# ATLA®

## ALL THINGS LIGHTING® ASSOCIATION

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# ATLA®

ALL THINGS LIGHTING® ASSOCIATION

Contributor- Ian Ashdown, Senior Scientist

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# GENERAL INFORMATION

# MESOPIC PHOTOMETRY AND STATISTICS

## LIES, DAMNED LIES, AND STATISTICTS

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2014/04/21

One of the joys of statistics is that you can never be PROVEN wrong …

In a previous ALL THINGS LIGHTING article titled "Understanding Mesopic Photometry" (October 8th, 2013), I wrote:

"Some publications on mesopic lighting have indicated that the s/p ratio of a lamp can be estimated from its correlated color temperature (cct), but this is incorrect …"

I continued on with an example that compared the spectral power distributions and scotopic-to-photopic (S/P) ratios of a phosphor-coated white light LED:

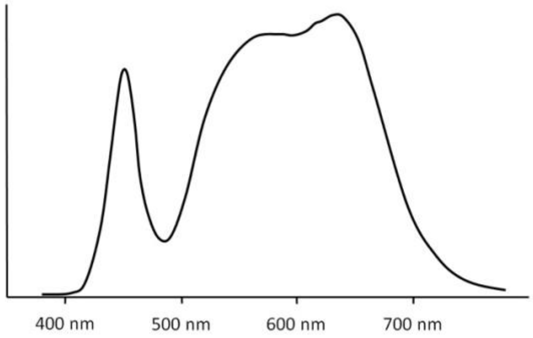

Fig. 1– Phosphor-coated LED module.

and a red-green-blue LED:

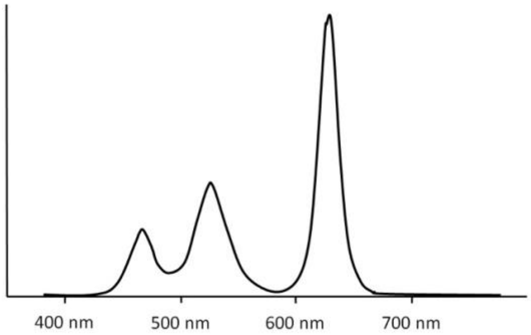

Fig. 2 – Red-green-blue LED module.

Both lamp modules had the same correlated color temperature (CCT) of 3500K, but their S/P ratios were 1.41 and 2.02 respectively. I concluded that:

> "Simply put, the only way to accurately determine the s/p ratio of a light source is through calculation using its spectral power distribution."

While this statement is technically correct, it is not particularly useful when you need to know the S/P ratio of a lamp or lamp module for mesopic roadway or area lighting calculations.

## Measurements and Equations

One of the publications I chose not to reference was the “City of San Jose Public Streetlight Design Guide” [Anon. 2011]. This report presented a list of eight light sources with their reported S/P ratios, which were derived from [CIE 2010] and [Berman 1992]:

| Source | S/P Ratio | CCT |
|---|---|---|
| Low pressure sodium | 0.25 | 1700 K |
| High pressure sodium | 0.65 | 2100 K |
| Warm white metal halide | 1.35 | 3500 K |
| Daylight metal halide | 2.45 | 5500 K |
| Warm white fluorescent | 1.00 | 3000 K |
| Cool white fluorescent | 1.46 | 3700 K |
| Triphosphor fluorescent | 1.54 | 4100 K |
| Daylight fluorescent | 2.22 | 7500 K |

Table 1 – S/P Ratio versus CCT [Anon. 2011]

This list is somewhat selective, as Berman reported the S/P ratio versus CCT of sixteen light sources:

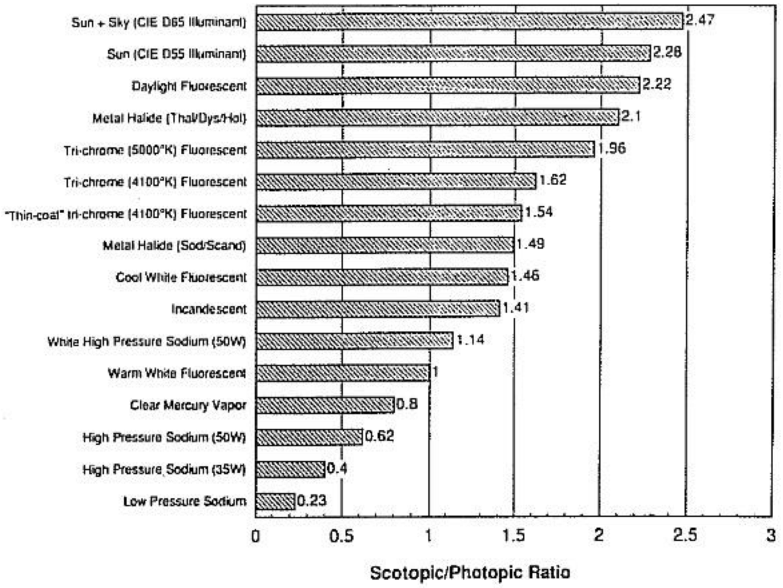

Fig. 3 – S/P Ratio versus CCT [Berman 1992].

The report noted:

> Although the s/p ratio is derived from the spectral power distribution of the light source, it approximately corresponds to the correlated color temperature of that source.

However, this was immediately followed by:

> To determine the s/p ratio for any given cct, the following equation can be used:
>
> S/P ratio = $-7 * 10^{-8} (CCT)^2 + 0.001 * CCT - 1.3152$

While I otherwise agree with the report, I must disagree with this statement. Of the tens of thousands of lamp types that are commercially available, you cannot fit a quadratic curve through a mere eight data points and generalize it to any light source. This is especially true when the light sources include the near-monochromatic spectral power distribution (SPD) of low-pressure sodium (LPS) lamps.

Worse, there is no indication of the expected error with this equation. You may calculate an S/P ratio for a given CCT, but you have no idea whether it is accurate. Is it for example 1.65, 1.6, or somewhere between 1.0 and 2.0?

### Statistics

Based on the work of [Berman 1992], it is evident that the S/P ratio of a white light source "approximately corresponds" to its CCT. However, the evidence in support of this conclusion is statistically weak, and further does not consider today's phosphor-coated white light LEDs.

What is needed is a random sampling of many commercial white light sources. Ideally, the work would be done by an independent photometric testing laboratory so as not to inadvertently skew the results towards the products of a single lamp manufacturer.

Having the results for many different light sources serves two purposes. First, it provides enough data points to have confidence that an equation fitted to the data fairly represents most commercial lamps and LED lamp modules.

Second, it provides the all-important confidence interval for any given S/P ratio. That is, given a calculated S/P ratio for a specific CCT, you can have (say) 95% confidence that the value is accurate to within a given range of values.

This is important because photometric measurements and calculations always include implicit confidence intervals. For example, electric lighting calculations are typically accurate to within ±10 percent when compared to careful in situ measurements of the completed project. It makes no sense therefore to perform (for example) mesopic roadway lighting calculations if your assumed S/P ratio varies by ±0.5.

### Recommendations

The good news is that we now have the necessary information. LightLab International Inc. (www.lightlabint.com) recently collated the results of some 90 tests of LED-based roadway and area lighting luminaires that they performed for their customers. In accordance with the requirements of LM-79 testing procedures [IESNA 2008], the test reports included spectral power distribution measurements, and with them (although not required by LM-79) calculated S/P ratios.

As you might expect, the lamp CCTs clustered around the industry-standard nominal values:

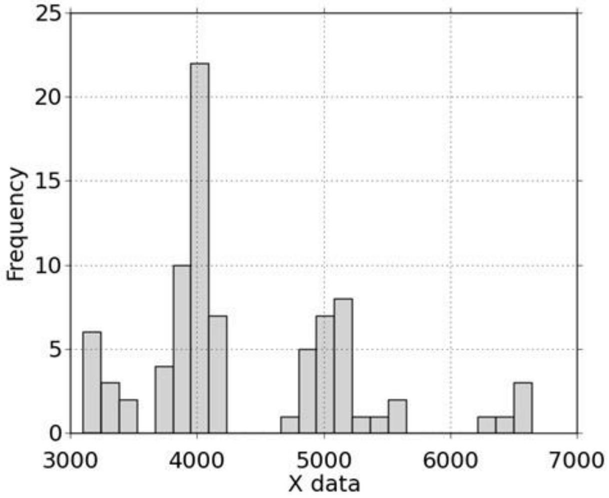

Fig. 4 – Lamp CCTs

Perhaps less expected is that they exhibited a reasonably linear relationship between S/P ratio and CCT:

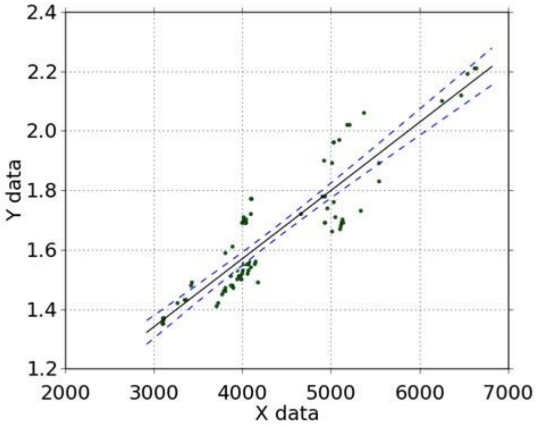

Fig. 5 – S/P ratio versus CCT.

I will not repeat the curve-fitting equation here, as it has a meaningless precision of 15 decimal points. What is important is this table of recommended values (where the 2700K values were extrapolated from the measured data):

| CCT | S/P Ratio Range |
|---|---|
| 2700 K | 1.1 – 1.4 |
| 3000 K | 1.2 – 1.5 |
| 3500 K | 1.3 – 1.6 |
| 4000 K | 1.4 – 1.8 |
| 5000 K | 1.6 – 2.0 |

Table 2 – S/P Ratio versus CCT for LED lamps

Note carefully that this table applies to LED-based white light sources only; it does not apply to fluorescent (including magnetic induction) or HID lamps, and certainly not to LPS lamps. (Metal halide lamps in particular as reported in Table 1 are outside of the range of this table.)

Looking at Figure 1, it is perhaps not surprising that LED lamps exhibit a strong correlation between S/P ratio and CCT. Virtually all of today's high-flux LEDs for roadway lighting applications rely on a blue pump LED (which accounts for the 450 nm peak in Figure 1) and broadband emission phosphors between 500 and 700 nm. With minor differences due to different phosphor combinations, most white light LED SPDs will look something like Figure 1, with the CCT mostly determined by the ratio of the blue peak to the phosphor emissions.

The counterexample of course is the red-green-blue LED SPD shown in Figure 2, with its anomalous S/P ratio of 2.02 for a CCT of 3500K. It is not coincidental that the SPD somewhat resembles that of a triphosphor fluorescent or metal halide lamp.

Ideally, we would have S/P ratio versus CCT data for thousands of white light sources. It is unlikely that the recommended S/P values above would change by more than 0.1 units, but it would improve our statistical confidence in the results.

On the other hand, these results show that the S/P ratio varies by ±0.2 for any given CCT, or about ±10 percent of the median value. This is commensurate with the expected accuracy of most electric lighting applications.

Granted, it would be preferable to have S/P ratios available for every lighting product. (S/P ratios are also integral to IES TM-24-13, Incorporating Spectral Power Distribution into the IES Illuminance Determination System for Visual Task Categories P through Y [IESNA 2013].) As was explained in Understanding Mesopic Photometry however, there are practical reasons why this is unlikely to occur.

In retrospect, this likely does not matter. Lighting designers can rarely assume the use of particular product when performing photometric calculations. With competitive bidding for commercial and government projects, it is best to simply specify luminaires with a given CCT. Given that most new roadway and area lighting installations will involve LED-based luminaires, Table 2 provides lighting designers with the confidence that they can assume a usefully narrow range of S/P ratios for design and specification purposes.

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## Acknowledgements

Thanks to Eric Southgate of LightLab International Inc. (www.lightlabint.com) for sharing the S/P versus CCT data on which this article was based.

Thanks also to Dawn DeGrazio of Lighting Analysts Inc. for invaluable editorial assistance.

# SOLID ANGLES

## TRULY UNDERSTANDING LUMINOUS INTENSITY

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published 2014/07/26

Do you suffer from math anxiety? A surprising number of us do (e.g., Wigfield 1988). I would tell you the exact numbers, but you would need to understand statistical analysis …

Fortunately, we can mostly muddle through our lives without having to deal with statistics, vector calculus, differential geometry, algebraic topology and all that. As an electrical engineer in the 1980s for example, I never needed anything more than a four-function calculator to do my work designing billion-dollar transportation systems.

Our fear (note the implicit “we”) can, however, disadvantage us in subtle ways. In studiously ignoring the mathematics of a topic, we all too often overlook the underlying concepts that help us better understand what we are interested in.

An example from lighting design: *luminous intensity*. We measure the luminous intensity of a light source in *candela*, which is defined as “one lumen per steradian” (IES 2010). A lumen is easy enough to understand, but what the blazes is a “steradian”?

The all-knowing Wikipedia has an answer: it is the measure of a “solid angle.” Going to the Wikipedia definition of this phrase, we see:

$$\Omega = \iint_S \frac{\overrightarrow{r \cdot \hat{n} dS}}{r^3} sr = \iint_S \sin\theta \, d\theta d\varphi$$

**Anxiety? What anxiety?**

But now for a trade secret: most mathematicians do not think in terms of equations like these double integrals. Instead, they *visualize*. Just as lighting designers can look at architectural drawings and imagine lighting designs, mathematicians can look at a set of equations — which are really nothing more than an arcane written language — and visualize new mathematical concepts and proofs.

I learned this from a professor of mine whose specialty was hyperspace geometry — he could “easily imagine” four- and five-dimensional objects by mentally projecting them into three-dimensional shapes and imagining how their shadows changed as he rotated the objects in his mind. Some people …

So, we start by visualizing a circle (FIG. 1):

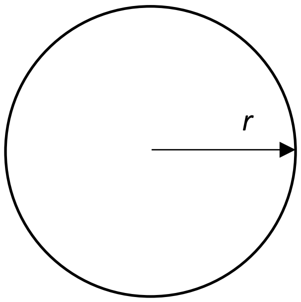

FIG. 1 – Circle with radius *r*.

If you remember anything at all from mathematics in school, it is that the circumference $C$ of a circle with radius $r$ is equal to two times $pi$ times its radius, or:

$$C = 2 * \pi * r$$

where $pi$ is approximately 3.14159. (Remember that 1980s-era four-function calculator – it is all you will need for this.)

What this means is that if we take a piece of string with length $R$, we will need to stretch it by a factor of two $pi$ (6.28328 …) to wrap around the circumference of the circle.

But suppose we wrap the string with length $r$ part way around the circle (FIG. 2). The resultant angle is precisely one *radian*, which is abbreviated *rad*.

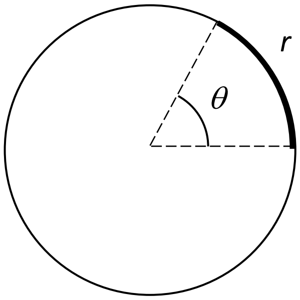

FIG. 2 – One radian.

Most of us are used to thinking of angles in terms of degrees ñ there are 360 degrees in a circle. (The reason for the magic number 360 is lost in history, according to Wikipedia.) This means that one radian is equal to 360 / (2 * π) = 180 / π degrees, which is approximately 57.3 degrees. Radians are more useful simply because they are related to the geometry of the circle rather than some magic number — they are easier to visualize and so understand.

Now, imagine a sphere with radius $r$, and with a cone-shaped section whose base has a surface area of $r * r$, or $r^2$ (FIG. 3):

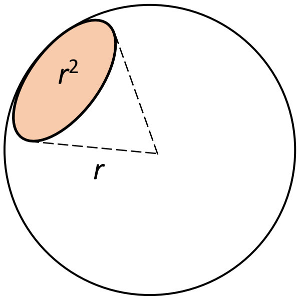

FIG. 3 – Solid angle.

This cone has a *solid angle* of precisely one *steradian* (or one “solid radian”), which is abbreviated *sr*.

No mathematics required — easy.

(To be precise, a solid angle does not need to be a circular cone-shaped section as shown in FIG. 3. The top of the cone can be any shape; all that matters is the ratio of the surface area of the base to the radius $r$.)

How many "square degrees" in a steradian? That's also easy: if one radian is equal to 180 / $\pi$ degrees, then one steradian is equal to (180 / $\pi$) * (180 / $\pi$), or approximately 3282.8, square degrees.

To be honest, I also suffer from math anxiety when first reading a set of equations. I do not really understand them until I can visualize what they mean. Mathematical equations are just the formal written language we use to express what we have visualized.

… now if only I could understand batting averages in baseball and cricket …

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# IN SEARCH OF LUMINANCE

## UNDERSTANDING WHAT WE SEE

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd.  Published: 2014/11/18

The IES Lighting Handbook, Tenth Edition (IES 2010), describes luminance as “perhaps the most important quantity in lighting design and illuminating engineering.” This is an accurate but curious description, as the editors neglected to include an entry for Section 5.7.3, Luminance, in the handbook’s index.

The section itself is a mere five paragraphs long, informing the curious reader that luminance is the “local surface density of light emitting power in a particular direction,” defined mathematically as:

$$L(\theta, \psi) = \frac{d^2\Phi}{d\omega dA \cos\theta}$$

which for most readers will be completely and absolutely … opaque.

This is unfortunate, as luminance is undeniably the most important quantity, and indeed the most fundamental concept, in lighting design and illuminating engineering. More than a mathematical definition, professional lighting designers need to understand what it is that we see.

### Luminance Understood

To understand luminance, we begin with a parallel beam of light. Ignore any thoughts of surfaces or light sources; just imagine a beam of light traveling through empty space in a given direction. Imagine also that this beam has a finite width; say, a rectangular beam one meter on a side.

If we take a cross-section of this beam at any point along its length, we can measure so many lumens of light (i.e., photons per second) per unit area. In photometric terms, this is the luminous flux $\Phi$ per unit area, or luminous flux density, of the beam. Being parallel, the beam does not diverge or converge, and so the luminous flux density remains constant along the length of the beam.

Now, what happens if the beam illuminates a real or imaginary surface at an angle? We have this:

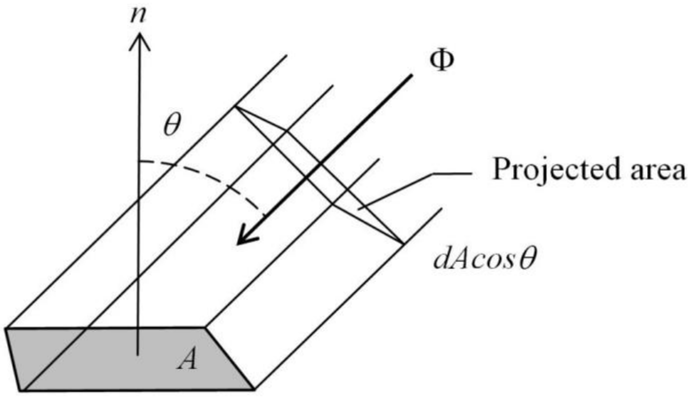

FIG. 1 – Illuminance of a surface *A*.

The luminous flux per unit area received by the surface $A$ is determined by the cosine of the angle of incidence $\theta$ from the surface normal $n$. Conceptually, as the angle of incidence becomes greater (i.e., more oblique), the illuminance $E$ (lumens per unit area) of the surface decreases. The expression $A \cos \theta$ represents the projected area of the illuminated surface, and is equal to the cross-sectional area of the beam.

This is nothing more than Lambert's Cosine Law (Lambert 1760):

$$E = \frac{\Phi}{A \cos \theta}$$

If we imagine the area $A$ as being infinitesimally small, we can designate it as $dA$ (for "differential area"). Similarly, the amount of luminous flux $\Phi$ within the infinitesimally narrow beam approaches zero, and so we designate it as $d\Phi$. This gives us:

$$E = \frac{d\Phi}{dA \cos \theta}$$

This is basic high school algebra! Ignore the symbols and concentrate on the underlying physical concept.

We can further imagine the beam not as a parallel beam that is infinitesimally narrow, but as an elemental cone whose infinitesimal solid angle we designate as dω. (See the previous article Solid Angles for an explanation of this concept.)

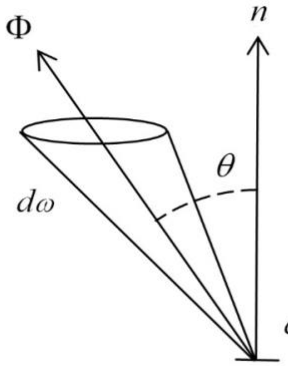

FIG. 2 – Luminance of a differential surface *dA*.

With this, we have the conceptual framework to understand the formal definition of luminance:

$$L(\theta, \psi) = \frac{dE}{d\omega} = \frac{d^2\Phi}{d\omega dA \cos \theta}$$

where the factor $d^2\Phi$ does not mean that the symbol $d$ is being squared. Rather, it simply means that the luminous flux $d\Phi$ is being divided by the solid angle of the elemental cone $d\omega$ and the area $dA$. Further, the parameter $\psi$ indicates that the luminance may also vary when the beam is rotated horizontally by angle $\psi$ around the surface normal $n$.

What this equation is saying is that the luminance $L$ of the surface $dA$ is equal to the amount of luminous flux $\Phi$ (lumens) leaving $dA$ in the direction $\theta$ and contained within the elemental cone (i.e., parallel beam) $d\omega$. This is equivalent to the IES Lighting Handbook description of "local surface density of light emitting power in a particular direction."

There is an important but underappreciated corollary to this definition of luminance. Recalling that the surface can be real or imaginary, we can imagine placing an imaginary surface that is perpendicular to the beam direction (i.e., $\theta$ is equal to zero) anywhere along its length. What this means is that the luminance of a parallel beam of light is constant along its length. In other words, luminance is not an intrinsic property of the surface, but of the beam itself. (As an example, the sky has a measurable luminance when viewed from the ground, but it has no real surface.)

Dispensing with the mathematics, we can therefore say:

Luminance is the amount of luminous flux per unit area as measured in a parallel beam of light in a given direction.

Photometry is traditionally taught using the concept that luminance is a property of real or imaginary surfaces. The problem with this approach is that you cannot easily explain why participating media such as the atmosphere, smoke, fog, colloidal suspensions in water, and so forth have measurable luminance. Thinking of luminance as a property of a beam of light rather than of surfaces eliminates this difficulty.

## Luminance Perceived

How do we perceive luminance? Imagine that you are looking at a blank sheet of matte white paper. Being an approximately ideal diffuser (except at very oblique angles), this paper will scatter incident light equally in all directions.

Now, imagine that each point of the paper's surface is a point source of light. In accordance with the inverse square law, the luminous flux density of this light will decrease with the square of the distance from the point source. That is:

$$E = \frac{I}{d^2}$$

where $I$ is the intensity of the point source, $d$ is the distance from the source, and $E$ is the illuminance of a surface (such as the cornea of your eye) at that distance … so why do we see and measure the luminance of the paper as being constant with distance?

To answer this, we need to look at the eye itself, which basically consists of a lens that focuses images onto the cones and rods of the retina. Each cone and rod has a finite width, and so it receives light from a finite area of the surface of the paper.

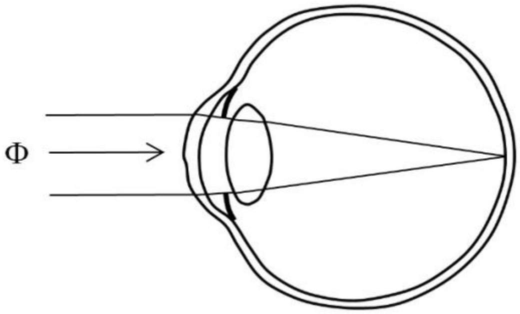

FIG. 3 – Eye focusing a parallel beam onto the retina.

But wait! This area of the paper is dependent on the distance of the paper from the eye. Moreover, it is proportional to the square of the distance … which exactly cancels out the inverse square law for a single point source. Therefore, we perceive the luminance of a finite area surface as being constant regardless of its distance from the eye.

There is a counterexample that emphasizes this point: the night sky. Even though the actual diameter of a star may be a million miles or so, it is so far away that we perceive its light as a parallel beam that is focused onto a single rod or cone of our retina. The luminance of this beam is constant, and so we see the star as having a specific perceived brightness (or visual magnitude). The inverse square law still applies to the starís emitted light, however ñ it is after all a point source ñ and so its magnitude depends on its distance from the Earth. All other things being equal, more distant stars are inherently fainter.

How the eye sees a parallel beam of light, however, is the key point: wherever we look, we see luminance. We do not see luminous intensity or illuminance; we see the luminance of beams of light. Luminance really is the fundamental concept of lighting design.

## Conclusion

A famous 20th-century physicist (whose name I regrettably cannot recall, even with Google's assistance) once observed that until you can visualize a problem, you cannot truly understand the mathematics that describe it. He was likely referring to quantum mechanics, which nobody yet fully understands, but the observation still applies. In particular, knowing the mathematical definition of luminance is not enough; we must understand the concept of luminance. With this understanding, we can better understand its importance to lighting design and illumination engineering.

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# ARCHITECTURAL INFORMATION

# THOUGHTS ON COLOR RENDERING

## QUANTIFYING COLOR

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2014/01/05

UPDATE 14/10/06 – LightingEurope, the "Voice of the Lighting Industry," has just published their LightingEurope Position Paper on Color Quality. To summarize:

1. LightingEurope supports to continue the use of the existing Color Fidelity metric CRI including eight reference colors.
2. LightingEurope supports to keep legal minimum requirements on CRI on the current level as defined in the EU Eco-design Regulation.

Lamp with a CRI of 90 or above, good. Lamp with a CRI of less than 80, bad. Is there anything else that lighting designers need to know about the Color Rendering Index (CRI) metric?

To be brutally honest … no. Despite all that has been written on the topic over the past decade, the importance of CRI to everyday lighting design today is minimal at best.

What is (or perhaps was) important is the history of color rendering metrics and the influence they had on fluorescent and LED lamp design. We can mostly ignore the issues of color rendering today precisely because of the CRI metric.

If you want to make senior citizens shudder, ask them what it was like to work in an office in the 1950s with fluorescent lighting. The linear fluorescent lamps of the time used calcium halophosphate phosphors that had a well-deserved reputation for making skin tones appear a sickly gray-green. Brightly-colored fabrics also looked disagreeably different from being viewed under daylight or incandescent lighting conditions.

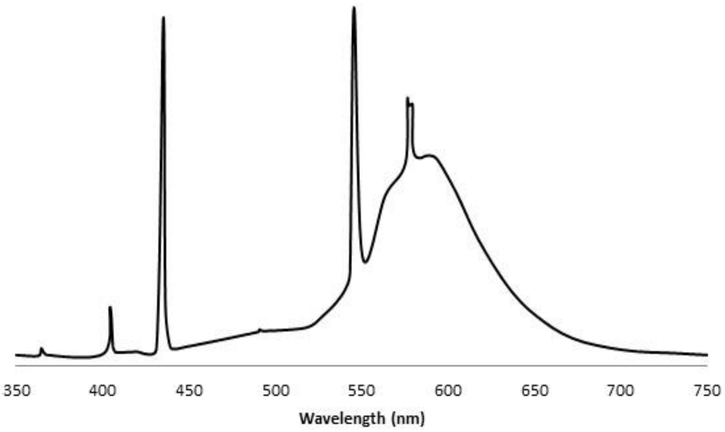

FIG. 1 – Halophosphate lamp spectrum.

Fluorescent lamp manufacturers could address this problem by varying the phosphor composition of their lamps. However, phosphors are expensive, and it is always difficult to convince consumers to pay more for products on the promise that they will “look better.” What was needed was an industry-standard metric.

Beginning in 1948, the Commission Internationale de l’Eclairage (CIE) began the quarter-century process of developing what is now the CIE General Colour Rendering Index, commonly referred to as the CRI metric (CIE 1995). The first version was published in 1965, and it was revised in 1974 to include the psychophysiological effects of chromatic adaptation.

An excellent description of the metric is available from Wikipedia (“color rendering index”), so there is no reason to repeat it here. All that needs to be said is its definition:

> *Color rendering: effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant.*

and a reminder that the two illuminants (i.e., light sources) must have the same correlated color temperature (CCT).

This metric worked reasonably well for ranking linear fluorescent lamps from the era. Quartz halogen lamps had CRIs of nearly 100, while warm white fluorescent lamps typically had CRIs between 50 and 60. These lamps were particularly deficient in the red region of the spectrum (see Fig. 1), with warm white lamps having CRI $R_9$ values as low as -111. (No, that is not a misprint; CRI values for specific test colors can be negative.)

Fluorescent lamp manufacturers could increase the red emission by mixing strontium and calcium halophosphates to create so-called “deluxe” phosphors. Lamps using these phosphors could achieve CRIs of approximately 90, but at the cost of roughly a one-third decrease in luminous efficacy (lumens output per electrical watt input).

This situation changed in the 1970s with two important discoveries:

1. Lamps with improved luminous efficacy and very good color rendering properties could *theoretically* be achieved with three narrow-band (red, green and blue) lamp spectra (Thornton 1971); and
2. The development of rare-earth phosphors for Thornton’s “triphosphor” lamps with CRIs of approximately 85 (Verstegen et al. 1974).

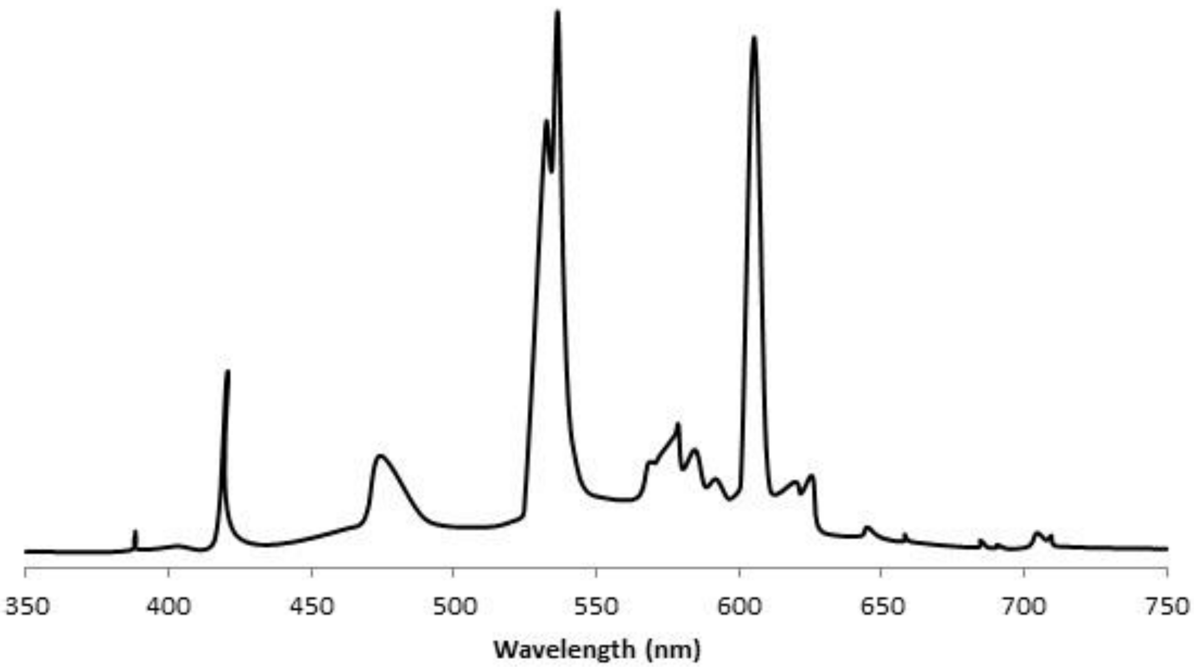

FIG. 2 – Rare-earth triphosphor lamp spectrum.

By themselves, these two discoveries may or may not have had a significant impact on the manufacture of fluorescent lamps. Looking back, the lighting industry at the time had little to no interest in color rendering issues.

What the lamp manufacturers did have however was a metric to compare products with, and with this the opportunity for an effective marketing campaign. As a result, the otherwise-obscure CRI metric appeared in every manufacturer's catalogs and sales literature, and it sold lamps.

With CRIs in the range of 85, triphosphor lamps have very good but not excellent color rendering properties. Lamp manufacturers therefore developed so-called "broadband" phosphors with four or five emission bands. With these, CRIs of 90 or so could be achieved.

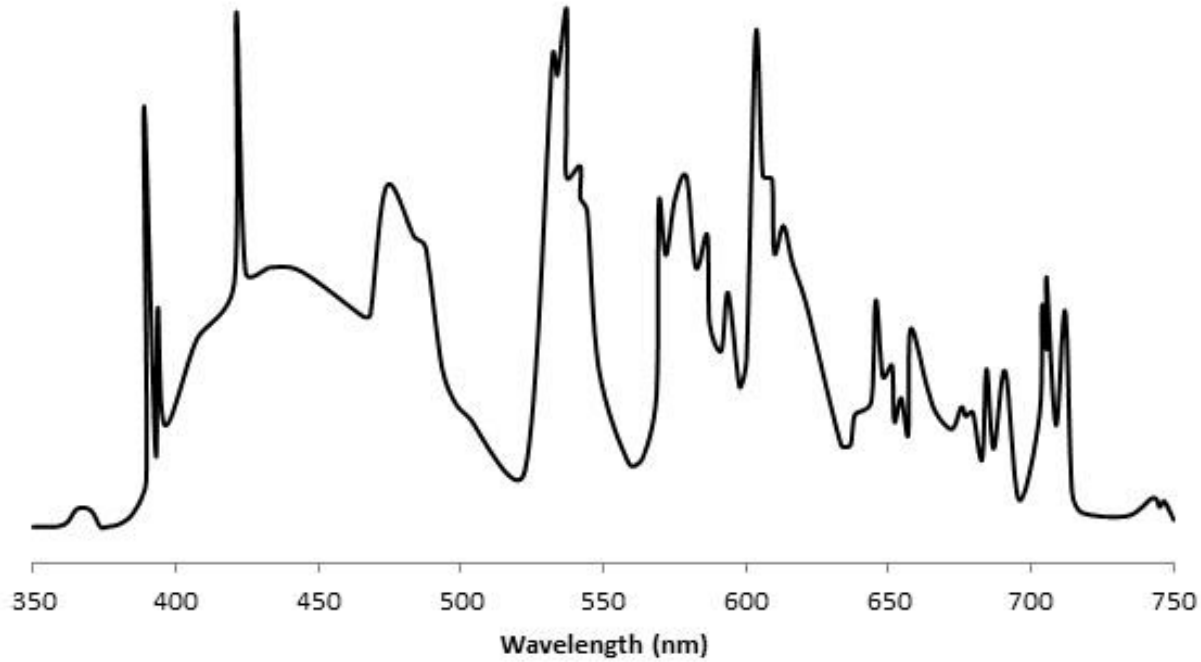

FIG. 3 – Rare-earth broadband lamp spectrum.

Marketing aside, did this really matter? For most commercial applications, the answer was probably no. In 1986, the CIE GUIDE ON INDOOR LIGHTING (CIE 1986) offered this helpful table:

| CRI $R_a$ | Examples of Usage |
|---|---|
| > 90 | Color matching, art galleries |
| 80 – 90 | Homes, restaurants, textile industry |
| 60 – 80 | Offices, schools, light industry |
| 40 – 60 | Heavy industry |
| 20 – 40 | Outdoors |

Table 1 – CRI examples of usage.

True, this list was likely influenced by the availability of halophosphate fluorescent lamps for indoor use, clear mercury vapor HID lamps for high-bay factory luminaires, and low-pressure sodium (LPS) lamps for roadway and area lighting. Still, it indicated how the CIE viewed its own metric at the time. CRI values were meant to be used as design guides rather than as precise numbers.

More tellingly, van Trigt (1999) presented a scholarly review of the CRI metric, in which he stated that “only a difference of some five points in the index is considered meaningful.”

The problem is that while the CRI metric $R_a$ can be calculated from the measured lamp spectral power distribution (SPD) with arbitrary precision, it is nevertheless based on a mathematical model (the von Kries transformation) of psychophysiological behavior. Given this, it makes sense that the difference between CRI values of for example 88 and 90 is essentially meaningless.

In a sense, the CRI metric has served its purpose in promoting the development and commercialization of rare-earth lamp phosphors. With fluorescent lamp CRIs typically being in the range of 85 to 95 these days, lighting designers and consumers have little need to know anything other than “90 and above good, less than 80 bad.”

But then along came solid-state lighting …

The first commercially-produced SSL luminaire designed expressly for architectural applications was the TIR Systems LEXEL, introduced at LightFair in April 2005 (Whitaker 2005). Based on a red-green-blue, high-flux LED die design, it generated white light whose color temperature could be varied from 3000 to 6500 kelvins.

Compared to the cool white LEDs with YAG phosphors and CRIs of approximately 75 available at the time, the white light produced by the LEXEL was widely acclaimed by the trade show attendees, particularly for its color rendering properties.

FIG. 4 – LightFair 2005 – TIR Systems Lexel™

What the attendees did not know was that (ahem) the CRI $R_a$ value varied from 25 at 3000K to 40 at 6500K (Speier and Salsbury 2006). By the standards of CIE 29.2, this was barely good enough for outdoor lighting only, along with clear MV and LPS lamps.

This seems odd, particularly when you compare the RGB LED lamp spectrum (FIG. 4) with that of a typical rare-earth triphosphor fluorescent lamp spectrum (FIG. 2). Based on this, you might guess that the CRI should be 85 to 90, not 25 to 40.

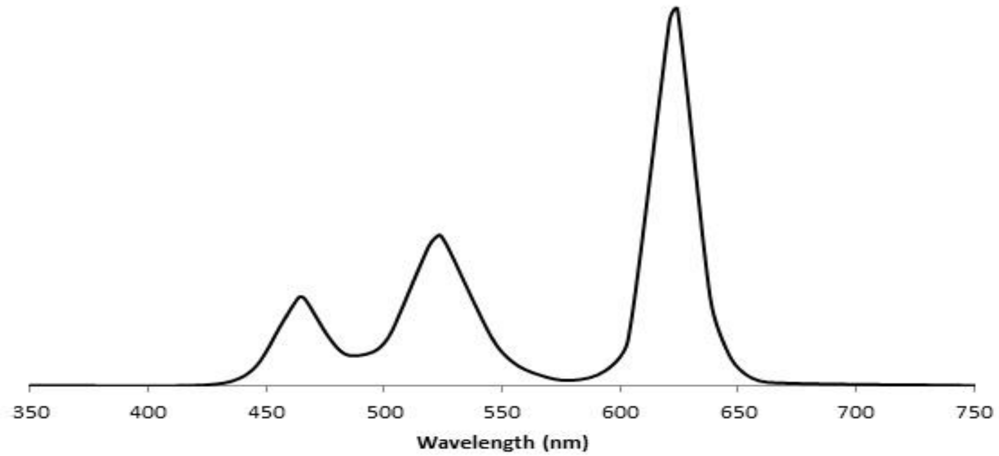

FIG. 5 – RGB LED lamp module spectrum.

The answer lies in the dominant wavelengths of the emission peaks. Thornton (1974) calculated that the ideal dominant wavelengths (what he called "prime colors") for triphosphor lamps were 450 nm (blue), 545 nm (green), and 610 nm (red). The dominant wavelengths of the LEXEL — and indeed most color-changing RGB LED luminaires on the market today — were 465 nm, 525 nm, and 615 nm. If you were to change the green wavelength from 525 nm to 545 nm, the CRI would be 85 or so.

Unfortunately, the maximum dominant wavelength of reasonably efficient green InGaN LEDs is approximately 530 nm. The white light produced by color-changing RGB LED luminaires looks wonderful, but it is doomed have unacceptably low CRI values.

If anything, this is an example of the abject failure of the CRI metric to predict the color rendering properties of RGB LED luminaires. CIE Technical Committee 1-62 acknowledged this problem (CIE 2007), and recommended the development of a new and improved color rendering metric for all white light sources.

CIE Technical Committee 1-69 was therefore established in 2008 to "investigate new methods for assessing the colour rendition properties of white-light sources used for illumination, including solid-state light sources, with the goal of recommending new assessment procedures." The committee investigated over a dozen proposals, but could only agree to bitterly disagree on any new metrics. As of this writing, the committee has yet to release its final report.

In response, the CIE recently established two new committees to further study the issue:

> TC 1-90: Colour Fidelity Index. To evaluate available indices based on colour fidelity for assessing the colour quality of white- light sources with a goal of recommending a single colour fidelity index for industrial use.
>
> TC 1-91: New Methods for Evaluating the Colour Quality of White-Light Sources. To evaluate available new methods for evaluating the colour quality of white-light sources with a goal of recommending methods for industrial use.

with reports due no earlier than 2015.

Despite numerous calls from the lighting industry for some clarity on color rendering metrics (e.g., Whitaker 2010, Colombo 2013), it is unlikely that the CIE will respond for at least a few more years. Again however, does any of this really matter? The solid-state lighting industry effectively gave up waiting a number of years ago and began using CIE Special Colour Rendering Index $R_9$ in addition to $R_a$ to quantify the color rendering properties of white light sources (including both semiconductor and organic LEDs) for saturated red colors. While this combination of $R_a$ and $R_9$ is not a perfect solution, it is nonetheless a recognized industry standard, and it generally works (especially for marketing literature).

More to the point however is that the solid-state lighting industry has, like the fluorescent lamp industry before it, mostly outgrown the need for color rendering metrics. As long as the lamp module CRI is 80 or above — which is the case for most commercial products these days — there is little need to worry about CRI except for applications requiring critical color judgment.

With this, it is interesting to look at another industry that relies on the CRI metric: architectural glass. If you think about it, daylight illuminating interior spaces is spectrally filtered by glass windows and curtain walls. What is the CRI of daylight inside the building? If it is less than 80, it is in danger of being banned altogether by the US Environmental Protection Agency in accordance with the minimum CRI requirements of its ENERGY STAR program (EPA 2013). (Just kidding … I think.)

It may surprise lighting designers to know that there is a European standard (BSI 2011) that specifies the calculation of indoor daylight CRI values, assuming a 6500 K daylight (CIE $D_{65}$) illuminant. Architectural glass manufacturers publish CRI values for different thicknesses of their glass and window assemblies, and it can be calculated using the International Glazing Database (windowoptics.lbl.gov/data/igdb) and the freeware Optics 6 program from LBNL (windows.lbl.gov/software/Optics/optics.html).

You might think that bronze glass for example would significantly affect the color of indoor daylight, but this is not the case. Taking one manufacturer (Pilkington Glass) as an example, most of their products have CRIs in the mid-90s, with the lowest ($R_a$ of 77) being for their Solar-E Arctic Blue low-emissivity glass with a blue body tint.

More interesting perhaps is that most architectural glass products have similar spectral transmittance spectra (Gombos et al. 2008). They are so similar in fact that the CIE has defined two "indoor daylight illuminants" ($ID_{50}$ and $ID_{65}$) that correspond to CIE daylight illuminants $D_{50}$ and $D_{65}$ as seen through generic architectural glass (CIE 2009).

As you might expect from architectural glass, the slight greenish tint is due to absorption of red light. This increases the effective color temperature of the incident $D_{50}$ and $D_{65}$ daylight to 5100 and 6600 kelvins, respectively.

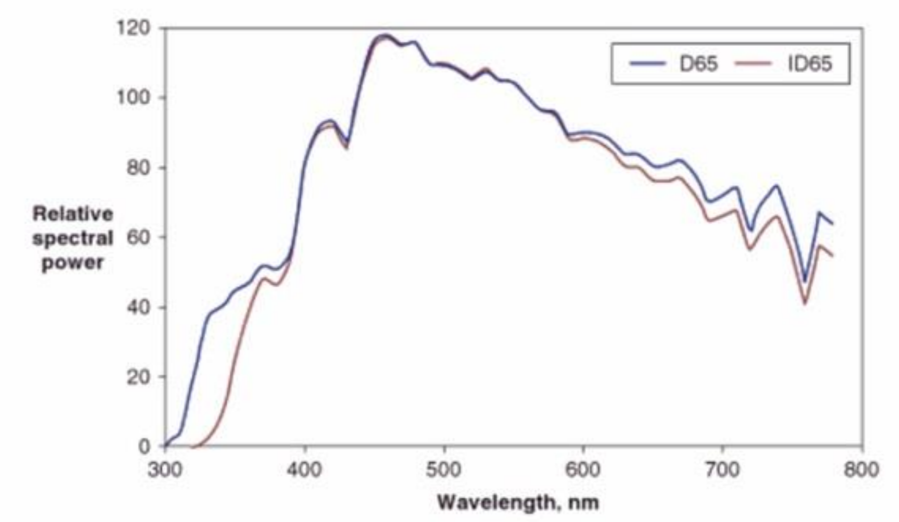

FIG. 5 – Indoor Daylight ID50 spectrum (5100K).

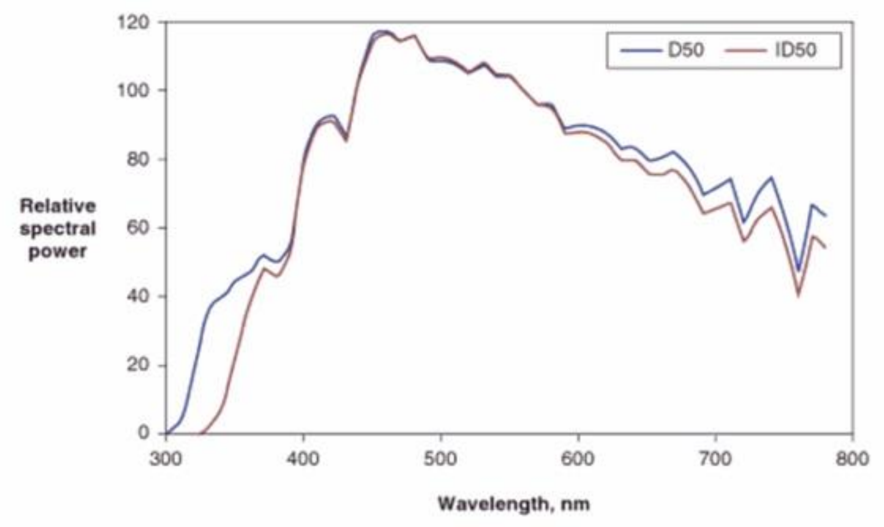

FIG. 6 – Indoor Daylight ID65 spectrum (6600K).

What makes this interesting for lighting designers is that architects and clients may obsess over the need for "high-CRI lighting" in their buildings. If the design involves both electric lighting and daylighting, one response could be to ask about the CRI of the building glass. If it is less than 90, there may be little point in worrying about the electric lighting.

Lamp with a CRI of 90 or above, good. Lamp with a CRI of less than 80, bad. This, plus the knowledge that "only a difference of some five points in the index is considered meaningful" is likely all you need to know (or talk) about CRI for most lighting design projects.

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# GIVING LIGHT

## A NEW PHILOSOPHY FOR LIGHTING DESIGN

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2014/05/12

GIVING LIGHT … this phrase symbolizes a new philosophy of lighting design, a philosophy in the sense of how we think about the lighting design process. Much like the modernist movement in architectural design a century ago, it offers a reconciliation of lighting design practices with today's rapid technological advancements and societal changes.

The innovations we are seeing in lighting hardware today are fascinating, but we are as always in danger of seeing these innovations in terms of existing technology. It is much like the first automobiles, which looked just like what they were called — horseless carriages. In some cases, these early and primitive vehicles came complete with buggy whip holders. As useless as they were, these accessories symbolized the inability of designers to fully adopt the new technology of internal combustion (and yes, electric) engines. The horse may have been absent, but it was still basically a 19th-century carriage.

Fig. 1 – Electrobat – first successful electric car (1894).

We may laugh at the silliness of such thinking, but in reality, we are no different. Look at today's solid-state lighting: we insist on emulating century-old incandescent lamp form factors and worse, attempting to control them with AC phase-cut dimmers. We may mutter about market acceptance and existing installations, but the truth is that we are not all that comfortable imagining what is possible with solid state lighting technology.

The innovations we are seeing in lighting hardware are not only fascinating, but part of a much larger movement now called the Internet of Things. Just as the first mobile phones have brought us today's smartphones, today's seemingly unrelated innovations in solid-state lighting are about to lead us into a brave new world of lighting design that we are only beginning to understand.

The question is, do we as lighting designers want to quietly accept whatever products the large corporations may develop and market, or do we want to direct the development of this brave new world?

We begin with a look at our current philosophy …

## The Philosophy of Lighting

For the past eight hundred millennia or more [1], we have had a clear and persistent understanding of light and lighting. Simply put, we view light as an intrinsic property of the light source. It is a world view that has both informed AND LIMITED how we approach the art and science of lighting design.

Our ancestors were intimately familiar with, and likely revered, fire as a source of light and lighting. Certainly fire occupied a central role in the religious beliefs of Zoroastrianism and Hinduism. Agni, the Vedic god of fire and sacrifice, took the form of fire, lightning, and the Sun. In Abrahamic theologies, the universe began with FIAT LUX — "let there be light."

We are no different today. We have a much better understanding of the physics of fire and its derivatives (including the cosmological "Big Bang," first introduced as a theory some eight centuries ago [2]), but we arguably still perceive and understand light and lighting as our distant ancestors did. It does not matter whether it is a burning torch, an incandescent lamp, or an organic light-emitting diode (OLED) — we think of emitted light as an intrinsic property of the light source.

We extend this thinking — this PHILOSOPHY — to our lighting systems in terms of controlling the emitted light. From trimming the wick of a smoking tallow candle to sending digital commands to wireless lighting networks from our smartphones, we similarly view lighting control as an intrinsic property of the lighting system.

There is a German word — WELTANSCHAUUNG — that translates as "world view." It is a framework of ideas and beliefs that form a global description through which we interpret our world and interact with it. In this sense, our understanding of light and lighting is very much a world view. We intuitively think of light as something which illuminates the space around us and of lighting systems as something that we interact with. Light and lighting systems are an integral part of this experiential world.

We have of course undergone numerous paradigm shifts (aka "revolutions") in lighting over the past two centuries or so, including gas lighting, incandescent lamps, fluorescent and high-intensity discharge lamps, electronic ballasts, fiber optics, solid-state lighting, and more. However, we have done so without changing how we think about light and lighting. To us, a light source is just that — a source of light.

## A Lighting Abstraction

“Let me give light, but let me not be light.”

Portia, The Merchant of Venice

FIG. 2 – Ellen Terry as Portia by Albert Joseph Moore (c. 1885).

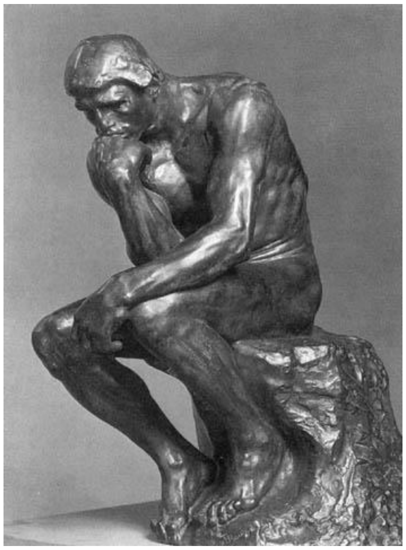
Shakespeare most likely meant “give light” in the sense of Portia having loose morals within her pending marriage. The phrase however is too evocative to ignore. The thought of us “giving light” is clearly an abstraction, but it is an exceedingly useful one from our perspective. It shifts the focus from designing for the illuminated environment to designing for people. The distinction is subtle but important.

But why an abstraction? The answer is that something as broad as a philosophy requires us to look at lighting design without being encumbered by any particular technology or hardware issues.

We all have our desires and preferences in terms of lighting, including intensity and dynamics, color temperature and color, and directionality and modeling. Wherever possible, we interact with lighting systems to satisfy our preferences. We turn the lights on and off when we enter or leave our offices, we dim the lights during a presentation in the conference room, and we open and close the blinds in response to daylight and weather conditions. We currently think of this in terms of controlling the light sources, of light being an intrinsic property of the light source.

### Thinking …

What however if we turn this thinking — this PHILOSOPHY — on its head? What if we consider light and light as intrinsic properties of OURSELVES? In this sense, we may abstractly “give light” to the environments we happen to be in.



– The Thinker by Auguste Rodin (1879 – 1889).

We may give light to our personal environments, including private offices and our residences. However, we also implicitly follow social norms. We rarely for example consider adjusting the lighting in common areas when other people are present, and we do not even think about controlling the lighting in public spaces such as restaurants, theatres, and hotel lobbies. Outdoor lighting in particular we simply accept for what it is, although we may occasionally complain about poor lighting design.

There are however socially-accepted exceptions to the rule. The introduction of solid-state lighting a decade ago brought with it a wealth of interactive public art displays wherein viewer interaction was not only encouraged, but often considered an integral component of the display. The artist in effect provided the public with a mostly blank canvas on which to express their lighting preferences.

– Philips Lighting Lumiblade OLEDs.

After ten years, the novelty of such displays has mostly gone. These were however early examples of people giving light to their illuminated environments.

## Personal Lighting Control

There are other examples of giving light to public spaces where different people may have different lighting preferences. Networked lighting systems for offices have been around for the past twenty years or so, with the first commercial system arguably being the ERGOLIGHT system from what is now Philips Ledalite. Its original product features today form the backbone of most networked lighting systems.

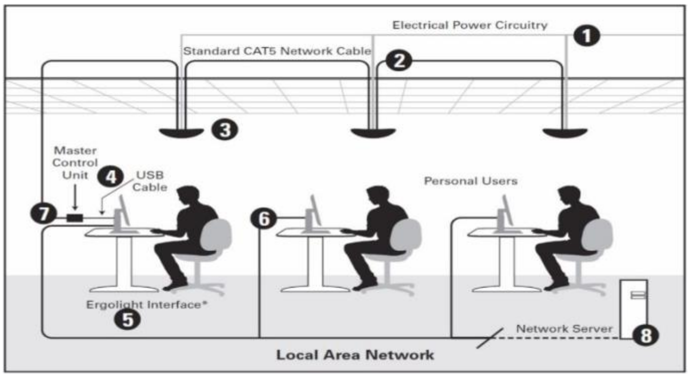


Fig. 5 – Philips Ledalite Ergolight (1996).

What is interesting about these lighting control systems is that they provide each worker with a considerable degree of control over the lighting of their workspaces. They can dim and switch the downlight from the overhead luminaires, while integral occupancy sensors and timers can dim or turn off the lighting when the worker is not present. Integral photosensors can also be used to implement daylight harvesting where appropriate.

What is surprising is that since its introduction, the concept of personal lighting control has never been seriously challenged. Numerous academic studies have shown that office workers in general approve of such lighting control systems [3]. Even better, their use contributes significantly to energy savings.

As lighting designers, we have therefore been enabling people to give light to their workplace environments for the past two decades. It has been a fundamental change in how we think about light and lighting design — a change so subtle that we barely noticed that it had occurred. More than an abstraction, giving light has long been an accepted lighting design practice.
But now it is time to take this design philosophy to a new and more exciting level …

## Our Networked Society

In 1959, the futurist Arthur C. Clarke wrote, "… the time will come when we will be able to call a person anywhere on Earth merely by dialing a number" [4]. A little over half a century later, there are reportedly some 4.5 billion mobile phone users in almost constant communication with each other. We are, in the words of the phone manufacturer Ericsson, a globally "networked society" [5].

Fig. 6 – Arthur C. Clarke – Profiles of the Future.

This is another change in our world view — who could have imagined a decade ago that we would so dependent today on cellular phones and smartphones for our daily activities? Even this however is only the beginning of the revolution — the Internet of Things (IoT) will connect us to almost every device and service imaginable in our daily lives. Analysts at Gartner, Inc. have predicted that by 2020, the installed base of IoT devices will be 26 billion units [6].

Lighting systems will of course be an important part of all this. Going beyond interactive public art displays and personal lighting control in open offices, we will soon have the technology to control lighting systems to a much greater extent than we do now. As lighting designers, we need to understand this technology and imagine the ways in which we can design lighting systems that benefit the user.

If we are to avoid thinking in terms of "horseless carriages," we need to look beyond the technologies to the lighting design process itself. The philosophy of giving light provides the necessary mental framework. With such a framework in mind, we can consider the implementation details.

## Identification and Geolocation

To control lighting systems, we first need to communicate with them. While such topics as wireless communications and networks may seem outside the realm of lighting design, they are anything but. It is not necessary to understand the technical details, but it is necessary to understand what is possible with today's mobile communication devices.

Most of us are aware that law enforcements agencies can track mobile phones through cell towers and global positioning system (GPS) satellites and determine their position (ìgeolocationî) to within some 500 feet or so. This is however but one example of "real-time location services" [7]. Using a combination of GPS, cell tower communications, WiFi hot spots, and Bluetooth Low Energy (BLE) devices, it is possible to geolocate a mobile phone in three dimensions with an accuracy of approximately two feet with 95 percent accuracy whenever the device is turned on [8].

We may not always carry our smartphones with us, but the trend today is towards smartwatches, wearable computers that are as unobtrusive as old-fashioned wrist watches. Featuring a long and growing list of capabilities, these will likely become indispensable accessories for life in our networked society. With GPS and BLE capabilities, they will also — with our permission — tell the world who and where we are.

Samsung Galaxy Gear 2 Smartwatch.

## Public Profile

“You have zero privacy anyway — get over it.” Scott McNealy, Sun Microsystems CEO (1999)

The operative word here is *permission*. We object to our loss of privacy mostly because it is being constantly invaded by corporations and governments without our knowledge, let alone our permission. Corporations harvest our personal information for the purposes of targeted advertising and business intelligence, while governments track us for various political reasons (and increasingly simply because they can). Commercial services such as for example Apple’s *iBeacon* have been developed expressly for commercial interests to track our movements and present us with targeted advertising … without our permission.

Suppose however that we consciously choose to publicly broadcast this information. Rather than having commercial and political interests trying to surreptitiously determine our preferences, we could maintain public profiles of ourselves. More than simple lists, these profiles would be even more richly detailed than those maintained by the retailers and credit card companies — but fully under our individual control. More important, these profiles would be electronically bound to our physical presence (albeit stored “somewhere in the cloud”). They would in a very real sense be an intrinsic property of ourselves.

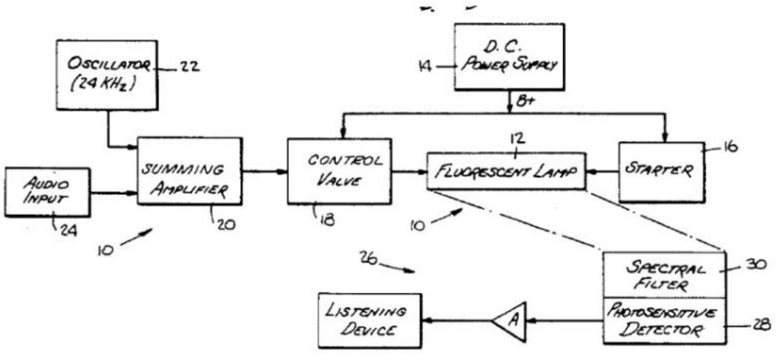
With this capability, we can choose to tell the world who and where we are. In terms of lighting systems, all we need to do is to wirelessly broadcast a unique identifier; the system can then access our public profile via the Internet to determine our desires and preferences related specifically to lighting (if we so choose).

## Visible Light Communications

From a lighting designer’s perspective, this is where it becomes interesting. The first lighting networks introduced some twenty years ago relied on wired RS-485 communications. These were superseded by faster Ethernet communications, and more recently by wireless mesh networks such as Zigbee Light Link [9].

An unfortunate disadvantage of wireless networks is that there can be numerous devices operating at the same frequency. As with shared Internet access and mobile phone usage, too many devices attempting to communicate at the same time may result in unacceptably poor system performance. This situation will only get worse as the Internet of Things gains traction.

Visible light communications, often referred to as "LiFi," provides a solution. Beginning in the 1970s, inventors began developing modulation techniques for fluorescent lamps that enabled the broadcasting of audio signals using general illumination [10]. These saw some commercial success [11], but it was the development of light-emitting diodes and solid-state lighting that has renewed particular interest in the technology [12].



US Patent 3,900,404 – Optical Communication System.

### The LiFi Advantage

LiFi offers several advantages over wireless communications. It is for example primarily line-of-sight, which results in potentially more secure communications. Solid-state lighting can also be modulated at high frequencies, providing up to four times the bandwidth of 3G mobile phone systems. Further, there are no restrictions on the carrier frequency or spectrum licensing requirements, so multiple systems can easily co-exist.

The one disadvantage is that LiFi is basically a broadcast system. Luminaires with LiFi capabilities can broadcast information, but receiving devices generally require infrared or wireless transmitters to respond. A local WiFi router or Bluetooth transceiver can for example receive the responses and communicate with the luminaires using Ethernet or a wireless network.

The true advantage of LiFi however is that it is no longer necessary for the lighting system to geolocate occupants with accuracies of a foot or less. All that is needed is for the luminaires to continually broadcast their unique identifiers, and for the occupant's smartphone or smartwatch to detect these identifiers with its camera or a photosensor. The device can then wirelessly respond, "I see you" with the occupant's public profile identifier. This is an exceedingly brief transaction that minimizes the device's battery power requirements.

What is exciting about this is that this is not some futurist's wish list for advanced technology. The technology already exists, and it is already being commercialized.

## Commercial Products

Royal Philips recently introduced an “intelligent in-store LED lighting system” that communicates information to shoppers via their smartphones and LED-based luminaires [14]. All the shoppers have to do is to point their smartphone cameras at the nearest overhead luminaire.

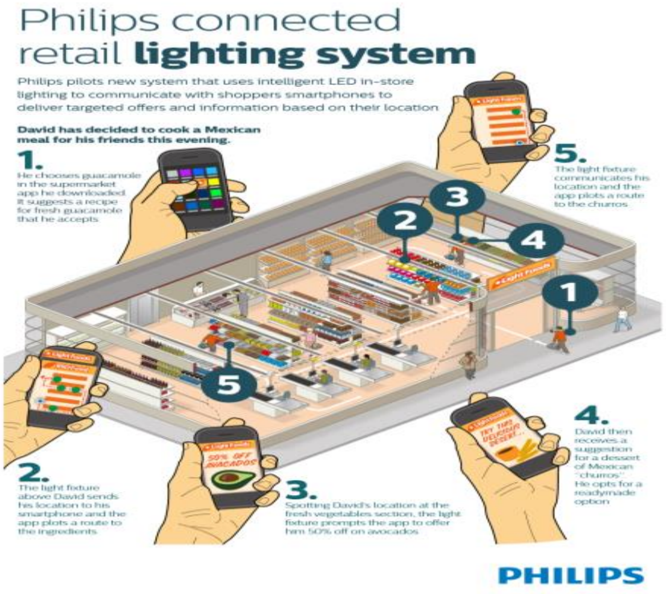


Fig. 9 - Philips Connected Retail Lighting System.

Philips has even more recently introduced a “smartphone-controlled connected office lighting system” [14]. This system enables office workers to control both the lighting and room temperature using their smartphones in communication with the overhead luminaires and Power over Ethernet (PoE). The feature set is no different from what was offered two decades ago with networked lighting systems, but now the communication relies on LiFi rather than wired network cables.

There are undoubtedly many more such products to come. However, they are still based on light as an intrinsic property of the light source. Something more is needed to implement the abstraction of “giving light.”

## Intelligent Lighting Control

Lighting researchers have been looking at the possibility of intelligent lighting control in buildings for over a decade [15]. Often referred to as “ambient intelligence” and “auto-adaptive” lighting, the basic approach has been to use artificial intelligence (AI) techniques such as neural networks and fuzzy logic to learn a user’s lighting preferences by observing their behavior [16]. Most of the research has assumed a single or typical user, although some work has been done on reconciling different users’ preferences [17].

An advantage of intelligent lighting control is that by learning the user’s behavior, it can anticipate what sort of lighting is desired without the user having to interact with manual controls. This may work well for offices and residences where the system has the opportunity to learn the user’s behavior, but it does not work well otherwise. At best, the system must default to an anonymous "typical user" whose behavior is the average of many users. (Regardless, intelligent lighting controls typically result in energy savings.)

This is where the "networked society" concept has so much to offer. If an intelligent lighting control system can identify the user and access their public profile, it can determine the user's desires and preferences and respond accordingly [18]. Even better, it can observe the user's behavior and update their public profile if desired. Learning goes from a single isolated system to wherever the user encounters intelligent lighting control systems, often without the user even being aware of their presence.

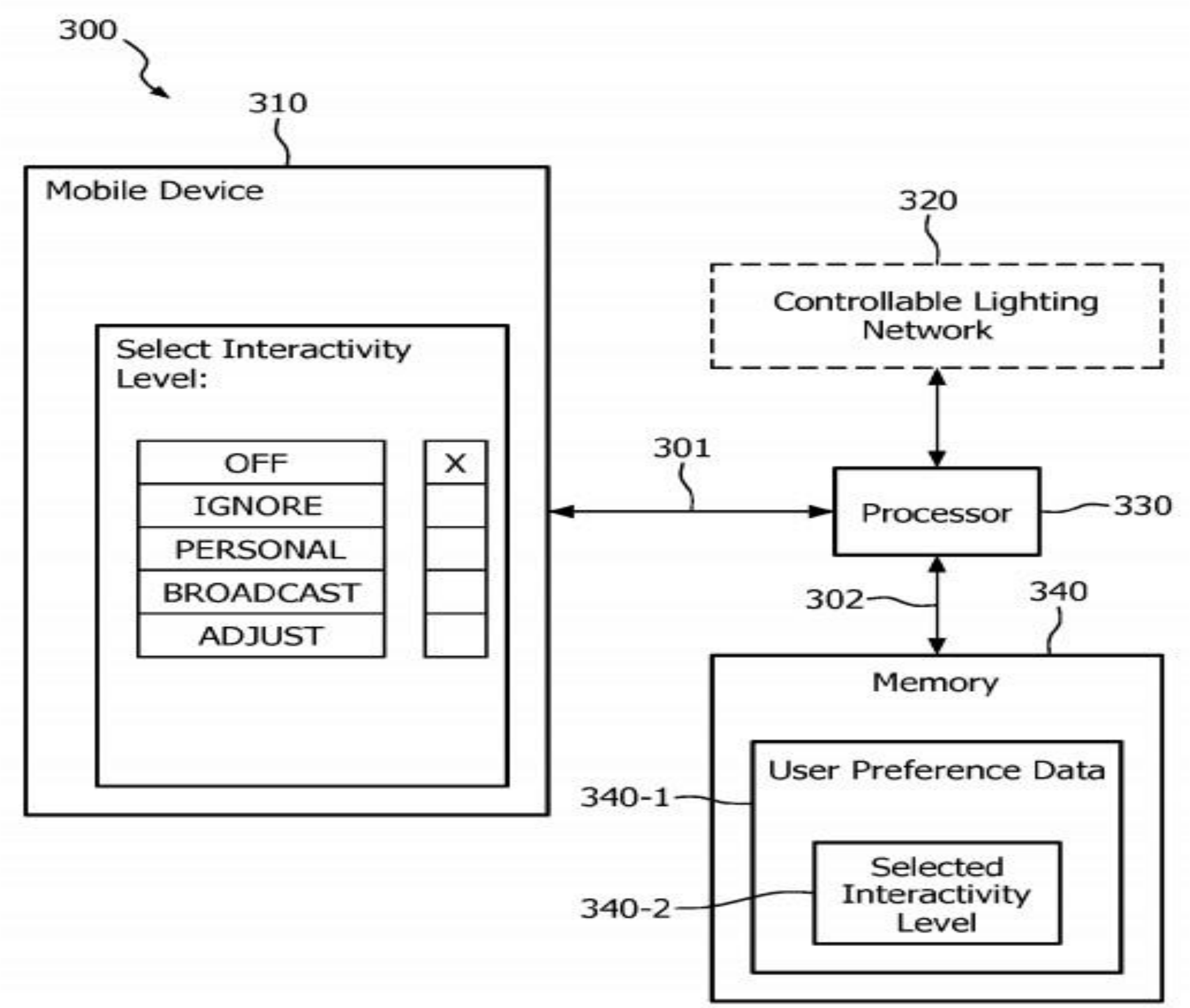


Fig. 10 – US Patent Application 2012/0184299.

## Public Places

The research to date has mostly focused on offices and residences, but it becomes even more interesting when public spaces are considered. Examples include retail stores and shopping malls, restaurants and hotel lobbies, bars and nightclubs, and even outdoor plazas and public parks at night. Normally, we never consider interacting with the lighting of such spaces. With public profiles however, we can easily give light to these environments in a socially acceptable manner.

As a prosaic example, consider walking through a park at night. Municipalities are already equipping pole-mounted walkway lighting with WiFi transceivers and occupancy sensors, which is all the technology that is needed for someone to turn on the lights using a smartphone [19]. It is a small step from here for the lighting system to recognize the person through their public profile and set the lights for a particular path.

Fig. 11 – Lighting in public places.

More interesting examples arise when we consider light itself as a social medium. Color in particular can be used to announce the arrival of VIPs at a nightclub or to announce goals during a game at a sports bar. Light levels in restaurants can adapt to the preferences of patrons and their activities. The list goes on with possibilities that are limited only by the creativity of the lighting designers who develop the systems and the users who interact with them.

## Language of Light

If anything, we may need to invent a new “language of light,” a non-verbal means of expressing not only our desires and preferences for lighting, but also of expressing our moods and social standing. More than likely, this will evolve by itself in the manner of cultural norms. We may however be surprised, if the prior introduction of personal lighting control is any indication. We may embrace the concept of giving light with the same aplomb as we have exhibited in adopting smartphones. It will become interwoven into the fabric of our lives, with our children wondering what light switches were for.

Just as it is difficult to explain a philosophy in five hundred words or less, it is difficult to explain the nuances of light as an intrinsic property of ourselves and the concept of “giving light” in a single discussion. It is all too easy to think of new technologies in term of what they replace, much as today’s LED lamps closely resemble A19 incandescent lamps. It is even more difficult here in that there are no new technologies involved; we already have the tools that we need.

All that is needed is for lighting designers to adopt a new philosophy and consider the possibilities.

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# HORTICULTURAL INFORMATION

# PHOTOMETRY AND PHOTOSYNTHESIS

## FROM ILLUMINANCE TO PPFD

Ian Ashdown, FIES, Senior Scientist, SunTracker Technologies Ltd. Published 2014/12/10

UPDATE 15/04/13 — This article was first published on December 10, 2014. A revised version was published as “LED Lighting for Horticulture” in the Mar/Apr 2015 issue of LED Professional Review (www.led-professional.com). This update includes information from the published article.

UPDATE 15/11/05 — due to several Excel spreadsheet errors, the lux-to-PPFD conversion factors presented in Table 2 were miscalculated. These errors have been corrected.

UPDATE 16/01/12 — the description of the Emerson effect has been corrected.

UPDATE 16/02/10 — Added discussion of calculating lux-to-PPFD conversion factors for overcast skies, as well as expanded notes and references on green and ultraviolet LEDs.

UPDATE 21/09/02 — Normalized lux to PPFD conversion factors.

Horticultural lighting these days is big business. As agricultural land becomes scarce, the weather becomes more unreliable, and the migration of people to megacities continues, it increasingly makes economic sense to cultivate plants indoors with electric lighting.

The problem is that lighting designers and horticulturalists generally do not speak the same language. Whereas we speak in terms of lumens and illuminance, horticulturalists speak in terms of *photosynthetically active radiation* (PAR) and *photosynthetic photon flux density* (PPFD). Ask for an explanation of these terms and you will hear talk of *micromoles*, and possibly *microeinsteins*, of photons. Instead of luminous flux, there is *quantum flux*. It can be very confusing, not to say frustrating.

We need however to understand each other. As the horticultural industry transitions from high-intensity discharge arc lamps such as high-pressure sodium (HPS) and metal halide (MH) to solid-state lighting (e.g., Massa et al. 2008, Mitchell et al. 2012, Nelson and Bugbee 2014), it becomes possible to tailor the spectral power distribution of multicolor-LED luminaires for individual crops and plant species. For lighting designers working with horticulturalists, the need to understand PAR and calculate PPFD values using lighting design software becomes critical.

### Photosynthetically Active Radiation

*Photosynthesis* is the process used by plants to convert electromagnetic radiation ñ light ñ into chemical energy that is used for growth and development. All that is needed for this process is carbon dioxide ($CO_2$), nutrients, and water. The process itself is not particularly efficient; only 4 to 6 percent of the absorbed radiation is converted into chemical energy (Zhu et al. 2010, Table 2). Still, it is the engine that drives most life on this planet.

*Photosynthetically active radiation* (PAR) is defined as electromagnetic radiation over the spectral range of 400 nm to 700 nm that photosynthetic organisms are able to use in the process of photosynthesis to fix the carbon in CO≠$_2$ into carbohydrates. Horticulturalists measure PAR for both plant research and greenhouse lighting design (e.g., Barnes et al. 1993) using specialized photometers (e.g., Biggs et al. 1971).

A common unit of measurement for PAR is *photosynthetic photon flux density* (PPFD), measured in units of moles per square meter per second[1]. In this case, every absorbed photon, regardless of its wavelength (and hence energy), is assumed to contribute equally to the photosynthetic process. This is in accordance with the Stark-Einstein law, which states that every photon (or *quantum*) that is absorbed will excite one electron, regardless of the photon's energy, between 400 nm and 700 nm. For this reason, photosynthetic photon flux is also referred to as *quantum flux*.

Whether a photon with a given wavelength is absorbed by a plant leaf is dependent on the spectral absorptance of the leaf, which in turn is determined largely by the leaf optical properties, including the concentration of plant pigments such as chlorophyll A and B, various cartenoids (carotenes and xanthophylls), and anthocyanins. The chlorophylls are responsible for the characteristic green color of leaves; the other pigments contribute to the yellow, orange, and red colors respectively of autumn leaves after the chlorophylls decompose.

Typical absorptance spectra for chlorophyll A, chlorophyll B, beta-carotene, and two isoforms of phytochrome are shown in Figure 1. It must be noted, however, that these spectra are approximate. They are measured IN VITRO by dissolving the pigments as extracts in a solvent, which affects their absorptance spectra. By themselves, they suggest that blue and red LEDs alone are sufficient for horticultural applications. In reality, however, the situation is much more complicated.

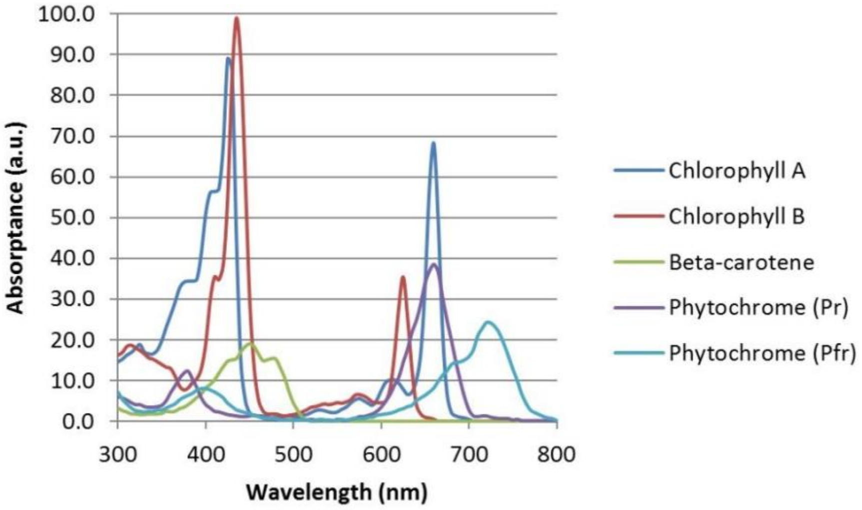


FIG. 1 – Photopigment spectral absorptances.

McCree (1972a) measured the spectral absorptance (FIG. 2) and *quantum yield* of $CO_2$ assimilation for the leaves of 22 species of crop plants[2]. Taking the average measurements at 25 nm intervals for all plant species (Table 1), he produced the *photon-weighted relative quantum yield* (Table 1) that is representative of most crop plants.

| **Wavelength (nm)** | **Relative Spectral Quantum Yield** |
|---|---|
| 400 | 0.42 |
| 425 | 0.68 |
| 450 | 0.70 |
| 475 | 0.63 |
| 500 | 0.65 |
| 525 | 0.72 |
| 550 | 0.82 |
| 575 | 0.91 |
| 600 | 0.97 |
| 625 | 1.00 |
| 650 | 0.90 |
| 675 | 0.90 |
| 700 | 0.48 |

Table 1 – Relative Quantum Yield (average of 22 field species)

### Yield Photon Flux

It is also possible to measure PAR in terms of energy rather than photons. The energy of a photon with wavelength Λ is given by the Planck-Einstein relation:

$$E = \frac{hc}{\lambda}$$

where E is the energy in joules, H is Planck's constant ($6.626 \times 10^{-34}$ joule-seconds), C is the speed of light ($2.998 \times 10^{8}$meters per second), and Λ is measured in meters. For example, one micromole of photons with a wavelength of 450 nm has 0.266 joules of energy. Scaling the photon-weighted relative quantum yield values by the wavelength and normalizing produces the *energy-weighted* relative quantum yield, also known as the *action spectrum* (FIG. 2). (An action spectrum is simply a plot of biological effectiveness as a function of wavelength of incident light.)

The energy-weighted photosynthetic photon flux is measured in watts (joules per second), and is referred to as the *yield photon flux* (YPF). (In terms of lighting design, it is synonymous with *irradiance*.) As shown by McCree (1972b), photon-weighted PPFD is a better predictor of photosynthesis when light sources with different spectral power distributions are considered. Given this, PPFD is the metric most commonly used by horticulturalists. However, energy-weighted YPFD is useful for energy-balance calculations involving photosynthetic organisms.

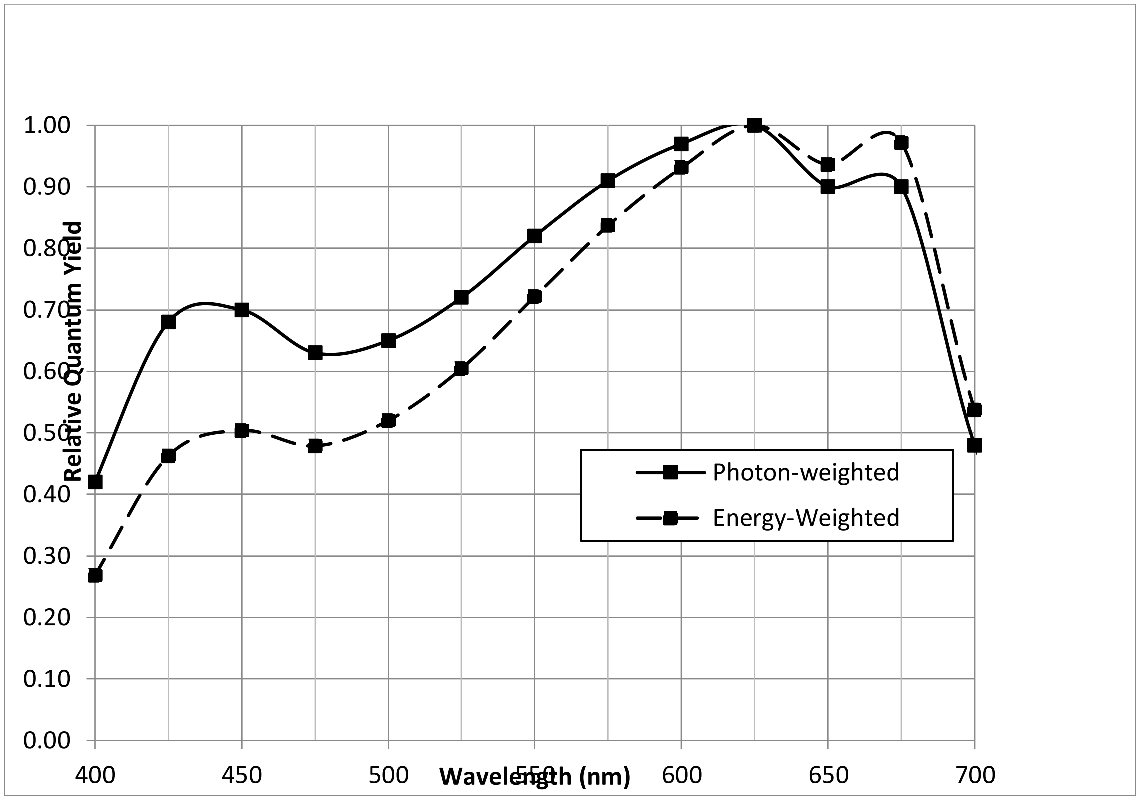


Fig. 2 – Relative quantum yield for crop plant photosynthesis.

As noted by McCree (1972a), neither PPFD (quantum flux density) nor YPFD (irradiance) are perfect measures of photosynthetically active radiation in that both systematically overestimate the effectiveness of blue light relative to red. As can be seen from FIG. 3, the error is greater for YPFD, which explains why PPFD measurements are preferred by horticulturalists. Nevertheless, they are useful in that they are independent of any particular plant species, and they can be measured both in the laboratory and in the field using a radiometer with a spectrally-calibrated quantum sensor such as the LI-190SA with LI-COR (www.licor.com).

## From Lumens to Photosynthetic Photon Flux

As lighting designers, we need some method of converting lumens to quantum flux and illuminance to quantum flux density (PPFD). We can do so however only if we know or can estimate the spectral power distribution (SPD) of the light source.

Suppose then that we have a light source with a known relative spectral power distribution (SPD), such as for example a 5000K "cool white" LED (FIG. 3).

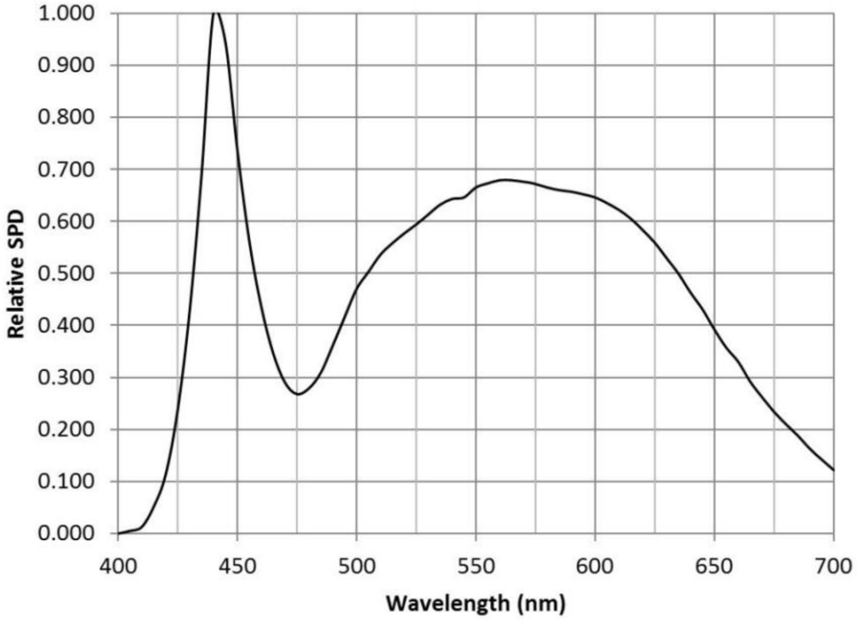


FIG. 3 – 5000K LED relative spectral power distribution.

One watt of radiant power at 555 nm is by definition equal to 683 lumens. Given the CIE 1931 luminous efficiency function (FIG. 5), we can calculate the spectral radiant flux $\Phi(\Lambda)$ in watts per nanometer for each lumen as:

$$\Phi(\lambda)/lm = \frac{W_{rel}(\lambda)}{683 * \sum_{400}^{700} V(\lambda) W_{rel}(\lambda) \Delta\lambda}$$

where $W_{REL}(\Lambda)$ is the relative spectral power distribution, $V(\Lambda)$ is the luminous efficiency function at wavelength $\Lambda$, and $\Delta\Lambda$ is the wavelength interval (typically 5 nm). For the above example, the spectral radiant flux per nanometer for each lumen at 440 nm is 22.5 microwatts, while the total radiant flux per lumen is 3.18 milliwatts.

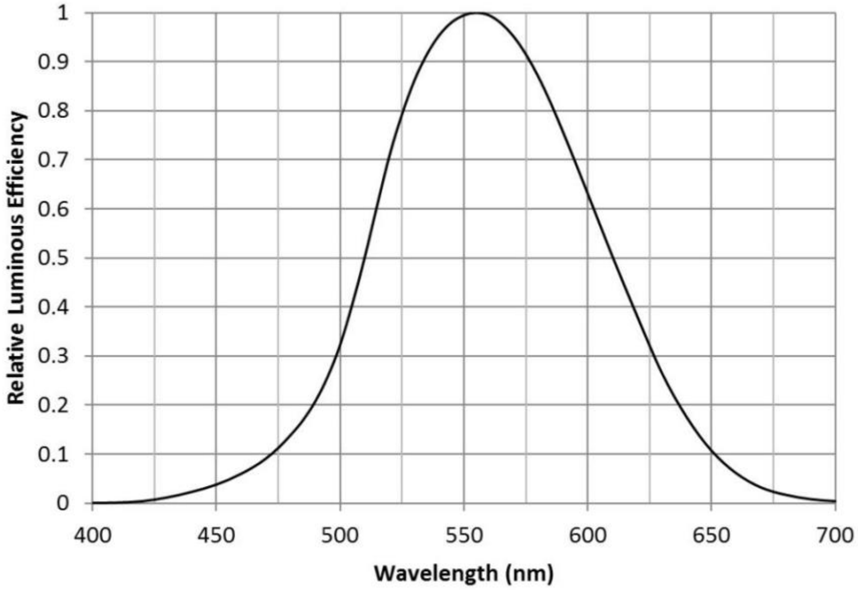


FIG. 4 – CIE 1931 luminous efficiency function V(λ)

With this, we can calculate the photosynthetic photon flux (PPF) per nanometer in micromoles per second per nanometer:

$$PPF/nm = 10^{-9} * \frac{\lambda\Phi(\lambda)}{(N_a * 10^{-6})hc}$$

(where $N_A$ is Avogardo's constant), while summing over the range of 400 nm to 700 nm yields the photosynthetic photon flux (PPF) per lumen for the given light source:

$$PPF = \frac{10^{-3}}{N_a hc} * \sum_{400}^{700} \lambda\Phi(\lambda)\Delta\lambda \approx 8.359 * 10^{-3} * \sum_{400}^{700} \lambda\Phi(\lambda)\Delta\lambda$$

Given an illuminance value (lumens per square meter) and knowing the light source SPD, we can similarly calculate the photosynthetic photon flux density (PPFD) in micromoles per second per square meter (µmol/sec-m$^2$) for the given light source. Again, for the above example, one lux is equal to 0.01462 µmol/sec-m$^2$.

### Conversion Factors

It is easy enough to find graphical representations of light source spectral power distributions, but it is considerably more difficult to find this information in tabular form suitable for the above calculations. Fortunately, this information is published in CIE 15:4, Colorimetry (CIE 2004). It does not include white light LEDs, but this information can be obtained by digitizing manufacturers' product catalog data (e.g., Philips 2014a).

Given such information, it possible to calculate lux-to-PPFD conversion factors for common light sources:

| Light Source | Conversion Factor |
|---|---|
| CIE A (incandescent, 2856K) | 0.0203 |
| CIE 5000K daylight (D50) | 0.0181 |
| CIE 5500K daylight (D55) | 0.0181 |
| CIE 6500K daylight (D65) | 0.0183 |
| CIE 7500K daylight (D75) | 0.0186 |
| CIE HP1 (standard high-pressure sodium, 1959K) | 0.0117 |
| CIE HP2 (color-enhanced high-pressure sodium, 2506K) | 0.0193 |
| CIE HP3 (high-pressure metal halide, 3144K) | 0.0144 |
| CIE HP4 (high-pressure metal halide, 4002K) | 0.0150 |
| CIE HP5 (high-pressure metal halide, 4039K) | 0.0163 |
| 2700K white light LED (Philips Luxeon Rebel LXW9-PW27) | 0.0181 |
| 3000K white light LED (Philips Luxeon Rebel LXW9-PW30) | 0.0171 |
| 3500K white light LED (Philips Luxeon Rebel LXW7-PW35) | 0.0146 |
| 4000K white light LED (Philips Luxeon Rebel LXW8-PW40) | 0.0143 |
| 5000K white light LED (Philips Luxeon Rebel LXW8-PW50) | 0.0146 |

Table 2 – Illuminance (lux) to PPFD (μmol/sec-m$^2$) conversion factors

Table 2 does not include commercial products such as the Sylvania SHP-TS Grolux (with a CCT of 2050K) because Sylvania and most other lamp manufacturers do not publish their lamp SPDs in tabular form. It is possible to digitize the graphical representations of white light LEDs because the bandwidth of the blue "pump" LEDs is at least 15 nm. With high-pressure sodium and metal halide lamps, however, it is impossible to digitize their published SPDs because the wavelength resolution is unknown. A subnanometer-wide line emission, for example, could vary in height by five times, depending on whether the wavelength binning is 1 nm or 5 nm.

### Overcast Skies

Table 2 presents conversion factors for the CIE Clear Sky with CCTs ranging from 5000K to 7500K. Their spectral power distributions (shown in the Appendix) were calculated in accordance with the equations published in CIE 15:4, Colorimetry (CIE 2004), which were in turn derived from the spectral distributions of 622 samples of daylight (skylight, and sunlight plus skylight), as discussed in Judd et al. (1964). Considering the variability of daylight, these SPDs are sufficient for most purposes.

What however about overcast skies? To answer this question, we reference "Colors of the Daytime Overcast Sky" by Lee and Hernández-Andréz (2006), who defined "overcast" as meeting two criteria: 1) no clear sky can be visible anywhere; and 2) cloud cover must be sufficiently optically thick that any cast shadows are indistinct.

The authors made over 9,100 spectral irradiance measurements in Granada, Spain, and Annapolis, Maryland on 40 overcast days, including days with drizzle, light rain and snow, with the Sun at least five degrees above the horizon. While the paper offers many interesting details, two items are of particular interest.

First, the correlated color temperature of overcast skies that the authors measured ranged from 5800K to 9300K, with their typical overcast skies having CCTs ranging from 6000K to 6600K. Second, the authors provided SPDs of their two most extreme skies, with CCTs of 5800K and 9300K. These SPDs were used to calculate illuminance (lux) to PPFD (μmol/sec-m$^2$) conversion factors of 0.0178 and 0.0205 respectively. From these values, the CCTs of typical overcast skies can be linearly interpolated to be 0.0182 ± 0.0002. In other words, no different from typical clear skies.

### LED Lighting for Horticulture

At this time, high-pressure sodium (HPS) lamps are the most common light source for greenhouse lighting, where it is commonly used to supplement daylight during the winter months. However, with the growing interest in urban horticulture that relies exclusively on electric lighting, light-emitting diodes offer many advantages. This is particularly true for multilayer cultivation, where the close spacing of plants in vertical rack-mounted trays make HPS lighting impractical.

McCree (1972a) noted that the relative quantum yield for crop plant photosynthesis has two peaks at 440 nm and 620 nm. He also noted however, the Emerson effect, which states that photosynthesis in the presence of two or more wavelengths can be more efficient than the sum of that due to the individual wavelengths. In particular, adding white or red light (less than 680 nm) to deep red light (greater than 680 nm) can beneficially increase the rate of photosynthesis.
Green light is also used in photosynthesis, as can be seen from the leaf action spectrum (FIG. 2). It has been established that green light drives photosynthesis more effectively than red or blue light deep within the leaf (Terashima et al. 2009). Further, the insects used in greenhouses as pollinators and

biological control agents see best in the green and ultraviolet regions of the spectrum. More interestingly, changes of even 10 nm in the peak wavelength of green light can have dramatic effects on the growth of plants such as lettuce (Johkan et al. 2012).

Plants also exhibit photomorphological responses (i.e., growth and development) to ultraviolet radiation (Zuk-Golaszewska et al. 2003). In the past, this has been mostly of theoretical interest to botanists. Now however with the rapid commercialization of ultraviolet LEDs (Shih 2015) with wavelengths covering the plant biologically-active spectrum of 280 nm to 400 nm, UV-A and UV-B LEDs will likely also find application in horticultural lighting.

It is likely for this reason that many horticultural LED modules feature efficient 450 nm indium-gallium-nitride (InGaN) deep blue LEDs and 660 nm aluminum-indium-gallium phosphide (AlInGaP) deep red LEDs. Typical examples of these LEDs are the Philips Luxeon Royal Blue (LXML-PRO1-0425) and Deep Red (LXM3-PD01) products (Philips 2014b). Both of these products are quite efficacious, converting some 45% of their electrical input power into visible light. Green LEDs, while beneficial, are rarely used because of their much lower radiant efficacies. (This may soon change, however, as OSRAM Opto recently announced the development of 530 nm InGaN green LEDs with 25% external quantum efficiency.)

Herein however lies a problem: 450 nm and 660 nm are close to the limits of our color vision (see FIG. 4). Consequently, Philips and other manufacturers typically express the optical performance of these products in radiometric rather than photometric terms — milliwatts instead of lumens.
So, the lighting design process becomes a bit more complicated. We first need to digitize the published LED spectral power distributions to determine the conversion factors between milliwatts and lumens — these will be needed for the lighting design simulations. These are given by:

$$\Phi_L = 0.683 * \frac{\sum_{400}^{700} \Phi_R(\lambda) V(\lambda)}{\sum_{400}^{700} V(\lambda)}$$

where $\Phi_L$ is the luminous flux, $\Phi_R(\Lambda)$ is the relative spectral radiant flux and $V(\Lambda)$ is the luminous efficiency function at wavelength $\Lambda$.

Using the Philips Luxeon Royal Blue and Deep Red products as an example, the respective conversion factors are approximately 0.07 and 0.03 lumens per milliwatt (lm/mW). However, these figures must be approached with some caution, as they apply to 450 nm and 660 LEDs only. If for example the peak wavelength of deep blue LED was 440 nm rather than 450 nm, the conversion factor would be 0.05 lm/mW. Similarly, if the peak wavelength of the deep red LED was 650 nm rather than 660 nm, the conversion factor would be 0.06 lm/mW. The Philips LED binning ranges are 440 to 460 nm and 650 to 670 nm respectively, which equates to (from FIG. 4) conversion factor uncertainties of +75%, -50% for blue and +60%, -30% for red. The above conversion factors are therefore decidedly approximate.
(Some horticultural LED module manufacturers bin their LEDs more tightly, as peak maxima shifts as small as 10 nm have been shown to have dramatic effects on plant growth. Unless however the binning policy is stated in the manufacturer’s product literature, this cannot be assumed.)

A further word of caution: even the best illuminance meters can be wildly inaccurate when measuring deep blue and deep red light levels. Commercially available photometers are usually classified according to their $F_1'$ number (with $F_1' < 3\%$ being preferred), which is basically a measure of how closely the spectral response of the meter matches that of the photopic visual efficiency function (FIG. 4). As noted in CIE 127:2007, MEASUREMENT OF LEDS (CIE 2007), this is useful for white light measurements only. To quote, "In the case of single-color LEDs, the spectral mismatch errors can be very large even if $F_1'$ is reasonably small, due to the fact that some LED spectra are peaking in the wings of the $V(\Lambda)$ function where the deviation makes little effects on $F_1'$ but can cause large errors."

With these conversion factors in hand, we can now calculate the illuminance-to-PPFD conversion factors for horticultural LEDs:

| Light Source | Conversion Factor |
|---|---|
| 450 nm deep blue LED | 0.01194 |
| 525 nm green LED | 0.00084 |
| 660 nm deep red LED | 0.01305 |

Table 3 – Illuminance (lux) to PPFD (μmol/sec-m$^2$) conversion factors

How horticulturalists choose to balance the ratio of red to blue light will likely depend on the specific plant species being cultivated and their stage of growth. Some plants like shade, while others prefer direct sunlight, with different SPD requirements. In addition, far-red 735 nm LEDs may be employed to induce flowering. Regardless, the above conversion factors will still be useful.

In addition to using chlorophylls and carotenoids for photosynthesis, plants use these and other photopigments for a wide variety of functions. The phytochromes $P_r$ and $P_{fr}$, for example, respond to 660 nm red and 735 nm infrared radiation respectively, and in doing so induce seed germination and flowering, regulate leaf expansion and stem elongation, and trigger photoperiod and shade avoidance responses (see Appendix A).

Other photopigments regulate phototropism (leaf and stem orientation) and circadian rhythms (for which blue light is the most effective), photomorphogenesis (plant shape), root growth, stomatal opening, chloroplast movement … the list goes on, as horticultural researchers continue to explore the role between lamp SPDs and optimal plant health and growth. (See www.photobiology.info for an informative summary of plant photobiology.)

## Summary

As a reminder, photosynthetically active radiation (PAR) does not consider the spectral response of plants (FIG. 3); it simply represents the number of photons (quanta) per unit area per second within the range of 400 to 700 nm. With the availability of color-tunable LED modules for greenhouse lighting, horticulturalists will likely want to experiment with different SPDs for specific crops and flowering plants, as well as both the directionality and daily timing (photoperiods) of the luminaires. Regardless, being able to convert predicted and measured illuminance values to PPFD values for common light sources will certainly ease the communication problem between lighting designers and horticulturalists.

## Acknowledgements

Thanks to Tessa Pocock of the Smart Lighting Engineering Research Center, Rensselaer Polytechnic Institute, for her review and comments on this article.

## Appendix A – Photosynthesis and Visible Light

For illumination engineers, it might seem suspicious that the photosynthetically active radiation is defined over the spectral range 400 nm to 700 nm — exactly the range we commonly assume for human vision. What about longer and shorter wavelengths?

When McCree [4] measured his 22 crop species both in the field and in laboratory growth chambers, he obtained the following action spectra:

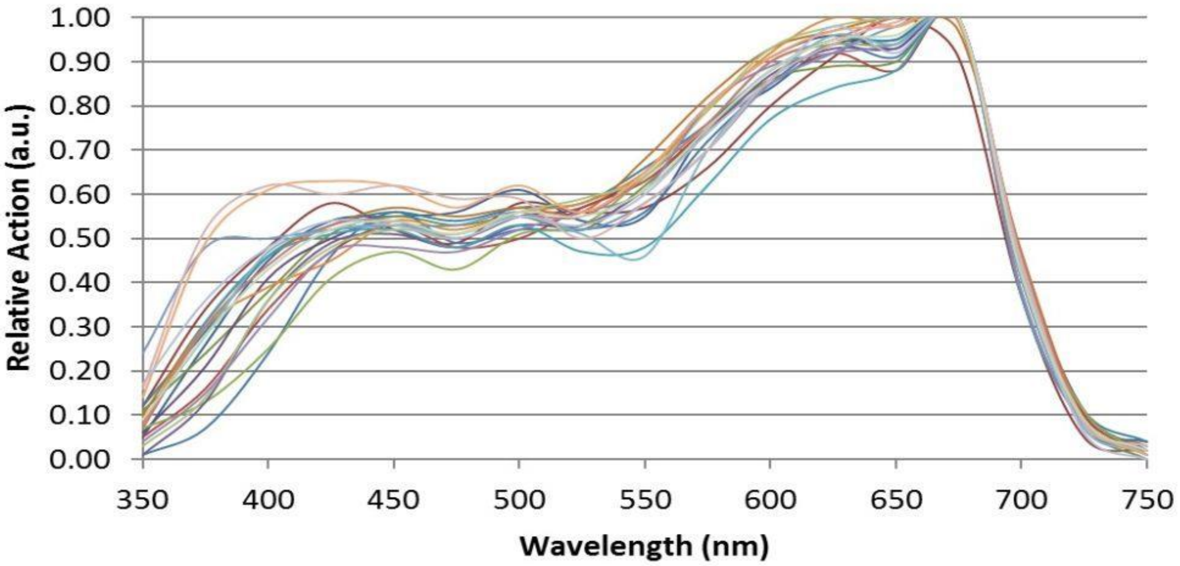


Fig. A1 – Growth Chamber Action Spectra.

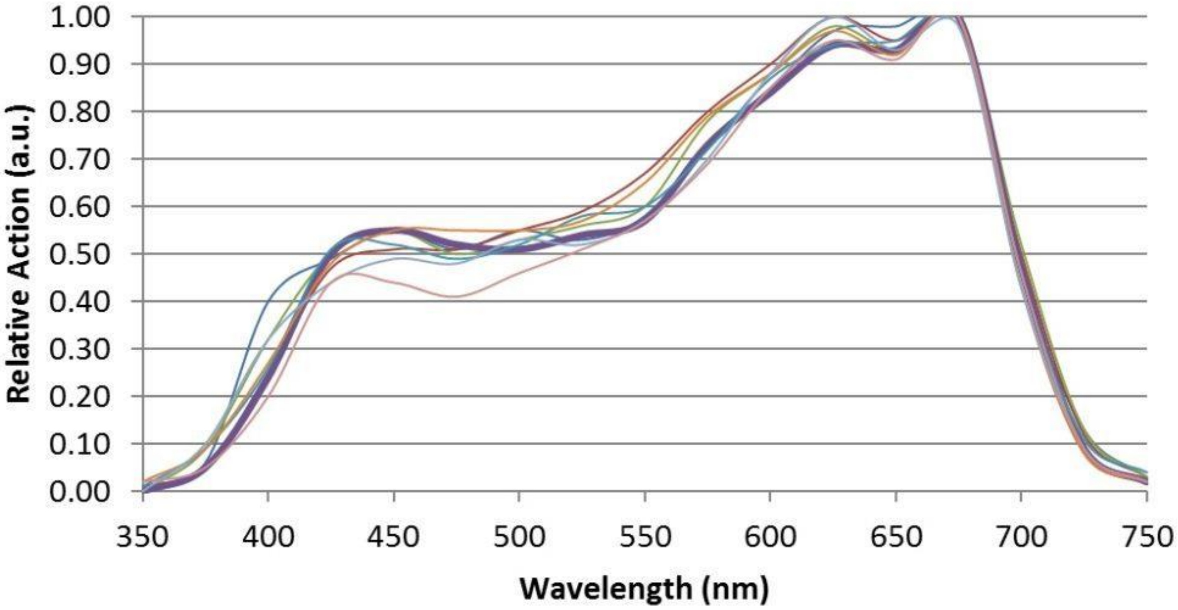


Fig. A2 – Field Action Spectra.

which clearly explain the logic of the 400 – 700 nm spectral range.

Below 400 nm, there is the risk of photooxidation that generates toxic radicals, which can destroy the cellís chlorophyll and other cellular components. Under intense UV radiation, violaxanthin (which is involved in photosynthesis) is converted via the xanthophyll cycle into zeaxanthin. In doing so, it receives excess energy from chlolorphyll and releases it as heat. This process thereby offers the plant photoprotection.

At the same time, other plant photopigments, including cryptochromes and phototropins, do have sensitivities (as measured IN VITRO) that extend into the ultraviolet, and likely respond under dim light conditions. However, these are likely suppressed under high light conditions by the xanthophyll process.

Above 700 nm, the photon energy is too low to activate the photosynthetic process via the chlorophylls and various cartenoids. However, the phytochrome photopigment, which is responsible for stem elongation, leaf expansion, shade avoidance, neighbor perception, seed germination, and flower induction, has two isoforms called $P_r$ and $P_{fr}$. In its ground state $P_r$, phytochrome has a spectral absorbance peak of 660 nm. When it absorbs a red photon, it converts to its $P_{fr}$ state, which has a spectral absorbance peak of 730 nm. When the phytochrome molecule absorbs a far-red photon, it converts back to its $P_r$ state, and in doing so triggers a physiological change in the plant.

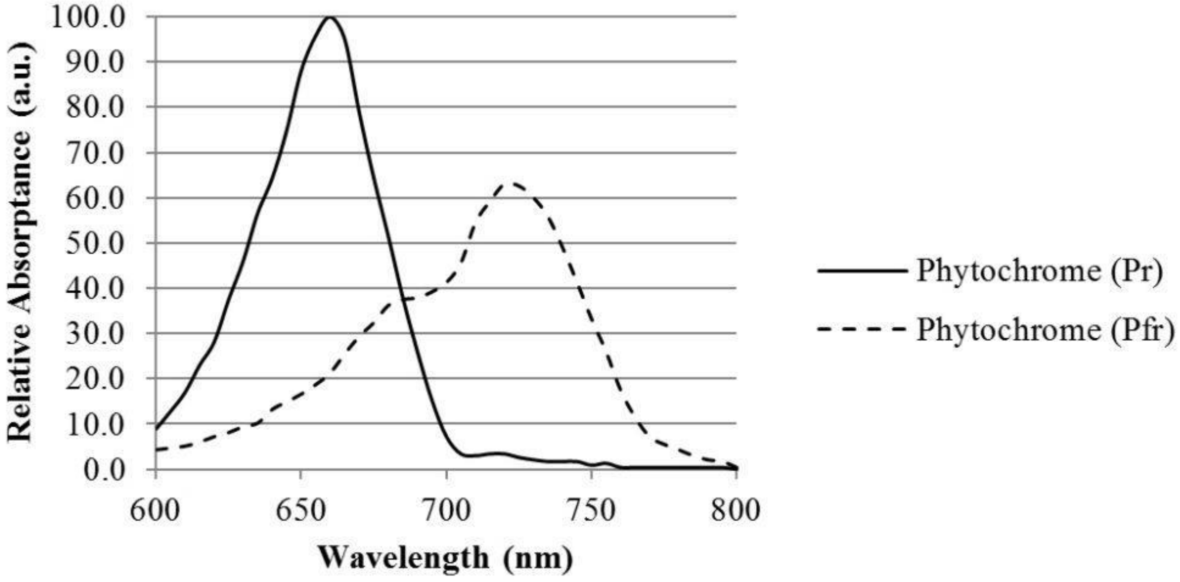
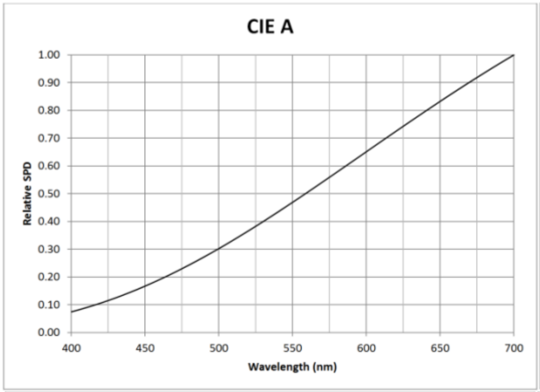
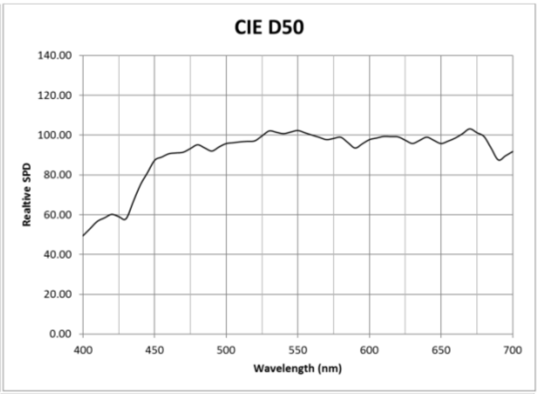


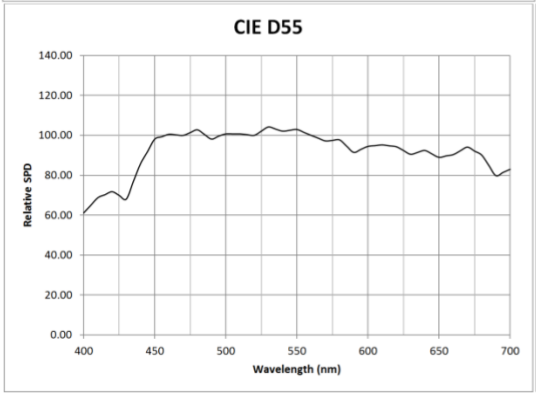
Figure A3 – Phytochrome Action Spectra.

Chlorophyllous leaves are transparent to infrared radiation, are so the phytochrome signaling mechanism is ideal for sensing the lighting environment on forest floors and in the presence of neighboring plants competing for available direct sunlight.

## Appendix B – Light Source SPDs


CIE A


CIE D50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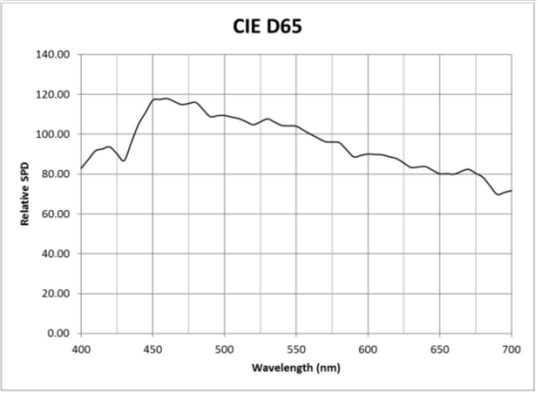
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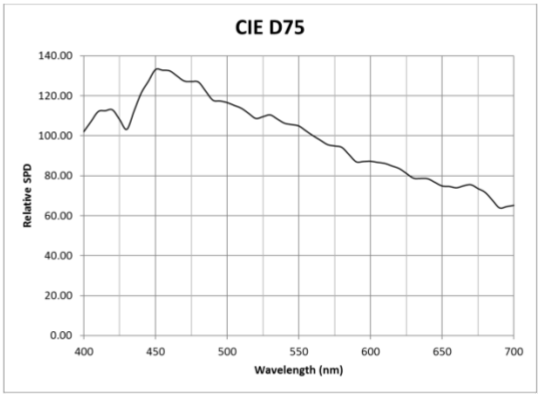
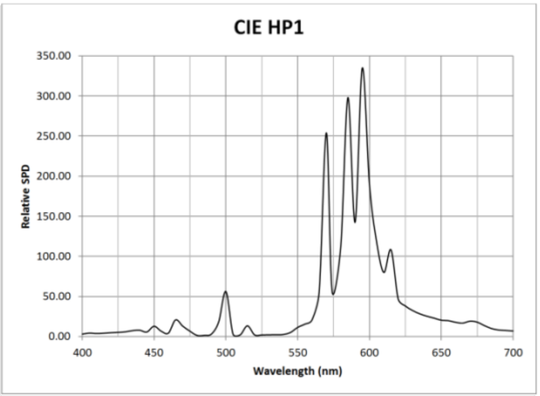
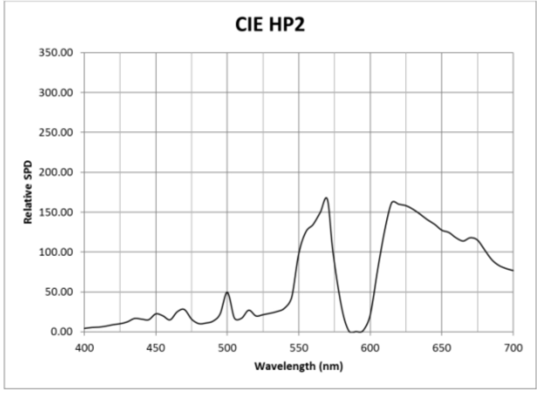
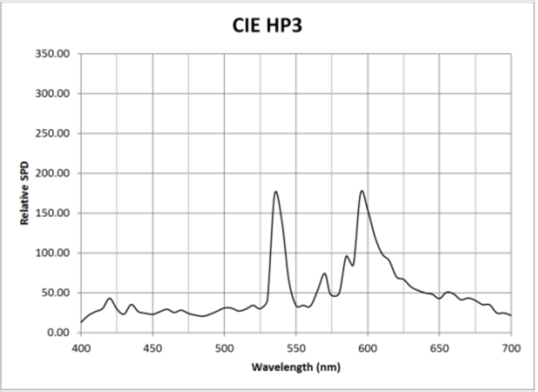

CIE D75
Relative SPD
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
400
450
500
550
600
650
700
Wavelength (nm)


CIE HP1
Relative SPD
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400
450
500
550
600
650
700
Wavelength (nm)


CIE HP2
Relative SPD
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400
450
500
550
600
650
700
Wavelength (nm)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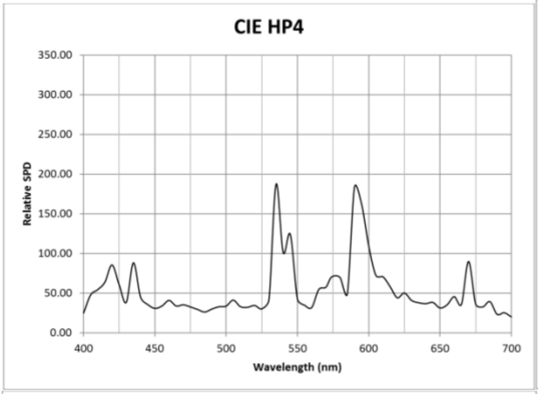
Relative SPD
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400
450
500
550
600
650
700
Wavelength (nm)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Relative SPD
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100.00
150.00
200.00
250.00
300.00
350.00
400
450
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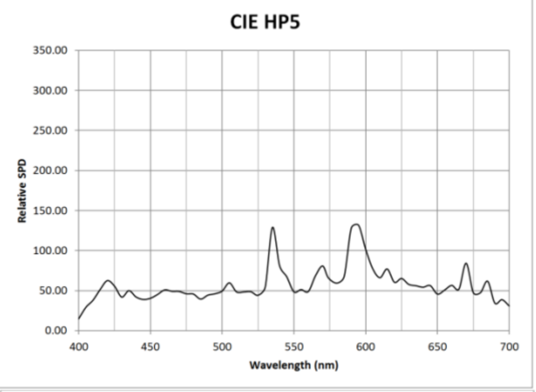
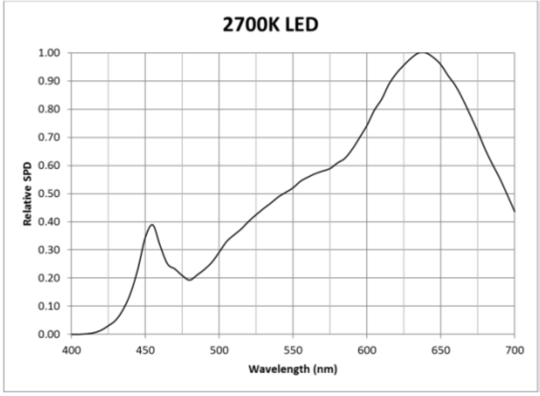
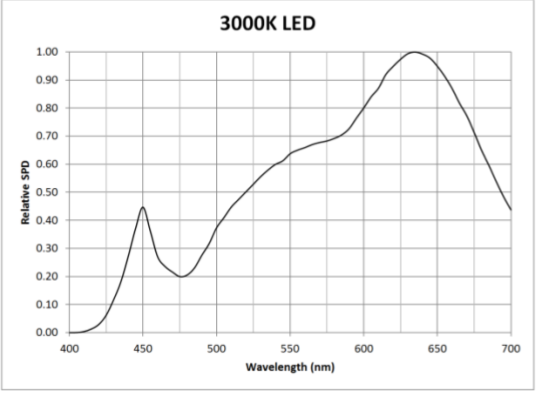
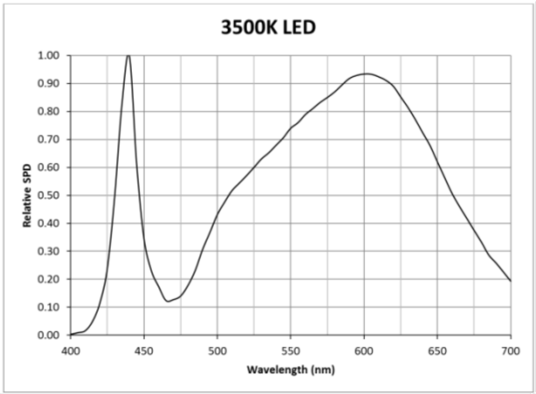
550
600
650
700
Wavelength (nm)

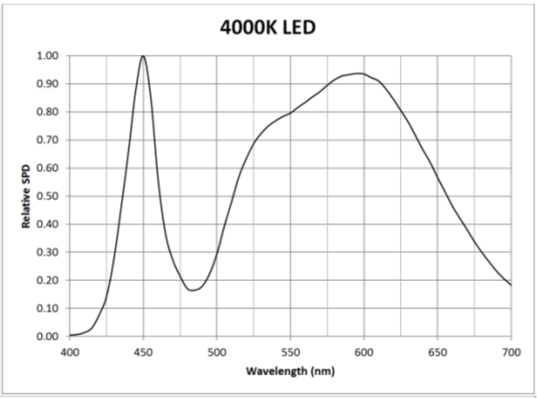

CIE HP5
Relative SPD
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400
450
500
550
600
650
700
Wavelength (nm)


2700K LED
Relative SPD
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
400
450
500
550
600
650
700
Wavelength (nm)

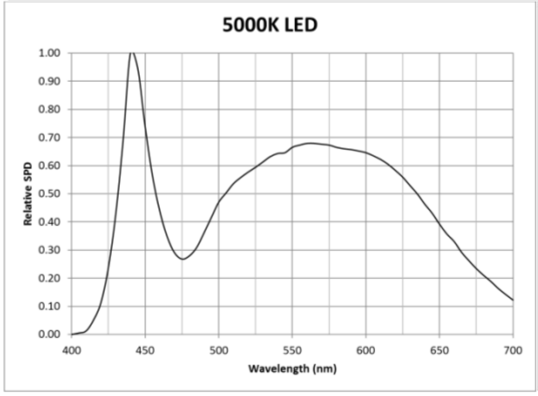

3000K LED
Relative SPD
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
400
450
500
550
600
650
700
Wavelength (nm)



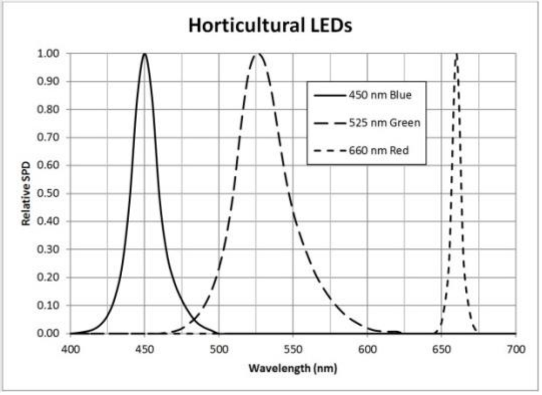
3500K LED



4000K LED



5000K LED



Horticultural LEDs

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[1] A MOLE is a unit of measurement used in chemistry to express the number of elementary entities in a substance that is equal to the number of atoms in 12 grams of the isotope carbon-12. It corresponds to the AVOGADRO CONSTANT, whose value $N_A$ is $6.022 \times 10^{23}$ particles (in this case photons) per mole. A MICROMOLE is one millionth of a mole. (A micromole [µMOL] of photons was sometimes referred to by plant scientists as a MICROEINSTEIN. However, this unit of measurement is not part of the International System of Units (SI), and so its use has been deprecated.)

[2] The QUANTUM YIELD in photosynthesis is defined as the micromoles of carbon dioxide fixed per micromole of photons absorbed.

# HEALTH INFORMATION

# IN THE BLOOD

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2014/06/25

We most often think of lighting design in terms of lumens, color temperature, and CRI, but there are occasional situations where a deeper analysis is required. One such situation is as close as your doctor's office: the examination room.

An examination room is typically windowless and illuminated only by linear fluorescent lamps. In examining the patient's skin for anything from bruises to lesions, the doctor relies on experience to assess skin color. Anything that influences this perceived color should be a concern, for it could potentially lead to a misdiagnosis.

As lighting designers, our usual criterion for selecting light sources is the CIE General Colour Rendering Index (CRI) metric (CIE 1995). Anyone who remembers the first generation of white light LED products will recognize that CIE Special Colour Rendering Index R9 is also important, as it determines the red content needed for acceptable skin tones.

This however may not be enough for applications involving medical diagnosis. It is an interesting exercise to ask what determines our skin color and whether different illuminants might lead to unexpected changes in perceived color.

## Skin Color

Skin color shows large variations across continental populations, but it is mostly due to the concentration of two biopolymers: eumelanin and pheomelanin (e.g., Parra 2007). Eumelanin is dark brown to black in color, while pheomelanin is yellow to reddish brown. Our skin produces melanin in response to exposure to ultraviolet radiation, causing the skin to visibly tan. (Melanin is a highly effective natural sunscreen.)

By itself, melanin is not particularly interesting from a lighting design perspective. As shown in FIG. 1, it has a smooth spectral absorption spectrum that increases monotonically with decreasing wavelength. Changes in the spectral power distribution of the light source will have little effect on perceived color as long as the light sources have the same correlated color temperature (CCT) and similar CRI values.

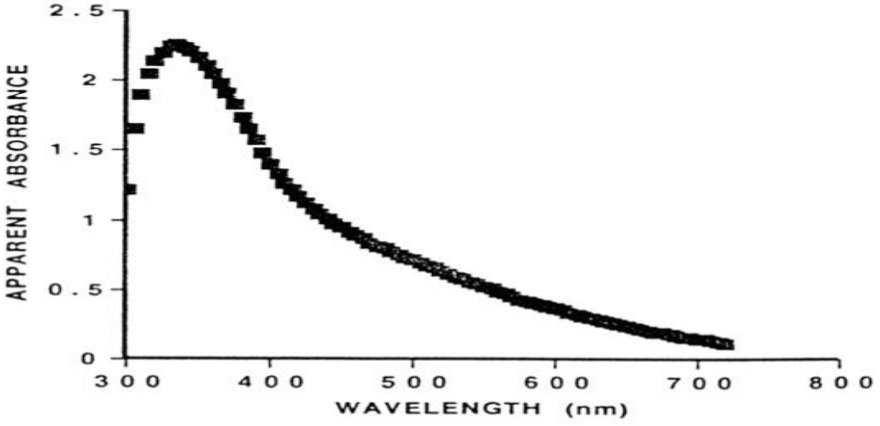

FIG. 1 – Melanin absorption spectrum (Kollias [1995]).

A secondary but still important determinant of skin color is the hemoglobin in our blood. It is responsible for example for the reddish color of sunburnt skin, as well as the inflammation that accompanies many skin infections. Its presence becomes more noticeable in fair-skinned individuals. There are two types of hemoglobin in our blood — oxygenated (designated $HBO_2$) and deoxygenated (designated HB). Unlike melanin, they have rather complex spectral absorption spectra, as shown in FIG. 2.

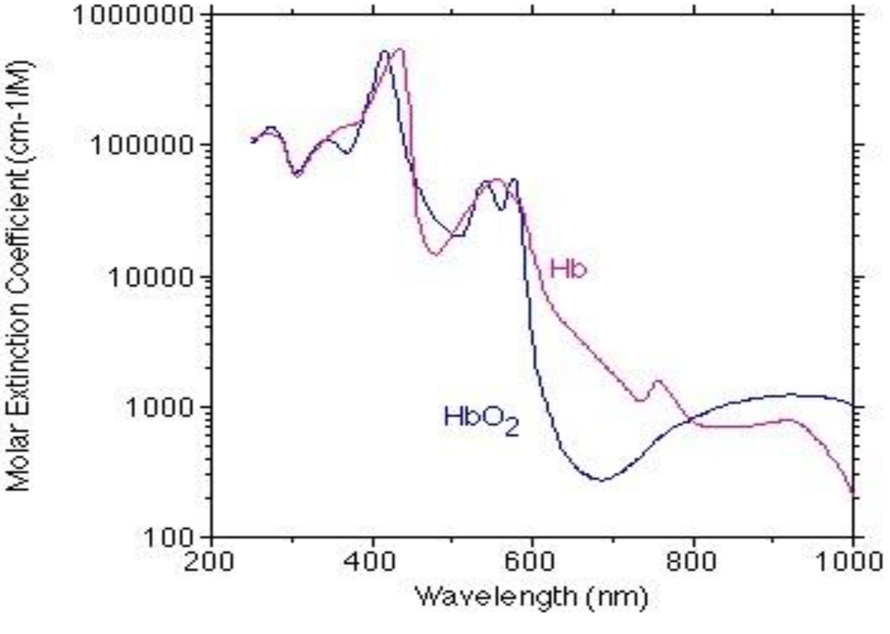

FIG. 2 – Hemoglobin absorption spectra (Prahl [1999]).

The contributions of both melanin and hemoglobin are evident in FIG. 3, which shows the variation in spectral reflectance of the inner upper arms (chosen to avoid suntan issues) of subjects from several different continental populations. Those with dark skin have smooth spectral reflectance distributions characteristic of melanin, while those with fair skin have complex spectral reflectance distributions due to the contribution of hemoglobin.

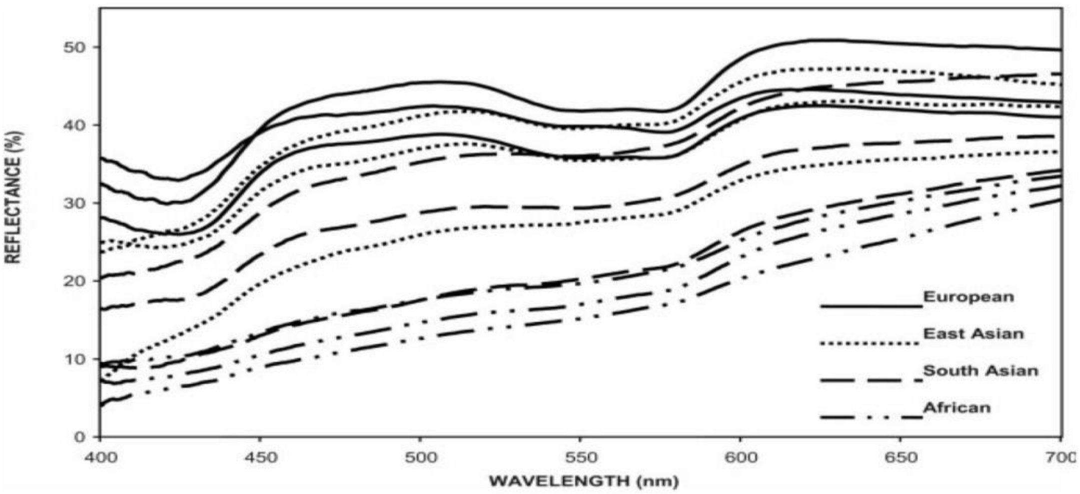

FIG. 3 – Skin spectral reflectance (Parra [2007]).

## Hypothesis

What is interesting about FIG. 3 is that Caucasian skin exhibits a pronounced dip in reflectance at 430 nm, presumably due to the absorption spectrum of both oxygenated and deoxygenated hemoglobin. This corresponds almost exactly with the narrowband emission of blue light from linear fluorescent lamps, which peaks at 435 nm as shown in FIGs. 4A – 4C.

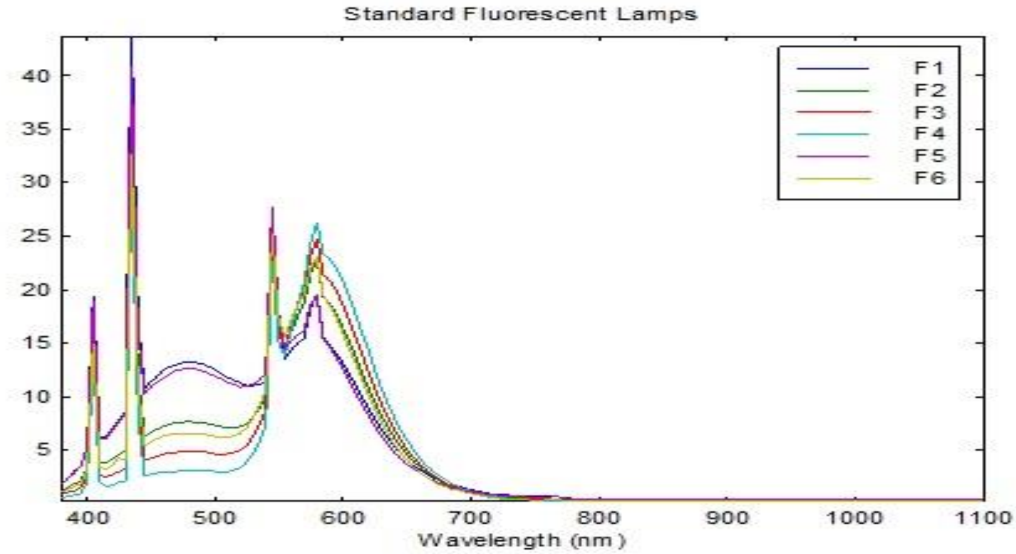

FIG. 4A – Halophosphate fluorescent lamp spectra (CIE 2004).

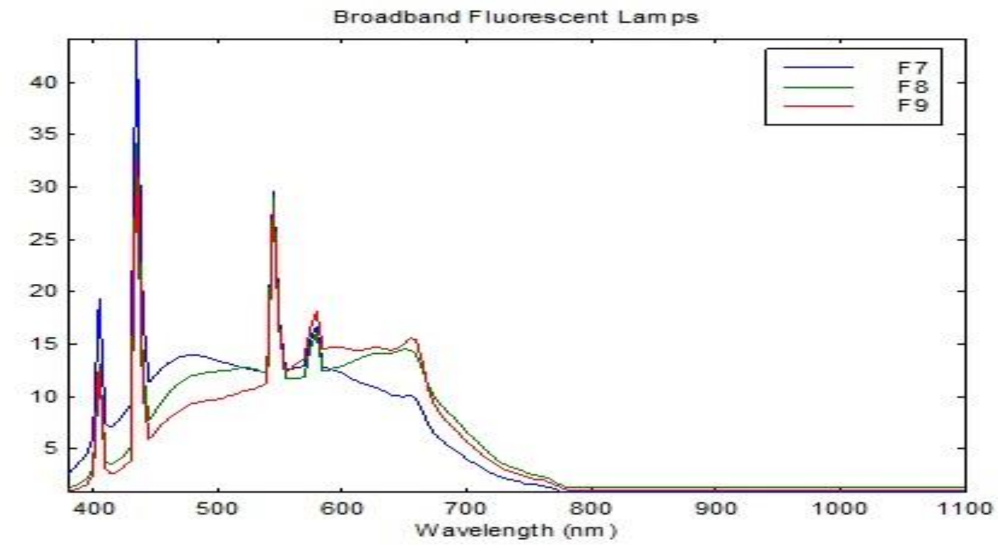

FIG. 4B – Broadband fluorescent lamp spectra (CIE 2004).

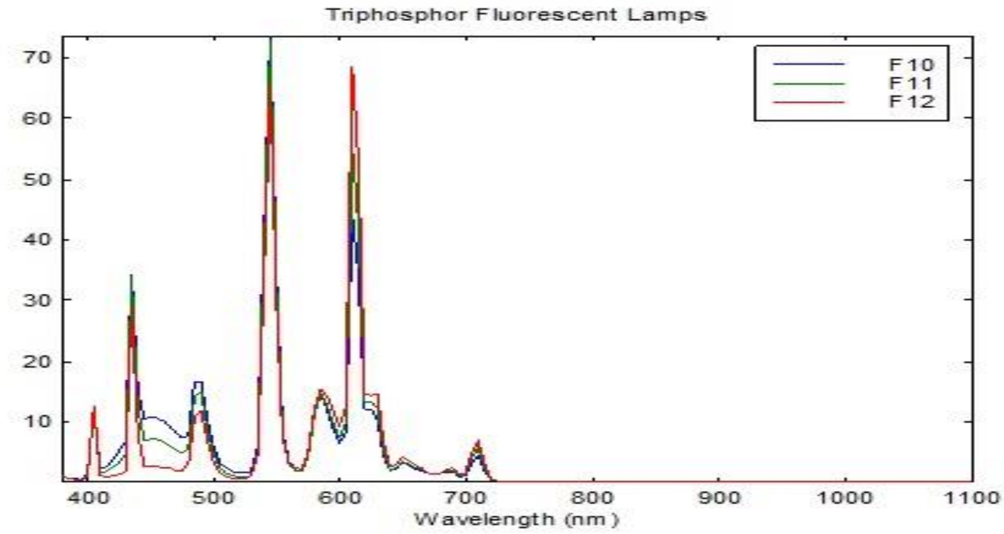

FIG. 4C – Triphosphor fluorescent lamp spectra (CIE 2004).

By comparison, FIG. 5 shows the spectral power distribution of a typical white light phosphor-coated LED (in this case a Philips LUXEON K LED array). The phosphor pump LED has a peak wavelength of 450 nm.

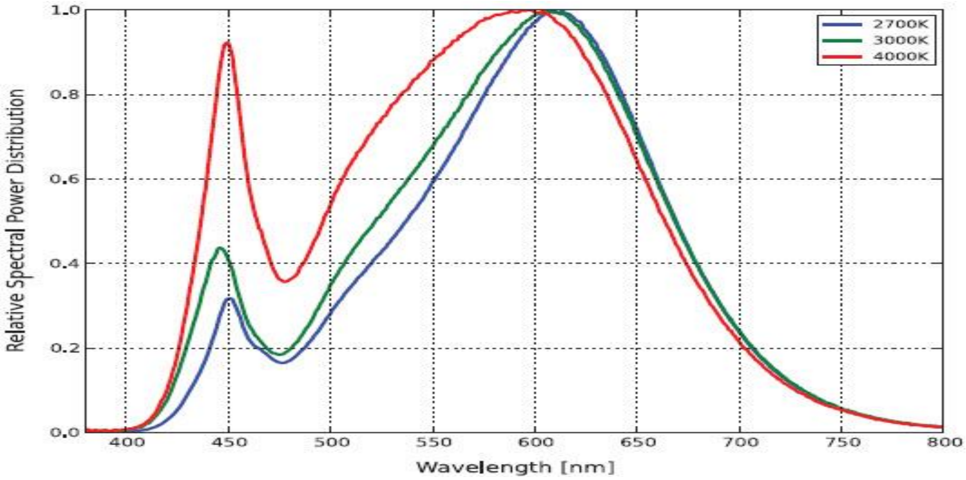

FIG. 5 – White light phosphor-coated LED spectra (Philips Lumileds 2014).

The hypothesis is this: even if an LED-based replacement lamp for a linear fluorescent lamp has the same CCT and similar CRI, the LED peak wavelength is not centered on the absorption peak of hemoglobin. As shown in FIG. 3, Caucasian skin reflectance at 450 nm can be some 25 percent greater than at 430 nm. Certainly increasing the amount of blue light from an RGB luminaire by 25 percent changes the color of the emitted light. The question is whether this will change the perceived skin color for medical diagnosis.

The issue is complicated by the finite width of the emitted blue light in the blue region of the spectrum. The LED has a full width half maximum (FWHM) value of 35 nm, while the fluorescent lamps appear to have FWHM values of less than 10nm. (The CIE lamp spectra are tabulated in units of 5 nm.)

The best way to test this hypothesis then is to calculate the theoretical perceived skin color (technically its chromaticity) using the lamp spectra and the worst-case skin (Caucasian) spectral reflectance distribution.

## Calculation Method

The calculation method is quite simple. We have the fluorescent lamp spectra tabulated at 5 nm, courtesy of Table T.6, “Relative spectral power distributions of illuminants representing typical fluorescent lamps,” from CIE 15:2004, Colorimetry (CIE 2004), over the range of 400 to 700 nm. To ensure comparable CCTs, we choose CIE F6 (4150 K), CIE F9 (4150K), and CIE F11 (4000K).

Philips does not provide tabulated spectral power distribution data for their LUXEON products, but it is easy enough to digitize the data using for example the freeware program PLOT DIGITIZER (http://plotdigitizer.sourceforge.net). Again, the 4000K product is selected.
Finally, the skin reflectance data can be digitized from the PDF file of the paper by Parra (2007).
With this, the CIE 1931 tristimulus coordinates $X$, $Y$, $Z$ for each light source can be calculated as the sums:

$$X = \sum_{400}^{700} s(\lambda)\, E(\lambda) \bar{x}(\lambda)$$
$$Y = \sum_{400}^{700} s(\lambda)\, E(\lambda) \bar{y}(\lambda)$$
$$Z = \sum_{400}^{700} s(\lambda)\, E(\lambda) \bar{z}(\lambda)$$

where S is the skin reflectance at the designated wavelength, E is the relative light source intensity, and X-BAR, Y-BAR, and Z-BAR are the CIE color matching function values (from CIE 2004). From these, we can calculate the CIE 1931 XY chromaticity values as:

$$x = \frac{X}{X + Y + Z}$$
$$y = \frac{Y}{X + Y + Z}$$

If we choose the CIE F11 triphosphor lamp as our reference illuminant, this gives us:

| Light Source | CCT | X | Y | DX | DY | JND |
|---|---|---|---|---|---|---|
| F6 | 4150K | 0.395 | 0.398 | -0.009 | +0.011 | 2 |
| F9 | 4150K | 0.393 | 0.383 | -0.011 | -0.004 | 1 |
| F11 | 4000K | 0.404 | 0.387 | +0.000 | 0.000 | 0 |
| Luxeon K | 4000K | 0.398 | 0.388 | -0.006 | +0.001 | 0 |

where JND represent one MacAdam ellipse (MacAdam 1942), or a “just noticeable difference” in perceived color under laboratory conditions from that of the reference lamp.

The halophosphate F6 fluorescent lamp results provide a useful sanity check. These 1970s-era lamps had very low red content and consequently CRIs in the low 70s. They tended to lend greenish color casts to Caucasian skin, which is shown by the two-MacAdam ellipse color shift towards green.
For modern triphosphor fluorescent lamps, however, we can see that there should be no perceptible color shift for normal skin color if they are replaced with white phosphor-coated LED products. In other words, the hypothesis is disproven.

**Disclaimer**

This analysis necessarily considers normal Caucasian skin color only, based on the published results of Parra [2007]. It does not consider the abnormal skin colors due to for example hypoxia (low oxygenated blood levels). Such conditions are most often diagnosed using quantitative techniques, such as pulse oximetry (which measures the relative difference in transmittance of HB and $HBO_2$ at visible and infrared wavelengths.) Research is also being conducted into whether “spectrally-tuned” light sources might increase the contrast of various skin conditions when viewed in visible light — see for example Litorja et al. (2007, 2009, and 2010), and Murai et al. (2012).

More important, this analysis has not been experimentally verified or peer-reviewed, and must not be taken as medical advice. If the question is asked, all that can be said is that, “theoretical analysis indicates that there should be no difference in the use of fluorescent versus LED-based replacement lamps for medical diagnosis of skin conditions.” If necessary, this analysis should be experimentally confirmed by a qualified physician who will be using the facility being designed.

## Conclusion

It is interesting that this analysis has produced what is effectively a negative result. As such, it is unlikely that it would be accepted for publication by a peer-reviewed journal. Regardless, the result (subject to the disclaimer) itself is informative for lighting designers.

Taking a broader view, this analysis highlights the need for an industry standard for the electronic transfer of spectral data, much as IES LM-63-02 and EULUMDAT enable the electronic transfer of photometric data. It is frustrating and error-prone to have to manually digitize spectral data from scans of printed documents and screen captures of PDF files.

Fortunately, this situation is about to change. As of this writing, the IES Board has approved the publication of IES TM-27-14, IES STANDARD FORMAT FOR THE ELECTRONIC TRANSFER OF SPECTRAL DATA. This document is scheduled for ANSI, and hopefully IEC, approval as an international standard. Once lamp and LED module manufacturers adopt this data format for their product specifications, studies such as this will become considerably easier to perform.

## Acknowledgements

The topic of this blog posting arose from discussions with fellow members of the Human Centric Lighting Committee.

### Update 2014/06/25

One of the joys of self-publishing through blogs is that you can post new information as it becomes available.

Cyanosis is the appearance of a blue or purplish discoloration of the skin due to the tissues near the skin surface having low oxygen saturation. I was aware of this medication condition while writing this article, but decided against discussing it on the advice of my family doctor, who had not seen a case of it in 25 years of family and sports medicine practice. If it is seen at all, it is likely in the emergency room, where pulse oximeters are usually available.

Regardless, there is a paper on the topic — “Lighting for Clinical Observation of Cyanosis” (Midolo and Sergeyeva [2007]) — and a government standard that lamps for hospital lighting in Australia and New Zealand must meet (AS/NZS [1997]) — the Cyanosis Observation Index (COI). There is also a now-outdated article on why older-style triphosphor lamps manufactured in the 1990s were not suitable for hospital lighting (LightLab [1997]).

Related to this is an interesting Philips white paper, “The Role of Lighting in Promoting Well-Being and Recovery within Healthcare” (Schlangen 2010). This 32-page publication on human-centric lighting for healthcare provides over 100 useful references to the literature.

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# BLUE LIGHT HAZARD… OR NOT?

## ARGUMENTUM AB AUCTORITATE

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2014/11/05

As a professional lighting designer, you will likely have read about the "blue light hazard" associated with white light-emitting diodes. You will have seen warnings like this (Willmorth 2014a):

"… *long term exposure to blue light at 441nm caused lesions on the retinas of rhesus monkeys,"*

and recommendations like this from the same author:

"Use the lowest cct led color with the highest cri available to suit the lighting application – including avoidance of high cct (> 5000k), low cri (<80) sources altogether, and eliminate use of blue-light rich products, such as those generating >5500K AT <65CRI."

and even this (Kitchel 2000):

"…all persons with vision problems should be removed from a light environment where the predominant light waves are a temperature above 3500k or a wavelength less than approximately 500 nm."

It is a confusing situation for lighting designers, as there are well-documented vision and health benefits to the use of high-CCT lighting. These benefits include circadian rhythm entrainment (e.g., Holzman 2010) and improved visibility (e.g., Berman et al. 2006). Taken together, the recommendations are at best contradictory.

As always, "… there is a need for more focused research leading to practical recommendations on this subject" (Willmorth 2014a). In the meantime, however, lighting designers need to make informed decisions on behalf of their clients. What to do?

There is no short answer. As this article demonstrates, the issue of blue light causing retinal lesions is based on a misunderstanding of vision research work done in the 1970s. It is still an open question as to whether long-term chronic exposure to blue light may cause vision problems, but the evidence to date (known to this author at least) is not persuasive. [UPDATE 14/11/08 – see concluding paragraphs and SCENIHR (2012).]

[UPDATE 14/12/11 – See revised concluding paragraphs and GLA 2012.]
The recommendation above – "*use the lowest cct led color with the highest cri available to suit the lighting application"* – also highlights the danger to journalists when combining reviews of the academic literature with design recommendations. While it could be construed from the article that this recommendation is based on concerns about vision problems, it is instead advice that the author would communicate to any client (Willmorth 2014b), regardless of the academic literature.

To be perfectly clear, this article is in no way meant as a criticism of Willmorth (2014a). It is instead an exploration of how scientific research can be misinterpreted and then promulgated in good faith as scientific fact. It is a problem that all science journalists face, myself included.

More to the point however, this article attempts to clarify some of the issues concerning the "blue light hazard." As lighting designers, it is important to realize that direct viewing of extremely high-brightness LEDs may cause eye damage. At the same time, it is important to understand that these concerns are distinct from everyday interior lighting design practices.

## Background

Lighting Research Center researcher John Bullough published "The Blue-Light Hazard: A Review" in the Journal of the Illuminating Engineering Society (Bullough 2000), in which he summarized the research on the role of short-wavelength (i.e. deep blue) light and ultraviolet radiation in retinal damage. Quoting from this paper:

"For practical purposes with 'white' light sources, any condition resulting in direct exposure to luminances under 10,000 cd/m2 is unlikely to present a risk of photochemical injury to the retina. for such sources, calculation of the blue light hazard is not necessary."

Putting this into context:

"*… might lead one to believe [that] fluorescent lamps present greater risk than incandescent lamps, because they produce a greater portion of their light in the short-range portion of the visible spectrum. however, because fluorescent lamps also have low luminances (t12 lamps: 8,000 cd/m2; t8 lamps: 11,000 cd/m2; t5 lamps: 20,000 cd/m2), their potential risk for photochemical injury is negligible …"*

Bullough examined potential risks in the context of medical equipment, industrial equipment, and high-flux theatrical lighting. In terms of extremely high-brightness LEDs, there is clearly a risk in viewing them directly. People with aphakia (absence of the lens of the eye, often due to surgical removal) may also be at risk. In general, however, *there is no blue light hazard for interior* lighting applications.

## Trust in Authority

So where did the current "blue light hazard" meme originate? Willmott (2014a) notwithstanding, why are lighting designers now being advised to avoid high-CCT lighting wherever and whenever possible? The underlying problem is that lighting designers cannot be expected to follow the medical literature on which these recommendations may be based. How many people for example outside of the medical profession read such journals as *Epidemiology and Biostatistics or Investigative Ophthamology & Visual Science?* (How many people can even spell "ophthalmology" correctly, for that matter?)

The solution is beguilingly simple: trust in those who are experts in such matters. Lighting designers read trade journals such as LIGHTING DESIGN & APPLICATION AND ARCHITECTURAL SSL because of these publications’ reputation for accurate and useful information. Their technical articles are after all either written by qualified experts, or by staff writers who consult them.

Who we trust however is subject to the logical fallacy of argumentum ab auctoritate, or “argument from authority” (including trust in those who, like me, quote Latin phrases). In more colloquial terms, “Just because you say it’s so don’t make it so!”

To illustrate this argument, consider the quotation above (Willmorth 2014a):

“… long term exposure to blue light at 441nm caused lesions on the retinas of rhesus monkeys.”

The article in question is titled, “The Dark Side of BLUE LIGHT,” which was written by Kevin Willmorth, Consulting Editor for Architectural SSL. Educated at the University of Phoenix, he has over 33 years of experience in lighting design and product development. Given this, there is no reason to question his authority per se. However, we need to ask where this worrisome statement came from.

Like most trade journals, Architectural SSL has an aversion to publishing full references in its technical articles. There are two likely reasons for this: 1) very few readers will be interested in reading the referenced papers; and 2) full references consume valuable advertising space. Regardless of the reasons, the author can do no more than identify the name of the researcher and possibly the paper’s title in the text of the article.

In other words, trust in authority.

## Full References

Thankfully, Willmorth was fairly specific in referencing (in the same sentence) “THE EFFECTS OF BLUE LIGHT ON OCULAR HEALTH (KITCHEL, E. AMERICAN PRINTING HOUSE FOR THE BLIND.” (The more common alternative is to simply say, “ACCORDING TO …”) A simple Web search leads directly to http://www.cclvi.org/contributions/effects1.htm. It is an online article, but it was originally published in the JOURNAL OF VISUAL IMPAIRMENT AND BLINDNESS (Kitchel 2000).

Elaine Kitchel is Low Vision Project Leader at the American Printing House for the Blind, with a Masters of Education from the University of Arizona. In her review article, she writes:

*“In an early study conducted by ham, Ruffolo, Mueller and Guerry, (1980) rhesus monkeys were exposed to high-intensity blue light at 441nm for a duration of 1000 seconds. two days later lesions were formed in the retinal pigmented epithelium (RPE.) these lesions consisted of an ‘inflammatory reaction accompanied with clumping of melanosomes and some macrophage invasion with engulfment of melanosomes which produce hypopigmentation of the RPE’ (ham et al., 1980, p.1110).”*

We now have a reference for the original quote, including a page number … or do we? Once again, the article does not include references, rather unhelpfully stating, “A bibliography is available separately.” Fourteen years after publication, it is unlikely that this unnamed document will still be available.

Trust in authority.

## Monkey Business

Fortunately, it is possible with some effort to ascertain the proper reference. It is:
HAM, W. T., JR., H. A. MUELLER, J. J. RUFFOLO JR., AND D. GUERRY. 1980. “*The Nature of Retinal Radiation Damage: Dependence on Wavelength, Power Level, and Exposure Time,” Vision Research 20(12):1105-1111.*

William T. Ham and his fellow researchers were at the time associated with the Department of Biophysics, Virginia Commonwealth University (Richmond, VA). Vision Research being a highly respected peer-reviewed journal, their paper of course included copious references.

Trust in authority? Not quite … if you obtain and read the review paper, you will find no mention of “blue light at 441 nm” on page 1110. Here is what the authors wrote:

“*Histological data, Ham et al., (1978), on the retina of the rhesus monkey demonstrate that short wavelength light plays a role in the clumping and phagocytosis of melanin. The appearance of a mild lesion in the RPE of the rhesus monkey at 90 days postexposure suggests a striking similarity to senile macular degeneration. In the opinion of the authors, long-term, chronic exposure to short wavelength light is a strong contributing factor to senile macular degeneration.”*

This is an interesting observation that is apparently still valid – see for example Berman and Clear (2014) – but it is not what we are after.

In reading the full paper, there is an interesting figure caption on page 1107:

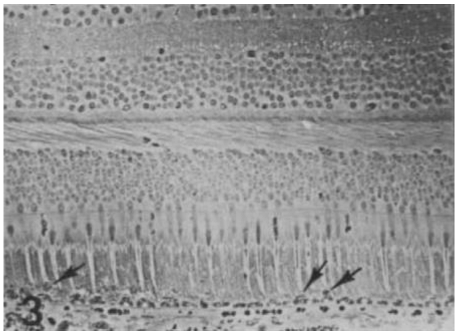

Fig. 3 – Retinal response in the same eye as Fig. 2 at 2 days after a 1000 sec exposure to 441 nm light (10 nm bandpass). the image diameter at the retina was 1 mm, and the radiant exposure was 33 j/cm2. FIG. 1 – Retinal damage due to laser light exposure. (Source: Ham et. al. 1980.)

This microphotograph of a rhesus monkey’s retina is from research reported by Ham et al. (1978), which was based on an earlier paper (Ham et al. 1976), both listed in the references. The arrows in the image indicate the observed lesions.

It helps to have some appreciation of the nature of this research. Ten rhesus monkeys were anesthetized and laser beams shone into their eyes in order to determine the damage threshold for various beam intensities and wavelengths. The primates were then later “sacrificed” and their eyes dissected to obtain the microphotographs showing possible radiation damage. This is clearly not the sort of research that can be conducted on human subjects.

In their paper, the authors reported the following radiation damage thresholds for a 441.6 nm helium-cadmium laser:

| 1 second | 16 seconds | 100 seconds | 1000 seconds |
|---|---|---|---|
| 0.91 watts / cm$^2$ | 0.41 watts / cm$^2$ | 0.20 watts / cm$^2$ | 0.03 watts / cm$^2$ |

(A joule is one watt-second, so 0.03 watts per square centimeter for 1,000 seconds is 30 joules/cm2, as indicated in Figure 3 above.)

In their 1978 paper, the authors replaced the laser beam with a 2,500-watt xenon lamp and a 6 nm bandwidth interference filter at 441 nm with associated optics to focus the beam onto a 1-mm diameter region of the monkey’s retina for up to 1,000 seconds. (Kids, don’t try this science experiment at home …)

Grim and disturbing details aside, we have finally answered the question – where did the information quoted by Kitchel and through her by Willmorth come from?

What we have not answered however is the question of whether this research is relevant to the “blue light hazard” issue.

### Inadmissible Evidence

It is true that Ham et al. (1976, 1978) established that exposure to blue light can cause retinal lesions, however microscopic. However, maximum exposure times of 1,000 seconds (16 minutes) are hardly “long-term exposure” as described by Willmorth (2014). Simply put, the research of Ham et al. did not address the issue of long-term exposure to blue light.

Equally interesting is this quote: (Ham et al. 1976):

*“… the solar retinal irradiance at 440 nm for a 20-nm spectral band is approximately 0.20 W/cm2 at midday for an eye gazing directly at the Sun at sea level for a 2-mm diameter pupil. In comparison, the threshold irradiance for a 100-sec exposure to the 441-nm laser line of He-Cd is 0.20 w/cm2. Thus, sungazing at bright midnoon for 100 sec can produce a threshold lesion … those subject to exposure to bright sunlight over long periods should take precautions to shield their eyes from the short wavelengths of solar radiation.”*

In other words, what Ham et al. discovered through careful experiment was the glaringly obvious: *do not stare at the noonday sun without blinking for longer than fifteen minutes.* This is not mockery of their research – Ham et al. were investigating the distinction between thermal and photochemical effects of high-intensity light on the retina. Their comparison with sungazing, while instructive, was merely by way of analogy to put the beam intensity levels into context for the reader.

This is not to say that long-term chronic exposure to blue-rich light does not result in adverse health effects, including cataracts and age-related macular degeneration. Ham et al. did their work nearly forty years ago. There may well be more recent research that is relevant to the "blue light hazard," such as for example Shang et al. (2014). (Whether this fundamentally flawed paper is applicable to human vision is a separate issue.)

Regardless, the research of Ham et al. is "inadmissible evidence" (to use the legal expression) with respect to the long-term effects of blue light exposure. It is not a question as to whether it is right or wrong, but simply that it does not apply.

The problem – the real problem – is that journalists are expected to interpret academic research for the general public. Like Willmott and Kitchel, they may have considerable knowledge in their fields of expertise. Unfortunately, the "blue light hazard" issue intersects research fields in both lighting and medicine. As such, journalists need to take particular care in interpreting published papers on the topic. For whatever reason, there was some miscommunication in this case.

## Conclusion

To summarize, there may possibly be persuasive evidence that long-term chronic exposure to blue-rich (i.e., high CCT) lighting may adversely affect our vision and health. Articles such as "The Dark Side of BLUE LIGHT" (Willmorth 2014a) and "The Effects of Blue Light on Ocular Health" (Kitchel 2000) have referred to the academic research literature (Ham et al. 1980) as evidence of danger. Unfortunately, all that this research proved in the context of the "blue light hazard" was the obvious: *do not stare at the noonday sun without blinking for longer than fifteen minutes.*

As Kevin Willmorth said, "*… there is a need for more focused research leading to practical recommendations on this subject."* In the meantime, however, this author at least is still looking for persuasive evidence that there is any significant blue light hazard associated with high-CCT LED lighting.

At the same time, I agree with Kevin when he says (Willmorth 2014b), "*I cannot recommend [that] anyone apply poor-quality, low color performance light sources of any type when alternative are available*" … but this is just our opinion. In the absence of evidence to the contrary, there does not appear to be any scientific reason to be concerned about blue-rich lighting in typical interior environments.

## **UP**DATE – November 8, 2014

In 2010, the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) published a 310-page report (in French) titled, "Health Effects of Lighting Systems Using Light-Emitting Diodes (LEDs)" (ANSES 2010), with an English-language opinion and summary (ANSES 2010b). Page 3 of the summary reads:

*“Some scientific studies [Dawson et al., 2001, Ueda et al., 2009], based on laboratory experiments with blue LEDs conducted on monkeys, give reason to suspect a danger for the retina related to exposure to light-emitting diodes.”*

Déjà vu, non?

The remainder of the summary offers recommendations that are reasonable in view of the photobiological risks of high-brightness LEDs. However, the risk of having the “reason to suspect” statement taken out of context in support of the “blue light hazard” meme remains.

Reading the referenced papers of course provides more information. Dawson et al. (2001) sacrificed five rhesus monkeys after exposing them to between 5 and 54 joules/cm2 of blue light from a 458 nm argon laser. Again, this is roughly equivalent to staring at the noonday sun without blinking for 3 to 25 minutes.

Ueda et al. (2009) sacrificed eight monkeys (two rhesus and six long-tailed macaque) after exposing them to between 20 and 60 joules/cm2 from Nichia NSPB550S blue LEDs with a dominant wavelength of 465 nm. Similar to the earlier studies of Hall et al. (1976), they reported retinal lesions after exposure to 35 joules/cm2, but no detectable results after exposure to 20 joules/cm2.

FIG. 2 – Long-tailed Macaque. (Photo credit: Lea Maimone)

There must be something apparently irresistible about such studies, as van Norren et al. (2011) provide a critical review of no fewer than 56 papers on the topic. What is interesting is that the results of eight such experiments (including Ham et al. 1976) yielded essentially the same results for rabbits and monkeys:

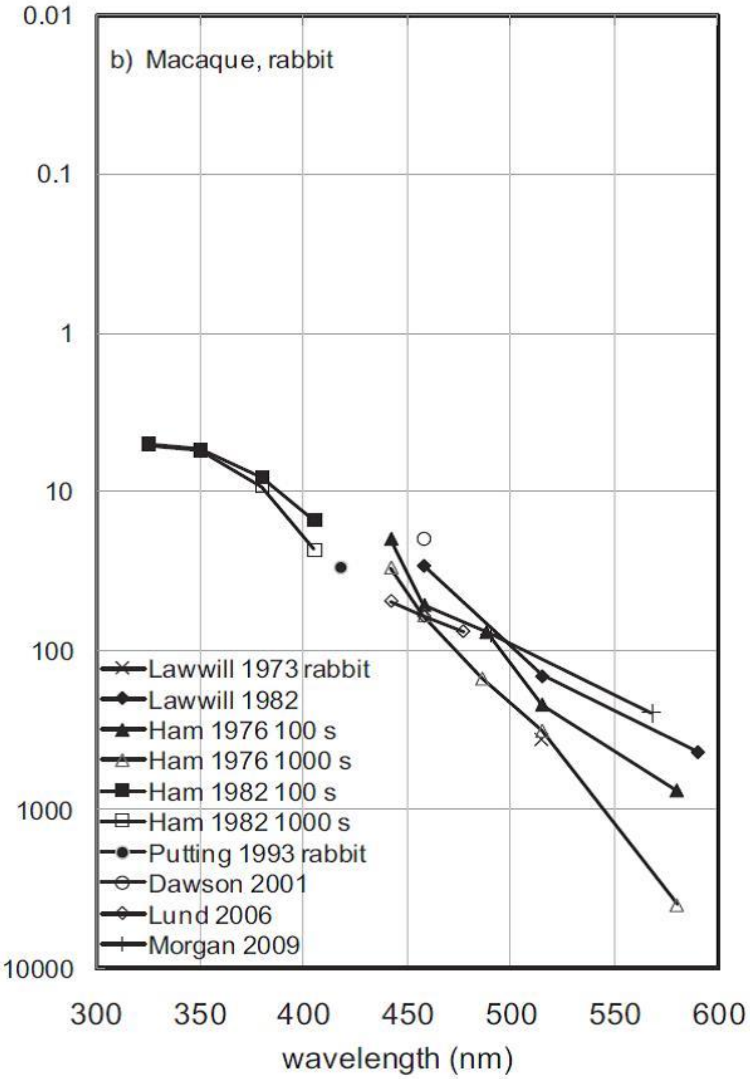

FIG. 3 – Dose for retinal damage versus wavelength. Source: Fig. 1(b), van Norren et al. (2011)

while the results for rodents (including both albino and pigmented rats) were equally similar. To summarize these results, do not stare at the noonday sun without blinking for longer than fifteen minutes. Once again, the evidence that long-term chronic exposure to blue-rich (i.e., high CCT) lighting may adversely affect our vision and health is not persuasive.

A much more interesting publication was recently published by the International Energy Agency (IEA 2014). Providing a wealth of information on the photobiological hazards of solid-state lighting, it concludes in Section 5.6.3, Potential Effects of Long-term Exposures, that:

*"The ICNIRP exposure limit values do not take into account the possibility of an exposure over an entire lifetime. Very little is known about the effects of life-long cumulated exposures to blue light emitted by LEDs. According to the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) of the European Commission [SCENIHR 2012], no evidence was found indicating that blue light from artificial lighting belonging to Risk Group 0 would have any impact on the retina graver than that of sunlight. The SCENIHR states that IEC 62471 gives limits that are protective against acute effects, while long-term effects are only marginally considered and estimated to be of negligible or small risk."*

Following the paper trail to its end, we have (SCENIHR 2012):

"*Evidence from in vitro experiments suggest that blue light at 10 W/m2 induces photochemical retinal damages (Class II) up on acute (hours) exposure, and animal experiments and in vitro studies suggest that cumulative blue light exposure below the levels causing acute effects also can induce photochemical retinal damage.*

*"There is no consistent evidence from epidemiological studies regarding the effect of long-term exposure to sunlight (specifically the blue component of sunlight) and photochemical damage to the retina (particularly to the retinal pigment epithelium), which may contribute to age-related macular degeneration (AMD) later in life. Whether exposure from artificial light could have effects related to AMD is uncertain.*

*"There is no evidence that artificial light from lamps belonging to RG0 or RG1 would cause any acute damage to the human eye. Studies dedicated to investigating whether retinal lesions can be induced by artificial light during normal lighting conditions are not available. Lamp types belonging to RG2 and higher are usually meant to be used by professionals in locations where they do not pose a risk. Chronic exposure to blue light from improperly used lamps could, in theory, induce photochemical retinal damage in certain circumstances. There is however no evidence that this constitutes a risk in practice. It is unlikely that chronic exposures to artificial light during normal lighting conditions could induce damage to the cornea, conjunctiva or lens."*

and finally, from the abstract (ibid):

*"There is no evidence that blue light from artificial lighting belonging to Risk Group 0 ("exempt from risk") would have any impact on the retina graver than that of sunlight. Blue light from improperly used lamps belonging to Risk Groups 1, 2, or 3 could, in theory, induce photochemical retinal. There is no evidence that this constitutes a risk in practice. Other damages to the eye from chronic artificial light exposure during normal lighting conditions are unlikely. Exposure to light at night (independent of lighting technology) while awake (e.g. shift work) may be associated with an increased risk of breast cancer and also cause sleep, gastrointestinal, mood and cardiovascular disorders."*

In the end, we have no option but to appeal to authority (argumentum ab auctoritate). SCENIHR (2012) represents the opinions of a dozen medical professionals who are presumed experts in the field. The difference however is that they are specifically addressing the issue of "blue light hazard" with full knowledge (circa 2012) of existing lighting technologies. Their 118-page report includes a staggering 341 references to the academic literature.

**UPDATE 14/12/11**:

The Global Lighting Association, representing ten regional lighting industry associations from around the world, released a white paper in March 2012 with the abbreviated title "Optical Safety of LEDs." There are two versions, one being a 22-page document with a detailed and in-depth analysis of the photobiological risks of common "white light" lamp types, and the other being a 4-page abridged document. Their well-documented position statement is simple: "*… based on accepted and widely* *adopted safety standards for lamps, is that all general lighting sources, including LED and CFL sources (either lamps or systems) and luminaires, can be safely used by the consumer when used as intended."*

There may be medical studies yet to be conducted that will demonstrate a blue light hazard for solid-state lighting in typical interior lighting applications. However, the absence of such evidence to date is highly persuasive: there is no scientific reason to be concerned about blue-rich lighting in typical interior environments.

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# DAYLIGHTING INFORMATION

# DAYLIGHT FACTORS

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 2014/03/05

Nine out of ten daylight simulation programs agree … and therein lies a story worth retelling.

## Daylight in History

The story begins in the sixth century with the publication of CORPUS JURIS CIVILIS ("Body of Civil Law") by order of the eastern Roman emperor Justinian I [Scott 1932]. Written in four volumes, it included the DIGEST, being extracts from the writings of earlier Roman jurists. Book VIII, Title 2, "Concerning Servitudes of Urban Estates," includes this legal distinction between daylight and views:

> *Light is the power of seeing the sky, and a difference exists between light and view; for a view of lower places may be had, but light cannot be obtained from a place which is lower.*

In a time when artificial lighting consisted of oil lamps, access to daylight was a critical issue. The Digest therefore had some 40 legal rulings on the rights of property owners concerning daylight. In some cases, a property owner whose newly-constructed building blocked a neighbor's access to daylight could be legally compelled to tear the building down.

Somewhat surprisingly, these rulings survived over the centuries to become what is referred to as the "ancient lights" law in European legal traditions. Modern use of this concept dates back to the British Prescription Act of 1832, which reads in part:

> *When the access and use of light to and for any dwelling house, workshop, or other building shall have been actually enjoyed therewith for the full period of twenty years without interruption, the right thereto shall be deemed absolute and indefeasible, any local usage or custom to the contrary notwithstanding, unless it shall appear that the same was enjoyed by some consent or agreement expressly made or given for that purpose by deed or writing*.

This enactment led of course to a new profession: RIGHTS TO LIGHT surveyors. These chartered professionals served as expert witnesses in legal disputes, and offered advice to architects. The surveyor Robert Kerr wrote a book on the topic in 1865, in which he took 55 pages to explain the practice of surveying access to daylight [Kerr 1865].

## Sky Factors

Complexity begets uncertainty however, and so it was that a chartered surveyor and lighting engineer named Percy J. Waldram proposed a much simpler way of determining adequate access to daylight [Waldram 1909]. It is today known in the United Kingdom as a "sky factor," and is defined as:

SKY FACTOR: THE RATIO OF THE ILLUMINANCE $E_{INDOOR}$ OF A HORIZONTAL PLANE AT A GIVEN POINT INSIDE A BUILDING DUE TO THE LIGHT RECEIVED DIRECTLY FROM AN OVERCAST SKY OF UNIFORM LUMINANCE SKY, TO THE ILLUMINANCE $E_{OUTDOOR}$ OF THE POINT DUE TO THE UNOBSTRUCTED SKY.

$$DF = ( E_{INDOOR} / E_{OUTDOOR} ) * 100\ \%$$

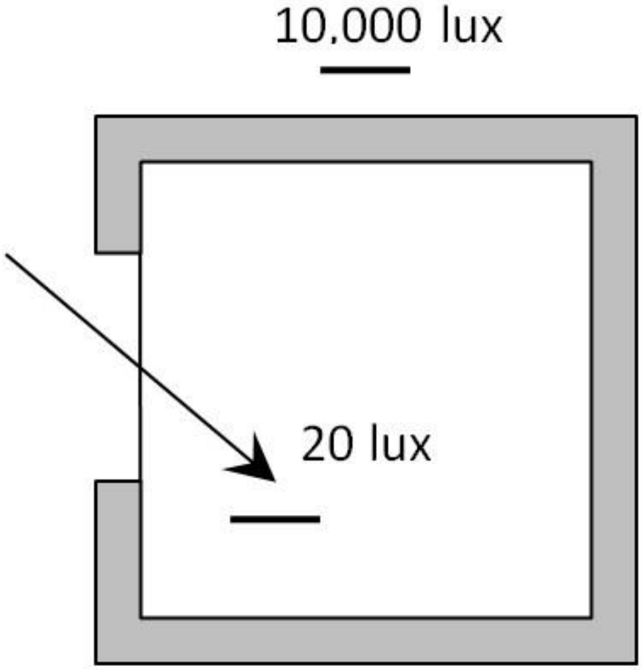

FIG. 1 – Daylight Factor.

Waldram and his son later suggested that a sky factor of 0.2 percent was sufficient “for ordinary purposes, comparable to clerical work” [Waldram and Waldram 1923]. Their seemingly offhand comment that this was the level at which “average reasonable persons would consistently grumble” became what is now referred to by British light surveyors in all seriousness as the “grumble point” [Chynoweth 2004].

The sky factor metric was accepted by the Commission Internationale de LíEclairage in 1932 [CIE 1932], and is still widely used in the United Kingdom by chartered surveyors. (It is however no longer recognized as a unit of light measurement by the British Standards Institution.)

Waldramís choice of 0.2 percent was simply a rule-of-thumb guess [Waldram and Waldram 1923], with no supporting research [Chynoweth 2005]. The Royal Institution of Chartered Surveyors recommends at least 0.5 percent (which on average is about 25 lux) [RICS 2010], but the British legal system still works on the assumption of 0.2 percent, or 10 lux [Chynoweth 2009]. This leads to the curious situation of a complex legal system that deliberately encourages and enforces poor daylighting practices.

## Daylight Factors

The sky factor metric is important in the United Kingdom because “rights to light” is a still-valid legal concept as an “easement right” that has descended from the rulings of ancient Roman jurists. This is not however the situation in American civil law, where access to daylight is considered a right only in exceptional circumstances [Unger 2005].

Regardless, the closely related “daylight factor” metric is widely used [CIE 1970]. This has the same basic definition as the sky factor above, with the exception that the CIE Standard Overcast Sky is used instead of a uniform luminance sky [IES 2013]. It also takes into account ground reflections, window transmittance, and interreflections from room surfaces.

This distinction is important. Both sky types are defined in CIE Standard S 011 [CIE 2003], where the CIE Standard Overcast Sky (Standard Sky Type 1) is described as, “steep luminance gradation towards zenith, azimuthal uniformity.” The sky factor metric however assumes CIE Standard Sky Type 5, “sky of uniform luminance.” (The “traditional” CIE Standard General Sky is now referred to as CIE Standard Sky Type 16; its luminance distribution near the horizon varies slightly from Sky Type 1.)

The advantage of a uniform luminance sky is that determining the sky factor for a given room is simply a matter of geometry. That is, the value of the sky factor is completely independent of the sky luminance distribution. It can in theory be calculated with the aid of Waldram diagrams using photographs or hand drawings [e.g., RICS 2010].

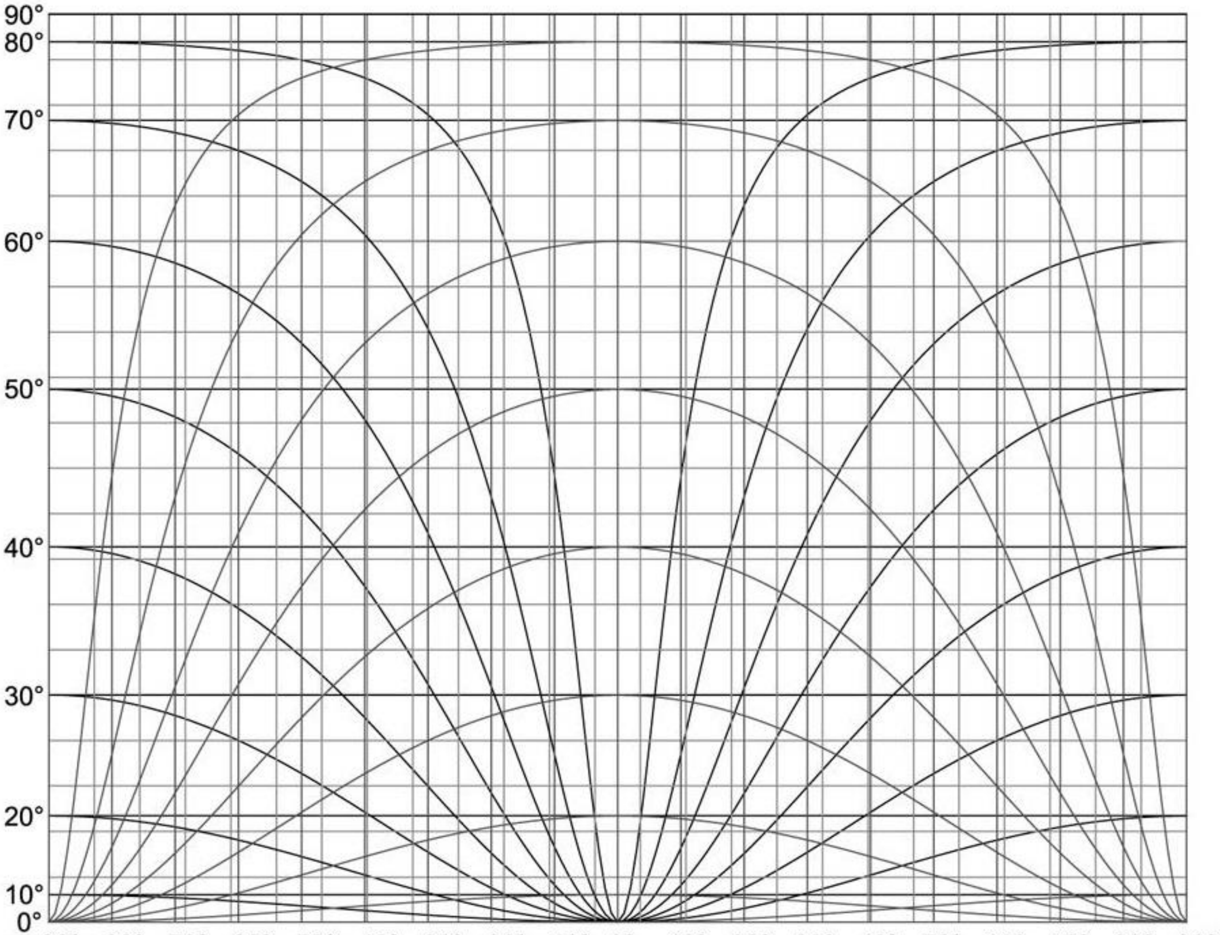

FIG. 2 – Waldram Diagram.

The same is not true of course for the calculation of daylight factors. The luminance distribution of the CIE Standard Overcast Sky varies continuously from the horizon to zenith, and so computer calculations with a 3D CAD model of the room are essential. (Accurate calculation of interreflections from room surfaces also requires computer calculations.)

### Limitations

As a lighting design tool, the daylight factor metric has numerous limitations. As noted by IES RP-5-13, Recommended Practices for Daylighting Buildings [IES 2013], it addresses only a single sky condition that is prevalent in its country of origin. It does not consider such daylighting design issues as direct and reflected sunlight, latitude, building orientation, time and date, or climatic conditions.

These are serious limitations in that satisfying a daylight factor requirement may result in excess daylight under clear sky conditions. IES RP-5-13 therefore recommends modern climate-based annual daylight performance metrics such as spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) in combination with Typical Meteorological Year (TMY) weather data files specific to a given geographical location [IES 2012].

As an aside, it is a myth that the sky factor metric was developed specifically for northern European climates. Prior to the widespread availability of electric lighting, access to diffuse daylight was preferred to that of direct sunlight. (The studios of artists and photographers for instance had north-facing windows and skylight wherever possible.) As the Victorian-era Keller wrote [Keller 1865]:

*In fact, it is this diffused daylight which is constituted, by the express intent of nature, the standard medium of human vision; for where there is one purpose of sight specially served by the direct and unobscured light of the sun, there must be a thousand for which the eye prefers the more genial agency of the diffused light of the atmosphere.*

(Is it any wonder that Keller needed 55 pages to explain the practice of rights to light surveying?) Even by the time of Waldram a half-century later, instruments for measuring daylight were not commonly available. Assuming a uniform luminance sky that allowed purely geometric calculations was therefore a matter of practical necessity.

Limitations aside, reports of the death of the daylight factor metric have been greatly exaggerated — it is still a useful if primitive tool, especially for students learning the basics of daylighting design. Climate-based annual daylight performance metrics such as sDA and ASE may be recommended for detailed analysis of architectural designs, but the daylight factor metric provides the necessary sanity checks.

### Nine Out Of Ten

As noted previously, calculating daylight factors requires a 3D CAD model and daylight simulation software, if only to accurately model the spatial luminance distribution of the CIE Standard Overcast Sky and room surface interreflections. The obvious question is, how accurate are daylight simulation programs?

This question was investigated some sixteen years ago, and the results were not encouraging. Point-by-point errors for clear sky conditions were as much as 18 times, and for overcast sky conditions as much as 10 times the measured values. Much worse, the average error for clear sky conditions was about ten times for two of the four programs investigated.

Today, the situation is markedly different. A recent study [Iverson et al. 2013] investigated the ability of nine daylight simulation programs to calculate the daylight factor metric in five typical rooms. Going well beyond the basic requirements of CIE 171, “Test Cases to Assess the Accuracy of Lighting Computer Programs” [CIE 2006], this study is exemplary of how the accuracy of lighting design and simulation software should be assessed.

The study included nine daylight simulation programs:

- Radiance
- Daysim
- Desktop Radiance
- IESve
- DIALux
- Relux
- Ecotect
- VELUX
- LightCalc

Given that these programs use a wide variety of radiosity and ray tracing techniques, you might hope to see at least reasonable agreement among their daylight factor predictions.

What the study revealed however was stunning: all but one of the programs agreed to within a few percent of each other.

Lighting Analysts’ AGi32 was not included in the study, but the lead author of the report kindly provided the CAD files for the test rooms so that Lighting Analysts could perform its own tests. The results were the same: agreement to within a few percent.

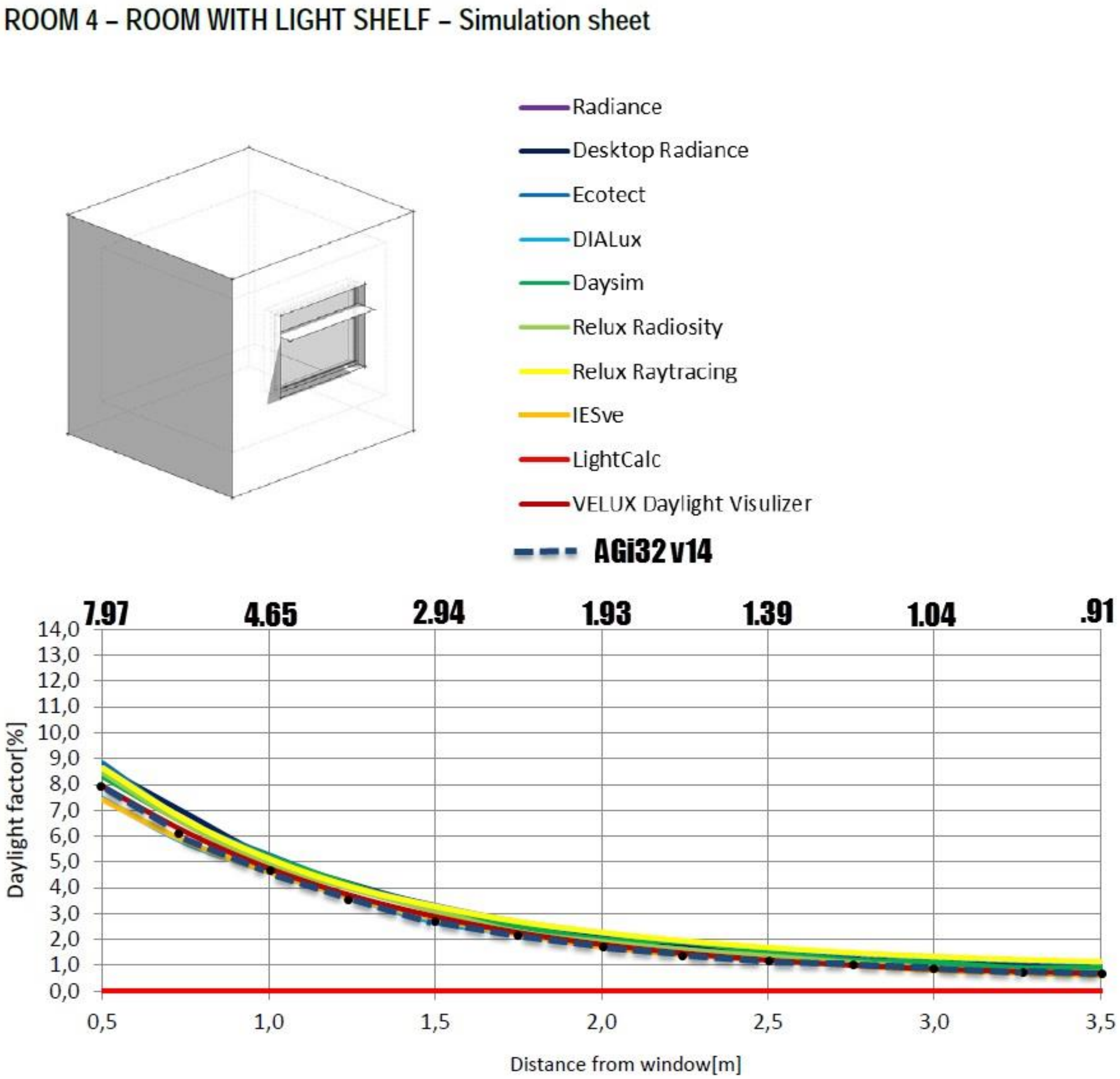

FIG. 3 – Test Room Example.

Nine out of ten lighting programs agree … *this is important news for lighting designers and architects involved in daylighting design.*

The test models used in the study took into consideration room dimensions, surface reflectances, glass transmittance, and exterior obstructions. What this study in effect says is that whatever daylight simulation program (with one important exception — and it was not LIGHTCALC) is chosen, daylight factor calculations will be within the ±10 percent accuracy range expected for such programs [Reinhart and Andersen 2006].

The full "Daylight Calculations in Practice" study is available here, and the Lighting Analysts follow-up study is available here.

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