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Street Lighting and Blue Light
Frequently Asked Questions

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Street Lighting and Blue Light – Frequently Asked Questions

These frequently asked questions (FAQs) have been assembled in response to ongoing discussion of the June 2016 American Medical Association (AMA) public release, *Guidance to Reduce Harm from High Intensity Street Lights*, which presented a number of recommendations related to possible health risks of increased short-wavelength content of outdoor lighting sources, with a particular focus on the continuing widespread conversion of older products to LED. The issues raised in the AMA guidance are complex, arising from new science and new lighting technology that are often misunderstood and misreported. These FAQs are intended to provide factual information and some clarity to the ongoing discussion in a format readily accessible to a general lighting audience.

Basics and terminology

What is "blue light"?

"Blue light" is a term often used as shorthand to describe a variety of ranges of wavelengths that play key roles in the health issues raised by the AMA. But the term can lead to confusion, because there's no consensus definition of blue light; light colors vary along a continuum, and there's no single, discrete definition of blue or any other color. For the sake of accuracy, it's important that any time the term "blue" is used, it's clearly defined, since different ranges of the spectrum apply to different concerns.

Figure 1 provides a list of definitions of blue and other spectral colors from four different reference documents. Together, these documents categorize blue light as falling somewhere in the range from 424 nm to 500 nm, but the specific ranges reported differ significantly.[1]

Wavelength ranges for monochromatic light (nm)

color		1	2	3	4
red		647–700	647–760	630–700	620–800
orange		585–647	585–647	590–630	590–620
yellow		575–585	575–585	570–590	560–590
green		491–575	491–575	500–570	480–560
blue		424–491	424–491	450–500	450–480
violet		400–424	380–424	400–450	400–450

[1] *CRC Handbook of Chemistry and Physics*. 1966.
[2] Hazel Rossotti. *Color*. Princeton University Press, 1983.
[3] Edwin R. Jones. Physics 153 Class Notes. University of South Carolina, 1999.
[4] Deane B. Judd. *Goethe's Theory of Colors*. MIT Press, 1970.

Figure 1. Wavelength ranges for monochromatic light as reported in four source documents. Source: http://physics.info/color/.

[1] Source: http://physics.info/color/

"Blue light" is also a term sometimes used by astronomers to describe lighting wavelengths that are scattered in the atmosphere at night and result in skyglow that interferes with the observation and appreciation of night skies. Along these lines, the Cégep de Sherbrooke, a Canadian university with a focus on astronomy and atmospheric science, broadly defines the blue range as 405-530 nm and recommends a metric called "% Blue," which sums the radiant power in that range, dividing by the total power emitted between 380 and 780 nm.[2]

None of the cited ranges for blue are more definitive than others, which means that generic terms such as "blue light," "blue-rich LEDs," and "blue content" are not very specific and in fact can be misleading, given that the term "blue" itself is not a defined quantity in terms of spectrum, visual outcome, or nonvisual outcome.

Moreover, the associated health and other impacts under discussion are caused by particular wavelengths of light, not by colors. The relevant wavelengths for any given effect don't necessarily coincide with what the human eye perceives as a particular color. The effects linked to "blue light" in the AMA release, for example, in actuality extend into violet, indigo, cyan, and green. Referring only to blue incorrectly discounts the effects of these other wavelength regions.

These FAQs thereby avoid use of the term "blue light," except where necessary to address specific use of the term in public media.

What is a spectral power distribution (SPD)?

The spectral power distribution (SPD) of a light source is the amount of radiant power it emits at different wavelengths across the visible spectrum. An SPD can be represented as a table of radiant-power values, or as a graph similar to those in Figure 2. In addition to determining the apparent color of the light, the SPD determines how the source affects the appearance of objects it illuminates, as well as its potential scattering characteristics within the atmosphere[3] and the potential for associated health effects (such as those brought up in the AMA guidelines). The SPD is the fundamental light-source information used in color science.

SPDs can vary widely, even within a given light-source technology. Two metal halide lamps that have correlated color temperatures (CCTs) of 4000 K can have very different SPDs, for example, as shown in Figure 2. This is also true of LED products, so it's important to keep in mind that no single SPD is entirely representative of a given light-source technology.

[2] http://galileo.graphycs.cegepsherbrooke.qc.CA/app/en/home

[3] This FAQ focuses primarily on potential health consequences of light at night. Discussion of the relationship between light at night and sky glow will be addressed separately by DOE in a forthcoming report.

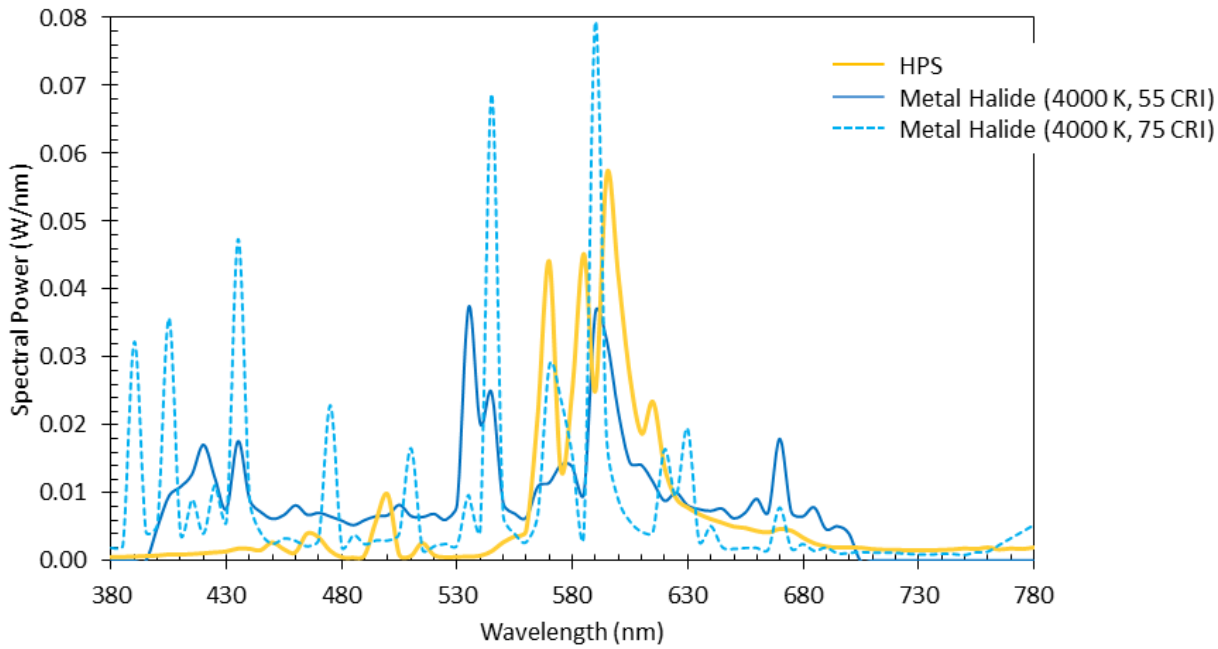

Figure 2 Two 4000 K metal halide SPDs showing variability in wavelength content, with one high-pressure sodium SPD for comparison.

What is correlated color temperature (CCT)?

Most white-light sources emit a range of wavelengths, which, when combined, produce the color of light perceived by the human eye. Correlated color temperature (CCT) is a shorthand way to describe the light's color, in terms of its apparent "warmth" or "coolness." CCT is expressed in kelvin (K), and the value corresponds to the color of light emitted by a heated mass (a theoretical blackbody radiator) at that physical temperature (although the light source is not actually operating at that physical temperature). So an LED with a CCT of 3000 K will appear to give off a color of light close to that of a tungsten filament operated at a physical temperature of 3000 K (tungsten being very close to an ideal blackbody radiator). The challenge is that light sources with very different SPDs can have the same CCT, as illustrated by the two 4000 K MH products in Figure 2. Similarly, sources with the same CCT can look different. For this reason, CCT is only a rough gauge of the actual spectral content of a light source. For more information, see the LED Color Characteristics Fact Sheet.

What are the five types of photoreceptor in the human eye, and what is an action spectrum?

There are five currently recognized photoreceptors in the human eye. These include three different types of cone photoreceptors, which are responsible for color and detail vision under well-lighted (or *photopic)* conditions. The different types of cone receptors are distinguished by their comparative sensitivities to short-, medium-, and long-wavelength light. In addition to the cones, there are rods, which provide monochromatic vision under low lighting (or *scotopic)* conditions. Rods are responsible

for vision at low light levels but don't detect color or detail. The eye's aggregate sensitivity shifts toward shorter wavelengths under scotopic conditions compared to photopic conditions (Figure 3). There are also the recently discovered intrinsically photosensitive retinal ganglion cells (ipRGCs), which are crucial for relaying light information to parts of the brain controlling the biological clock.[4] Relevant primarily to circadian physiology, pupil dilation, and other nonvisual effects, the ipRGCs contain melanopsin, a photopigment that has a peak photosensitivity at 480 nm. For a variety of reasons, the peak response of the ipRGCs in vivo appears to be at about 490 nm,[5] though this value is still being refined.

Figure 3 shows the spectral sensitivity (or *action spectra)* for each of the five known types of photoreceptors, which combine in various ways to allow for visual and nonvisual processes. The mechanisms underlying some of these processes are well-known, such as how the three cone photoreceptors provide for the perception of color; whereas other mechanisms, such as those involving the body's circadian systems, are only beginning to be understood. Importantly, the responses of the photoreceptors are not static, but change based on the amount and duration of light present.[6] The role of ipRGCs at various light levels is still being investigated. The response of the ipRGCs is usually referred to as the *melanopic* response.

[4] Lucas RJ, Peirson SN, Berson DM, Brown TM, Cooper HM, Czeisler CA, Figueiro MG, Gamlin PD, Lockley SW, O'Hagan JB, Price LA, Provencio I, Skene DJ, Brainard GC. 2014. Measuring and using light in the melanopsin age. Trends in Neurosciences, 37(1), 1-9.

[5] CIE. 2015. TN 003:2015: Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013.

[6] Joshua J. Gooley, Kyle Chamberlain, Kurt A. Smith, Sat Bir S. Khalsa, Shantha M. W. Rajaratnam, Eliza Van Reen, Jamie M. Zeitzer, Charles A. Czeisler, and Steven W. Lockley. Exposure to Room Light before Bedtime Suppresses Melatonin Onset and Shortens Melatonin Duration in Humans. J Clin Endocrinol Metab. 2011 Mar; 96(3): E463–E472.

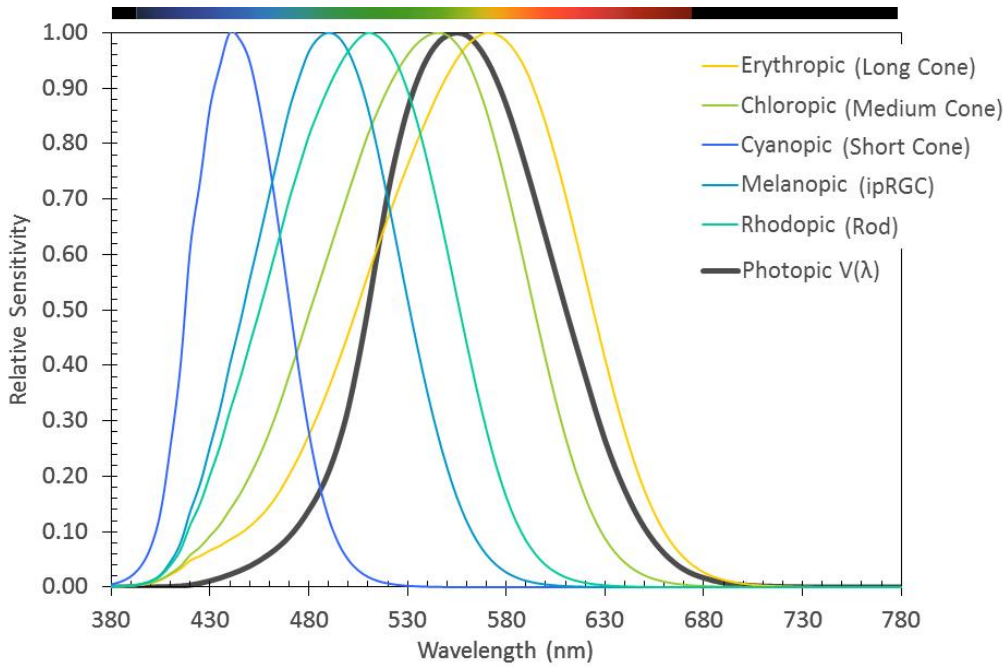

Figure 3. Spectral sensitivity (action spectra) of the five known human photoreceptors, along with V_λ, the photopic response curve used to define and quantify lumen output from a light source. Data from CIE TN 003:2015.

As it pertains to the issues related to "blue light," the corresponding melanopic action spectrum encompasses a wide range of wavelengths that extends well beyond the nominal definitions of "blue." In other words, while some portion of the melanopic response occurs with short wavelengths that are typically recognized as blue, it's also influenced by colors outside of those wavelengths. Furthermore, it should be noted that ipRGCs don't act in isolation when it comes to influencing the biological clock; that is, the rods and cones also play a role, although the full extent of their contributions is not fully understood at this point.[7]

How do LEDs create white light?

The most common white LEDs today employ blue-pump LED chips that, at the chip level, produce an SPD peak centered somewhere in the range of about 445 to 465 nm. Light from the LED chip passes through a phosphor layer that converts most of the chip's output into longer wavelengths, typically in the green, yellow, orange, and red parts of the spectrum. The mix of these colors produces white light.

However, there are other methods of producing white light, which are less common but offer greater flexibility for adjusting the SPD. One such method is to combine LEDs of different colors – such as

[7] Lucas RJ, et al, op cit.

phosphor-converted LEDs (PC-LEDs) in combination with other LEDs that emit specific colors (see Figure 4) – or to combine multiple LEDs of various colors, which can be varied in relative output to attain any apparent color of light desired. Systems offering dynamic adjustability tend to be more expensive and thus have been employed less frequently in street lighting and other outdoor applications to date.

Figure 4. PC amber-cyan-violet flat lens chip array (ledengin.com).

Health concerns

Why is so much attention being paid to "blue light" right now?

In the last two decades, the medical research community has learned much about light's role in the physiology of plants and animals,[8] some of which has focused on the influence of short-wavelength light. Researchers have demonstrated, for example, the ability of such light to affect circadian rhythm (the 24-hour "biological clock"). Humans and other organisms have evolved this biological response to regular periods of daylight and darkness. In the early 2000s, researchers were able to identify a class of previously unknown photoreceptors, the ipRGCs (see "What are the five types of photoreceptor in the human eye, and what is an action spectrum?") that links directly to parts of the brain outside the visual cortex.[9] The peak sensitivity of this type of photoreceptor in a 32-year old male is at approximately 490 nm, with the raw sensitivity of its photopigment (melanopsin) at around 480 nm.[10] Both of these peaks fall at the upper end of the range commonly described as "blue."

Simultaneously with the rise in our understanding of nonvisual photoreception, LEDs have emerged as a viable light source for general illumination. Because of the rise in use of white LEDs for outdoor lighting, and their relatively greater short-wavelength content compared to the high-pressure sodium (HPS) products they're typically replacing, concerns have arisen that the potentially increased presence of short wavelengths in the night environment may be detrimental to health.

[8] For a review, see Lucas RJ, et al, op cit.
[9] Berson DM, Dunn FA, Takao M. 2002. Phototransduction by retinal ganglion cells that set the circadian clock. Science 295(5557):1070-3.
Hattar S, Liao HW, Takao M, Berson DM, Yau KW. 2002. Melanopsin-containing retinal ganglion cells: architecture, projections, and intrinsic photosensitivity. Science 295(5557):1065-70.
[10] CIE. 2015. TN 003:2015: Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013.

However, it's important to note that the spectral content of LEDs can be engineered to provide any action spectrum desired – for example, to provide more ipRGC stimulation, or less of it. This characteristic has also contributed to the discourse of how LEDs could help –or harm – lighting users.

What are the specific lighting-related health concerns that have been raised?

Two examples, taken together, summarize the issues. One source concluded:

> "These findings indicate that room light exerts a profound suppressive effect on melatonin levels and shortens the body's internal representation of night duration. Hence, chronically exposing oneself to electrical lighting in the late evening disrupts melatonin signaling and could therefore potentially impact sleep, thermoregulation, blood pressure, and glucose homeostasis."[11]

Another summary of the issues as of 2013 reported:

> "It is now clear that electric lighting, including indoor evening light levels, has strong effects on human circadian rhythms in physiology, metabolism, and behavior. Recent experimental evidence in humans has shown, for example, that the lighting commonly used in the typical home in the evening is enough to delay melatonin onset and blunt its nocturnal peak (36). Even the display screens of personal computers, which often emit light rich in the blue portion of the visible spectrum, can alter melatonin production in the evening (41). It is not certain that these alterations can, in fact, increase breast cancer risk; that evidence is accumulating but is not yet conclusive. However, chronic disruption of circadian rhythmicity has the potential to yield serious long term health consequences."[12]

Is short-wavelength light harmful to the eyes?

This question refers to the risk of physical damage to the retina as a result of direct exposure to short-wavelength light, and is separate from the circadian-disruption concerns that are the main focus of the AMA guidelines*. In typical situations using common electric light sources, there is no danger to the eyes from short wavelengths, regardless of the source type***.** The DOE Fact Sheet *Optical Safety of LEDs* makes

[11] Gooley et al, Conclusions.

[12] Richard G. Stevens, PhD, George C. Brainard, PhD, David E. Blask, PhD, MD, Steven W. Lockley, PhD, and Mario E. Motta, MD. Breast Cancer and Circadian Disruption from Electric Lighting in the Modern World, CA Cancer J Clin. 2014 May; 64(3): 207–218.

this clear and provides a detailed description of retinal hazards posed by lighting in more specialized situations, along with references to international standards on the safe use of lighting products.[13]

Why not remove shorter-wavelength emissions from our outdoor light sources?

Short wavelengths are a fundamental component of the visible spectrum and have their benefits, ranging from aesthetics to safety. White light sources containing short-wavelength light generally render nighttime colors more similarly to daylight, aiding in identification (e.g., of vehicles, clothing, people) and improving contrast between an object (e.g., road debris) and its surroundings. Short wavelengths are also acknowledged (e.g., in IES TM-12 *Spectral Effects of Lighting on Visual Performance at Mesopic Lighting Levels)* as providing enhanced peripheral vision at the low levels of illuminance typically associated with street lighting. Researchers have found improvements in detection threshold and reaction times in simulated outdoor viewing tasks under light sources with broader spectra and better color rendering properties; these improvements occurred when target light levels were in the mesopic vision range (i.e., at typical street lighting levels).[14] It stands to reason that improved visual performance can bring associated safety benefits.

However, there are some instances where the benefits of omitting the short wavelengths outweigh any detriments from doing so – for example, in areas harboring endangered species that are particularly affected by short wavelengths. In such situations, it's possible to engineer the SPD of the light source to precisely match the need. This is especially true with LEDs, whose spectra are more easily manipulated than those of most conventional light sources.

What factors contribute to potential health concerns about light at night?

Spectrum, light level measured at the eye, duration of exposure, and timing of exposure relative to an individual's circadian cycle are believed to be the principal contributing factors to light's effects on health.[15] (See also "Are some wavelengths of more concern than others?") The underlying issues are complex and involve factors that are sometimes interrelated, and sometimes external to the lighting system.

Are any of the factors that are related to health concerns about light at night unique to LEDs?

None of the factors or concerns raised are unique to LEDs. At the same given wavelength, there is no difference between a radiant watt of light emitted by an LED and one emitted by any other type of light source. What varies between sources is the particular combination of wavelengths in the overall output,

[13] For example, IES RP-27.1-05, Photobiological Safety for Lamps and Lamp Systems - General Requirements.
[14] AL Lewis (1999). "Visual Performance as a Function of Spectral Power Distribution of Light Sources at Luminances Used for General Outdoor Lighting," Journal of the Illuminating Engineering Society, 1999. 28(1): p. 37–42.
[15] CIE TC3-46-2016: Research Roadmap for Healthful Interior Lighting Applications.

and the relative amount of radiant power at each wavelength. In addition to LEDs, all conventional white light sources used for street lighting (mercury vapor, metal halide, fluorescent, induction) have SPDs with a greater proportion of their radiant power in short wavelengths than do the orange HPS sources that have dominated street and roadway lighting over the last several decades.

How do light-exposure levels from street lighting compare with those from other sources?

All light at night can potentially contribute to the biological responses and related health concerns described in these FAQs, to varying degrees. At least two journal articles, for example, note that the primary concern about the effects of light at night on human health is driven by interior light levels in homes and workplaces,[16] [17] although exterior sources can also play a role if people (or other living organisms) are exposed to high enough light levels for sufficiently long durations. If the intensity and duration are identical, white light sources with higher proportions of short wavelengths (typically characterized as higher *melanopic content*) are more of a concern in this respect than are orange or amber sources with lower proportions of short wavelengths. The exact wavelengths of concern depend on the specific action spectrum. Because research is still ongoing, melanopic content is presently used as a proxy for most health concerns related to light at night.

Table 1 lists a few relevant characteristics of various lighting products used in both interior and exterior applications, including some products that are available at different CCTs. The "% Blue" column in the table divides the radiant power delivered in the wavelengths between 405 and 530 nm (a range used for similar purposes in a number of published reports pertaining to sky glow[18]) by the total radiant power delivered from 380 to 780 nm (approximately the visible spectrum) for each light source. The melanopic content of a light source, listed in the last column, is the source spectrum weighted by the spectral efficiency of the ipRGCs (see "What are the five photoreceptors in the human eye?"), and is an indicator of the source's potential to stimulate a melanopic response (i.e., a response by the ipRGCs).

Values in the table are normalized first to a uniform lumen output, to enable "apples to apples" comparisons among sources; and then, in the last two columns, the values are normalized relative to HPS to illustrate impact compared to the most common incumbent type of street lighting. The table lists values of % Blue, Relative Scotopic Content, and Relative Melanopic Content for a number of specific light sources. LED sources are shown with a range of values, because at any given CCT there are many LEDs with varying spectra. Conventional light sources are all listed with single values rather than a range, but they, too, would be most accurately characterized with some amount of variability.

[16] Richard G. Stevens, PhD, George C. Brainard, PhD, David E. Blask, PhD, MD, Steven W. Lockley, PhD, and Mario E. Motta, MD. Breast Cancer and Circadian Disruption from Electric Lighting in the Modern World. CA Cancer J Clin. 2014 May; 64(3): 207–218.

[17] Joshua J. Gooley, Kyle Chamberlain, Kurt A. Smith, Sat Bir S. Khalsa, Shantha M. W. Rajaratnam, Eliza Van Reen, Jamie M. Zeitzer, Charles A. Czeisler, and Steven W. Lockley, 2010. Exposure to Room Light before Bedtime Suppresses Melatonin Onset and Shortens Melatonin Duration in Humans. J Clin Endocrin Metab. doi:10.1210/jc.2010-2098

[18] Percent blue calculated according to LSPDD: Light Spectral Power Distribution Database, http://galileo.graphycs.cegepsherbrooke.qc.CA/app/en/home

Importantly, reducing the total luminous flux from a light source (e.g., by 50%, as is common when converting from HPS to LED streetlights) reduces the melanopic content by that same amount (i.e., by 50% in this example). Proper application of the values in Table 1, then, must also account for pre- and post-installation light output, in order to accurately compare pre- and post-melanopic content.

Table 1. Characteristics of Various Light Sources

Row	Light source	Luminous Flux (lm)	CCT (K)	% Blue*	Relative Scotopic Content	Relative Melanopic Content**
A	PC White LED	1000	2700	17% - 20%	1.77 - 2.20	1.90 - 2.68
B	PC White LED	1000	3000	18% - 25%	1.89 - 2.39	2.10 - 2.99
C	PC White LED	1000	3500	22% - 27%	2.04 - 2.73	2.34 - 3.57
D	PC White LED	1000	4000	27% - 32%	2.10 - 2.65	2.35 - 3.40
E	PC White LED	1000	4500	31% - 35%	2.35 - 2.85	2.75 - 3.81
F	PC White LED	1000	5000	34% - 39%	2.60 - 2.89	3.18 - 3.74
G	PC White LED	1000	5700	39% - 43%	2.77 - 3.31	3.44 - 4.52
H	PC White LED	1000	6500	43% - 48%	3.27 - 3.96	4.38 - 5.84
I	Narrowband Amber LED	1000	1606	0%	0.36	0.12
J	Low Pressure Sodium	1000	1718	0%	0.34	0.10
K	PC Amber LED	1000	1872	1%	0.70	0.42
L	High Pressure Sodium	1000	1959	9%	0.89	0.86
M	**High Pressure Sodium**	**1000**	**2041**	**10%**	**1.00**	**1.00**
N	Mercury Vapor	1000	6924	36%	2.33	2.47
O	Mercury Vapor	1000	3725	25%	1.82	1.95
P	Metal Halide	1000	3145	24%	2.16	2.56
Q	Metal Halide	1000	4002	33%	2.53	3.16
R	Metal Halide	1000	4041	35%	2.84	3.75
S	Moonlight	1000	4681 †	29%	3.33	4.56
T	Incandescent	1000	2836	12%	2.23	2.73
U	Halogen	1000	2934	13%	2.28	2.81
V	F32T8/830 Fluorescent	1000	2940	20%	2.02	2.29
W	F32T8/835 Fluorescent	1000	3480	26%	2.37	2.87
X	F32T8/841 Fluorescent	1000	3969	30%	2.58	3.18

***** Percent blue calculated according to LSPDD: Light Spectral Power Distribution Database, http://galileo.graphycs.cegepsherbrooke.qc.CA/app/en/home

****** Melanopic content calculated according to CIE Irradiance Toolbox, http://files.cie.co.at/784_TN003_Toolbox.xls, 2015

Source: MSSLC Light Post (http://energy.gov/eere/ssl/downloads/light-post-july-2016)

† Moonlight CCT measured and provided by Telelumen, LLC.

Key: PC – Phosphor Converted; LED – Light Emitting Diode

Are some wavelengths of more concern than others?

Medical research has identified an action spectrum of wavelengths having the potential to stimulate ipRGCs (see "What are the five types of photoreceptor in the human eye, and what is an action spectrum?"). Although the reported profile of ipRGC photosensitivity varies a bit among research

groups, the U.K.'s University of Manchester convened a workshop in 2013 to seek consensus,[19] and this was followed by a CIE Technical Note in 2015, which included an approximate photosensitivity represented by the curve shown in Figure 5. The action spectrum is centered on 490 nm and extends from approximately 380 to 600 nm. Hence, green and other nominally labelled color groups also contribute to the melanopic content of a light source, which explains why even the SPD for HPS, as shown in Figure 2, has potential for stimulating the ipRGCs. Likewise, metal halide, incandescent, and fluorescent sources all possess levels of melanopic content that are determined by their particular SPDs.

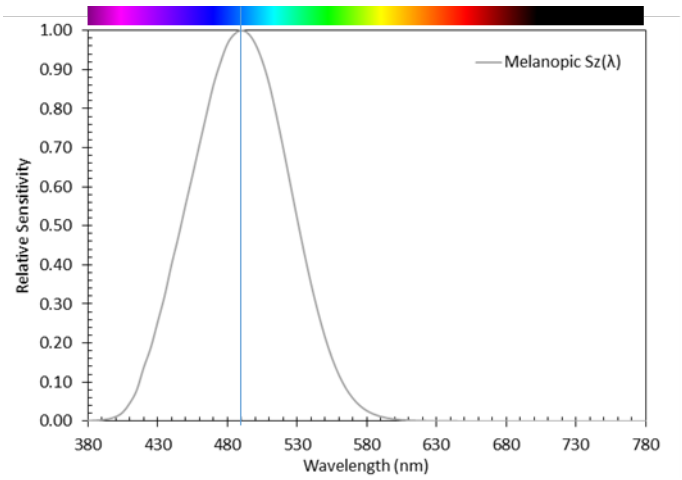

Figure 5. Melanopic action spectrum. Source: CIE TN 003:2015, Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013, published 2015.

What about the "blue spike" in LED SPDs? Does it suggest an above-average content of short wavelengths?

Plots of SPDs can be confusing, and the narrow peak in LED curves can be easily misinterpreted as suggesting an unusually high "blue light" content. SPDs for phosphor-converted LEDs do generally exhibit a local peak in the short-wavelength region of the spectrum, typically centered near 450 nm for most blue-pump products, as can be seen in Figure 6. Note, however, that the chart on the left in Figure 6 is portrayed in relative power terms (i.e., on a percentage scale where the maximum value is drawn at 100% and the magnitudes of other wavelengths are displayed relative to that value). A critical element not conveyed in this common plotting format is the *absolute* magnitude, or total quantity, of that radiant power, in radiant watts, which is displayed in the chart on the right of Figure 6 for the very same products. The red line in both charts displays an incandescent SPD for comparison, and all three products (two LED, one incandescent) have the same nominal CCT of 2800 K.

[19] Lucas RJ, et al, op cit.

The absolute magnitudes of radiant power values determine both the lumen output and melanopic content of a given product. Relative values, in contrast, are independent of lumen output. As an illustration, one of the products on the left in Figure 6 might be emitting 10 lumens and another one 10,000 lumens, and there's no way of discerning that difference from this format. The relative format by itself is thus of limited use in comparing any two actual light products in terms of their melanopic content or any other "real-world" characteristics.

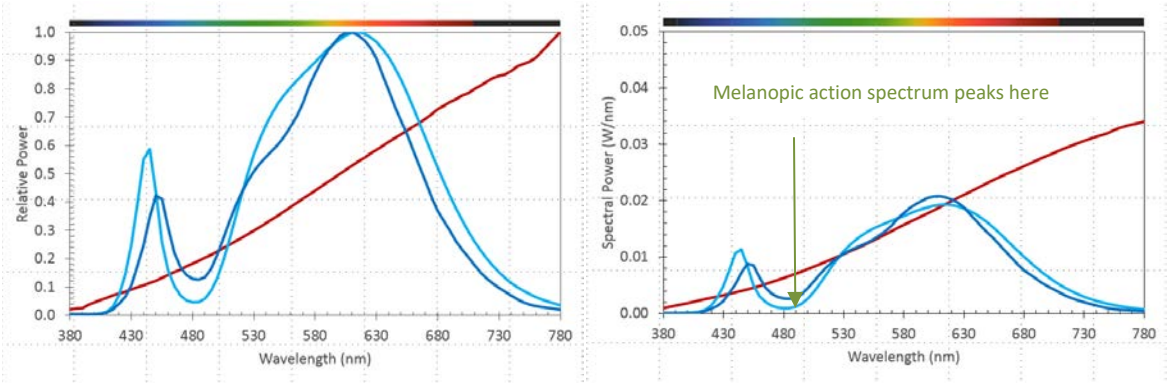

Figure 6. SPDs for two LED products displayed in terms of both relative (left) and absolute (right) magnitude of radiant power (W/nm). The red line displays an incandescent SPD. All products are nominal 2800 K CCT. The absolute magnitude plots on the right are normalized for lumen output.

It's also important to note where the peak in the short wavelengths occur. The LED "blue spikes" in Figure 6 occur some distance away from the peak of the ipRGC action spectrum (which was shown in Figure 3), indicated here by the arrow at 490 nm. In fact, the radiant power of the LEDs is in a trough at this point. In comparison, the incandescent source exhibits a significantly higher amount of radiant power at this particular wavelength, which explains why the incandescent listed in Table 1 (Row "T") shows a higher melanopic content than the majority of the LED products at 3000 K (Row "B"), even though the latter are at higher CCT. In fact, the melanopic content of the incandescent falls roughly in the midpoint of the range listed for LED products at 4000 K CCT (Row "D"). Such a result is likely to come as a surprise, based on a first impression derived from viewing the chart on the left in Figure 6.

Are brightness and glare particular problems for LED?

Glare and perceived brightness are both related to the spectral content, light output, and optical design of a luminaire, as well as the perception of the viewer. For a variety of reasons that haven't been entirely identified by the lighting research community, the same installation may be perceived quite differently by different viewers.

A common approach in the early implementation of LED lighting products was to replace incumbent HPS products on an equivalent average illuminance basis. This often resulted in an overly bright appearance,

according to typical comments received at the time. [20] Such early feedback compelled city engineers to reduce the target light levels when using LED products, which largely eliminated the corresponding complaints. LEDs can still appear bright and/or glaring if the observer has a direct view of them, however – especially from viewing angles near the streetlight's maximum intensity.

Among the factors influencing a perception of glare are the luminance of a given object, the apparent size of the object, the luminance of the background, the position of the object with respect to the observer's line of sight, and the pattern of luminance across the light-emitting surface. While all lighting sources can potentially cause glare, the small surface area of LEDs translates into a high luminance that can emphasize this characteristic if not sufficiently addressed in the luminaire's design. Fortunately, the manufacturers of quality lighting products – LED and traditional – have developed a number of approaches for mitigating glare. With LED sources these approaches often involve limiting direct viewing of the LEDs – for example, using diffusing materials or wave guides to reduce luminance by increasing the apparent size of the emitting area – but use other methods as well, such as limiting luminance at high emission angles.

The numerous low-glare products available on the market today attest to the fact that careful product design can strike an acceptable balance between performance and obtrusive light. Neither glare nor excessive brightness is a necessary compromise when using LEDs or any other type of light source.

Is CCT a good predictor of the impacts of lighting on health?

CCT is an approximate but unreliable metric for gauging the potential health and visibility influences of a lighting source. Although CCT roughly tracks with short-wavelength content (higher CCT *often* corresponds to higher short-wavelength content, and vice versa), the SPDs of different light sources vary enough that they can't be used as reliable predictors of that content.

The relationship between CCT and melanopic content is markedly weaker for sources that combine narrowband emissions than for sources with a more continuous spectrum. An example is LED products using individual red-green-blue (RGB) emitters. Figure 7 uses a wide range of products to illustrate the unreliability of using CCT to predict melanopic/photopic (M/P) ratios, an indicator of relative melanopic content.

In Figure 7, higher M/P ratios indicate products with relatively greater potential for stimulating the ipRGCs. A fair amount of variability in M/P ratio (as shown by position on the y-axis) can be seen among sources even of the same type at a given CCT. But the greatest variability is evident in products identified on the chart as "LED Mixed." (e.g., see "How do LEDs create white light?" and Figure 4 in

[20] A common explanation put forth was that products of higher CCT are always perceived as brighter. However, a variety of studies have not supported this conclusion; e.g., see the review of 70 studies of spatial brightness perception in S Fotios, D Atli, C Cheal, K Houser and A´ Logadóttir. Lamp spectrum and spatial brightness at photopic levels: A basis for developing a metric. Lighting Res. Technol. 2015; Vol. 47: 80–102.

particular.) LEDs that incorporate increasingly sophisticated combinations of chip types, each with different spectral characteristics, are expected to become increasingly common and will increase the variety of SPDs available. For these products in particular, CCT is at best a dubious metric for their ability to influence health in the manner under discussion. Similarly, selecting products based only on CCT is clearly not a reliable approach to minimizing ipRGC stimulation.

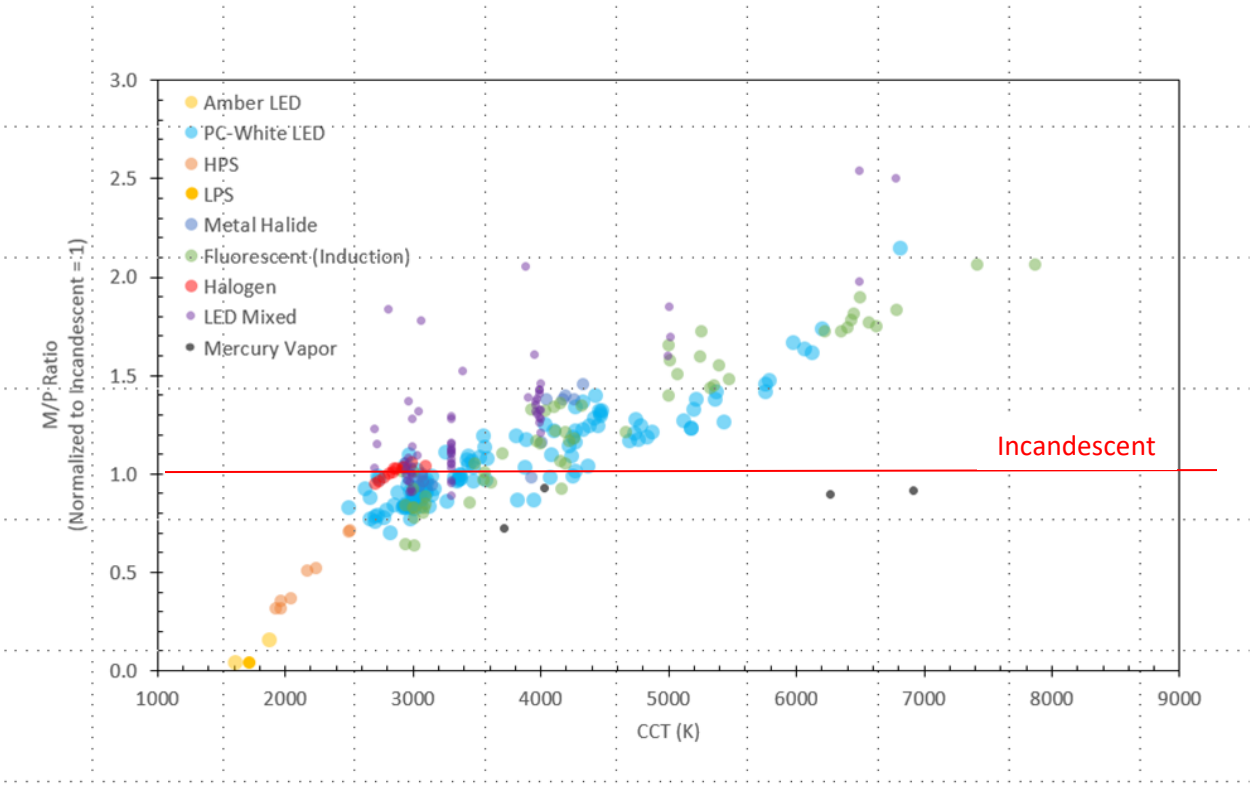

Figure 7. Calculated M/P ratio vs. CCT for a wide range of light sources, relative to incandescent.

If seeking to reduce potential impact from short-wavelength content, how does reducing light output compare with changing the CCT?

The melanopic content values listed in the last column of Table 1 are given as ratios that are normalized for equivalent lumen output; they scale (i.e., they increase or decrease) linearly with changes in that output. Thus it's easy to compare the effectiveness of selecting spectral content versus reducing light output as alternatives for reducing melanopic content. For example, assuming that midpoint values of the listed ranges in Table 1 represent each product, substituting a 3000 K LED (melanopic content of 2.55) for a 4000 K LED (melanopic content of 2.88) achieves an averaged reduction in melanopic content of 11.5%, all other things being equal. Alternatively, an equivalent reduction can be achieved by reducing the output of the 4000 K LED luminaire by a similar amount (11.5%), by either reducing the luminaire's light output or dimming it.

These two approaches are not mutually exclusive and can be combined to achieve even greater reductions. However, dimming offers some additional distinct advantages:

- The reduction achieved by substituting a lower CCT depends entirely on the actual SPDs of the various products being considered. In contrast, dimming the lights by whatever percentage of full output achieves a corresponding reduction independent of SPD, and can be carried out all the way to 100% dimming at certain times of night (if acceptable from safety and other perspectives).
- Dimming is accompanied by direct reductions in energy use and associated costs of operation, and may offer longer product life.
- Dimming can also be used to address complaints of brightness or overlighting, whereas substituting a lower CCT may or may not address such complaints.

If done well, dimming is an effective approach for addressing the potential influences of short-wavelength content. Relatively few dimming systems for street lighting have been installed in the U.S. to date, but the existing installations have confirmed the anticipated benefits of this approach. For example, the city of Cambridge, MA, dims its 4000 K LED streetlight system by 50% after midnight (Figure 8), with corresponding reductions large enough that the system subsequently produces less melanopic content than the HPS system it replaced.[21] Notably, the system's designers report that not a single complaint about the dimming of the system has been received following its implementation.[22] An increasing number of municipalities are considering dimming systems for inclusion with their lighting conversions.

[21] See further detail in the July 2016 Light Post newsletter.
[22] Personal communication, Paul Lutkevich, WSP | Parsons Brinckerhoff.

Figure 8. 4000 K LED Street Lighting System in Cambridge, MA, shown at initial startup at dusk (left) and 50% dimmed after midnight (right). Photos: WSP | Parsons Brinckerhoff

LED street lighting

When did LED streetlights first appear on the general illumination market?

Although monochromatic LEDs first gained prominence in the electronics industry in the 1960s, the first high-brightness blue LED didn't appear until the 1990s. White LEDs were later built using blue LEDs by passing the short-wavelength light through phosphors to produce a mix of different wavelengths, which yielded white light. The high cost-to-performance ratio of these early white LEDs kept them at relatively low market penetration for the first few years after their introduction, but the situation quickly changed as prices dropped. For example, DOE's 2013 LED Market Adoption report estimated that only 200,000 LED streetlights had been installed cumulatively as of 2010 in the United States, but this number had jumped to 1 million units only two years later.

How many LED lights with CCT of 5000 K or higher have been installed outdoors?

Although the actual number is unknown, it's believed that relatively few such LED lights have been installed outdoors in the U.S. There's no known documented inventory of installed outdoor LED products categorized by CCT, and estimates differ by application.[23] There were a few smaller-scale pilot studies and other installations involving products with CCT ≥ 5000 K in the first few years of LED outdoor lighting installations, but the street and roadway lighting community quickly converged around a warmer 4000 K as soon as that CCT became widely affordable (around 2010). From then to 2016, the vast majority of municipalities and utilities (including, for example, the cities of Seattle, Los Angeles, Las Vegas, Boston, New York, New Orleans, Detroit, Kansas City, and many others) favored 4000 K CCT products for LED street and roadway lighting applications. More recently, with continued improvement of the technology, a number of cities are now considering 3000 K and, in some cases, even lower CCTs.

Why did early LEDs have CCTs of 5000 K or more?

High-CCT white LEDs were more available, more efficient, and less expensive than lower-CCT versions during the technology's early years. In PC-LEDs, narrow-band short-wavelength light produced by semiconductor material is passed through phosphors that convert most of it into other colors; the resulting light spectrum appears white to the human eye. Efficiency losses occur during the color conversion, and these losses are greater when creating warmer CCTs, translating into lower luminous efficacies (lumen output per watt of electrical input power). Because the early-production white LEDs were relatively low in efficacy, manufacturers emphasized sales of more-efficacious higher-CCT products. Since then, however, LED technology has advanced to the point where even warmer-CCT products are highly efficacious, especially when compared to traditional lamp technologies. However, even today a higher-CCT LED continues to be more efficacious than a similar LED at lower CCT, all other things (e.g., color quality and color rendering ability) being equal. [24]

Why is there so much emphasis on efficiency in the implementation of LED lighting products?

Efficiency, or *luminous efficacy* (lumen output per watt of input electrical power) in the case of lighting, translates into lower utility costs and environmental benefits from reduced energy use. Even small improvements in efficacy can lead to large benefits on a national scale, in terms of energy cost and power-plant emission reductions, for example.

[23] For example, due to the "sparkle" offered by higher-CCTs, 5000 K appears to be the favored choice for service stations. Residential areas tend to show a greater preference for CCTs lower than 4000 K.

[24] Both the variation in efficacy by CCT and the overall trend of efficacy during the last several years can be seen in the Outdoor Area Lighting CALiPER Snapshot.