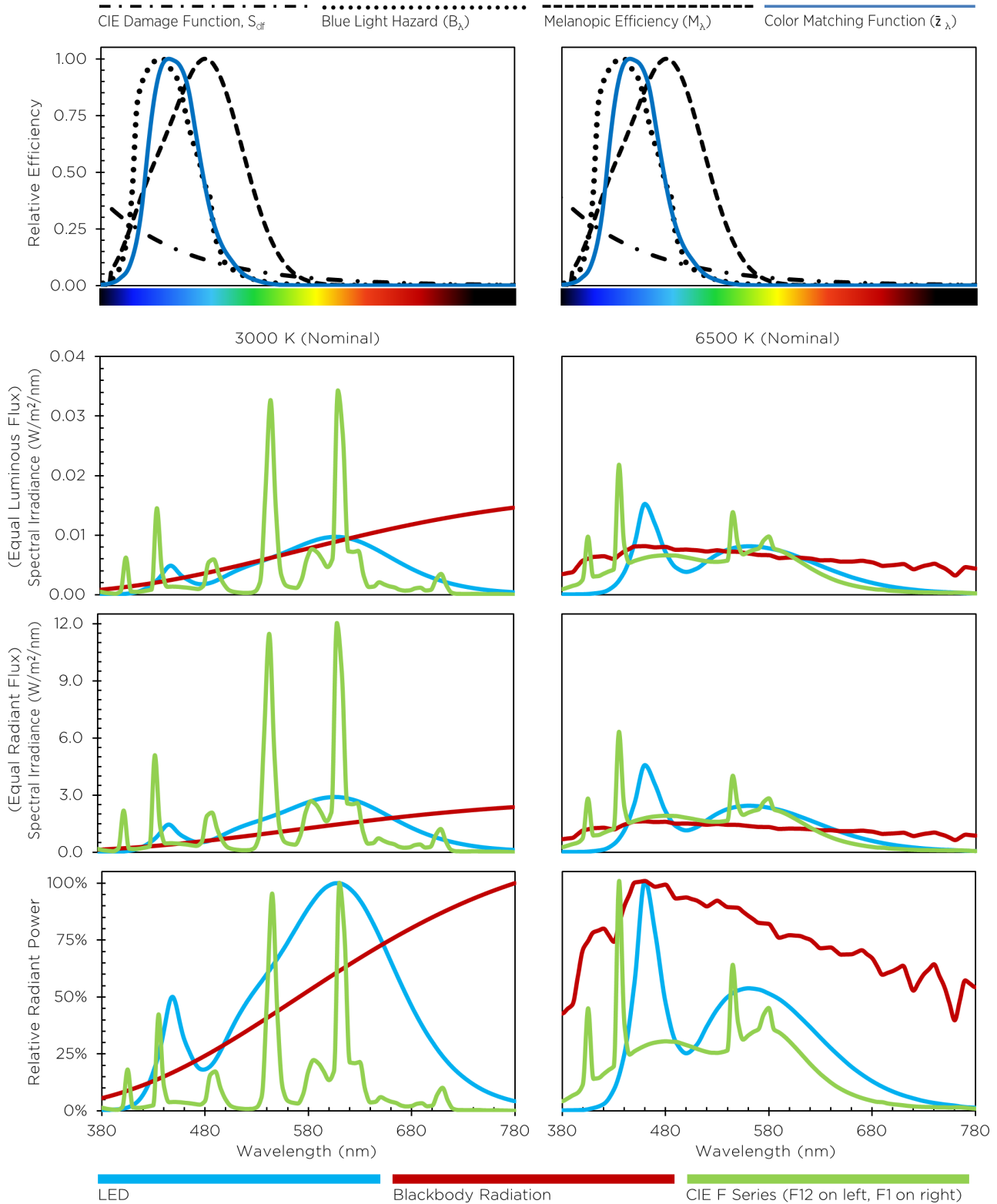
Figure 2. TOP: Spectral weighting functions for three of the blue light safety concerns. The two plots are the same; both are provided to allow visual comparison of the SPDs below. The wavelengths at the peak of the functions contribute most to the associated hazard. Also shown is one of three color matching functions, which are used in conjunction to derive chromaticity and derivatives, such as CCT. The CIE material damage function peaks at 300 nm (not shown). **BOTTOM: Three ways to plot SPDs, shown for nominally 3000 K products (left) and 6500 K products (right).** The first row shows SPDs equalized based on lumen output. The second and third rows are equalized for radiant flux and relative power, respectively, which leads to comparisons that are not physiologically relevant—that is, comparisons that are not relevant to lighting for visual tasks.

Specific Concerns about LED Spectral Power Distributions

Most often, concerns regarding LED SPDs focus on "blue light," and are centered on the specific concerns highlighted in the inset below. This is likely due to the peak in short-wavelength optical radiation that is present in the SPD of most LED products; but exactly what type of optical radiation is harmful? There are no specific boundaries within the electromagnetic spectrum that define blue light; pure, monochromatic radiation with a wide variety of wavelengths (e.g., 410 to 500 nm) may be nominally considered blue. Thus, trying to quantify the amount of "blue" in a source by evaluating a peak emission is mostly irrelevant to any of the specific concerns documented in the inset, which all have a defined action spectrum that includes a range of wavelengths, as shown in Figure 2. Similarly, trying to quantify blue light using only a defined wavelength range (e.g., 430 to 460 nm) is unrealistic, as no human visual or nonvisual function is known or believed to have this behavior.

To reiterate: just because there may be a distinct blue peak in their SPD—in contrast with some other light sources, such as incandescent or daylight—LEDs do not necessarily have greater potential to cause retinal, material, or photobiological harm. In fact, typical, commercially available LEDs present approximately the same risk in those three areas as other sources having the same CCT, as documented in the next three sections. In short, the correlation between CCT and optical safety, material safety, or photobiological safety exists because CCT calculations also include a weighting function covering the blue light region (shown in Figure 2). Thus, if the proportion of blue light (and thus any associated risk) changes, so too does the CCT. Of course, there is some error in the correlation because CCT only characterizes one dimension of chromaticity (i.e., it does not consider D_{uv} and because the color matching function ($\bar{z}_\lambda$) does not perfectly match the action spectrum for each risk type).

Optical Safety

The optical safety of LEDs was thoroughly discussed in a DOE SSL Fact Sheet, *Optical Safety of LEDs*. That document illustrates the strong correlation between CCT and $K_{B,v}$ (blue light hazard efficacy, or risk per lumen) for all types of light sources, which occurs principally because the $\bar{z}_\lambda$ color matching function and the blue light hazard function, B_λ, are very similar (see Figure 2). Further, based on current standards, it can be concluded that white-light architectural lighting products do not pose a risk for blue light hazard, although non-white light sources (e.g., blue LEDs) and some specific applications with high-risk populations should be considered more carefully.

Figure 3 shows the correlation between CCT and $K_{B,v}$ for the aforementioned blue-pump LED sources, two violet-pump LED sources, blackbody radiation at several color

temperatures, CIE D series illuminants (daylight models) at 5000 K and 6500 K, as well as the CIE F series illuminants (models of fluorescent sources). The plot demonstrates a strong linear correlation for all sources ($R^2 = 0.95$), and for the blue-pump LEDs alone ($R^2 = 0.97$). Expanded regression models for the standard LED products using CCT, D_{uv}, and CRI as predictors indicate that D_{uv} can provide some additional explanatory value (i.e., is statistically significant), but that CRI does not.

If anything, the optical safety of blue-pump LEDs is slightly better than blackbody radiation, which is essentially the type of emission provided by an incandescent or halogen lamp, although the effect is not likely to be statistically significant. In principle, this occurs because blackbody radiation (and daylight) both emit more very-long-wavelength (deep red and infrared) radiation than LEDs. The emission must be balanced by increased shorter-wavelength (blue) radiant energy to maintain the same CCT. Neither very-long-wavelength nor very-short-wavelength radiation contributes much to lumen output.

Concerns about Spectrum

Optical Safety—Can LED products damage our retinas? This potential health risk is known as Blue Light Hazard, and is characterized with a spectral weighting function, $K_{B,v}$.[1] Besides spectrum, intensity and duration of exposure also contribute to the risk potential.

Material Safety—Can LED products increase the rate of degradation for important artwork or other materials? One spectral weighting function that characterizes this attribute is the CIE Damage Function, S_{df}.[2]

Photobiological Safety—Can exposure to LED products at inappropriate times (e.g., at night) cause unwanted shifts to our circadian photobiology, and thus result in a host of undesirable consequences? Because this concern is relatively new, there is no standard spectral weighting function for characterizing photobiological potential, but M_λ[3] and CS[4] are two functions used in this fact sheet.

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1 For more information, see the DOE SSL fact sheet, Optical Safety of LEDs. Relevant standards documents include: CIE S009:2002, ANSI/IES RP-27, IEC/EN 62471, IEC/TR 62471-2, and IEC/TR 62778.

2 More information is available in CIE 157:2004. Although current research has questioned the importance of this metric, it is valuable in this context for helping to understand the relative spectral emission of common light sources.

3 Provencio I, Rodriguez IR, Jiang G, et al. 2000. A Novel Human Opsin in the Inner Retina. J Neurosci 20(2):600-605.

4 Rea MS, Figueiro MG, Bullough JD, Bierman A. 2005. A model of phototransduction by the human circadian system. Brain Res Rev 50:213-218.
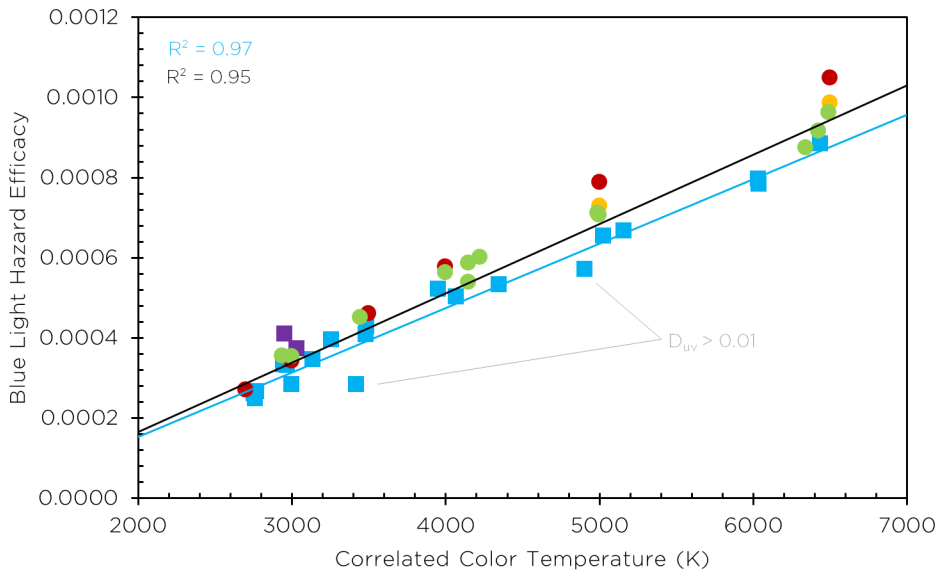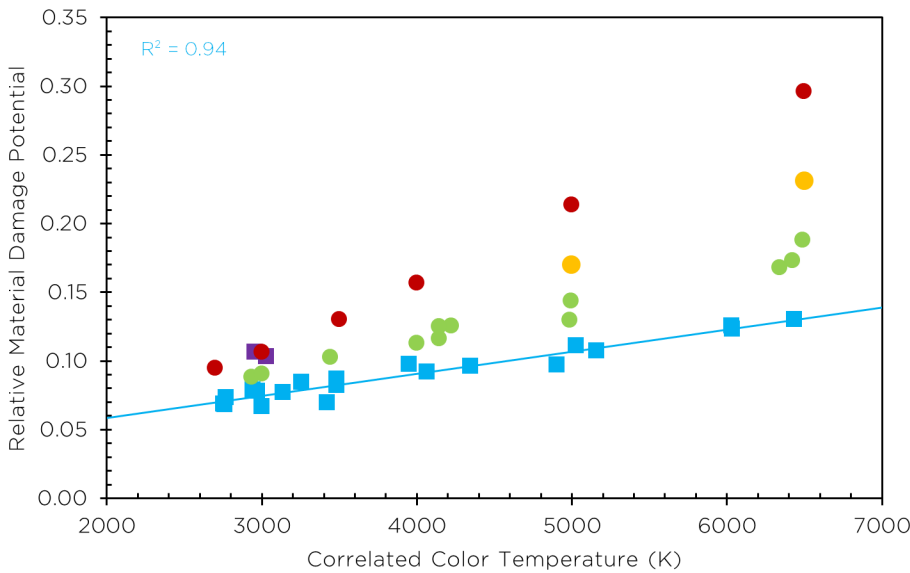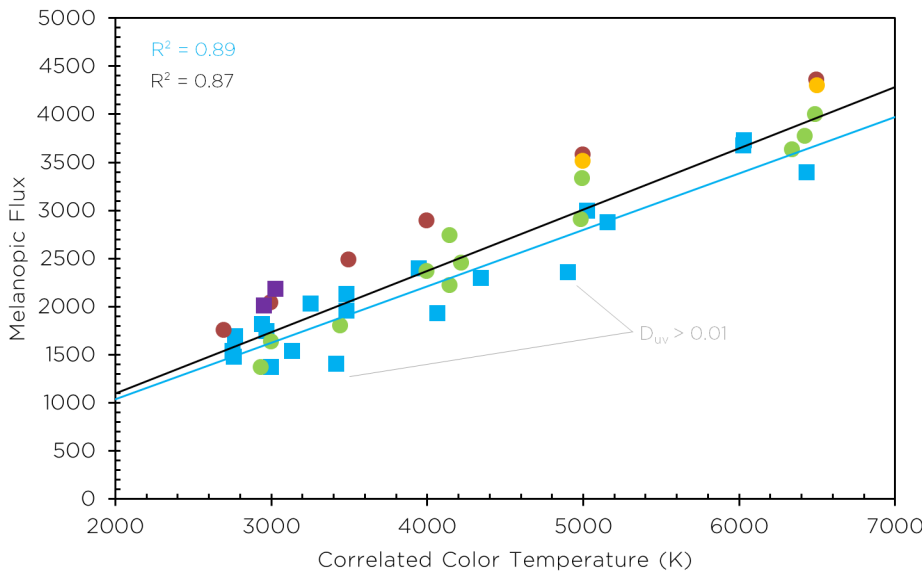
Figure 3.

TOP: Blue light hazard efficacy ($K_{B,v}$) versus CCT. Across all source types, there is a strong correlation between retinal damage potential per lumen and CCT. The denoted outliers have a D_{uv} of greater than 0.01, which is outside ANSI-defined limits for white light. Adding D_{uv} to the regression model for blue-pump LEDs increases R^2 to 0.99.

MIDDLE: CIE spectral damage potential (S_{df}) versus CCT. While the linear correlation between damage potential and CCT is high for any given product type, there is clear stratification between technologies (and subgroups of technologies). Importantly, standard blue-pump LEDs have the lowest damage potential at a given CCT, whereas unfiltered incandescent and halogen sources—approximated here using blackbody radiation at 2700 K and 3000 K—tend to have the highest.

S_{df} is a metric intended to describe the potential of a light source to degrade materials, such as fading paints. It can be altered by changing a coefficient, which was set at 0.12 for this analysis. While the relevance of the S_{df} metric has been debated, it helps to document the blue light risk (or lack thereof) that is present in LED sources. All products are normalized to the same lumen output.

BOTTOM: Melanopic flux versus CCT. The analysis demonstrates a strong linear correlation between melanopic flux and CCT across all types of light sources. Adding either CRI or D_{uv} to the regression model can improve the correlation to $R^2 \geq 0.97$. CRI and D_{uv} are moderately correlated to each other.

Input from melanopsin-containing ipRGCs is an important factor in circadian phototransduction, but other photoreceptors also contribute. Because more advanced models have not reached consensus, melanopic flux, determined using M_λ, is used as a proxy for circadian sensitivity in this report.

Products with a positive D_{uv} tend to have lower risk potential than otherwise similar products with a less positive (or negative) D_{uv}. This is intuitive, although perhaps not applicable in practice, because a positive D_{uv} indicates a green tint, whereas a negative D_{uv} indicates a purple or pink tint. Further, the statistical significance of D_{uv} in the linear regression model illustrates CCT's limitations. However, considering only ANSI-defined-white-light sources[6] can mitigate this uncertainty to some degree and provide greater confidence in the correlation between CCT and blue light risks.

Material Safety

The potential for LEDs—and all light sources—to degrade materials, such as important works of art, gained mainstream attention in 2012 and 2013. While the myth that LEDs are particularly damaging has been debunked by museum and lighting experts, some uncertainty lingers.

One way to characterize the potential of a light source to damage materials is the CIE spectral damage function (S_{df}) which includes a coefficient to tailor the action spectrum to various materials. Although this methodology for characterizing damage potential is very generalized, using it in this analysis simply illustrates further that LED products carry the same or less risk as other sources of the same CCT.

As shown in Figure 3, there is a strong linear correlation between damage potential and CCT among each source type (e.g., $R^2 = 0.94$ for blue-pump LEDs), but not for all source types combined. However, for each source type, there is a predictable increase in damage potential as CCT increases. One contributing factor is that the CIE damage function, which more heavily weights radiant energy as the wavelengths become shorter, is not very similar to the $\bar{z}_\lambda$ color matching function. Simultaneously, the different source types all have a different point at which their emission becomes negligible, regardless of CCT. For example, standard LEDs do not emit much energy below 400 nm, but blackbody radiation and the D Series illuminants do.

It is also important to note that blue-pump LEDs are generally the least likely product type to cause material degradation at any given CCT, at least among the products considered. Even the example violet-pump LEDs pose no more risk than a typical incandescent or halogen lamp.[7]

Photobiological Safety

As with material and optical safety, it is sometimes argued that LED sources have greater potential to affect the circadian system, which may have undesirable consequences if it occurs at the wrong time for the individual. As with the other risks, concerns often arise from the short-wavelength peak of a blue-pump LED package, which leads to the perception that LEDs emit more blue light. The situation may appear especially alarming if relative SPDs are shown.

However, there are two important things to consider. First, the overall sensitivity of the human circadian system is still being rigorously debated. It is known that photic input to the nonvisual system comes not just from melanopsin-containing ipRGCs (intrinsically photosensitive retinal ganglion cells), but also from rods and cones, the photoreceptors typically associated with visual function. Further, nonvisual photosensitivity is potentially mediated by a person's state of adaptation, the time of day, and the quantity of light. Thus, modeling circadian stimulation with a simple spectral weighting function is generally insufficient. However, to address claims of increased risk, this analysis investigates the nonvisual phototransduction potential of LED and conventional sources using the M_λ function, one of several proposed efficiency functions for melanopsin.

The analysis again shows a strong correlation between blue-pump LED melanopic flux and CCT ($R^2 = 0.89$) for sources normalized for equal luminous flux. Adding CRI and D_{uv} to the regression model did provide some additional information, increasing the coefficient of determination ($R^2 = 0.98$).

Does CRI change the amount of blue light?

While CCT is highly correlated with blue light-related consequences, CRI is generally not. In fact, for phosphor-based LED products at the same CCT and equal lumen output, products with a lower CRI may be the least damaging, as shown in Figure 4. This may be surprising, and arguments to the contrary have been made. It is true that achieving a higher CRI for standard LEDs requires converting more of the blue emission to longer wavelengths, thus decreasing blue emission. However, converting more energy to long wavelengths may also reduce lumen output, and the ratio of risk-specific blue light to lumen output can increase.

The photobiological effects of light are related to the spectrum and intensity of light, but are not specific to any type of light source. Especially when nighttime exposure is a concern, choosing lower-CCT sources will generally reduce the photobiological risk potential. In critical applications, evaluations beyond CCT are warranted.

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6   The dataset analyzed in this report includes three products with a D_{uv} outside of ANSI-defined tolerances (IES/ANSI C78.377).

7   In some applications, such as museums, halogen lamps may be filtered to reduce or eliminate emissions below about 430 nm, which also reduces their material damage potential. The blackbody radiation used in this analysis does not represent filtered lamp emission.
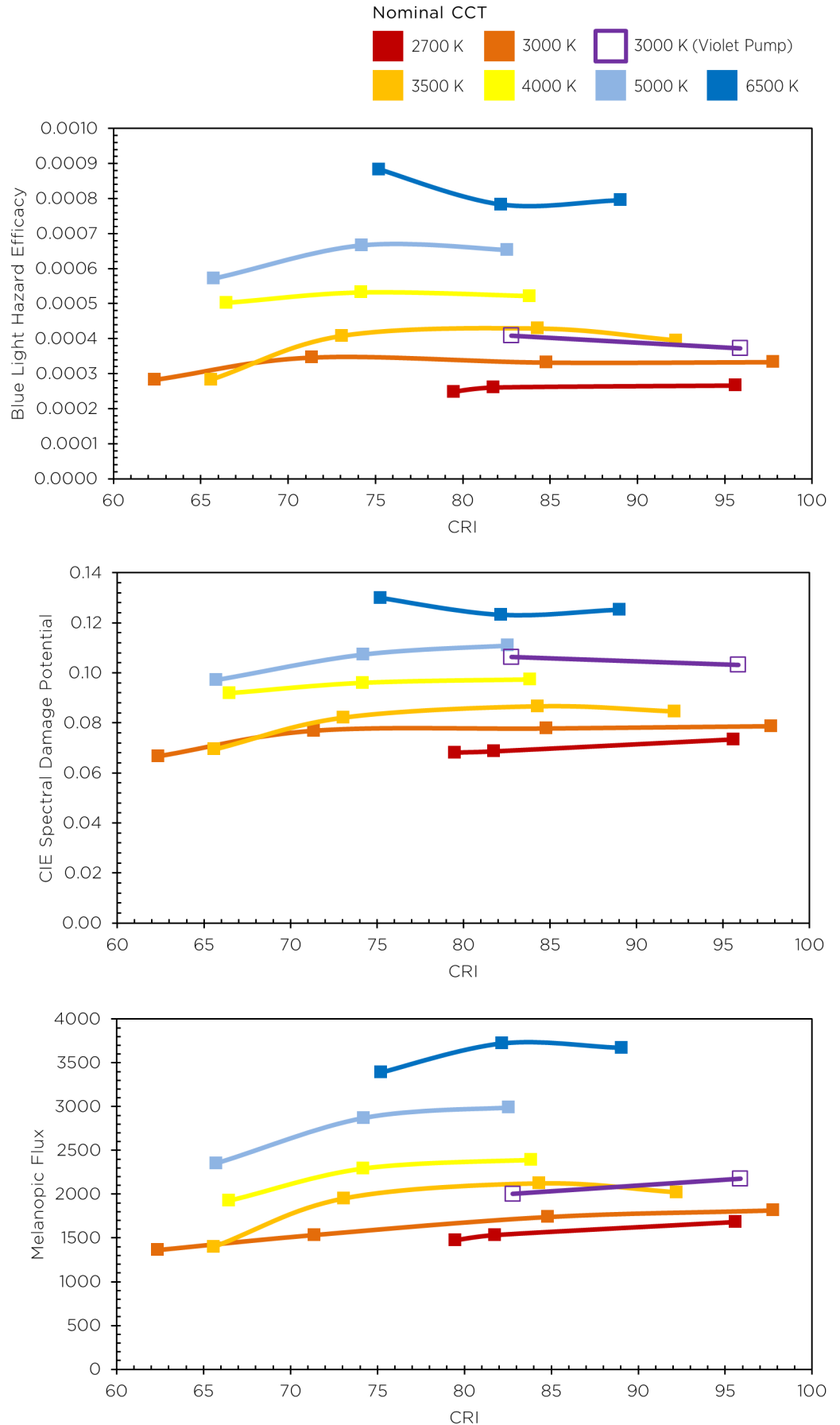
Figure 4.

TOP: Blue light hazard efficacy ($K_{B,v}$) versus CRI for the LED dataset

MIDDLE: CIE spectral damage potential (S_{df}) versus CRI for the LED dataset

BOTTOM: Melanopic flux versus CRI for the LED dataset

Across all three measures considered, CRI showed minimal correlation. Even for melanopic flux, where CRI provided some extra predictive power, the charts show that substantial changes in CRI are equivalent to relatively small changes in CCT. Further, the observed correlation was positive, meaning lower CRI products were less photobiologically stimulating. Notably, CRI may be confounded with other variables, such as D_{uv}.

Each point in each chart represents a single SPD. While the included SPDs cover a wide range of products, they are not representative of all SPDs in the same nominal CCT and CRI bin.
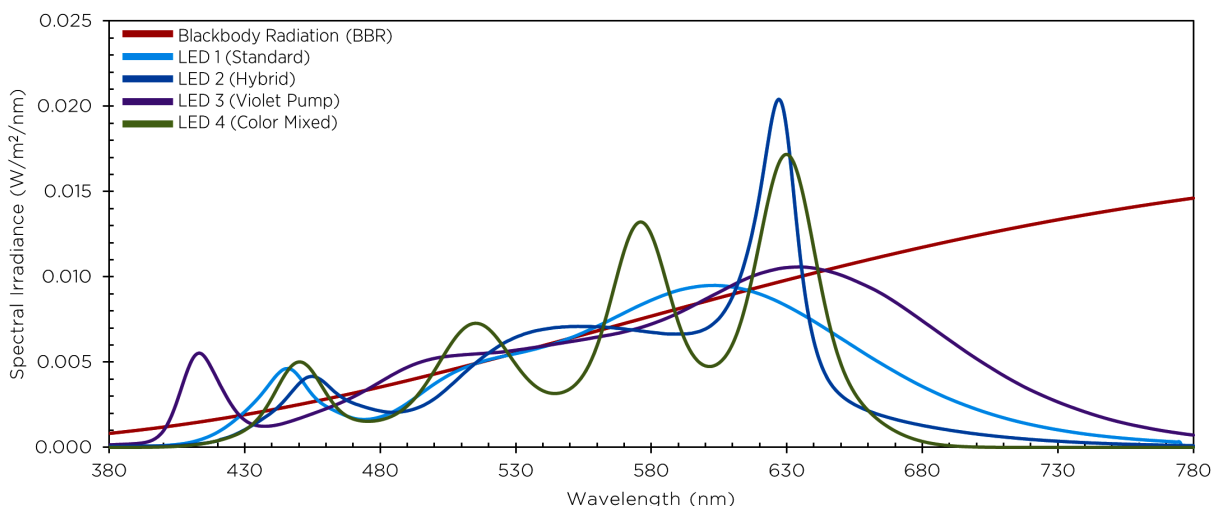
The dataset exhibited a linear correlation ($R^2 = 0.38$) between CRI and D_{uv}; sources with a higher CRI tended to have a lower D_{uv} (i.e., closer to zero or negative). Sources with a lower D_{uv} generally contain slightly more short-wavelength radiant energy than their counterparts at the same CCT and lumen output.

The End Result

One important characteristic of LEDs is that they are easily engineered to have any CCT desired. In contrast, incandescent and halogen lamps are generally between about 2700 and 3000 K. Fluorescent and metal halide lamps are also available in a wide range of CCTs, although they are most commonly found between 3500 and 5000 K. Although this analysis focused on standard blue-pump, phosphor converted LEDs, the conclusions are expected to hold for other types as well (see Figure 5).

Although at the same CCT and output, LED lamps and luminaires do not emit any more blue light than their counterparts, increasing the CCT does necessitate a higher proportion of blue light. In general, CCT can be used as an effective predictor of short-wavelength content across various source types, and specifically as a predictor of optical safety, material degradation, and (in a simplistic way) circadian stimulation.

If any of the aforementioned blue light concerns are a key design criterion, further investigation should be undertaken. Color temperature is a good correlate, but it is also possible to maximize or minimize any of the specific risks, since the spectral weighting functions involved are not perfectly aligned with the $\bar{z}_\lambda$ color matching function and because CCT further distills chromaticity to a single number. ∎

	LED 1	LED 2	LED 3	LED 4	BBR
Correlated Color Temperature (CCT)	2945	3008	3031	3000	3000
Distance from Black Body (D_{uv})	0.000	0.002	0.002	0.000	0.000
Color Rendering Index (CRI)	98	96	96	91	100
Relative (Normalized) Risk					
Optical	0.89	0.78	1.00	0.83	0.92
Material	0.74	0.69	0.97	0.71	1.00
Photobiological	0.83	0.82	1.00	0.87	0.94

Figure 5. LEDs are not a homogenous group. The four example LED products, which represent a variety of LED product types, have similar color characteristics but are rated differently by the three risk functions considered in this report. While the difference between the LED products can be substantial (up to 26%), none of the products exceeds blackbody radiation by more than 8% for any of the risks considered.