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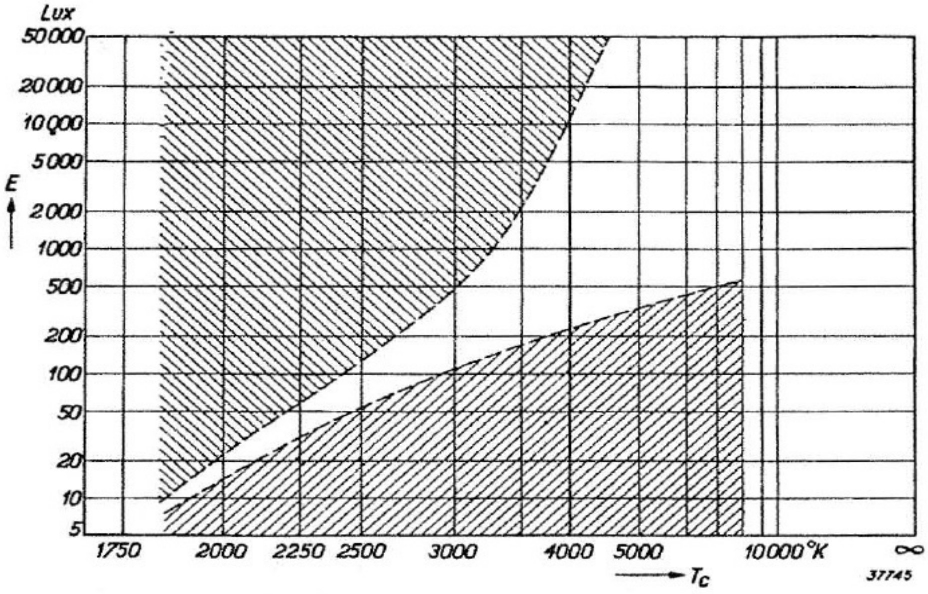
ARCHITECTURAL INFORMATION

THE KRUITHOF CURVE

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2015/01/12



UPDATE 16/04/09 – This metastudy:
Fotois, S. 2106. "A Revised Kruithof Graph Based on Empirical Data," Leukos. (Published online 08 April 2016, DOI 10.1080/15502724.2016.1159137.) critically examined 29 studies in which the Kruithof curve was investigated. The author concluded that "… these [studies] do not support Kruithof. For pleasant conditions, these data suggest only avoiding low illuminances and do not favor any CCT."

After 75 years of misconception and misuse, may this finally mark the end of the Kruithof Curve. If a lighting designer has a personal preference for warm or cool colors, fine — but *PLEASE*, do not try to justify it with scientific mumbo-jumbo.

[**UPDATE** 15/01/20 – Added Bartleson (1960) reference.]

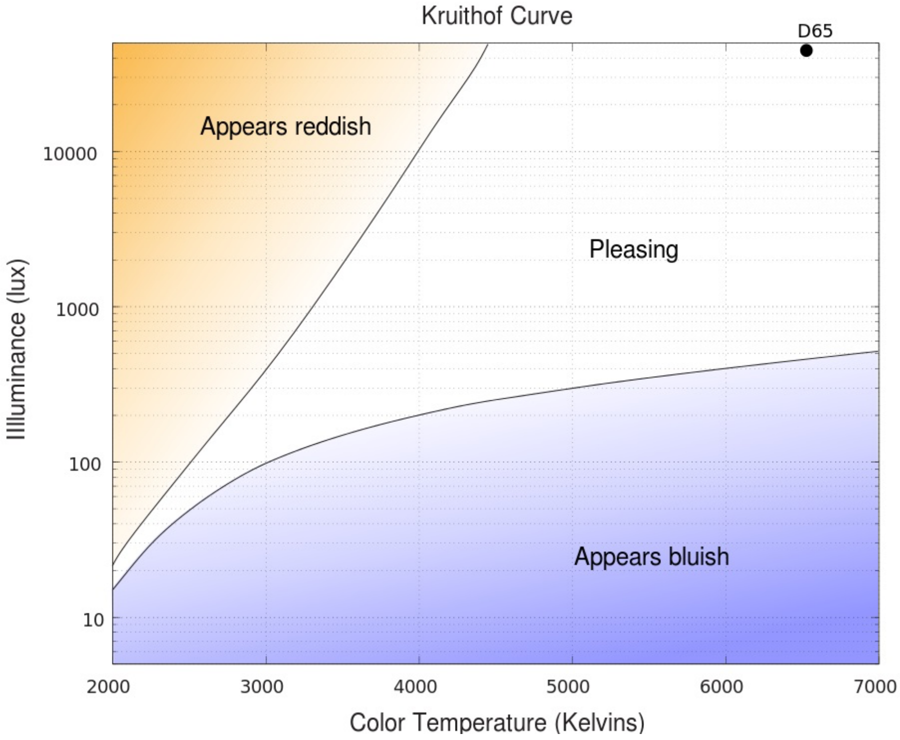


FIG. 1 – Kruithof curve, modern version (source: Wikipedia).

Lighting designers today will surely recognize the Kruithof curve, in which the color temperature of the light source is related to a range of illuminances that we find “pleasing.” In its modern form, the Kruithof curve has become supposedly irrefutable evidence that the correlated color temperature (CCT) of LED-based lighting should not exceed 4000K for indoor applications.

In the process, luminaire manufacturers are being lambasted for promoting products with CCTs of 5000K and higher. Worse, some government agencies and non-profit organizations are adopting CCT limits that are presumably based on the Kruithof curve. The DesignLights Consortium, for example, stipulates that luminaires on its Qualified Products List must have CCTs of 5000K or less for most indoor applications.

Unfortunately, the modern version of the Kruithof curve is different from what A. A. Kruithof published 75 years ago. The upper and lower curves are approximately the same, but their interpretation is different from what Kruithof intended. In fact, the Kruithof curve appears to have been basically misinterpreted for the past three-quarters of a century.

The Kruithof curve itself was thoroughly debunked a quarter-century ago with three exhaustive studies involving up to 400 participants (as opposed to two people in Kruithof’s study, including himself). The Kruithof curve was somewhat belatedly removed from the IES Lighting Handbook five years ago (IES 2010).

This article is however not so much about the validity of the Kruithof curve as it is about a careful re-examination of his 1941 paper. While Kruithof has been rightly criticized over the years for not providing experimental details, he wrote enough for us to infer how he arrived at his findings. When you realize that he was working with early prototypes of the first fluorescent lamps, it is in itself an interesting story.

In the Beginning

The year was 1941. Captain America made his first appearance in a comic book, Europe was being torn asunder by World War II … and Philips Research was quietly developing its own fluorescent lamp technology in Eindhoven, the Netherlands. As part of this effort, *PHILIPS TECHNICAL REVIEW* published a paper by A. A. Kruithof titled, "Tubular Luminescence Lamps for General Illumination" (Kruithof 1941).

Kruithof's paper was primarily about fluorescent lamp technology, which had been commercially released by General Electric in 1938. His experimental meter-long T12 "luminescence lamp" (FIG .2) was designed have a luminous flux output of 1000 lumens.

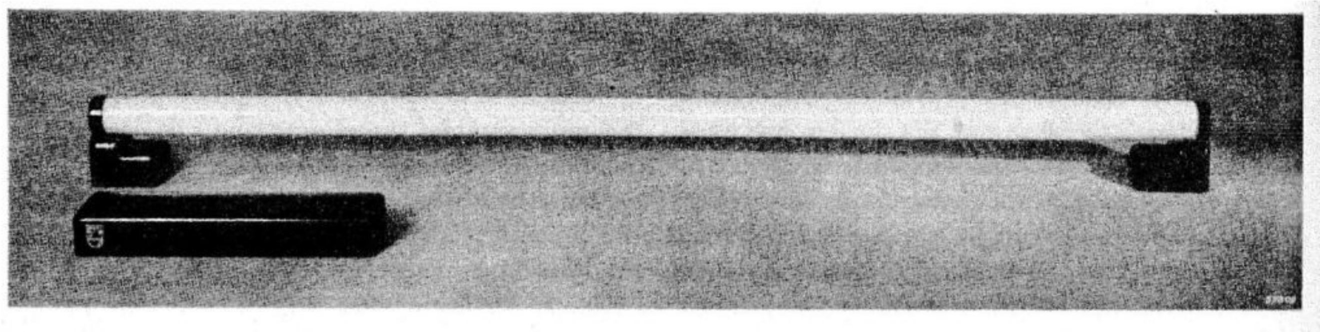


FIG. 2 – Philips "luminescence" lamp (from Kruithof 1941).

Halophosphate-based phosphors were not invented until the following year (McKeag and Ranby 1942), and so these "white" fluorescent lamps used a combination of cadmium borate, willemite (zinc orthosilicate), and magnesium tungstate, which respectively fluoresce red, green, and blue when excited by the ultraviolet radiation emitted by the mercury-argon gas fill.

By themselves, the phosphors resulted in maximum luminous efficacies of approximately 70 lumens per watt for willemite and 35 lumens per watt for cadmium borate and magnesium tungstate. By combining the phosphors in various proportions, it was possible to generate white light with CCTs ranging from 2650K to 10000K.

Kruithof fabricated fluorescent lamps with CCTs of approximately 4200K and 5800K, plus a third lamp type that was so far off the blackbody curve as to be considered colored rather than white. Comparing these to the extant incandescent lamp technology with its typical 15 lumens per watt luminous efficacy, Kruithof was well justified in writing, "These properties give reason to expect that luminescent lamps will be widely used in the future."

Kruithof also performed an extensive analysis of the color rendering capabilities of his lamps by observing the color shifts of 313 color cards (as opposed to the eight colors used for the CIE General Colour Rendering Index Ra). Using the phosphor and visible mercury line spectra published in his paper, it is possible to estimate CRI values of his lamps as:

Lamp CCT	Ra	R9
4200K	36	-110
5800K	54	-60

As for the original form of the Kruithof curve (FIG. 3), the paper includes a description of what the author referred to decades later as a "pilot study" of lamp CCT versus illuminance level. To fully understand this study, it is necessary to quote Kruithof (1941) extensively, beginning with:

> "*IN THE FIRST PLACE AT A GIVEN LEVEL OF ILLUMINATION IT IS FOUND THAT THE COLOUR TEMPERATURE MUST LIE WITHIN CERTAIN LIMITS IF THE EFFECT OF THE ILLUMINATION IS TO BE PLEASING. ROUGHLY, IT MAY BE SAID THAT A LOW OR A HIGH COLOUR TEMPERATURE CORRESPONDS TO A LOW OR A HIGH LEVEL OF ILLUMINATION, RESPECTIVELY. WE HAVE INVESTIGATED THIS RELATION EXPERIMENTALLY SOMEWHAT MORE CLOSELY BY INTRODUCING IN A ROOM A VARIABLE NUMBER OF ELECTRIC LAMPS WHOSE CURRENT (I.E., THE TEMPERATURE OF THE FILAMENTS) COULD BE VARIED.*"

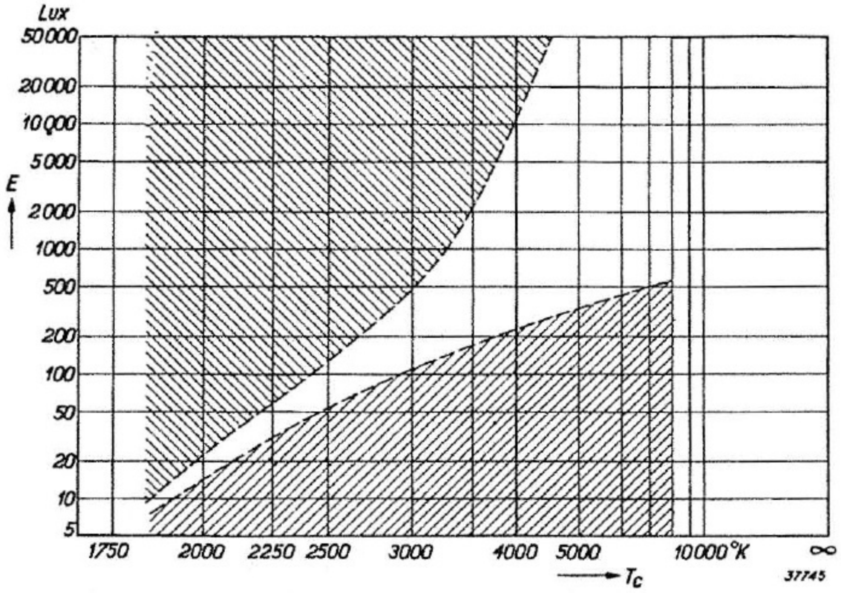


FIG. 3 – Kruithof curve, original version (from Kruithof 1941).

With vague phrases like "pleasing" illumination, "a room," and a "variable number of electric lights," we can at best only infer the experimental conditions that were used to develop this curve. Kruithof continues:

> "*BELOW THE LOWEST CURVE THE ILLUMINATION IS 'DIM' (AT LOW COLOUR TEMPERATURE) OR 'COLD' (AT HIGH COLOUR TEMPERATURE). ABOVE THE HIGHEST CURVE THE UNNATURAL COLOUR REPRODUCTION WAS UNPLEASANT.* "

There are two items of immediate interest here:

1. Kruithof used the adjectives "dim" and "cold" rather than the modern interpretation of "appears bluish."
2. Kruithof used the adjectives "unnatural" and "unpleasant" rather than "appears reddish."

It could be argued that the modern interpretation is intuitively valid, but that is not the point. Kruithof measured a specific psychometric parameter that he termed "pleasing" illumination. Recasting the results to support a different hypothesis effectively invalidates the experiment.

In terms of the illumination referenced in FIG. 1 appearing reddish or bluish, it must be noted here that no academic studies published to date support this hypothesis. The modern form of the Kruithof curve appears to be an interpretation with no scientific evidence to support it.

Continuing:

> "*THESE OBVIOUSLY VAGUE LIMITS WITHIN WHICH THE ILLUMINATION IS CONSIDERED 'PLEASING' COULD IN OUR EXPERIMENTS BE DETERMINED AT LEAST WITH AN ACCURACY OF 20 OR 30 PERCENT."*

This is a blazing red flag that something may be seriously wrong with this study — how can you measure something as subjective as "pleasing" with an accuracy of 20 to 30 percent in terms of illuminance? What Kruithof said — *WITHOUT PROVIDING ANY EVIDENCE* — is that we can apparently tell the difference between say 100 lux and 125 lux of illumination. This is not a side-by-side comparison of two illuminated surfaces, but by simply walking into a room and deciding whether or not the colors are "unnatural."

Much has been written in the following years that Kruithof did not provide any significant details of his experimental apparatus or protocols, and so it is difficult to accept the Kruithof curve as being valid. However, the rest of his paper is reasonably detailed and informative, indicating that Kruithof was a careful researcher. He must therefore have had some reason for claiming an accuracy of 20 to 30 percent.

Continuing with Kruithof, the extensive caption he wrote for FIG. 3 reads in part:

> *"THE LEFT-HAND PART OF THE LIMITING CURVES, UP TO A COLOUR TEMPERATURE OF 2850 ºK, IS RECORDED BY ALLOWING ELECTRIC LAMPS WITH VARIABLE (DECREASED) CURRENT TO BURN IN A ROOM, AND VARYING THE NUMBER OF LAMPS. THE ILLUMINATION INTENSITY ON A TABLE 80 CM HIGH WAS HERE MEASURED. IN THE RIGHT-HAND PART THE LOWEST LEVEL WHICH DOES NOT GIVE THE IMPRESSION OF COLDNESS WAS DETERMINED BY EXPERIMENTS WITH DAYLIGHT ITSELF AND WITH THE DAYLIGHT LUMINESCENCE LAMPS TO BE DESCRIBED BELOW."*

This is all frustratingly vague, but there is a key point: "… varying the number of lamps."

Continuing:

> *"THE SHAPE OF THE UPPER CURVE HAS BEEN EXTRAPOLATED IN THIS REGION WITH THE HELP OF THE FACT THAT IN DIRECT SUNLIGHT (COLOUR TEMPERATURE 5000 ºK) EVEN WITH THE HIGHEST ILLUMINATION INTENSITIES OCCURRING (10^4 OR 10^5 LUX) THE COLOUR RENDERING IS NEVER FOUND 'UNNATURAL'."*

This is a crucial quote in that Kruithof decided that direct sunlight was not — and by definition *COULD NOT* — be "unnatural." This brings us back to the question of the upper curve for color temperatures below 2850K (FIG. 3), where dimmed incandescent lamps were used.

Looking deeper into the question of "unnatural color reproduction," Kruithof stated that he used a selection of color cards from the Ostwald Color Atlas, a contemporary color classification scheme of the Munsell color system we use today (FIG. 4). With respect to this, he wrote:

> *"WHILE THE COLOUR RENDERING CAN BE JUDGED BY COMPARISON WHEN LUMINESCENCE IS USED IN COMBINATION WITH OTHER LIGHT AND THE DESIGNATION OF THE COLOUR IMPRESSION OBTAINED AND THE SATURATION OF THE COLOUR OBTAINED MUST AGREE, WHEN ONLY LUMINESCENCE LAMPS ARE USED NO COMPARISON IS POSSIBLE. IN JUDGING THE COLOUR RENDERING THEREFORE IN THIS CASE ONE MUST HAVE RECOURSE TO 'COLOUR MEMORY' WHICH IS CHIEFLY CONFINED ONLY TO THE DESIGNATION OF COLOURS."*

FIG. 4 – Ostwald color atlas (source: Wikipedia).

This is even more puzzling in that our ability to recall colors is mediocre at best. In general, we tend to remember colors as being more saturated than they really were (Bartleson 1960). It therefore makes even less sense that an accuracy (or more properly repeatability) of 20 to 30 percent could be perceived.

It *DOES* make sense, however, if Kruithof switched lamps on and off to vary the illuminance while maintaining constant color temperature. This would be a form of flicker photometry. We are mostly insensitive to absolute illuminances, but we are highly sensitive to *CHANGES* in illuminance. Switching illumination levels would reveal even subtle changes in the perceived chromaticities of the color cards.

… which brings us to the first of two color appearance effects, the *Bezold-BRÜCKE* hue shift effect. This effect was first reported in the 1870s, but it was not studied extensively until the 1930s (Purdy 1931). Even then, the study was published in the *AMERICAN JOURNAL OF PSYCHOLOGY*. A lamp research engineer like Kruithof could be excused for not being aware of the paper and its implications.

The Bezold-Brücke effect results in perceived color hues changing with changes in luminance. As shown in FIG. 5, the wavelength shifts required to maintain constant perceived hue for monochromatic colors can be huge, particularly for red and cyan, with a ten-fold increase in luminance. The effect on Kruithof's color cards would have been generally less noticeable, but may have been still evident with, for example, saturated red colors.

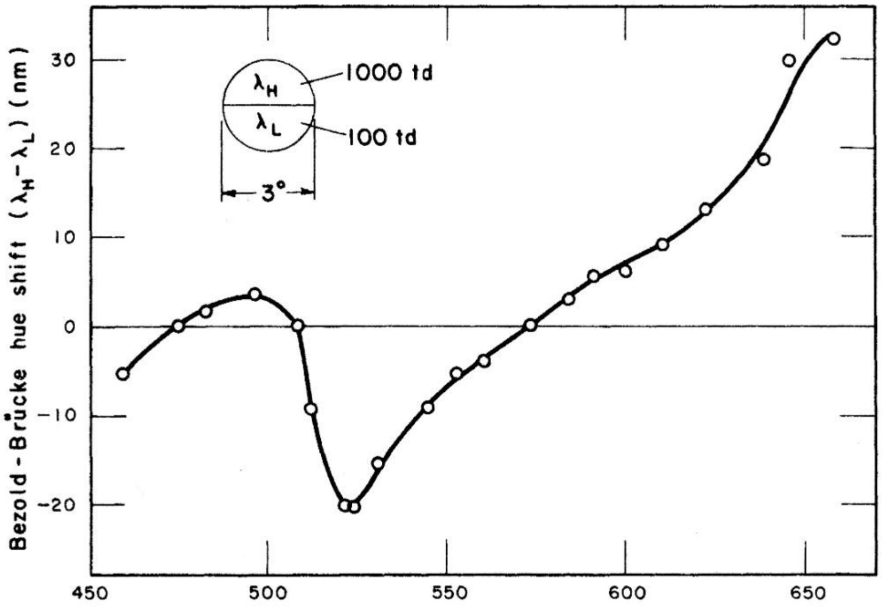


FIG. 5 – Bezold-Brücke effect for monochromatic light (from Wyszecki & Stiles 1982, Fig. 2(5.9)).

The second color appearance effect would not have been known to Kruithof because it was not reported until the 1950s. The *HUNT EFFECT* (Hunt 1950, 1952, 1953) results in the perceived chroma (i.e., colorfulness) of illuminated objects increasing with increased illuminance. This effect is important enough to have been built into the CIECAM02 color appearance model that is widely used for color management for displays, printers, and other imaging devices.

For a given CCT, Kruithof presumably began with a low illumination level and then increased the illuminance until color appearance of the color cards more or less matched his color memory of them. The changes in perceived color would presumably be due to both the Bezold-Brücke and Hunt effects. As however he continued increasing the illuminance, the continuation of these effects would result in the colors no longer matching his color memory. This would result in, to use Kruithof's own words, "unnatural color reproduction."

If Kruithof had reduced the daylight illuminance using, for example, neutral density filters, he would likely have observed the same behavior. However, even if he had done so, the time taken to move the filters into position would likely have masked the color differences. He also would have had the conundrum of having to call natural daylight "unnatural" and "unpleasant."

In Kruithof's defense, he may have been one of the first researchers to observe the Bezold-Brücke and Hunt effects using white light illumination with constant CCT. Certainly, color shifts with changes in CCT were well-known at the time and modeled by the *VON KRIES CHROMATIC ADAPTATION MODEL*. Color shifts with constant CCT were, however, a different matter.

Kruithof was certainly aware of the color shifts that his fluorescent lamps produced, as shown by FIG.6 and FIG. 7, where the circled areas labelled '2' represent "clearly appreciable" color shifts.

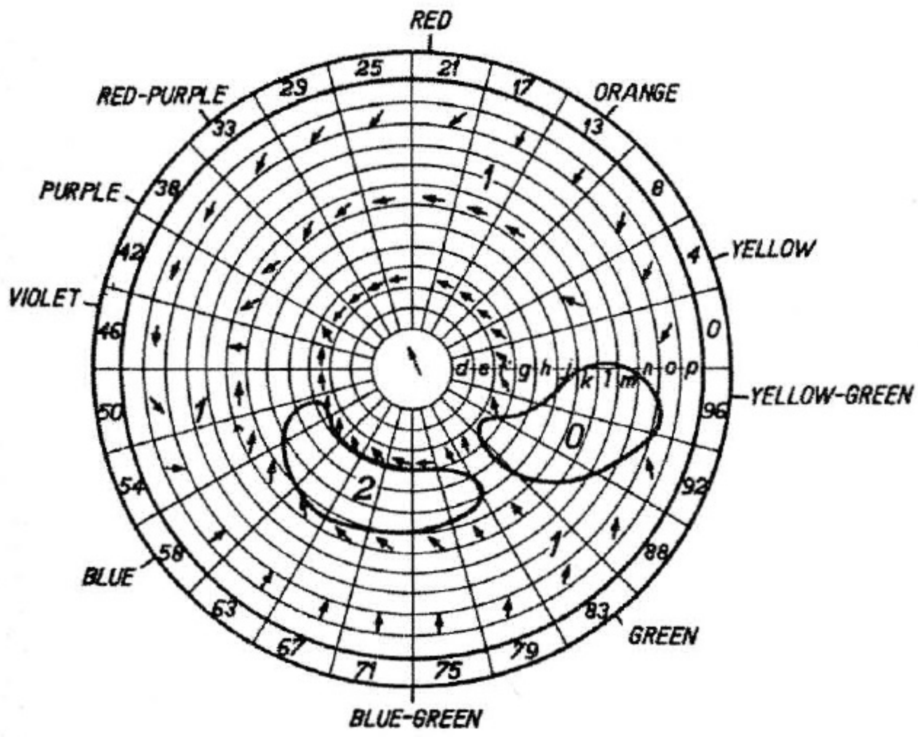


FIG.6 – Color shifts between daylight and 5800K fluorescent lamp (from Kruithof 1941).

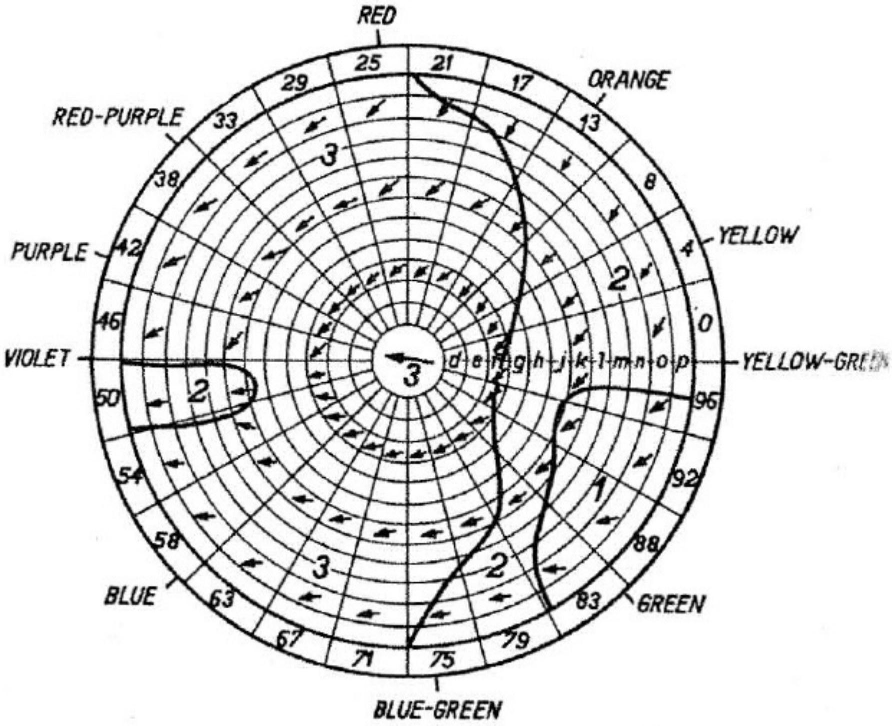


FIG. 7– Color shifts between electric light and 4200K fluorescent lamp (from Kruithof 1941).

Interestingly, Kruithof wrote:

> *"MOST COLOURS ARE SOMEWHAT LESS SATURATED IN LUMINESCENCE LIGHT THAN IN DAYLIGHT."*

which is exactly what you would expect from the Hunt effect. Nevertheless, Kruithof had little choice but to describe the 5800K lamp as generating "pleasing" illumination above some threshold.
It must be emphasized, however, that this is only a hypothesis — it would need a carefully designed large-scale experiment to determine whether in fact the Bezold-Brücke and/or Hunt effects can satisfactorily explain Kruithof's results. Even then, it will be impossible to know with any certainty because Kruithof described his experiments so frugally. On the other hand, they at least offer a plausible explanation of his claim to 20 to 30 percent repeatability.

Time Marches On

If Kruithof considered his work to be a mere "pilot study," the follow-up studies have been anything but. Bodman (1967) for example performed studies wherein he varied the illuminance in a conference room illuminated by fluorescent lamps. Remarkably, more than 400 subjects took part in these studies. Like Kruithof, he found that people had a preferred illuminance range over which 90 percent of the subjects found the lighting to be "good." However, As can be seen from FIG. 8, the preferences appear to be influenced more by the lamp spectral power distributions than by their CCTs. At the time that these studies were conducted, "deluxe" fluorescent lamps had CRI values of 90 or so, but warm white fluorescent lamps with their halophosphate phosphors had CRI values as low as 50.

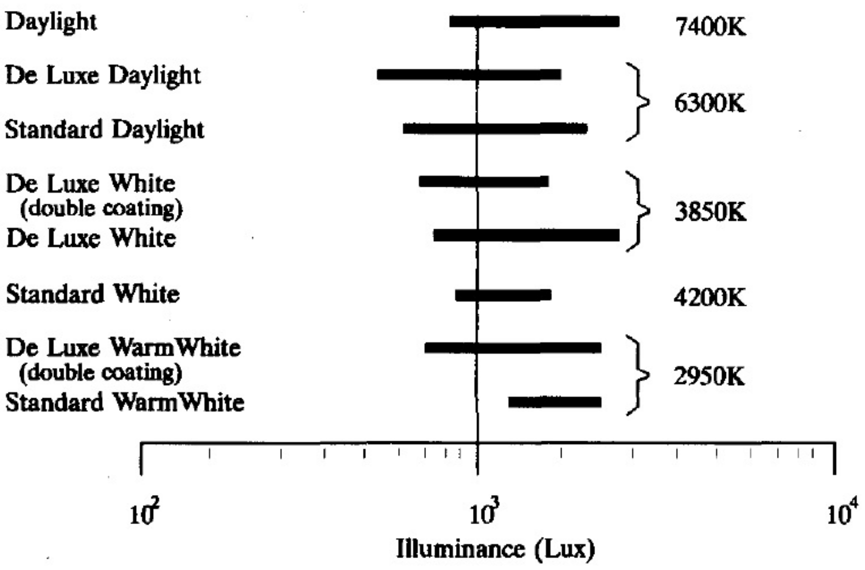
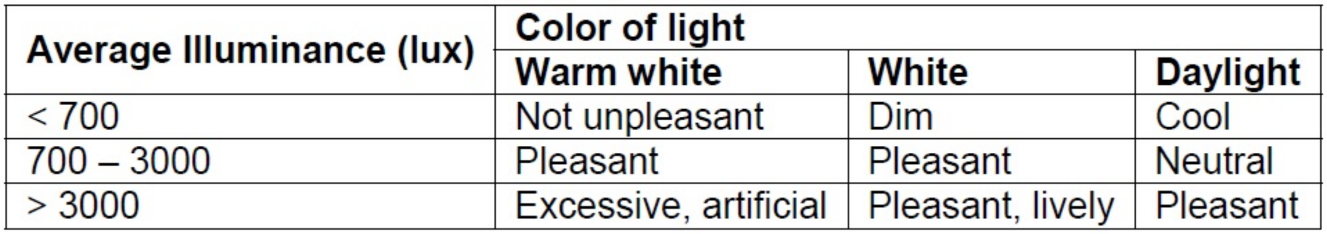


FIG. 8 – Preferred illuminance range versus fluorescent lamp type (from Bodman 1961).

What are interesting are the terms that Bodman's subjects used to describe the lighting (FIG. 9). The warm white fluorescent lighting (CCT < 3000K) was described as "excessive" and "artificial" (terms which may have influenced by the low CRI values) at high illuminances, but for white (CCT ~ 4000K) and daylight (CCT > 6000K), the terms used were "pleasant" and "lively." This is consistent with what you might expect from an increase in colorfulness as provided by the Hunt effect.



Average Illuminance (lux)	Color of light		
	Warm white	White	Daylight
< 700	Not unpleasant	Dim	Cool
700 – 3000	Pleasant	Pleasant	Neutral
> 3000	Excessive, artificial	Pleasant, lively	Pleasant

FIG. 9 – Subjective impressions of illumination levels (Bodman 1961).

Boyce and Cuttle (1990) performed similar experiments using fluorescent lamps with CCTs ranging from 2700K to 6300K, and with average illuminances ranging from 30 to 600 lux, to illuminate a small office space. All of the fluorescent lamps had CRI values ranging from 82 to 85.

Doing a detailed statistical analysis of 410 questionnaires completed by 15 subjects who spent 20 minutes becoming visually adapted to the room, the authors found that the lamp CCT had no statistically significant influence on the subjective assessments. Instead, the major factor in both color discrimination tests and subjective assessments was illuminance.

Interestingly, none of the subjects who were unfamiliar with lighting design used the terms "warm" or "cool" to describe the lighting.

Davis and Ginthner (1990) also performed similar experiments with 40 test subjects. Using 2750K and 5000K fluorescents lamps with CRI values of 90 and illuminance levels of 270, 600, and 1350 lux, they confirmed the findings of Boyce and Cuttle (1990) that the subjective ratings of preference were influenced by illuminance only. They also found that low light levels were rated as less colorful than high light levels for the same CCT, which again suggests the Hunt effect.

Finally, Viénot et al. (2008) performed experiments designed to investigate the validity of the Kruithof curve using LED modules rather than fluorescent lamps. To ensure high CRI with variable color temperature, they used LED clusters with independently-controlled blue, cyan, green, amber, orange, red, cool white, and warm white LEDs. These provided CRI values from 91 to 96 over an illuminance range of 150, 300, and 600 lux and a CCT range of 2700K, 4000K, and 6500K.

Unlike the previous studies, however, the Viénot et al. (2008) experimental setup was not a room but a light booth measuring some 41 x 35 x 38 cm (16 x 14 x 15 inches) that had an 80-degree field of view with a dark surround. It is debatable whether the results of the 20 subjects can be applied to offices spaces, but the authors concluded that:

> “In one sense, we have validated Kruithof’s statement that high CCT at low illuminance is unpleasant. Nevertheless, we cannot conclude that low CCT should be confined to low illuminance to arouse pleasant sensations.”

And:

> *“WHEN THE COLOUR RENDERING INDEX IS VERY HIGH AND THE LIGHT SPECTRUM IS UNDER CONTROL, THERE IS NO INDICATION THAT HIGH COLOUR TEMPERATURE IS JUDGED MORE PLEASANT THAN LOW COLOUR TEMPERATURE AT HIGHER ILLUMINANCE LEVELS.”*

Summary

There have been many more studies related to the Kruithof curve, including Cockram et al. (1970), Denk et al. (2014), Dikel et al. (2014), Fotois et al. (2013), Hu et al. (2006), Ishi and Kakitsuba (2003), Juslén (2006), Küller et al. (2006), Logadóttir and Christoffersen (2008), Mills et al. (2007), Naoyuki and Tomimatsu (2005), Navvab (2001), Park et al. (2010), Pinto et al. 2008), Weintraub (2000), and Zhai (2014).

None of these, however, are as focused or comprehensive as those of Bodman (1967), Boyce and Cuttle (1990), and Davis and Ginthner (1990). The common conclusion of these authors is that while dim lighting at any CCT is seen as unpleasant, there is no observational evidence in support of Kruithof’s upper curve (FIG. 3).

What this discussion has shown, however, is that Kruithof may not have meant “unpleasant” in the sense of poor lighting quality, but rather in the sense of optimal color reproduction.

It must be remembered that Kruithof was working with incandescent lamps with CCTs varying from 1800K to 2850K, 4000K and 5800K fluorescent lamps that probably had CRI values of less than 60, and “natural” daylight with unknown CCT. He likely would have never seen chromaticity shifts with changes in illuminance at constant CCT prior to his experiments, and probably (and quite reasonably) saw them as unnatural and hence unpleasant. This despite the fact that he observed exactly this when comparing his 5800K lamp with daylight, and explicitly commented on the fact.

Conclusion

The conclusion is straightforward, and indeed was established more than a quarter-century ago with three major studies: the Kruithof curve is essentially meaningless. There is no upper boundary to "pleasant" illumination at any CCT, and the best that can be said about the lower boundary is the obvious: dim lighting can be unpleasant, regardless of the CCT.

At the same time, however, Kruithof deserves credit for having been the first to investigate the topic. His failure to describe his experiments in more detail is regrettable, but perhaps understandable. Done as a pilot study, the brief discussion in his paper is basically a progress report with preliminary findings.

It has basically been through our continued misunderstanding of his term "pleasing" that the Kruithof curve continues to persist in lighting design practice. If Kruithof were able to comment on this today, he would likely have only two words to say (in Dutch):

> *"STOP DAARMEE!"* (English translation: "Stop that!")

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KRUITHOF REVISITED

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A previous blog article — *THE KRUITHOF CURVE* — examined the history of the Kruithof curve (Kruithof 1941]) shown in FIG. 1:

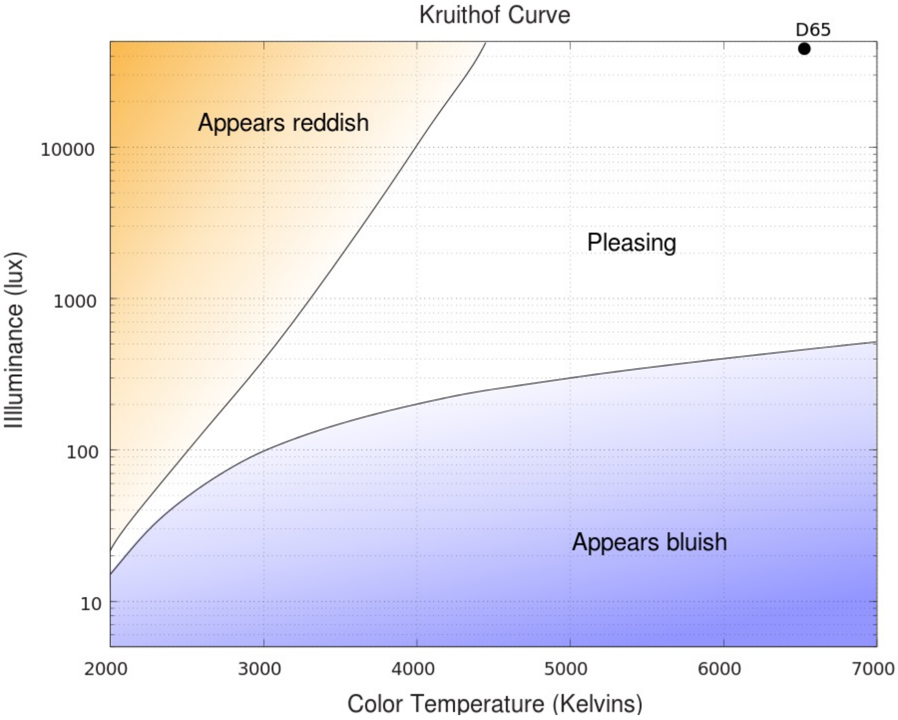

FIG. 1 – Kruithof curve, modern version (source: Wikipedia).

To summarize the article, “The Kruithof curve itself was thoroughly debunked a quarter-century ago with three exhaustive studies involving up to 400 participants (as opposed to two people in Kruithof’s study, including himself).” These studies were Bodman (1967), Boyce and Cuttle (1990), and Davis et al. (1990).

In other words, the weight of scientific evidence is firmly against use of the Kruithof curve as a guide to modern lighting design practices. Case closed, yes?

No.

The problem with the above studies — and indeed any studies to date that have addressed our preferences regarding correlated color temperature (CCT) versus illuminance — is that they were based on constant CCT light sources.

This is completely understandable in that while we have had dynamic color-changing luminaires for over a decade (e.g., Ashdown 2006), color-changing luminaires for general illumination purposes have only become available in the past year or so. However, it begs the question: is there a relationship between CCT preferences and circadian rhythms?

Circadian Rhythms

Another blog article — *ENTRAINING CIRCADIAN RHYTHMS: INTENSITY VERUS COLOR* — examined the question of whether the change in yellow-blue color ratio during twilight is more efficient in entraining circadian rhythms than changes in daylight intensity.

As noted in this article, the research (Walmsley et al. 2015) considered the behavior of wild mice rather than humans. The problem, of course, is that humans and mice see the world very differently in terms of perceived color. Whereas our retinal cones are responsive to the visible spectrum ranging from approximately 400 nm (violet) to 700 nm (deep red), those of wild mice are responsive to a spectrum ranging from below 330 nm (ultraviolet UVB) to 625 nm (medium red). Being dichromatic, mice are also likely to have poor color-distinguishing capabilities compared to humans.

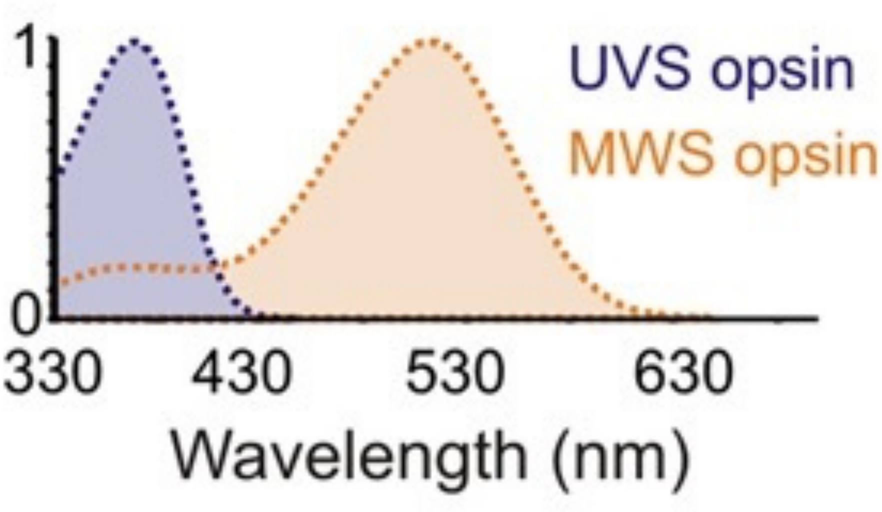

Figure 2 – Wild mouse spectral responsivity. Source: Walmsley et al. (2015).

Regardless, Walmsley et al. make a compelling argument that the ratio of yellow-to-blue light remains reasonably constant throughout the day, whereas the intensity of daylight may vary randomly and markedly due to cloud cover. From an evolutionary perspective, it therefore makes sense that human circadian rhythms are primarily entrained by changes in daylight color at dawn and dusk rather than changes in illuminance.

We must also remember, however, that illuminance and color are not the only factors influencing our circadian rhythms. Yetish et al. (2015) studied the sleep patterns of three pre-industrial societies: the Hadza in Tanzania, the Kalahari San in Namibia, and the Tsimane in Bolivia. What they found was that all three groups exhibited similar sleep patterns. With no cross-cultural influences, it is reasonable to assume that these represent core human sleep patterns for pre-industrial *HOMO SAPIENS*.

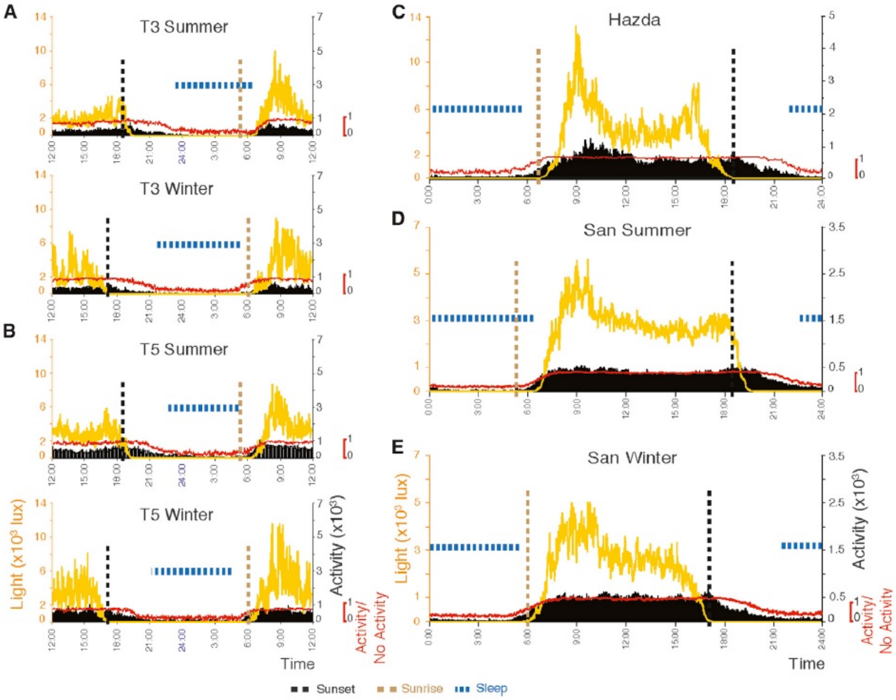

FIG. 3 – Light versus activity plots (Yetish et al., 2015).

The patterns are interesting. The hunter-gatherer/horticulturalists sleep on average 6.4 hours a day, with one more hour in winter than in summer. Most surprising, they fall asleep about 3.3 hours after sunset, during the nightly period of falling temperature. Further, they usually awaken before sunrise, when the daily temperature is lowest.

From a lighting perspective, it is equally interesting that light exposure was maximal in the morning and greatly decreased at noon, with all three groups seeking shade (FIG. 2). This is likely attributable to all three groups living in the tropics, but it has the effect of providing maximal light activation of the suprachiasmatic nucleus (SCN) and its influence on circadian rhythms in the morning.

From this, the authors surmise that the daily cycle of temperature change, "largely removed from modern sleep environments," may be more important than daily changes in illumination in regulating sleep patterns. With near-constant temperatures in our offices and residences (and presumably sleep laboratories), temperature changes become yet another variable in establishing a baseline for circadian rhythm disruption studies.

Illuminance, color, ambient temperature … could it get any more complicated? Yes, of course! A paper published just today in *CELL METABOLISM* (Breton et al. 2015) has shown that our appetites for food are controlled not only by our brains, but by intestinal bacteria telling us via proteins they produce that they are sated, and that we should stop eating on their behalf. Designing experiments to elucidate circadian rhythm behavior therefore involves much more than simply dimming the lights. When and what the test subjects eat or drink is a critical factor in designing repeatable and relevant circadian rhythm experiments.

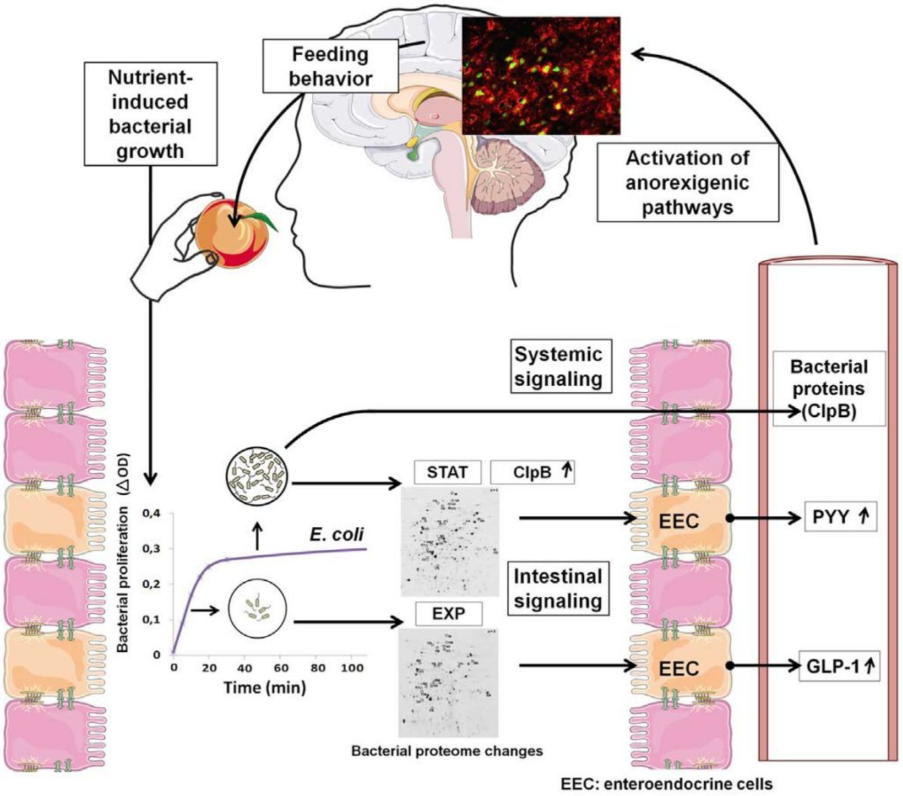

FIG. 4 – Intestinal bacteria signaling pathway (Source: Breton et al., 2015).

So what does this say about the Kruithof curve?

Circadian Kruithof

The problem with ascertaining preferences of any kind is that experiments need to be designed to control all the factors that may be involved. In doing so, the resultant laboratory conditions are often far removed from the real world.

This is precisely the problem with the Kruithof curve studies such as Bodman (1967), Boyce and Cuttle (1990), Davis et al. (1990), and others — they all (necessarily at the time) relied on constant CCT light sources, and ignored the test subjects' circadian rhythm states.

Surprisingly, a review of the academic literature on this topic reveals … almost nothing. The closest relevant discussion is Poldma (2009), in which the author merely proposes "integrating [static] color and light theories with new contexts of dynamic, integrated human experiences of color and light in interior spaces." Ellis et al. (2013a, 2013b) considers luminaire color temperature, but only in the context of matching daylight CCT for elderly patients with dementia.

The evidence of Walmsley et al. (2015) suggests that our preferences for CCT versus illuminance may be intimately associated with the state of our circadian rhythms. The popularity of products such as the Philips Wake-Up Lights with their simulated sunrise colors would certainly indicate that this is the case.

FIG. 5 – Philips HF3510/60 Wake-up Light.

There are of course many other examples, including “romantic mood” lighting in restaurants and CCT preferences for outdoor street and area lighting in residential areas. Our CCT preferences may vary throughout the day based on the state of our circadian rhythms and our activities.

At the end of the day, the modern interpretation of the Kruithof curve as shown in FIG. 1 remains “thoroughly debunked.” (The original curve presented by Kruithof in 1941 addressed a different issue.) However, it provides a framework for further research focused on human-centric lighting and circadian rhythms.

The problem, of course, lies in how to design an experiment that quantifies these preferences. It may be that the problem is intractable, at least in a laboratory setting. Perhaps the best answers will come from crowdsourced experiments — give millions of people the ability to change the luminaire CCTs in their environments and see what they prefer.
Today, this is mostly a theoretical approach. However, with the expected deployment of pervasive Internet-of-Things device in every luminaire over the coming few years, the necessary data will become available. Such an experiment may then be as simple as writing an appropriate search string for Google Analytics to process.

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HEALTH INFORMATION

ENTRAINING CIRCADIAN RHYTHMS

INTENSITY VERSUS COLOR

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2015/04/21

There is a fascinating research paper called "Colour as a Signal for Entraining the Mammalian Circadian Clock" that has just been published in the open access journal PLOS Biology (Walmsley et al. 2015). While it is an exceedingly technical paper, the basic premise is this: the change in yellow-blue color ratio during twilight may be more effective in entraining circadian rhythms (at least in mice) than changes in daylight intensity.

Why is this important to professional lighting designers? Well, the answer involves the current interest in *circadian-based* (or *biologically-effective*) lighting. Quoting a recent LD+A article called "The Case for Circadian Correct Lighting" (Roos 2015), lighting designers are advised to:

> "*Expose normal populations to high-levels of blue-rich light near 460 nm in the morning through early afternoon, and eliminate these shorter wavelengths and reduce light levels in the late-afternoon. After 10 p.m., total darkness is ideal – or if this is not practical – very low levels of warmer red-rich light. Even an incandescent lamp can disrupt the circadian cycle if it is too bright.*"

The goal, of course, is to provide electric lighting that mimics the temporal changes in natural daylight that we as a mammalian species experienced on a daily and seasonal basis prior to the introduction of electric lighting. Roos's advice – which is reasonably good – is based on numerous medical studies over the past decade or so concerning our circadian rhythms and their relation to light exposure.

The latest paper, however, demonstrates in no uncertain terms that our knowledge of circadian rhythms is incomplete. While it does not necessarily negate the above advice, it does bring to mind new questions and possible opportunities for lighting design.

Circadian Rhythms

To better understand this topic, we begin with circadian rhythms, which Wikipedia defines as "any biological process that displays an endogenous [i.e., self-sustained], entrainable oscillation of about 24 hours." In humans, these daily rhythms include those shown in Figure 1.

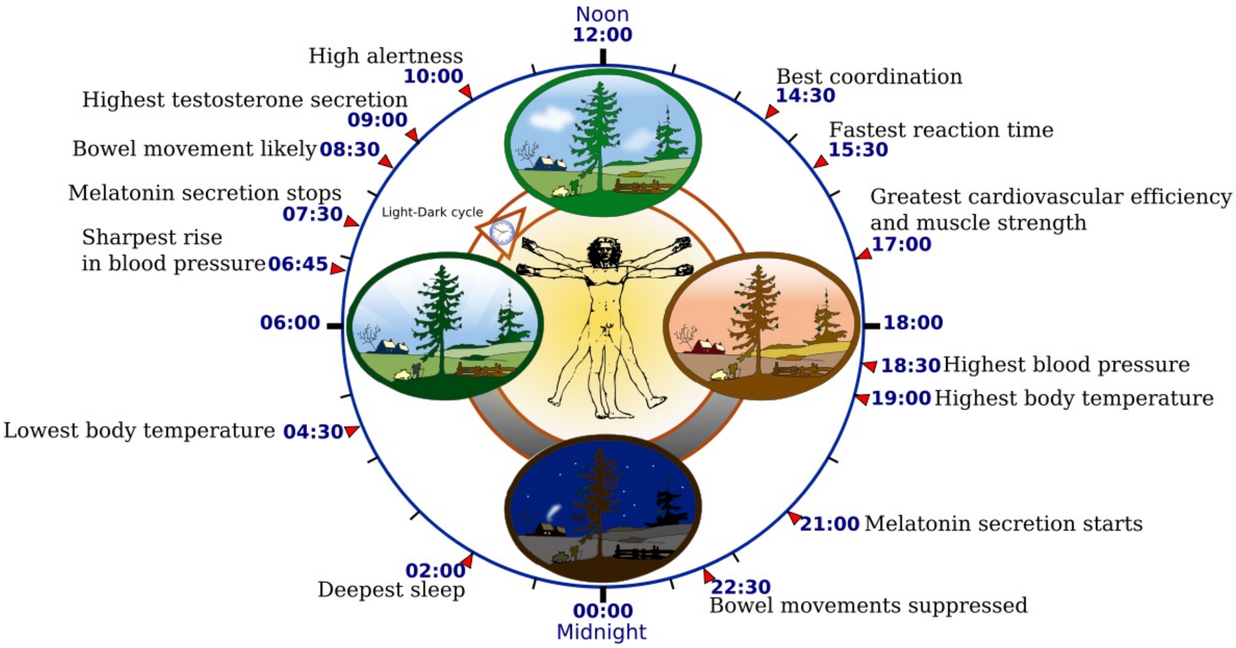

Figure 1 – Human circadian rhythms. Source: Wikipedia.

These rhythms are entrained (i.e., synchronized) by external cues called zeitgebers (“time-givers”), the most important being – as you might expect – changes in daylight. We become acutely aware of these rhythms when we suffer from jet lag. Specifically, the change in daylight schedule disrupts our circadian clock, leaving us physically exhausted and having difficulties sleeping.

From a clinical perspective, there are several ways of measuring circadian rhythms in human subjects. One way is to measure the core body temperature, but this involves placing a temperature sensor somewhat uncomfortably “where the sun don’t shine” in the subject’s body. Another more reliable method is to measure the concentration of the hormone melatonin in the subject’s blood or saliva (e.g., Benloucif et al. 2005). The disadvantage, of course, is that the subject is sleeping when melatonin is present in measurable quantities. In short, reliably measuring circadian rhythms in humans is not an easy task.

There are numerous studies that correlate the secretion of melatonin in the body with circadian rhythms (e.g., Revell et al. 2005). What is more interesting to lighting designers, however, is the relation between melatonin secretion and the human eye.

Retinal Ganglion Cells

In addition to the cones and rods that provide us with color and night-time vision respectively, the mammalian retina has intrinsically photosensitive retinal ganglion cells (ipRGCs) that play a major role in entraining our circadian rhythms (e.g., Zaidi et al. 2007). The relationship between ipRGCs and melatonin secretion has been extensively studied (e.g., Lucas et al. 2013). These cells are connected to a region deep in the brain called the suprachiasmatic nucleus (SCN). When the ipRGCs do not receive light for an hour or more, the SCN triggers the pineal gland within the brain to begin secreting melatonin, which in turn promotes sleep in humans.

Of particular interest to lighting designers is the spectral responsivity of the ipRGCs. Whereas our cones and rods have spectral responsivities defined by the V(λ) and V'(λ) functions for photopic and scotopic vision, ipRGCs have a different spectral responsivity, referred to as melanopic (FIG. 2).

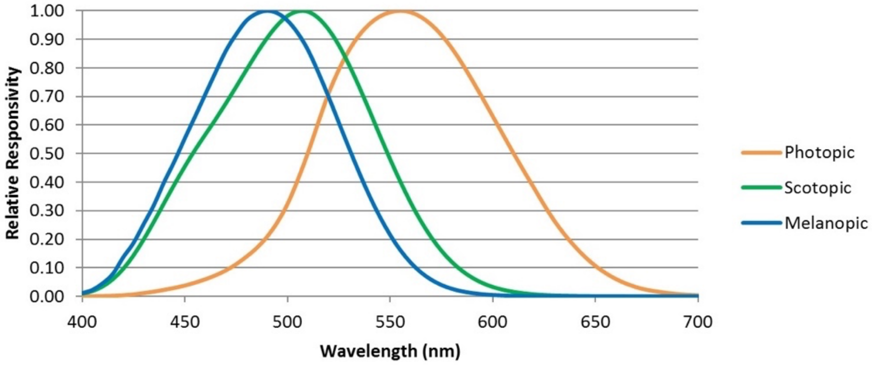

Figure 2 – Human spectral responsivity.

This has become the basis for today's evolving recommended practices in circadian-based (aka "biologically-effective" in Europe) lighting. For example, DIN SPEC 67600, Biologically Effective Illumination – Design Guidelines (DIN 2013) bases its recommendations solely on melanopic illumination. Similarly, luminaire manufacturers are currently looking at ways of optimizing the spectral power distributions of their products to produce biologically-effective white light; that is, white light with an abundance of blue light centered on the melanopic peak wavelength (e.g., Roos 2015).

... but science is all about endlessly attempting to prove that everything we think we know is either wrong or incomplete.

Experimental Design and Bias

Designing biological experiments is intrinsically difficult. You begin by hypothesizing that some action *x* will result in some event *y*. You then design an experiment in an effort to determine the correlation between the action and the event. For example, you may want to administer a vaccine and see whether it protects human subjects from contracting some viral disease.

The difficulty comes in designing the experiment. You do not, for example, want to administer an Ebola vaccine to a group of subjects living in North America – the likelihood of their being exposed to the Ebola virus is essentially zero. The experimental design in this case would be clearly biased towards an extremely positive (but essentially meaningless) correlation.

Taking circadian rhythms as another example, one problem is that the variability of retinal illuminance due to daylight exposure is typically both high and unpredictable due to cloud cover. The solution to this problem is appealingly simple: ensure that the subjects are exposed to electric lighting whose intensity and spectral power distribution (or at least its correlated color temperature) can be tightly controlled. By eliminating uncontrolled variables such as daylight, the experiment becomes more predictable and, most important, repeatable.

This solution however introduces significant experimental bias. In particular, the researcher typically assumes that:

1. ipRGCs are sensitive primarily to blue light;
2. ipRGCs are solely responsible for melatonin suppression; and
3. Melatonin secretion is an indicator of the circadian rhythm associated with sleep.

These assumptions are of course based on many previous experimental results. They are still however assumptions – what if they prove to be wrong or incomplete?

Intensity Versus Color

In their paper "Colour as a Signal for Entraining the Mammalian Circadian Clock," Walmsley et al. (2015) began with a markedly different hypothesis. Noting that the mammalian circadian clock must have evolved over hundreds of millions of years, they reasoned that it makes sense to begin with natural daylight as the zeitgeber. They therefore began by measuring the spectral power distribution of daylight from 280 to 700 nm over a period of 41 days (September through October) from a location in Manchester, UK. The data were then carefully averaged to obtain a typical day in terms of absolute spectral irradiance.

The results were surprising. As shown in Figure 3, the variation in twilight color (horizontal axis) over 41 days is much less than the variation in irradiance (vertical axis), a result the authors attribute to ozone absorption in the upper atmosphere when the sun is below the horizon (Hulbert 1953).

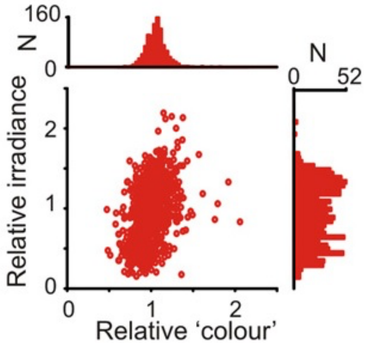

Figure 3 – Daylight color versus irradiance variability. Source: Walmsley et al. (2015).

The key here was not to assume, for example, that ipRGCs influence melatonin production and so eliminate as many experimental variables as possible, but to recreate as natural a luminous environment as possible for the test subjects (which in their experiments were laboratory mice).

(As an aside, it should be noted that there is evidence that circadian rhythms are influenced by input from not only ipRGCs, but also the retinal rods and cones. The authors cite half a dozen papers that address this topic.)

Using this information, the authors designed a LED-based lighting system for their laboratory mice. Unlike humans with their red-, green-, and blue-sensitive cones (technically long-, medium-, and short-wavelength sensitivity, designated SWS, MWS, and LMS respectively), the retinal cones of wild mice are primarily sensitive to ultraviolet (UVS) and green (MWS) wavelengths (FIG. 4), as determined by the various photosensitive opsins found in these specialized cells.

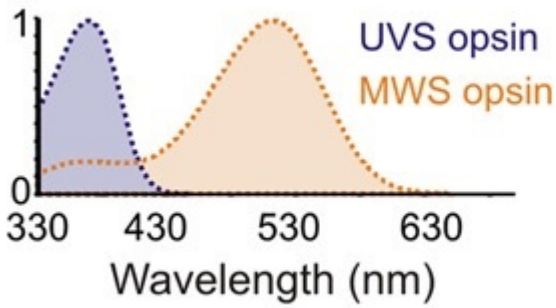

Figure 4 – Wild mouse spectral responsivity. Source: Walmsley et al. (2015).

Unfortunately, the green-sensitive (MWS opsin) cones overlap in sensitivity with the rod (scotopic) and ipRGC (melanopic) sensitivities, which complicate the issue of measuring circadian clock entrainment. The authors therefore used a transgenic breed of mice called *Opnlmw*^{R}, in which the MWS opsin cones are replaced by human long-wavelength sensitive (LMS) cones. These mice basically see ultraviolet (365 nm peak) and amber-red light (564 nm peak) only, regions of the spectrum to which the rods and ipRGCs have little to no sensitivity (Walmsley 2015, Lucas 2014).

The authors therefore used 400 nm ultraviolet and 590 nm amber high-flux LEDs for one of their lighting systems. The advantage of course is that these wavelengths minimally excite the rods and ipRGCs that presumably contribute to circadian rhythm entrainment. They further used *Cnga3*$^{-/-}$ mice, which lack cones but have retinal rods and ipRGCs, to confirm that rods and ipRGCs were not being significantly influenced by the bicolor illumination. (They also used a separate system with 365 nm, 460 nm, and 600 nm LEDs for experiments with normal “wild” mice.)

Rather than measuring melatonin levels, the authors surgically implanted tiny temperature loggers in the mice to measure core body temperature as a biological marker for circadian rhythms. The mice were then exposed to temporal lighting conditions that recreated a summer’s day in Stockholm, Sweden, including twilight, over a period of two weeks. The northern latitude was chosen specifically to achieve a protracted period of twilight and so maximize its influence on circadian rhythm entrainment.

The rest of the experiment involved some rather gruesome details involving decapitation and sliced brains in order to measure responses of the SCN to amber and ultraviolet light. What the authors found was that the ratio of amber-to-ultraviolet light (which correspond to the yellow-blue light ratio in humans[1]) had a considerably greater effect on circadian rhythm entrainment than did the variation in absolute intensity of amber-plus-ultraviolet light with constant color ratio.

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[1] In humans, our neural circuitry combines the signals received from the short-wavelength sensitive (SMS) cones with the combined signals from the medium-wavelength sensitive (MWS) and long-wavelength sensitive (LWS) cones to generate blue-yellow discrimination. This opponent color theory posits that our color vision consists of blue-versus-yellow, red-versus-green, and black-versus-white channels that our brains further process. Given evolution’s penchant for recycling good ideas, it may be that the blue-versus-yellow signal also contributes to circadian rhythm entrainment. The authors speculate that this may even have been the original evolutionary purpose of color vision.

What is significant about this is that the ratio of yellow-to-blue light remains reasonably constant throughout the day, but changes drastically *and consistently* before sunrise and after sunset (FIG. 5) over a period of about 30 minutes (that is, twilight). Conversely, the intensity of daylight may vary randomly and markedly throughout the day due to cloud cover. From an evolutionary perspective, it therefore makes more sense for the mammalian circadian clock to have evolved to respond to color rather than intensity changes in daylight as its zeitgeber.

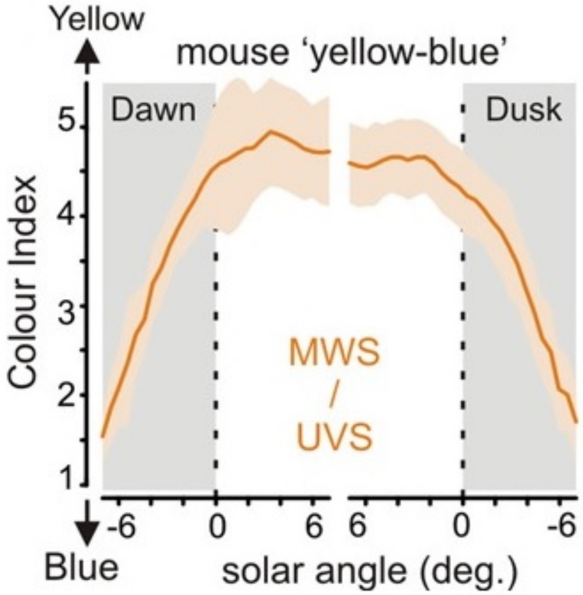

Figure 5 – Yellow-blue daylight ratio. Source: Walmsley et al. (2015).

From an electrical engineering perspective, it also makes sense that the color change (which happens rapidly and predictably) would become an important zeitgeber. In terms of phase-locked loop design, a sudden but consistent periodic pulse is better for entrainment than a variable and noisy signal such as daylight intensity.

This is not to say of course that ipRGCs and rods do not also play a role in circadian rhythm entrainment – they do (e.g., Güler et al. 2008). Further studies will (as always) be required to tease out the relationship between cones, rods, and ipRGCs in this process.

Lighting Design Perspective

From a lighting designer's perspective … well, the world of circadian-based lighting has become considerably more interesting. Until now, it has been assumed that circadian rhythms are driven by input from the ipRGCs alone, and that these in turn are excited by blue-green light centered on 490 nm. (Melanopsin has a peak sensitivity at 480 nm [e.g., Lucas et al. 2014], but the ipRGC response is skewed towards 490 nm by the spectral transmittance of the adult human cornea, which preferentially absorbs blue light.)

This paper shows that the science may be much more complicated. Its value as an academic study is that it demonstrates that under "natural" conditions involving daylight, blue-yellow color discrimination complements, and may even dominate intensity changes via ipRGCs in circadian rhythm entrainment.

At the same time, however, these natural conditions do not reflect the decidedly artificial conditions we subject ourselves to with electric lighting, particularly at night or at the end of a night shift. It has, for example, been established that several hours of exposure to high-CCT illumination from tablet computers can significantly disrupt our circadian rhythms (van der Lely et al. 2015).

It is also important to recognize that it is the *change* in yellow-blue color ratio that influences circadian rhythm entrainment in natural lighting conditions, not the color ratio itself. Studies using lighting with constant color temperature (e.g., Bellia et al. 2014), which found that different color temperatures have little effect on circadian stimulus, may be eliminating precisely those experimental variables that are of the most interest.

Without predicting the results of future studies, suppose that the dominant geitzeber for circadian rhythm entrainment is the change in yellow-blue color ratio of daylight rather than constant or even changing melanopic illuminance. If this proves to be true, then the current recommendations for circadian-based / biologically effective lighting may be in serious need of revision.

If this does prove to be true, however, it may simplify the lighting design requirements. It would, for example, be much easier to use color-tunable luminaires with programmable color temperatures that change to signal the beginning and end of the day, than it would be to ensure absolute levels of melanopic illuminance.

There are conflicting opinions about whether we know enough about the circadian system in humans to design biologically-effective lighting systems. The current paper will do nothing to resolve this debate, as it shows how little we really do know.

On the other hand, I prefer to take a positive approach. It is difficult to imagine a situation where any reasonable lighting system design can physically harm people. Given this, I have no problem with taking the “best available science” and designing lighting systems accordingly. Whatever recommendations we have will most likely involve programming of color-tunable luminaires with varying spectral power distributions and intensity on a daily cycle. The beauty of this is that as the science improves, the lighting systems will only require a software or driver firmware update.
In the meantime, more research is (as always) required.

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SEEING ULTRAVIOLET

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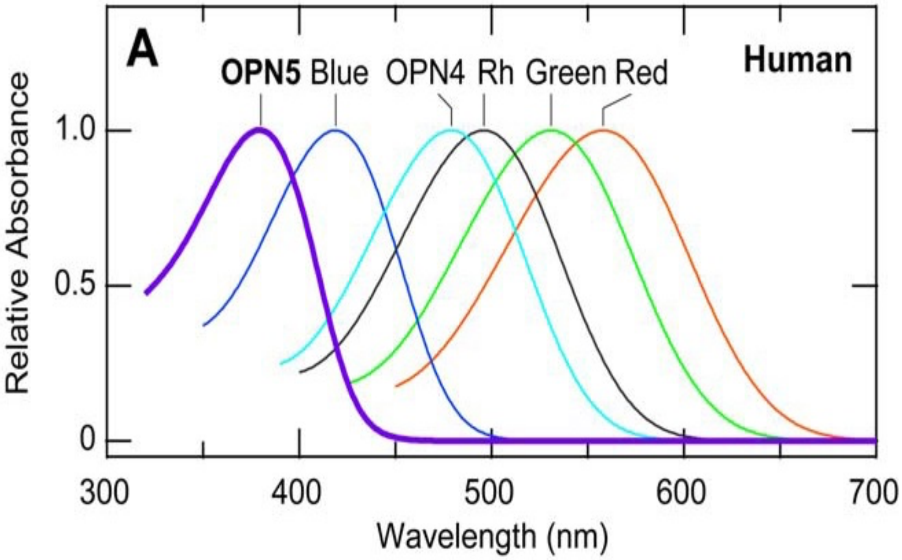

UPDATE 15/11/08 – The following text briefly notes that some people can see near-ultraviolet radiation following cataract surgery due to the UV transmittance of their artificial intraocular lens. An example of this is reported in considerable detail here.

What does it mean to "see?" The word is ubiquitous in the English language, with dozens of different meanings. However, according to the Oxford English Dictionary, the most common definition is to "perceive with the eyes." It is so common, in fact, that it ranks as one of the thousand most frequently used words in English.

"I see," said the blind man, "what you mean."

What we see are photons with varying wavelengths. Our eyes are most sensitive to photons with a wavelength of 555 nm, which we perceive as yellow-green. This sensitivity decreases towards ends of the visible spectrum, as shown by the CIE 1931 luminous efficiency function (FIG. 1). For all practical purposes, we cannot see photons with wavelengths shorter than 400 nm (deep violet) or longer than 700 nm (deep red). We are in particular blind to ultraviolet radiation (photons with wavelengths ranging from 100 nm to 400 nm) … or are we?

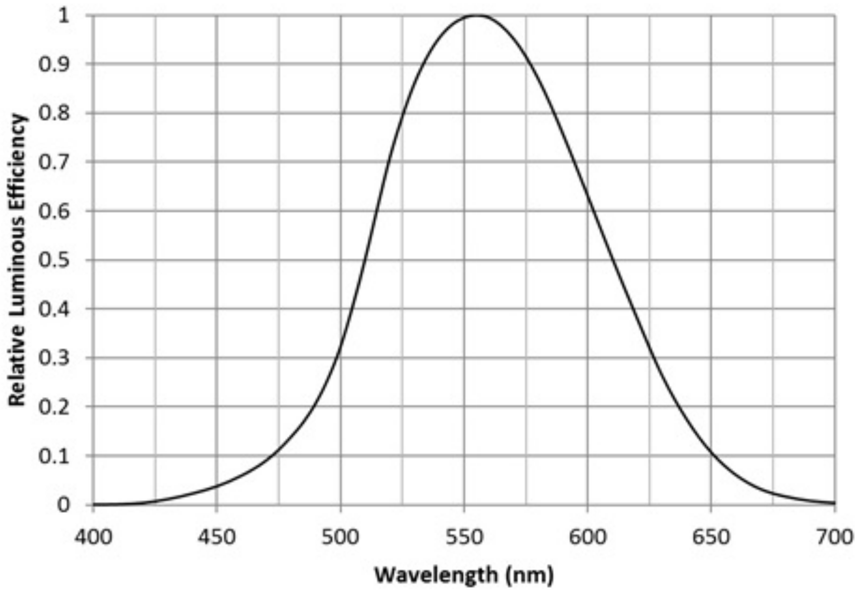

FIG. 1 – CIE 1931 luminous efficiency function.

Ultraviolet Radiation

The CIE Lighting Vocabulary classifies ultraviolet radiation as follows:

Name	Wavelength Range
UV-A	315 nm to 400 nm
UV-B	280 nm to 315 nm
UV-C	100 nm to 280 nm

Ultraviolet radiation offers both benefits and dangers to human health. UV-B radiation, for example, induces the production of vitamin D in exposed skin. This essential vitamin helps regulate bone health, and debatably provides other health benefits. Both UV-B and UV-A radiation promote the formation of melanin in the skin, which in addition to causing the skin to visibly tan, protects the skin cells from UV-B radiation damage.

The dangers of ultraviolet radiation include skin damage (sunburn and possible skin cancer through both direct and indirect DNA damage), and eye damage. Short-term exposure to UV-C (present in welders' electric arcs) and UV-B (present in direct sunlight) can cause photokeratitis ("snow blindness" — basically sunburnt cornea), while long-term cumulative exposure can lead to the formation of cataracts in the lens of the eye and other eye diseases.

Given these dangers, it should come as no surprise that we cannot see ultraviolet radiation. The lens of the human eye is opaque to UV-A radiation, while the cornea blocks UV-B and UV-C radiation (FIG. 2). (Cataract removal operations involve the replacement of the lens with an artificial intraocular lens.

These lenses were originally made from molded PMMA plastic, which were transparent to UV-A radiation. As a result, some patients could subsequently perceive ultraviolet radiation.)

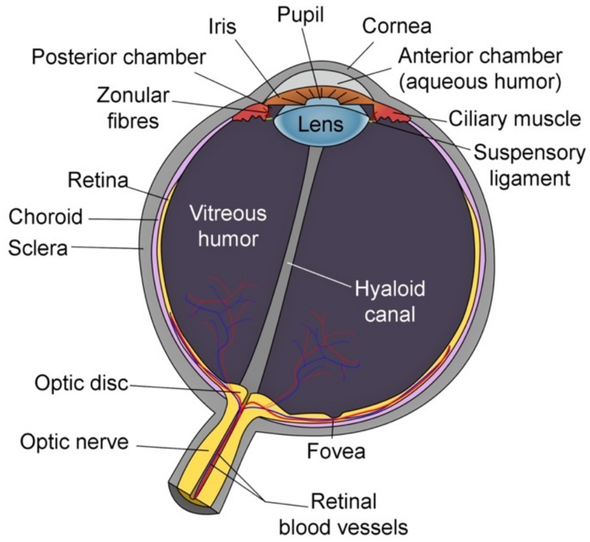

FIG. 2 – Human eye. Source: Wikipedia.

We may not be able to see ultraviolet radiation, but other animals certainly can. Wild mice, for example, can see both UV-A and UV-B radiation (Kojima 2011). Other animals include birds, reptiles, fish, insects, and crustaceans, which use their ultraviolet vision for identifying food, sex recognition, and celestial navigation. Many nocturnal insects, for example, navigate by the ultraviolet emissions of celestial objects, and so are disoriented by and attracted to ultraviolet "bug zapper" traps.

Humans, on the other hand, are diurnal animals. Being active in the daytime under the tropical sun, it makes sense that our eyes evolved to protect the retina from ultraviolet radiation damage, notwithstanding the potential advantages of being able to see ultraviolet identification patterns on food sources. Ergo, we cannot see ultraviolet radiation … or can we?

Opsins

We know that our eyes perceive more than just visual images projected onto the rods and cones of the retina. In addition to an estimated 4.5 million cone cells and 90 million rod cells (Curcio et al. 1990), there are also some 3,000 intrinsically photosensitive retinal ganglion cells (ipRGCs) in the retina (Dacey et al. 2005). The high density of cones and rods is necessary to form visual images; the ipRGCs need only detect light.

Lighting designers familiar with circadian-based lighting (e.g., Roos 2015) will recognize ipRGCs. These cells contain melanopsin, which is most sensitive to cyan light with a peak at 490 nm. Upon activation, the cells send electrical signals to the suprachiasmatic nucleus (SCN), a tiny region of some 20,000 cells located in the hypothalamus of the brain. The SCN is the master clock which controls our circadian rhythms.

Melanopsin (OPN4) is but one of a thousand or so known opsins, a group of light-sensitive proteins that occur in prokaryotes (single-celled organisms), some algae, and all animals (Terakita 2005, Shichida et al. 2009). Of particular interest are the "vertebrate visual opsins" that occur in human retinas:

Name	Peak sensitivity	Photo-receptor
Rh1 (rhodopsin)	510 nm	Rod
OPN1SW ("blue opsin")	440 nm	Cone
OPN1MW ("green opsin")	545 nm	Cone
OPN1LW ("red opsin")	570 nm	Cone
OPN4 (melanopsin)	490 nm	ipRGC

Rhodopsin provides us with scotopic vision, while the three "cone opsins" provide us with photopic color vision.

There are also other opsins in the human body, including OPN3 (encephalopsin), which is found mostly in the brain (Blackshaw et al. 1999), and OPN5 (neuropsin), which is found in the neural tissues of both humans and mice (Tarttelin et al. 2003, Kojima et al. 2011). Being photosensitive, their functions have been hypothesized to be related to the entrainment of our circadian and/or seasonal clocks in some manner, but the mechanisms are unknown.

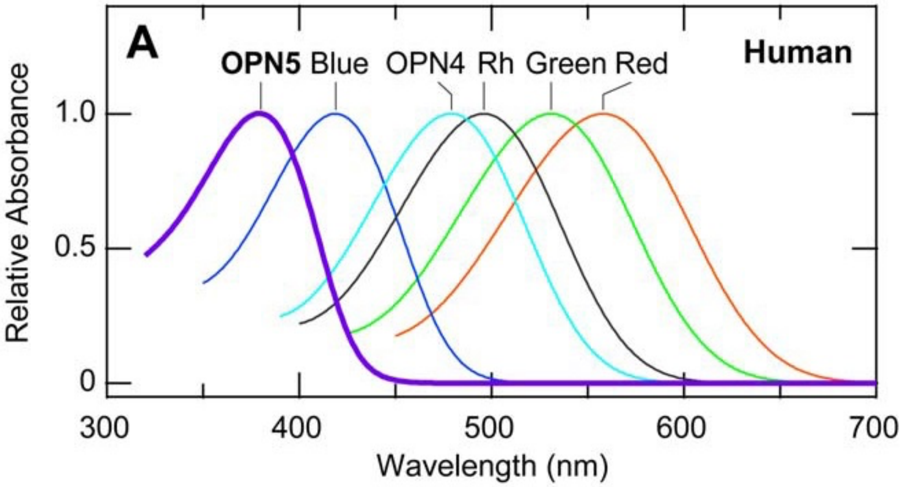

FIG. 3 – Photosensitive opsins in the human retina. Source: Kojima et al. 2011.

Neuropsin is mostly sensitive to UV-A radiation, with peak sensitivity at 380 nm. When it absorbs ultraviolet photons, it converts into a blue-absorbing photoproduct with maximum absorption at 470 nm, which is stable in the dark. Orange illumination then converts it back into its ultraviolet-absorbing state (Kojima et al. 2011). It is present ("expressed") in the retinal neurons of mice, which makes sense — they can see ultraviolet radiation (FIG. 4). However, it has also been found to be present in the cornea of the mouse eye, and presumably is also present in the cornea of the human eye (Buhr et al. 2015). What is it doing there?

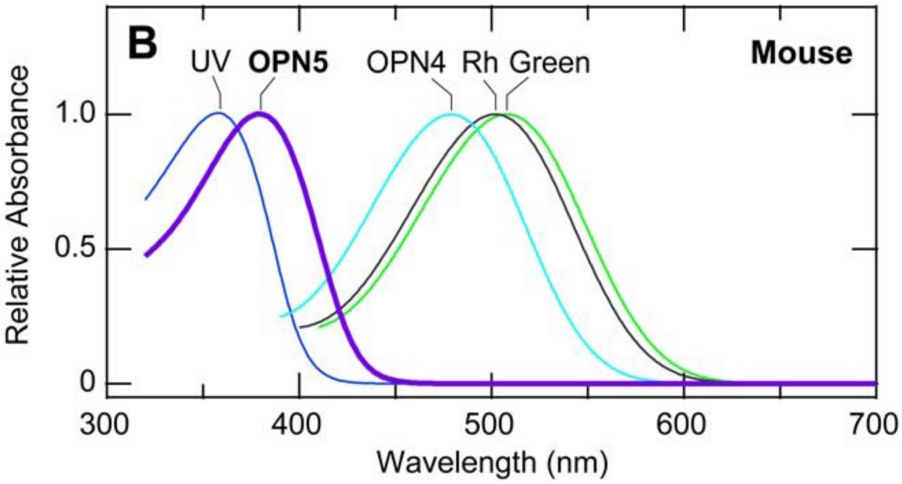

FIG. 4 – Photosensitive opsins in the mouse retina. Source: Kojima et al. 2011.

(It should be noted that mouse and human opsins are not chemically identical, but rather are orthologsthat evolved from common ancestors (Terakita 2005). Human blue opsin and mouse UV opsin, for example, evolved from a common ancestor but have different spectral responses. For neuropsin, however, it is assumed that they are biologically equivalent.)

Cellular Clocks

When we refer to the "circadian clock" in our bodies, we must remember that it is not a single mechanism located somewhere in our brain, but a holistic component of our entire body (Albrecht 2012). We have literally trillions of cells in our bodies, each of which (with a few rare exceptions) has a cellular clock to determine when to use energy, when to rest, when to repair or replicate DNA, and so on. This all happens on the molecular level of proteins and gene expression, with the SCN serving as the master timekeeper for the body, in part by instructing the pineal gland to secrete the hormone melatonin while we are sleeping.

The retina of the human eye has its own local circadian clock that is not synchronized with signals from the SCN (Storch et al. 2007). One of the more curious functions of this clock is to control the electrical coupling between the rods and cones (Ribelayga et al. 2008). Our rods are sensitive to dim light, while our cones are sensitive to bright light, giving us scotopic and photopic vision respectively. During the day, the electrical coupling between adjacent rods and cones is weak, which means that they operate independently in forming visual images. At night, however, the electrical coupling becomes remarkably robust. As a result, the cone circuitry is able to receive signals from the rods under low light-level conditions; this presumably facilitates the detection of large dim objects at night. How the retinal circadian clock was entrained by the day-night cycle remained unknown until recently, when it was shown that entrainment was due to the presence of neuropsin in the mammalian retina and cornea (Buhr et al. 2015). Surprisingly, none of the other retinal opsins appear to be involved.

Kojima et al. (2011) noted that even if neuropsin is present in the human retina, there does not appear to be sufficient retinal irradiance to activate it. Our lenses are basically opaque to ultraviolet radiation, and even our sensitivity to violet light drops significantly as we age and our lenses turn progressively yellow (Fig. 5).

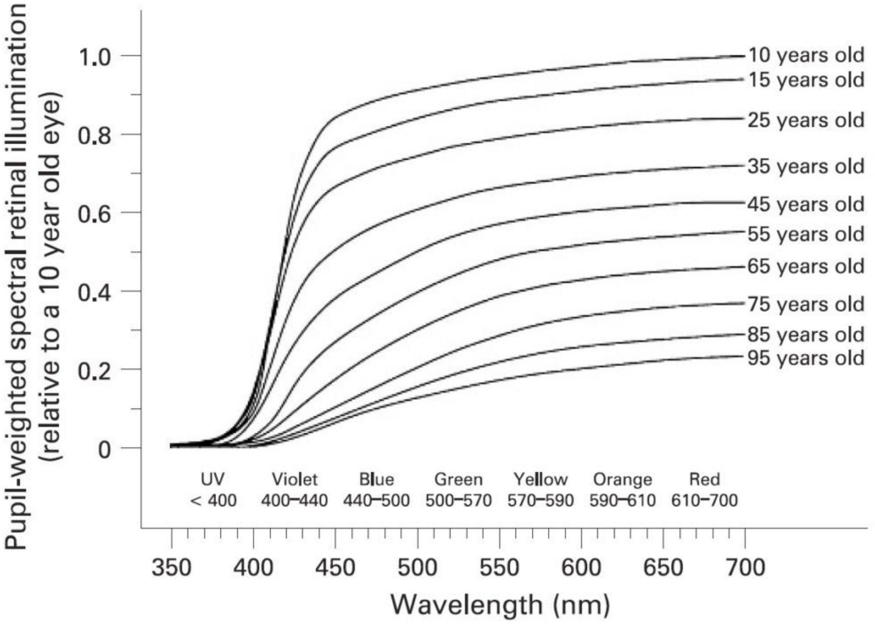

Figure 5 – Human eye lens spectral transmittance. Source: Turner et al. 2008.

(As noted by Turner et al. (2008), ipRGCs play a vital role in human physiology and health. As the lens transmittance in the blue and violet region of the visible spectrum decreases with age, we become increasingly susceptible to insomnia, depression, cognitive decline, and numerous systemic disorders due to the lack of circadian rhythm entrainment.)

These results notwithstanding, Buhr et al. (2015) reported that a breed of laboratory mice lacking rods, cones, and ipRGCs were still able to synchronize their retinal circadian rhythms to light/dark cycles, presumably by means of neuropsin in their retinas. Conducting their experiments *EX VIVO* with fresh and cultured tissues, they conclusively demonstrated that OPN1SW (blue opsin) and OPN3 (encephalopsin) were not involved.

What they did not discuss is that Kojima et al. (2011) identified the epidermal and muscle cells of the outer ears as major sites of neuropsin expression in mice. Given that mouse ears typically have few hairs on their surfaces, it was hypothesized that the outer ears may perceive UV-A radiation (but it noted that further studies are required). Thus, while Buhr et al. (2015) demonstrated the role of ocular neuropsin in retinal circadian entrainment, it is not yet clear whether it is solely responsible for entrainment *IN VIVO*.

Contradicting Kojima et al. (2011), Buhr et al. (2015) surmised that even in humans with essentially UV-opaque lenses, there may be enough retinal irradiance in blue light to activate the retinal neuropsin when the eyes are exposed to full sunlight. This is possible but unlikely — it implies a presumably important biological function that relies on marginal signaling conditions. (Turner et al.

2008 note that the threshold for circadian rhythm entrainment via melanopsin appears to require daylight illuminance levels, especially for the elderly. The human lens and cornea, however, are mostly transparent to cyan light.)

The presence of neuropsin in the cornea is equally puzzling. Buhr et al. (2015) again surmised that it may involve an ocular (i.e., not just retinal) photoentrainment that is separate from SCN entrainment. However, the corneal cells which host this opsin are not as yet known, nor are the biochemical details of how it functions *IN VIVO*.

So what is neuropsin doing in the cornea? It is photosensitive, but then it is also found in the brain, where it has an unknown role. On the other hand, by being present in the human cornea, it is fully exposed to UV-A radiation. This suggests that it is involved in ocular photoentrainment.
Regardless of these unknowns, it is evident that the retinal circadian clock is dependent on neuropsin, and that it involves UV-A radiation rather than visible light. Ergo, we most likely perceive ultraviolet radiation.

Ultraviolet Radiation Requirements

From a human-centric lighting perspective then, this raises an interesting question: do we need exposure to ultraviolet radiation in order to maintain the health and nighttime performance of our eyes? Fluorescent lamps emit a small but significant amount of ultraviolet radiation, with eight hours of exposure at interior illumination levels roughly equivalent to one minute of direct sunlight exposure (NEMA 1999). However, LED lamps and modules emit no ultraviolet whatsoever. Whether this will affect, for example, long-term care patients who do not have daily access to sunlight or other near-ultraviolet radiation sources is an open question.
Yet another hypothesis — more research is required.

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DAYLIGHTING INFORMATION

SOLAR ILLUMINATION

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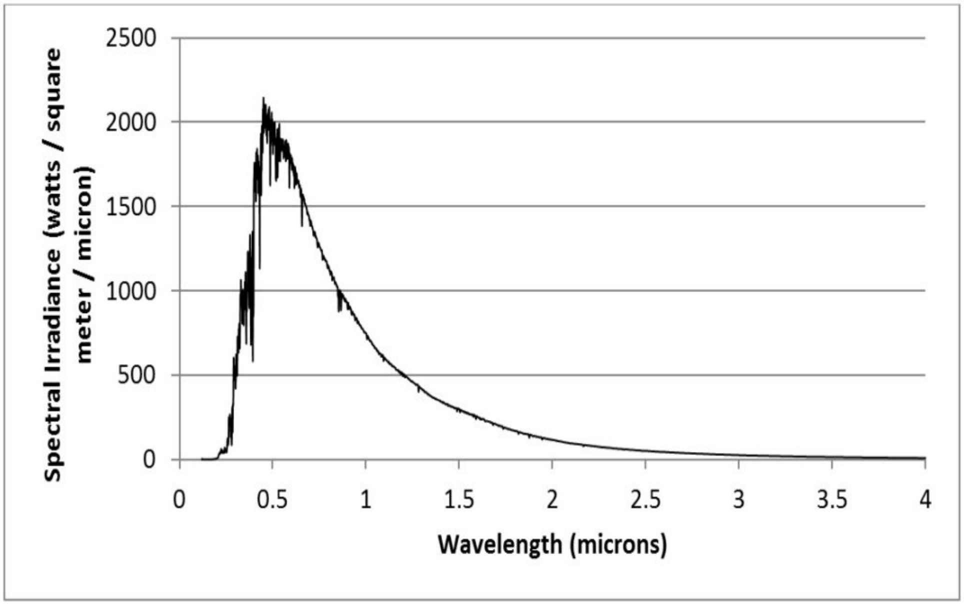

Lighting design is based in part on the reasonable assumption that photometric units have precise definitions. The *CANDELA*, for example, has a precise mathematical definition:

> *"THE CANDELA IS THE LUMINOUS INTENSITY, IN A GIVEN DIRECTION, OF A SOURCE THAT EMITS MONOCHROMATIC RADIATION OF FREQUENCY 540×10^{12} HERTZ AND THAT HAS A RADIANT INTENSITY IN THAT DIRECTION OF 1/683 WATT PER STERADIAN."*

and from this all-other photometric units are derived, including luminous flux, luminous intensity, luminance, illuminance, and so forth.

You might expect then that the same applies for daylighting design … but you would be wrong.

Solar Constant

We begin with the *solar constant*, which is defined as the solar irradiance (measured in radiant watts per square meter) incident on a plane perpendicular to the Sun at a distance of one astronomical unit (AU), which is roughly the mean distance from the Sun to the Earth.

Defining the solar constant is easy; measuring it is not. Although it was first roughly measured in 1838, accurate measurements must be performed using a satellite above the Earthís atmosphere. You then have to correct for the distance of the Earth from the Sun, which varies due to the ellipticity of the Earthís orbit. (The actual direct solar irradiance at the top of the atmosphere varies by some 6.9% over the course of a year.)

The technology of precision spectroradiometers has of course improved over the years, and with it increasingly precise measurements of the solar spectrum and the solar constant. By 1993, satellite measurements had a precision of 0.01 percent (Kittler and Darula 1996).

Today, the extraterrestrial solar spectrum is formally defined by ASTM International Standard E490-00a (2014), "Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables." This standard defines the solar spectrum (FIG. 1) over a range of wavelengths from 200 nanometers (far ultraviolet) to one millimeter (far infrared).

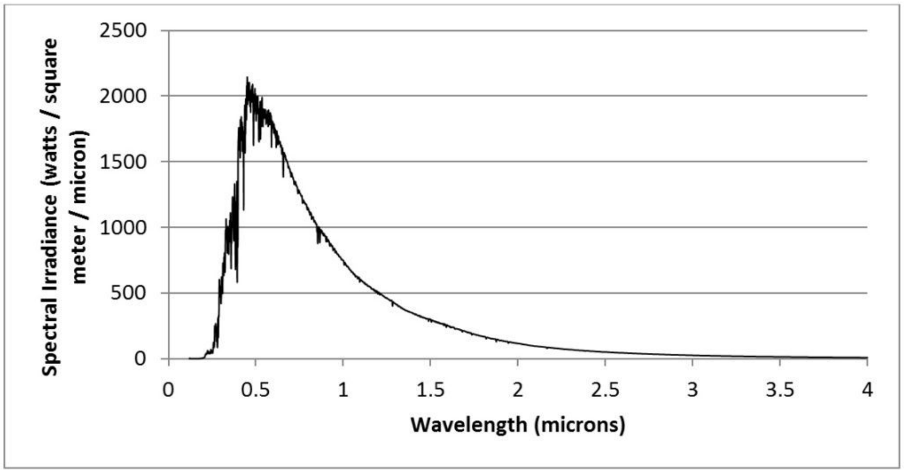

FIG. 1 – Solar spectrum (Source: ASTM 2014).

Integrated over the entire solar spectrum, the solar constant is 1366.1 ± 0.58 watts per square meter. This is of course something of a fiction, as the total radiation output of the Sun varies by approximately 0.1 percent due to the 11-year sunspot cycle and other longer-term effects. In general however, the output has varied by less than 0.2 percent over the past two millennia.

Solar Illumination Constant

The solar constant is useful for things like satellite design and climate studies. For lighting design purposes, however, only visible light in the range of 380 nm to 780 nm is important. By multiplying each wavelength by the CIE 1931 luminous efficiency function *V*(λ), according to:

$$\Phi_v = 683\ lm/W\ * \sum_{380}^{780} \Phi_e(\lambda)\, V(\lambda) \Delta\lambda$$

the solar illumination constant can be calculated.

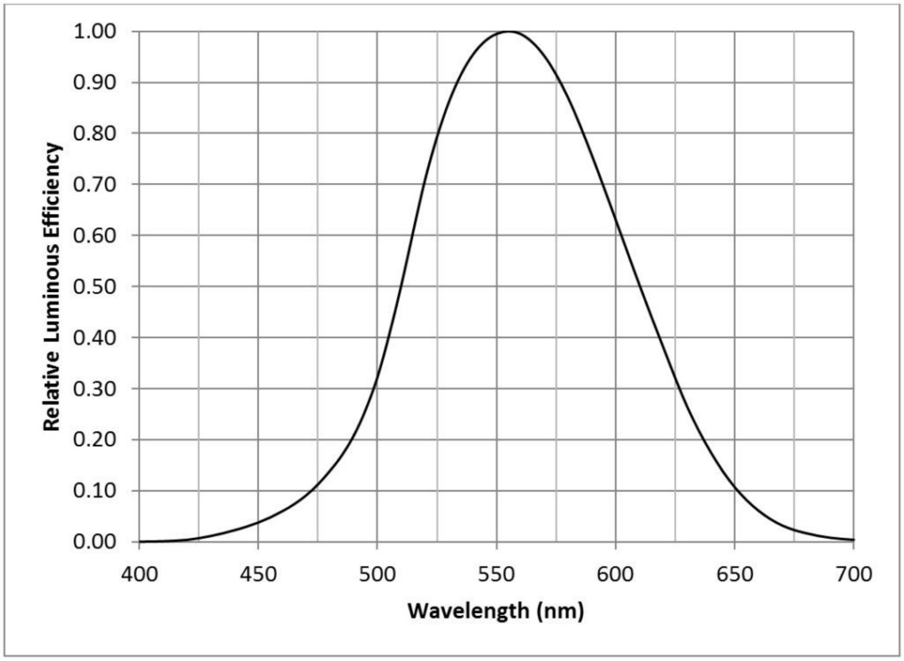

FIG. 2 – CIE 1931 luminous efficiency function.

Based on ASTM (2014), the calculated solar illumination constant E_{sc} is 133.1 kilolux (IES 2010). There is nothing controversial here … right?

DAYLIGHTING DESIGN

The lighting design and simulation program *RADIANCE* has long been a standard tool within the daylighting research community. The name "program" is a bit of a misnomer, as *RADIANCE* is a set of hundreds of Unix-based utility programs that are executed via command-line scripts. One of these programs is *GENDAYLIT*. This is an essential tool for daylighting research, as it calculates the absolute sky luminance distribution in accordance with the Perez sky model (Perez et al. 1993).

The issue is that *GENDAYLIT* was written in 1994. At that time, the standard solar spectrum was Wehrli (1985), which resulted in a solar constant of 1367 watts per square meter and a solar illumination constant of 127.5 kilolux. These values were hard-coded as constants in *GENDAYLIT*.

When the IES Lighting Handbook, Tenth Edition, was being prepared, the solar illumination constant was recalculated based on ASTM E-490-00a(2006). This document was first published in 2000, and has since been reapproved and published as ASTM E490-00a(2014).

So herein lies the problem: which solar illumination constant should be used? To be compatible with the IES Lighting Handbook, Tenth Edition, it should be 133.1 kilolux. However, to be compatible with the "gold standard" *RADIANCE* used by the daylighting research community, it should be 127.5 kilolux.

This is not exactly an academic question, as the difference is 4.4 percent. This difference permeates all absolute daylighting values calculated using the Perez sky model. For annual daylight metric calculations such as spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), this difference can be significant (IES 2012).

It is an open question.

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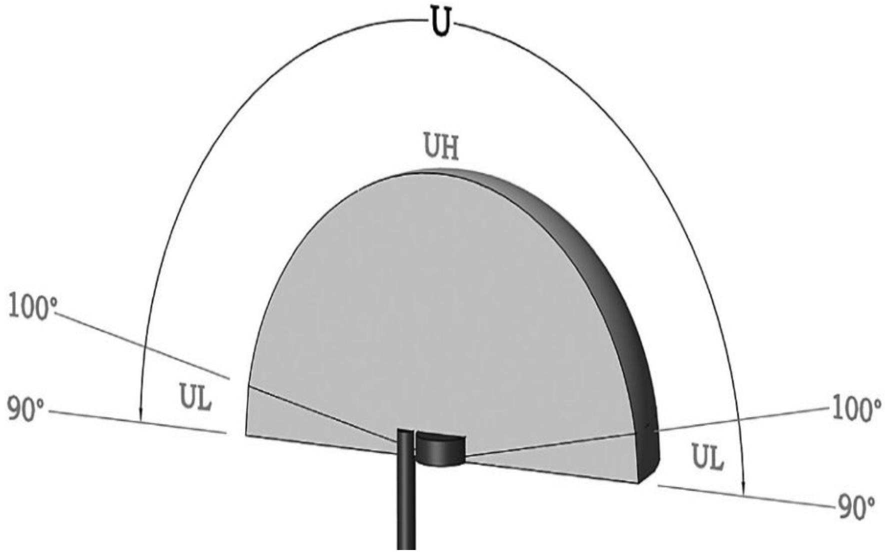
Light Pollution Information

LIGHT POLLUTION AND UPLIGHT RATINGS

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2015/07/20



"Oh, East is East, and West is West, and never the twain shall meet."

When Rudyard Kipling wrote this line in his poem *THE BALLAD OF EAST AND WEST* (Kipling 1892), he was referring to cultural misunderstandings between the British and their colonial subjects in India (where "twain" means two). As a proverb, however, it has worked equally well for the lighting industry and the astronomical research community for the past four decades.

The meeting concerns light pollution, wherein roadway and area lighting contribute to the diffuse sky glow that limits our ability to observe the stars at night. The International Dark-Sky Association (IDA) has campaigned since 1988 to limit the use of outdoor lighting, and to employ luminaires that are designed to limit undesirable spill light. Unfortunately, the equivalent of cultural misunderstandings have until recently worked against this effort.

Those in the lighting industry will be familiar with IES TM-15-11, Luminaire Classification System for Outdoor Luminaires with its BUG (Backlight-Uplight-Glare) rating system (IES 2011); those in the astronomical research community will be familiar with Garstang's light pollution model (Garstang 1986) and its derivatives. These documents have led to the development of the IDA/IES Model Lighting Ordinance (IDA/IES 2011) by the lighting industry and the lesser-known Pattern Outdoor Lighting Code (Luginbuhl 2010) by the astronomical research community.

Of particular interest to professional lighting designers is the BUG rating system of IES TM-15-11. While the IDA/IES Model Lighting Ordinance (MLO) has seen at best sporadic adoption by individual municipalities and states, BUG ratings are integral to the LEED v4 Light Pollution Reduction credit. While it is only one credit, it may make the difference between, for example, LEED Silver and Gold certification.

Related to this is the IDA's Fixture Seal of Approval program, which "provides objective, third-party certification for luminaires that minimize glare, reduce light trespass, and don't pollute the night sky." While it is not directly related to IES TM-15-11 or LEED v4, outdoor luminaires with this "dark-sky friendly" certification are useful in promoting environmental responsibility in building design.

Curiously, recent changes to this program have removed all references to the BUG rating system, replacing it with the much simpler requirement that the luminaires be full-cutoff, or to quote the IDA FSA Web site, "fixtures must emit no light above 90 degrees." In other words, after campaigning for lighting pollution control and working with the lighting industry through the Illuminating Engineering Society for the past decade or more, the International Dark-Sky Association apparently no longer recognizes the IES BUG rating system.

What happened here … and why is your humble scribe looking guilty?

History – Astronomical Research

Going back to 1973, the astronomer P. S. Treanor wrote a paper called, "A Simple Propagation Law for Artificial Night-Sky Illumination" (Treanor 1973). In it, he developed an empirical equation for the overhead sky brightness at night due to light pollution from a distant city. As befits the astronomical research community, his equation involved Mie scattering from aerosol particles (dust and smoke), atmospheric density, and extinction coefficients — topics not in the lexicon of most lighting designers. The light source was modeled as a single point source with constant intensity.

In 1986, the astronomer R. H. Garstang wrote a paper called, "Model for Artificial Night-Sky Illumination" (Garstang 1986). Again, as befits the astronomical research community, his equations involved Rayleigh scattering from air molecules, Mie scattering from aerosol particles, reflections from the ground, and more. Most important, he empirically modeled the luminous intensity distribution of roadway cobrahead luminaires that were prevalent at the time.

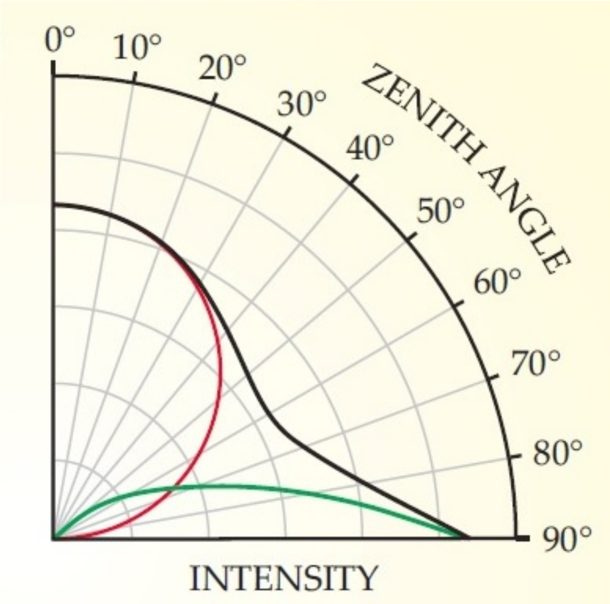


FIG. 1 – Garstang's luminous intensity function (green line). (Source: Luginbuhl et al. 2009).

In his own words, however," the choice of the function … is purely arbitrary … these properties seem to be true for most street lights and for at least some other forms of outdoor lighting."

FIG. 2 – Typical cobrahead roadway luminaire.

… and never the twain shall meet. The lighting industry has relied on measured luminous intensity distributions to characterize luminaires for nearly a century. It would be unthinkable for a lighting researcher to model such distributions with a "purely arbitrary" function that might "seem to be true."

In Garstang's defense, however, a metropolis illuminated with randomly oriented cobrahead luminaires circa 1986 probably did have a composite luminous intensity distribution (i.e., for the entire city) that was reasonably approximated by his empirical function. As evidence of this, recent studies by Duriscoe et al. 2013 and others have mostly validated the sky glow predictions made by Garstang's model.

That, however, was three decades ago. Things have changed.

History – Lighting Industry

The IDA/IES Model Lighting Ordinance has a long and somewhat contentious history. It was first developed by the IDA without significant input from lighting industry. One of the early drafts defined outdoor luminaires in terms of their wattage, with no reference whatsoever to their luminous flux output. East is East and West is West …

An IES meeting of outdoor lighting industry representatives first saw this proposed ordinance as an existential threat, as recorded in the meeting minutes. Eventually however, it was decided that it was better to work with the astronomical research community rather than to fight it. In 2005 therefore, the Joint IDA/IES Task Force was formed to collaboratively develop the MLO.

This led in turn to the development of the Luminaiure Classification System (LCS), published in IES TM-15-07, with the BUG rating system added in 2009 and subsequently revised in IES TM-15-11. The first public review of the MLO occurred in 2009, the second public review in 2010, and the final *JOINT IDA-*

IES MODEL LIGHTING ORDINANCE (MLO) WITH USERÍS GUIDE document was published in June 2011 (IDA/IES 2011). The BUG rating system of IES TM-15-11 is incorporated in the MLO as Table C, Maximum Allowable Backlight, Uplight and Glare (BUG) Ratings.

Referring to IES TM-15-11, it defines six uplight ratings for luminous flux (maximum zonal lumens) emitted above 90 degrees by the luminaire (Table 1). There are two uplight zones, designated UL for vertical angles 90 to 100 degrees and UH for angles 100 to 180 degrees (FIG. 3).

	U0	**U1**	**U2**	**U3**	**U4**	**U5**
UH	0	10	50	500	1000	>1000
UL	0	10	50	500	1000	>1000

Table 1 – IES TM-15-11 Uplight Ratings (maximum zonal lumens)

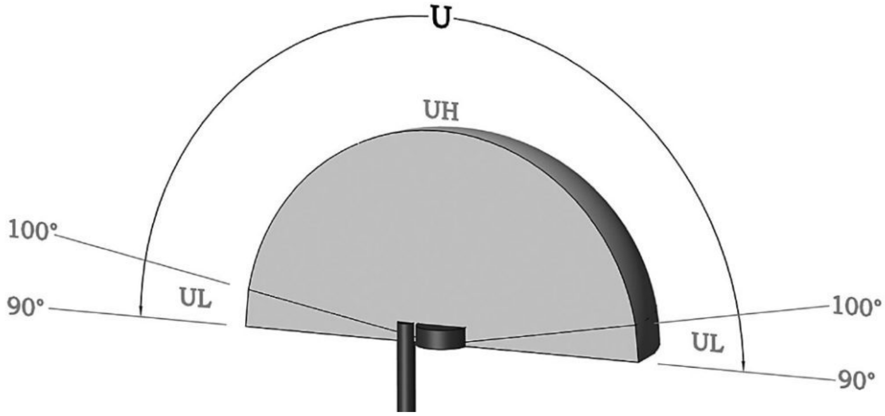


FIG. 3 – IES TM-15-11 BUG uplight zones (Source: Chinnis et al. 2011).

The question that must be asked, however, is where did these lumen values come from? The only publicly-available documentation appears to be a *LEUKOS* paper titled “IES TM-15 BUG Value-Setting and Adjustment Methodology” (Chinnis et al. 2011). One quote from this paper is of particular significance:

“The BUG values were established by the [IDA/IES MLO Task Force] based on professional experience and analysis efforts with a very wide variety of outdoor lighting applications, including variations in ambient brightness, site geometry and function.”

Referring to the astronomical research comment above, it would be unthinkable for an astronomer to specify values in a standard “based on professional experience and analysis efforts” without providing the data needed for impartial and independent verification.

East is East and West is West … as easy as it may be to poke fun at both sides in this matter, it is not constructive. As long as the BUG rating system is being used as a basis for the LEED v4 Light Pollution

Reduction credit, there is a need to understand whether the maximum zonal lumens shown in Table 1 are appropriate.

Sadly, they are not.

Measuring Uplight

A year after IES TM-15-11 was published, another *LEUKOS* paper titled "Photometric Imprecision Can Limit BUG Rating Utility" investigated the practical issues of measuring luminaires in the laboratory for BUG uplight ratings (Ashdown 2012). The abstract, while extensive, usefully summarizes the results:

> "There are, however, limits to what can be measured in the laboratory. IES TM-15-11 requires that a luminaire with an uplight rating of U0 emits zero lumens into the upper hemisphere, while a U1 uplight rating or a G0 glare rating for high viewing angles requires fewer than 10 lumens. Given that the luminaire is emitting thousands of lumens and that the laboratory room surfaces have a diffuse reflectance of at least two percent, it is physically impossible to measure zero lumens, and extremely difficult to measure fewer than 10 lumens. Consequently, a U0 glare rating can only be obtained by physical examination of the luminaire and post-processing of the measured photometric data. Similarly, a U1 uplight rating or a G0 glare rating for high viewing angles is likely the result of data manipulation."

The paper explained that "post-processing of the measured photometric data" is indeed a common practice in photometric laboratories. If the laboratory technician can clearly see that the luminaire emits no light at or above 90 degrees, it is entirely reasonable to zero out the data for vertical angles greater than zero degrees, as these only record the diffuse interreflections from the laboratory room surfaces.

Of course, it is also possible that the laboratory technician saw that there was some stray light being emitted into the UL zone, but decided that it was *PROBABLY* less than 10 lumens and so reason enough to zero out the data. (Estimating total emitted lumens simply by looking at a luminaire presumably requires professional experience.)

From an engineering perspective, this is an untenable position. The problem is that if you cannot measure something, then it is pointless to divide it into different categories (in this case U0 through U2 uplight ratings).

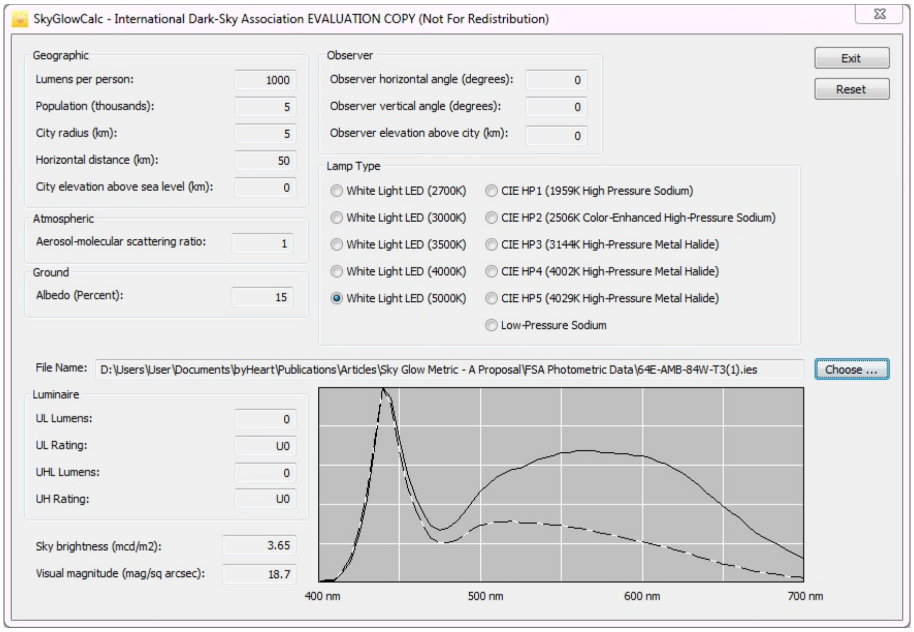
Calculating Uplight

Kipling's pessimism aside, it is possible to reconcile the interests of the lighting industry on one hand and the astronomical research community on the other. The approach is simple: given that Garstang's light pollution model has been validated, it is entirely straightforward to substitute measured luminous intensity distributions for Garstang's generic and arbitrary distribution (FIG. 1). It did not make sense to do this in 1986, but it certainly does today with the emphasis on BUG ratings. The question to be answered is, what influence do various UL and UH ratings have on light pollution if you assume that the same luminaires are used throughout an entire metropolis?

To be fair, the astronomical research community has addressed this question in several papers, including Aubé et al. (2005), Aubé (2015), Baddiley (2007), and Cizano and Castro (2000). In particular, an open-source software program for sky glow modeling called *ILLUMINA* imports IES LM-63 photometric data files. The problem, however, is twofold: 1) the papers were written for and published within the astronomical research community; and 2) software programs such as *ILLUMINA* are sophisticated research tools that are designed to answer more pressing questions than whether the BUG uplight rating lumen values are appropriate.

This need not dissuade us, however. Garstang's light pollution model is not particularly complicated, and it was clearly described in the original paper. It is also not particularly difficult to implement in software — it was after all originally developed to run on a 1980s-era Apple II computer (Garstang 1986). The only difference is that calculations that likely took days to weeks to run in 1986 now execute in a few seconds.

The result is *SKYGLOWCALC*, a program written expressly to answer the above question for the IDA Task Force (FIG. 4). The software was developed on a volunteer basis in the author's capacity as a member of the Task Force, mostly because the question itself was inherently interesting.



SkyGlowCalc - International Dark-Sky Association EVALUATION COPY (Not For Redistribution)

Lumens per person: 1000
Population (thousands): 5
City radius (km): 5
Horizontal distance (km): 50
City elevation above sea level (km): 0
Aerosol-molecular scattering ratio: 1
Albedo (Percent): 15
Observer horizontal angle (degrees): 0
Observer vertical angle (degrees): 0
Observer elevation above city (km): 0

○ White Light LED (2700K)
○ White Light LED (3000K)
○ White Light LED (3500K)
○ White Light LED (4000K)
● White Light LED (5000K)
○ CIE HP1 (1959K High Pressure Sodium)
○ CIE HP2 (2506K Color-Enhanced High-Pressure Sodium)
○ CIE HP3 (3144K High-Pressure Metal Halide)
○ CIE HP4 (4002K High-Pressure Metal Halide)
○ CIE HP5 (4029K High-Pressure Metal Halide)
○ Low-Pressure Sodium

File Name: D:\Users\User\Documents\byHeart\Publications\Articles\Sky Glow Metric - A Proposal\FSA Photometric Data\64E-AMB-84W-T3(1).ies

UL Lumens: 0
UL Rating: U0
UHL Lumens: 0
UH Rating: U0
Sky brightness (mcd/m2): 3.65
Visual magnitude (mag/sq arcsec): 18.7

FIG. 4 – SkyGlowCalc

This program is, of course, more than what Garstang envisioned some three decades ago. In addition to importing IES LM-63 photometric data files, it also allows the user to specify common lamp types with their different spectral power distributions (SPDs). The program then calculates the resultant SPDs of the emitted light contributing to sky glow at a remote observing site. As shown in FIG. 4, the wavelength-dependent effects of Rayleigh scattering greatly increase the blue content at the observing site (dashed line). A more detailed discussion of this is presented in the blog article, *COLOR TEMPERATURE AND OUTDOOR LIGHTING*.

For astronomical purposes, the most important output of this program is the sky brightness or its equivalent limiting visual magnitude. The goal was to take the photometric data files of 63 commercial luminaires from the IDA Fixture Seal of Approval program and see what differences in sky brightness there would be, assuming that all the luminaires emitted the same amount of luminous flux and all other parameters were equal (as shown in FIG. 4). The results of this analysis are shown in Table 2.

UL Uplight Rating	LPS	CIE HP1	3000K LED	5000K LED
U0	24.4	21.4	19.0	18.7
U1	24.4	21.4	19.0	18.7
U2	24.3	21.3	19.3	18.6

Table 2 – Uplight Rating versus Limiting Magnitude

The visual magnitude of the calculated sky glow determines the faintest stars you can see directly overhead at midnight on a moonless night. With the unaided eye, we can see stars as faint as magnitude 6; telescopes gather more light and so allow us to see fainter stars. The scale is logarithmic, with a difference of 0.1 magnitude representing a difference of approximately 10 percent in photometric intensity. These differences are near the limit of our ability to distinguish differences in intensity.

Simply put, not only can we not measure the differences between U0, U1 and U2 ratings in the laboratory with luminaires, we cannot distinguish the resultant differences in sky glow in the night sky.

Shortly after these results were presented to the IDA Task Force, the decision was made to remove BUG rating requirements from the IDA Fixture Seal of Approval program.

Model Lighting Ordinance

As noted above, the BUG rating system is incorporated in the IDA/IES Model Lighting Ordinance (IDA/IES 2011) as Table C. However, there is a twist that is often overlooked (FIG. 5).

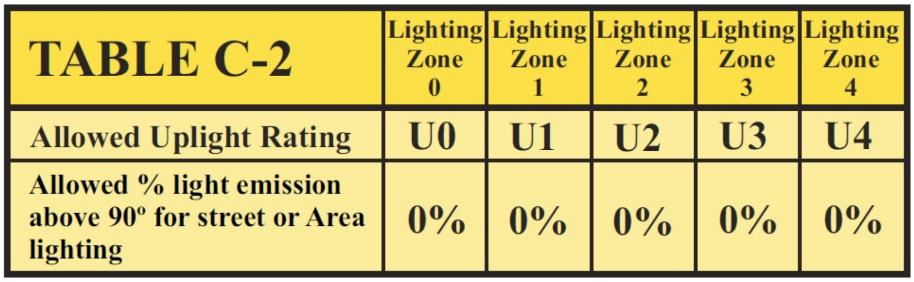


TABLE C-2	Lighting Zone 0	Lighting Zone 1	Lighting Zone 2	Lighting Zone 3	Lighting Zone 4
Allowed Uplight Rating	U0	U1	U2	U3	U4
Allowed % light emission above 90º for street or Area lighting	0%	0%	0%	0%	0%

FIG. 5 – Model Lighting Ordinance Table C-2.

Put another way, Table C-2 says that different uplight ratings are permitted for different lighting zones, but only for luminaires that are *NOT* used for street lighting or area lighting. In other words, only luminaires with U0 ratings are permitted for street and area lighting (which basically includes all significant outdoor lighting).

Conclusions

Prior to 2007, roadway luminaires were classified as having *CUTOFF*, *SEMICUTOFF*, *NONCUTOFF*, and *FULL CUTOFF*luminous intensity distributions, with “full cutoff” meaning luminaires with no luminous flux emitted at or above 90 degrees vertical, as well as limited intensity at or above 80 degrees (IES 2011). The BUG rating system was developed by the Joint IDA/IES MLO Task Force to address light pollution issues, thereby replacing these mostly empirical definitions.

It seems, however, that we mostly have come full circle — the International Dark Sky Association no longer makes use of the BUG rating system in its Fixture Seal of Approval program. All that is required is that the luminaires do not emit luminous flux above 90 degrees vertical.

This is not an example of backtracking. Rather, it is how science (and hopefully standards development) works. The IDA executive presumably reviewed the above analysis and concluded that the BUG rating system offers no value to light pollution abatement policies. The FSA program requirements were simply updated in accordance with the best available information. (LEED v4 authors, please take note.)

As for Kipling, the problem has always been that the lighting industry and the astronomical research community speak different languages. The International Dark-Sky Association has been accused in the past of “selling out” to the lighting industry in partnering with the Illuminating Engineering Society, but this is unfair. Having reviewed the original MLO drafts in the 1990s, it was painfully clear that neither side understood the other, from technology to terminology. The Joint IDA/IES MLO Task Force did a credible job of bridging this cultural gap over four years, but “professional experience and analysis” can only go so far. *SKYGLOWCALC* was developed solely to assist both sides in finally bridging the communications gap. (The author is himself an amateur astronomer.)

As for the BUG rating system, it must be remembered that its backlight and glare components (except G0) are still presumed valid, and so it is still useful in environmentally responsible lighting design. It rightfully retains its position in the IDA/IES Model Lighting Ordinance.

Postscript

The reason why uplight from U0- and U1-rated outdoor luminaires has so little effect on sky glow is simple. Taking the full-cutoff 250-watt metal halide luminaire from IES TM-15-11 as an example, it emits 13,553 lumens downwards. Assuming that the ground has a reflectance (albedo) of 15 percent (Gillet and Rombauts 2001), the amount of light diffusely reflected into the upper hemisphere is 2,033 lumens. The portion of light reflected into the UL zone is 406 lumens, with the remaining 1,627 lumens being reflected into the UH zone. In other words, the luminaire *IN ITS NATURAL SURROUNDINGS* has a UL rating of U2 (nearly U3) and a UH rating of U4. Adding a few more lumens of directly-emitted luminous flux will not make any difference.

Together, roadway and outdoor parking luminaires account for over 80 percent of all outdoor lighting on a per-lumen basis (Navigant 2012). If we are to tame light pollution, it must be through a combination of limiting roadway and parking lot illuminance requirements, and perhaps more important employing smart networked lighting technologies to dim or turn off the luminaires when they are not needed.

In the meantime, the twain have hopefully and finally met.

Acknowledgements

Thanks to Dawn DeGrazio for editorial assistance and historical clarifications.

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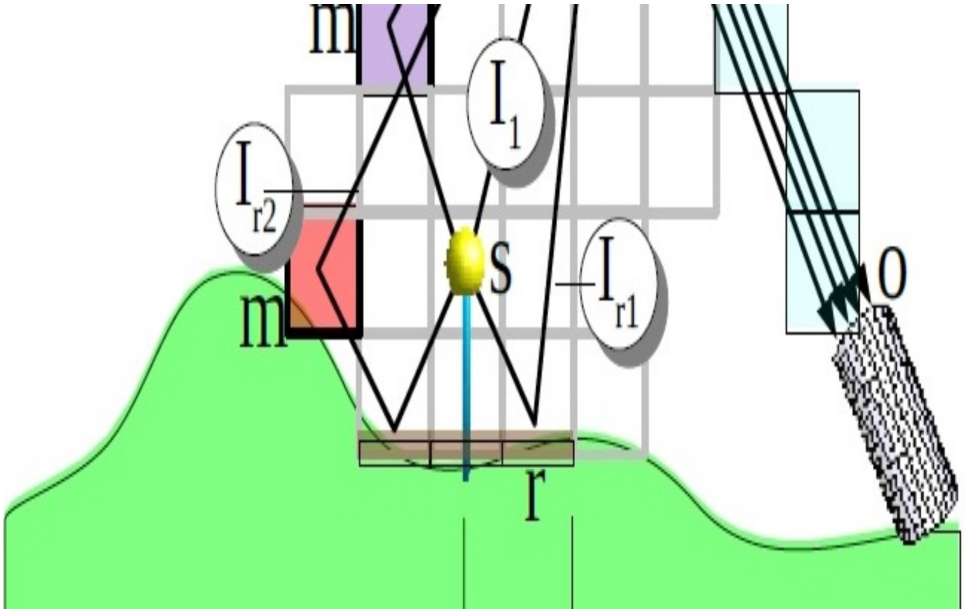
COLOR TEMPERATURE AND OUTDOOR LIGHTING

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2015/07/22



UPDATE: Sports field lighting analysis added 15/10/12.

[An edited version of this article was published as “STREET LIGHTS: Light pollution depends on the light source CCT” in the October 2015 issue of LEDs Magazine.]

Most of you will be familiar with the International Dark-Sky Association (IDA), which was founded in 1988 to call attention to the problems of light pollution. It reminds us that light pollution threatens professional and amateur astronomy, disrupts nocturnal ecosystems, affects circadian rhythms of both humans and animals, and wastes over two billion dollars of electrical energy per year in the United States alone.

The IDA’s Fixture Seal of Approval program “provides objective, third-party certification for luminaires that minimize glare, reduce light trespass, and don’t pollute the night sky.” Recent changes to this program have reduced the maximum allowable correlated color temperature (CCT) from 4100K (neutral white) to 3000K (warm white). Previously-approved luminaires with CCTs greater than 3000K will have one year to comply with the new standard.

There are several reasons for this revised CCT limit. One reason is that many people prefer low-CCT outdoor lighting, especially in residential areas. As noted by Jim Benya in his LD+A article “Nights in Davis” (Benya 2015), the City of Davis was obliged to replace newly-installed 4800K street lighting with 2700K luminaires at a cost of $350,000 following residents’ complaints. As was noted in the article, “2700K LEDs are now only 10 percent less efficacious than 4000K,” so here was presumably minimal impact on the projected energy savings.

But another, arguably more important, reason is that high-CCT luminaires contribute more to light pollution on a per-lumen basis than do low-CCT luminaires. This is perhaps best demonstrated by the widely-disseminated graph presented in Luginbuhl et al. (2014) and shown in FIG. 1:

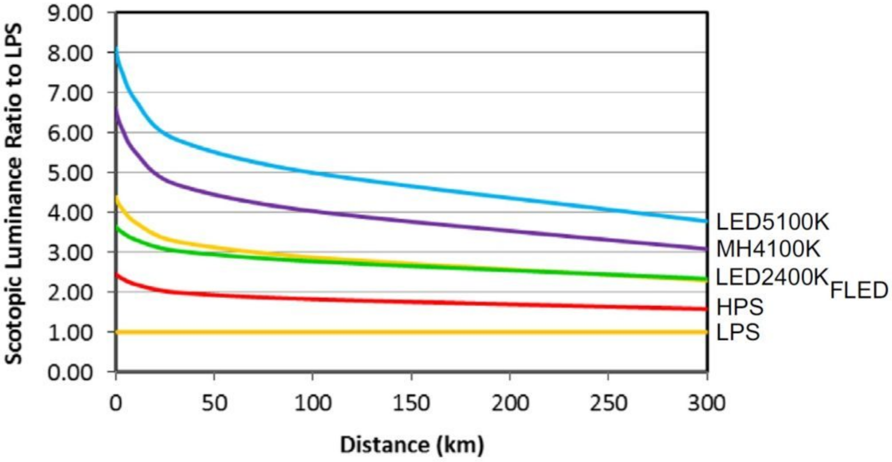


FIG. 1 – Overhead scotopic sky brightness ratio (Source: Luginbuhl et al. 2014).

Luginbuhl et al. calculated this graph using a modified version of Garstang's sky brightness model (Garstang 1986). What it shows is that the light pollution due to 5100K cool-white LED street lighting is approximately twice that of equivalent 2400K warm-white LED street lighting. According to the model, this relationship holds true regardless of the distance from the city to the remote astronomical observing site.

From the perspective of both professional and amateur astronomers as publicly represented by the International Dark-Sky Association, this graph is reason enough to require a maximum CCT of 3000K for the IDA's Fixture Seal of Approval program.

There is however more to this story. While the graph shown in FIG. 1 may present clear evidence of the relationship between CCT and light pollution, we must remember that its data were *CALCULATED* rather than measured. The question is whether it is reasonable to trust Garstang's sky brightness model and its modification by Luginbuhl et al.

Garstang's Model

Garstang's sky brightness model is conceptually simple. Referring to FIG. 2, imagine a city **C** and a distant observer **O**. The sky glow as seen by the observer is due to light emitted by the city streetlights that is scattered by the air molecules and aerosols in the atmosphere along the path of the observerís view direction. At any point along this path, the light will be scattered from the volume **dV**. The sky glow as seen by observer **O** is simply the sum of the scattered light for all such volumes along the path due to all of the luminaires within the city **C**.

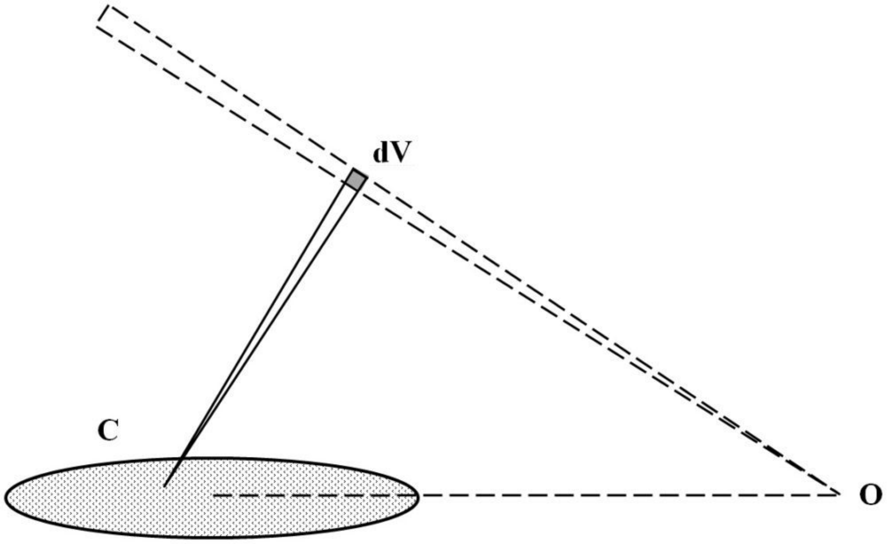


FIG. 2 – Garstang’s sky brightness model.

Understanding the mathematics of Garstang’s model requires a reasonably good understanding of atmospheric optics (e.g., Liou 2002). This topic will not be discussed here beyond presenting (without explanation) Garstang’s equation for sky brightness *B*:

$$\begin{aligned} b = \pi N_m \sigma_R \exp(-cH) \iint (dxdy/\pi R^2) \int_0^\infty du \\ \times I_{up}\, s^{-2} (EF)_{\mathrm{XQ}} (EF)_{\mathrm{QO}} (DS) \\ \times \{\exp(-ch) 3(1 + \cos^2[\theta + \phi])/(16\pi) \\ + \exp(-ah)\, 11.11\, Kf(\theta + \phi)\} \ . \end{aligned}$$

What is important for this discussion is that Garstang’s model assumes that the street lighting is monochromatic. He assumed a wavelength of 550 nm as being representative for visual astronomy. We can have confidence that Garstang’s sky brightness model is reasonably accurate, based on recently-published validation studies by, for example, Duriscoe et al. 2013. With cities ranging from Flagstaff, AZ to Las Vegas, NV however, it is simply not possible to measure the influence of correlated color temperature on light pollution.

Wavelength Dependencies

Light pollution is due to both Rayleigh scattering from air molecules and Mie scattering from aerosols such as dust, smoke, and haze. Rayleigh scattering is strongly wavelength-dependent, with a probability proportional to λ^{-4} , where λ is the wavelength. The sky is blue because of Rayleigh scattering. Mie scattering is wavelength-independent, which is why the clear sky appears pale blue or white in heavily-polluted urban areas. (As an aside, the average distance a photon of blue light will travel through the atmosphere at sea level before undergoing Rayleigh scattering — its *MEAN FREE PATH* — is about 50 km. By comparison, the mean free path for a photon of red light is about 200 km.)

Luginbuhl et al. (2014) used these relationships to extend Garstang's model for visible wavelengths between 400 nm and 700 nm in order to calculate FIG. 1:

$$\sigma_R(\lambda) = \sigma_R\left(\frac{550}{\lambda}\right)^4 \qquad \text{Rayleigh scattering}$$

$$\sigma_a(\lambda) = \sigma_a\left(\frac{550}{\lambda}\right) \qquad \text{Mie scattering}$$

While justifiable, this modification to Garstang's model is somewhat *AD HOC*. In particular, the original model is a gross simplification of an exceedingly complex physical situation. While it has been validated in terms of sky brightness, this says nothing about whether Luginbuhl's modifications result in similarly accurate solutions.

Radiative Flux Transfer

There have been more advanced light pollution models developed over the intervening thirty years, including Garstang 1991, Cinzano et al. 2000, Gillet et al. 2001, Aubé et al. 2005, Baddiley 2007, Kocifaj 2007, Luginbuhl et al. 2009, Kocifaj 2010, Kocifaj et al. 2010, Cizano and Falchi 2012, Kocifaj et al. 2014, Luginbuhl et al. 2014, and Aubé 2015.

Perhaps the most comprehensive light pollution model developed to date is *ILLUMINA*, an open source program that was described in Aubé et al. 2005, and which is still under development. Unlike Garstang's model (which was designed to execute on a 1980s-era Apple II computer), *ILLUMINA* is a voxel-based radiative flux transfer program that can require weeks of computer time on a supercomputer with several thousand CPUs and terabytes of RAM (Aubé 2015).

The situation is similar to weather prediction models, where a simple model will give you a rough idea of what is going to happen, but it requires a supercomputer to perform massive amounts of data processing in order to have full confidence in the predictions. Simply put, *ILLUMINA* models light pollution in a manner that would have been inconceivable thirty years ago.

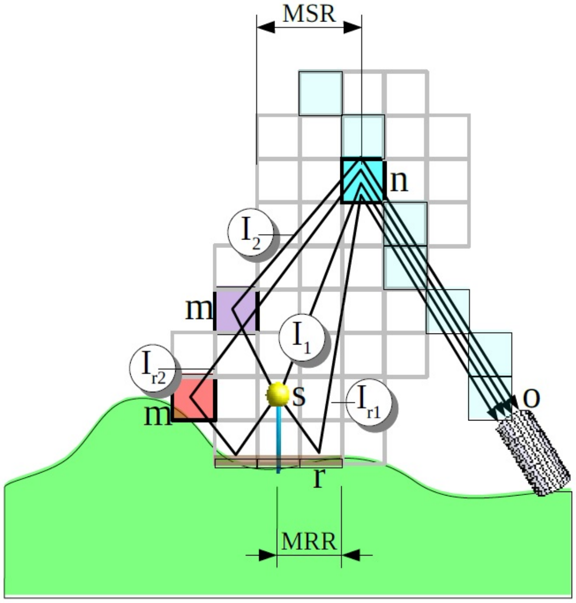


FIG. 3 – Illumina calculation model (Source: Illumina Web site).

Unlike Garstang's model, *ILLUMINA* explicitly considers diffuse reflections from the ground and in-scattering of scattered light from volumes **m** into the volumes **n** visible to the observer. Garstang's model includes an entirely *AD HOC* term for double scattering, but it is impossible to determine whether it correctly models the atmospheric optics.

The details of the program, however, are not as important for the purposes of this article as are the results recently reported by its author (Aubé 2015).

Modeling Sky Glow

What Aubé found with *ILLUMINA* is that the combination of Rayleigh and Mie scattering results in a wavelength dependency described by $\lambda^{-\alpha}$, where α varies from 3.6 to 2.7 as the distance from the city center increases (FIG. 4).

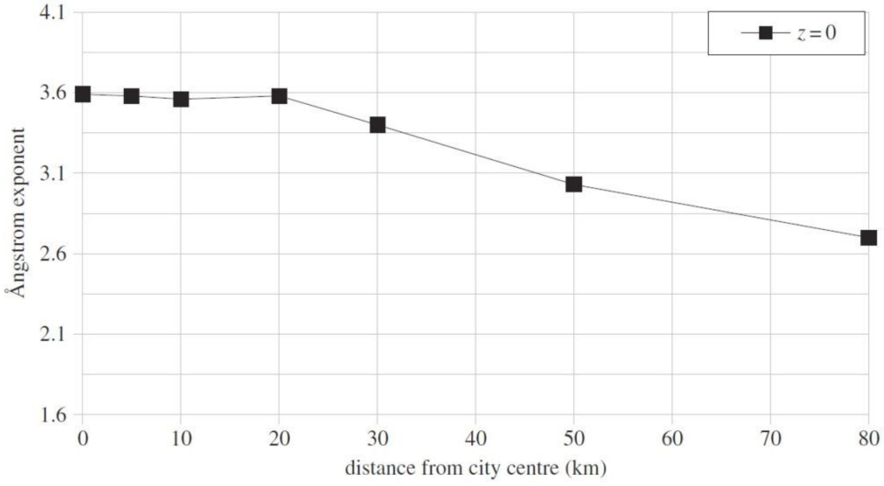


FIG. 4 – Wavelength-dependent scattering exponent (Source: Aubé 2015, Fig. 20).

What FIG. 4 shows is that near the city center, Rayleigh scattering dominates. This is to be expected, as Rayleigh scattering is not directional — the light is scattered equally in all directions, including back down towards the observer.

FIG. 4 also shows that away from the city center, Mie scattering begins to dominate. This is also to be expected, as Mie scattering is directional — the light is preferentially scattered in the forward direction. It is therefore more likely to be scattered to a remote observer as it travels horizontally through the atmosphere.

Sky Glow versus CCT

To apply Aubé's results to the question of the influence of CCT on sky glow, we first need some representative white light LED spectral power distributions. The following normalized SPDs were digitized from Philips Lumileds' *LUXEON REBEL* product catalog (FIG. 5):

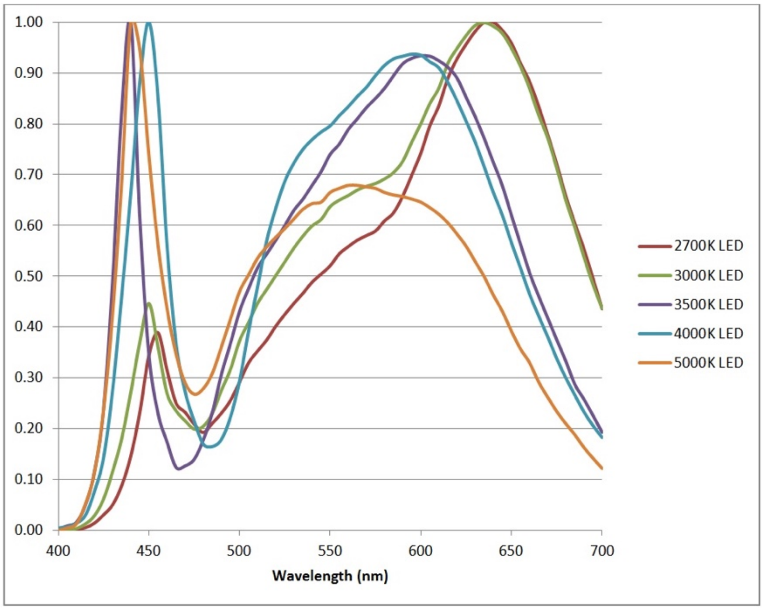


FIG. 5 – Typical LED spectral power distributions (normalized).

To provide a fair comparison, these SPDs need to be scaled such that the LEDs generate the same luminous intensity. To do this, we multiply the SPDs by the photopic luminous efficiency function at 5 nm intervals (FIG. 6):

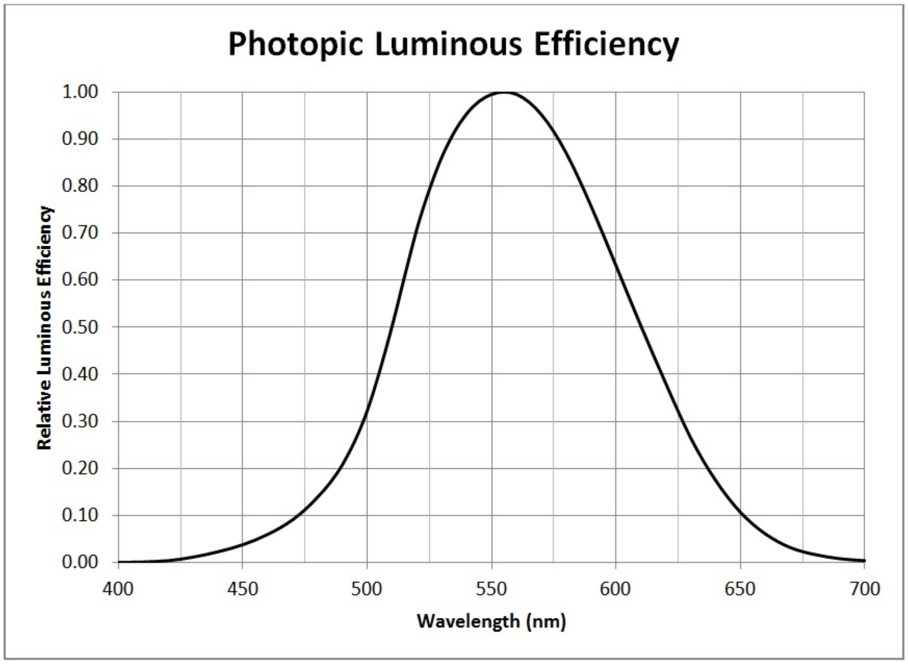


FIG. 6 – Photopic luminous efficiency function V(λ).

and then sum the results to obtain the relative photopic intensities:

CCT	Relative Luminous Intensity
2700K	0.88
3000K	1.00
3500K	1.12
4000K	1.17
5000K	0.94

Table 1

Dividing the normalized SPDs by these values gives:

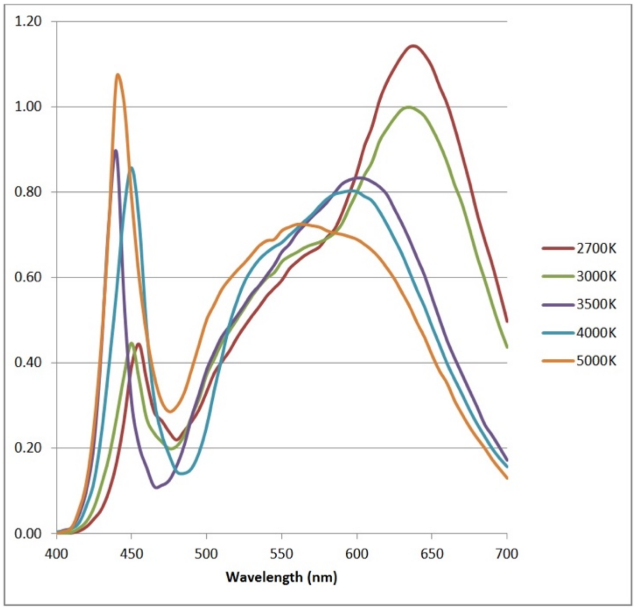


FIG. 7 – Typical LED spectral power distributions (constant luminous flux).

What FIG. 7 shows are the different spectral power distributions of the street lighting at city center for each CCT, assuming the same luminous flux output.

Now, using Aubé's results and assuming an observing site 80 km (50 miles) from the city center, we multiply each 5 nm interval by $(\lambda/550\ \mathrm{nm})^{-2.7}$ to represent the wavelength dependency (FIG. 8):

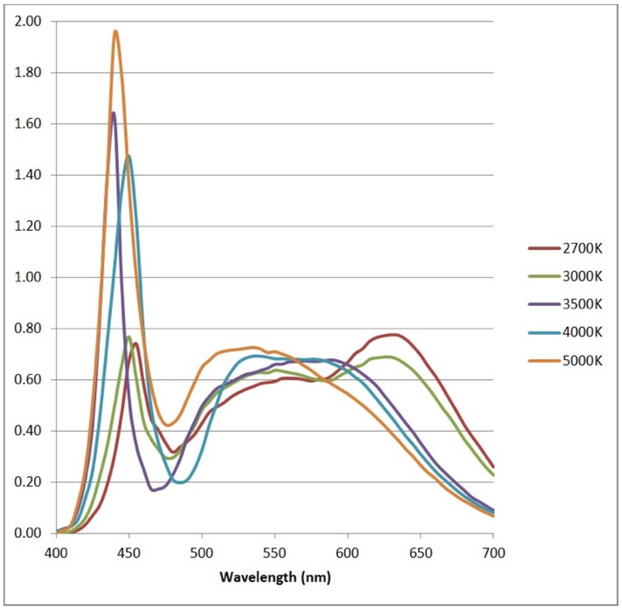


FIG. 8 – Overhead sky glow spectral power distribution at 80 km.

This is precisely what we might expect — blue light is preferentially scattered, bolstering our assumption that high-CCT lighting results in increased sky glow. (These SPDs represent the relative spectral radiance distribution at zenith from the observing site, which is perhaps the most useful definition of sky glow.)

If we assume scotopic (i.e., dark-adapted) visual observing conditions, we need to multiply these SPDs by the scotopic luminous efficiency function at 5 nm intervals (FIG. 9):

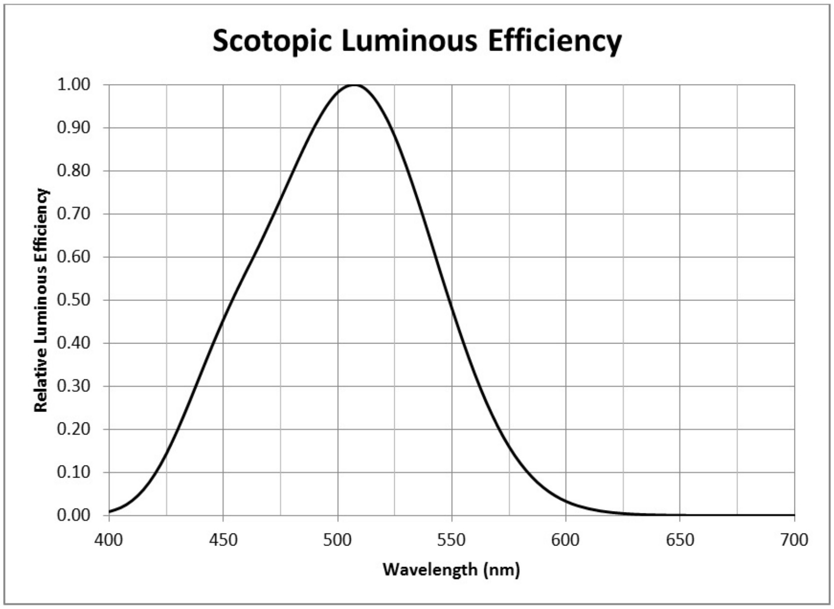


FIG. 9 – Scotopic luminous efficiency function.

and sum the results to obtain the relative scotopic zenith luminance. The results are shown in Table 2:

CCT	Relative Scotopic Luminance
2700K	0.96
3000K	1.00
3500K	1.04
4000K	1.12
5000K	1.42

Table 2 – Relative sky glow luminance at 80 km

This however is for a remote astronomical observing site, such as a dark-sky preserve. To understand what happens within the city center, we repeat the above procedure with α = 3.6 as per FIG. 4. Rayleigh scattering predominates, as shown by FIG. 10 with its greatly exaggerated blue peaks.

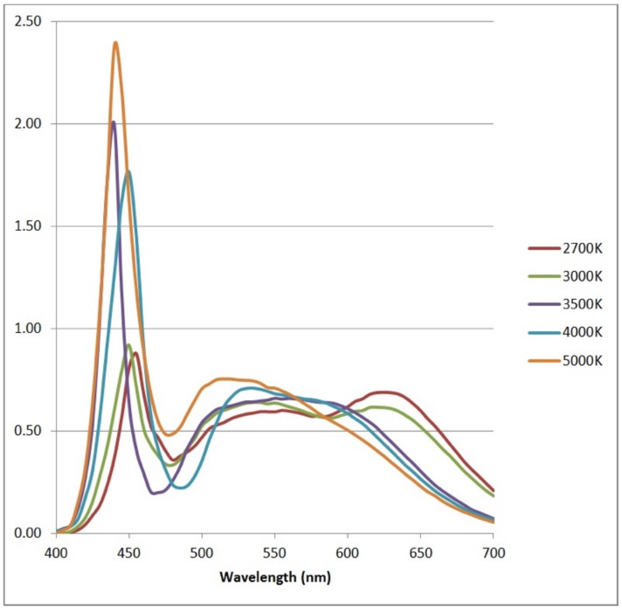


FIG. 10 – Overhead sky glow spectral power distribution at city center.

When we calculate the relative scotopic luminance of sky glow, however, we find almost identical results (Table 3).

CCT	Relative Scotopic Luminance
2700K	0.96
3000K	1.00
3500K	1.05
4000K	1.14
5000K	1.45

Table 3 – Relative sky glow luminance at city center

This assumes, however, that the observer is completely dark-adapted. In an urban setting, the surrounding street lighting will most likely result in only partial dark adaptation, and so mesopic vision will apply. This means a blending of the photopic and scotopic luminous efficiency functions (FIG. 6 and FIG. 9). With the photopic function being much less sensitive to 450 nm blue light, the differences in relative sky glow luminance at city center will be (depending on the visual adaptation field of the observer) somewhere between that of Table 3 and Table 4, which assumes photopic adaptation:

CCT	Relative Photopic Luminance
2700K	0.99
3000K	1.00
3500K	1.01
4000K	1.02
5000K	1.06

Table 4 – Relative sky glow luminance at city center (photopic adaptation)

Of course, with full photopic adaptation, the observer will not be able to see anything but the brightest stars and planets in the night sky, so it is best to rely on Table 3 for comparison purposes. Given the above, the answer to our question is yes, it is reasonable to trust Garstangís sky brightness model and its modification by Luginbuhl et al. Aubé's results, based on the much more comprehensive radiative flux transfer model used by *ILLUMINA*, basically confirms the relationship between CCT and sky brightness as calculated by Luginbuhl et al. (2014).

Astronomical Considerations

According to Table 2, the increase in scotopic sky brightness for 4000K LEDs compared to 3000K LEDs is only 12 percent. Our perception of brightness, following Steven's Power Law for extended light sources, means that we would see an increase in *PERCEIVED* sky brightness of only four percent! Surely this is not a reasonable justification for the IDA reducing the maximum allowable CCT from 4100K to 3000K for its Fixture Seal of Approval program?

Professional and amateur astrophotographers would vehemently disagree. Richard Wainscoat, Principal Investigator of the NASA-funded Pan-STARRS search for Near Earth Objects at the University of Hawaii, aptly called spectral power distributions of high-CCT LEDs such as that shown in FIG. 8 the "nightmare spectrum" (Betz 2015). Unfortunately, the peak 450 nm emission is right in the spectral region where natural airglow is low and there are important astronomical hydrogen and oxygen emission lines. Unlike the basically monochromatic emissions of low-pressure sodium lamps, it is impossible to filter out the blue LED emissions with band rejection filters. Limiting the CCT to 3000K reduces the contribution to light pollution in the blue region of the spectrum by a factor of two to three.

Allowing 4100K LEDs may be acceptable for casual stargazing, but not for astronomical research or astrophotography.

Ecological Considerations

According to the Fixture Seal of Approval requirements on the IDA Web site:

> *THE CASE AGAINST BLUE LIGHT IS WELL FOUNDED WITH REGARD TO DISCOMFORT GLARE, CIRCADIAN RHYTHM DISRUPTION, LIGHT SCATTERING, SKY GLOW, AND BIOLOGICAL SYSTEM DISRUPTION IN WILDLIFE.*

> *OUTDOOR LIGHTING WITH HIGH BLUE LIGHT CONTENT IS MORE LIKELY TO CONTRIBUTE TO LIGHT POLLUTION BECAUSE IT HAS A SIGNIFICANTLY LARGER GEOGRAPHIC REACH THAN LIGHTING WITH LESS BLUE LIGHT. IN NATURAL SETTINGS, BLUE LIGHT AT NIGHT HAS BEEN SHOWN TO ADVERSELY AFFECT WILDLIFE BEHAVIOR AND REPRODUCTION. THIS IS TRUE EVEN IN CITIES, WHICH ARE OFTEN STOPOVER POINTS FOR MIGRATORY SPECIES.*

The comment about cities is particularly germane in view of FIG. 10, where the light pollution in the blue region of the spectrum from 5000K LEDs is nearly three times that from 3000K LEDs. (To be fair however, this applies to clear skies only. For cloudy skies, Mie scattering from the water droplets dominates, and so the spectral power distribution of the reflected street lighting is essentially that of the lighting itself. On the other hand, much more light is reflected back towards the ground, greatly increasing light pollution.)

Summary

The purpose of this article was to examine the International Dark-Sky Association's requirement of LEDs with CCTs of 3000K or less for their Fixture Seal of Approval program. Using recent research results based on a comprehensive light pollution model (Aubé 2015), it was found that the concerns over high-CCT LEDS are well-founded. While 4000K LEDs may be acceptable for casual star-gazing, they are anathema for astronomers and wildlife.

In short, requiring LED street lighting with CCTs of 3000K or less is completely justifiable.

UPDATE 2015/10/12

The analysis presented above assumes a gray world with spectrally neutral reflectance. This is a reasonable assumption in that most roadway surfaces — concrete and asphalt — are not strongly colored. In other words, the light reflected from the ground will have approximately the same spectral power distribution as the incident light.

Suppose, however, that we have an outdoor sports arena with a grass field. The spectral reflectance distribution for Kentucky bluegrass (*Poa pratensis*) is shown in FIG. 11. The pronounced green peak is expected, given the grass-green color. What is more interesting, however, is the relatively low reflectance in the blue region of the visible spectrum.

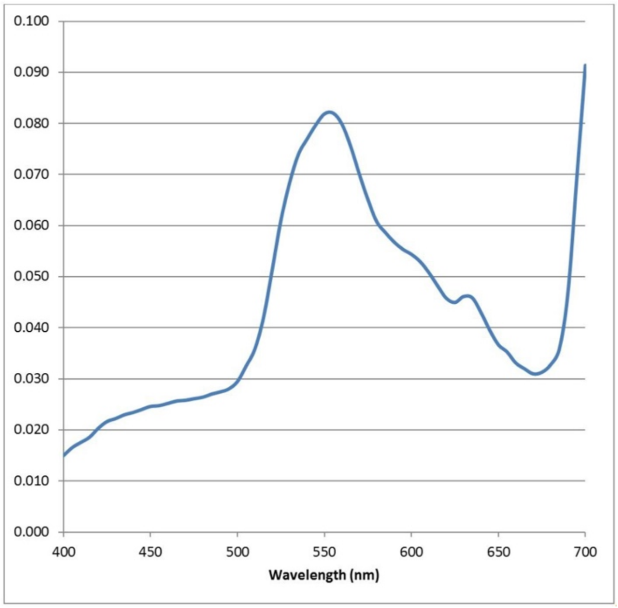


FIG. 11 – Kentucky bluegrass (Poa pratensis) spectral reflectance distribution.

If we multiply the typical LED spectral power distributions shown in FIG. 7 with the grass spectral reflectance distribution on a per-wavelength basis, the overhead sky glow spectral power distribution at 50 km from the city center becomes that shown in FIG. 12. The blue peaks are still present, but they have been reduced by a factor of four relative to the remainder of the spectral power distribution.

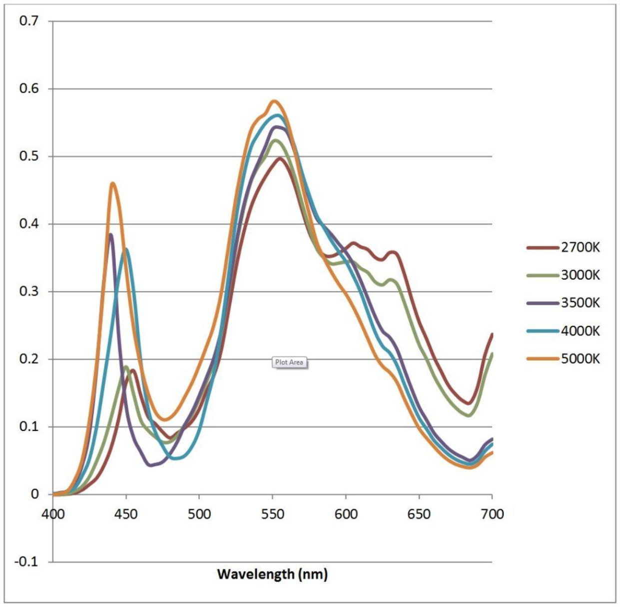


FIG. 12 – Overhead sky glow spectral power distribution at 50 km due to grass field.

The number of outdoor sports arenas may be relatively small, but they generate a surprising amount of light when they are illuminated at night. Using data from the U.S. Department of Energyís 2010 U.S.

Lighting Market Characterization report (DOE 2012), it can be estimated (with reasonable assumptions for typical lamp lumens) that the distribution of outdoor lighting in the United States is:

Outdoor Lighting	**Percent Lumens**
Roadway	48.2
Parking	34.0
Building Exterior	10.2
Stadium	6.0
Billboard	0.8
Traffic Signals	0.7
Airfield	0.1
Railway	0.0

Table 5 – Light pollution sources (approximate)

This is, of course, a global view — light pollution next to a large outdoor sports arena can be a significant concern for residential neighborhoods. The best that can be done is shield the luminaires appropriately, and to turn on the sports field lighting only when it is needed.

In terms of correlated color temperature, the Federation Internationale de Football Association (FIFA) specifies a minimum CCT of 4000K for football stadiums (FIFA 2007), while the National Football League (NFL) requires a CCT of 5600K (Lewis and Brill 2013). These are arguably acceptable in that green grass fields greatly alleviate the “nightmare spectrum” problem.

(Thanks to Brad Schlesselman of Musco Lighting for providing the grass spectral reflectance distribution and thereby inspiring this analysis.)

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