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GENERAL

INFORMATION

RETHINKING THE PHOTOMETRIC DATA FILE FORMAT

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If you perform lighting design calculations today, you can thank the efforts of the IES Computer Committee (IESCC) some thirty years ago. Its members recognized an industry need, and so developed and published IES LM-63-86, IES Recommended Standard File Format for Electronic Transfer of Photometric Data. With the growing popularity of the IBM Personal Computer for business applications, it was an idea whose time had come.

The need was clear: Lighting Technologies (Boulder, CO) had released its *LUMEN MICRO* lighting design and analysis software product in 1982, and luminaire manufacturers needed to provide photometric data for their products. For them, IES LM-63 was a god-send in that it established an industry-standard file format[7].

In keeping with the technology of the time, the file format was human-readable ASCII text, something that could be printed with a dot-matrix printer. It also resulted in files of only a few kilobytes, a definite advantage when data files were transferred by mail on 5-1/4-inch floppy diskettes capable of holding 360 kilobytes of data. The file format itself revealed something of its origins by limiting line lengths to 80 characters — the width of an IBM Hollerith punch card in the 1960s (FIG. 1).

FIG. 1 – IBM Hollerith 80-character punch cards

Thirty years later, our personal computers are one thousand times faster, with one million times the memory capacity and ten million times more data storage capacity. Data is transferred by fiber optic cable and satellite links at gigahertz rates … and we are still using IES LM-63 photometric data files!

The "we," of course refers mostly to North America. In Europe, the equivalent file format is EULUMDAT, which was introduced in 1990 for use with Microsoft's MS-DOS 3.0 operating system[14]. Again, in keeping with the technology of the time, it was also human-readable ASCII text.

It is a testament to something … exactly what is unclear … that these two file formats have met the lighting industry's needs for so long. Coming from an era of floppy diskettes and dial-up modems with acoustic couplers (FIG. 2), they should have become extinct decades ago. (The Chartered Institute of Building Services Engineers in the United Kingdom introduced its CIBSE TM14 file format specification in 1988, but it has since slipped into obscurity[2].)

FIG. 2 – Modern communications technology circa 1986.

To be fair, LM-63 was revised in 1991, 1995, and 2002. These revisions, however, at best tweaked the file format specification to resolve various ambiguities and add a few minor features. What we have today is basically what was published in 1986, a time when the pinnacle of lamp technology was the compact fluorescent lamp with an electronic ballast.

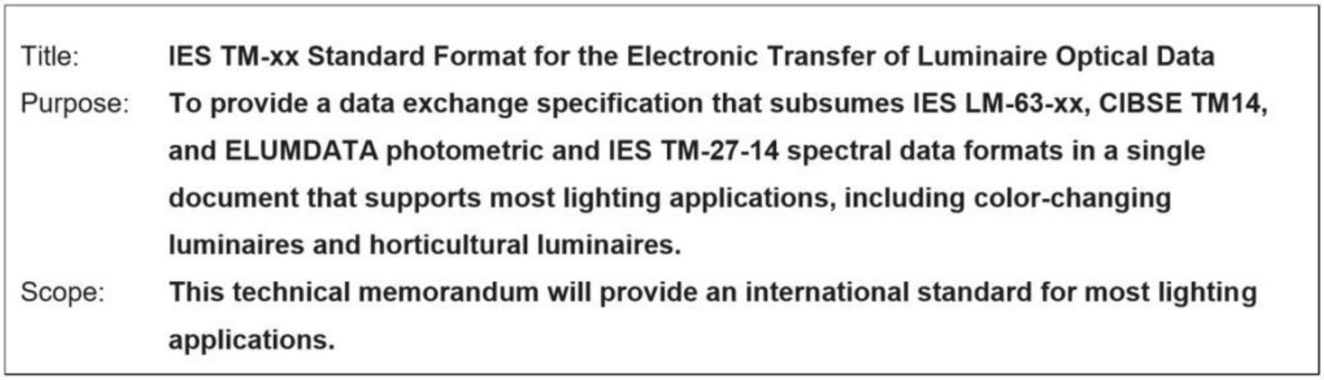
If the LM-63 file format has an advantage, it is that it is an ANSI/IES standard that is maintained by an internationally recognized standards organization. EULUMDAT, on the other hand, is a *DE FACTO* standard that has been essentially frozen in time since its publication in 1990[á]. Without the authority of a standards organization such as ANSI/IES or CEN (European Committee for Standardization) to maintain the file format, it can never be revised.

The problem is that while LM-63 and EULUMDAT are still useful in terms of characterizing architectural and roadway luminaires, the lighting industry has moved beyond luminous intensity distributions. As professional lighting designers, we now have to consider color-changing luminaires, theatrical lighting, human-centric lighting, horticultural lighting, ultraviolet sterilization units, radiant heating devices, and more. We need to consider spectral power distributions, radiant intensity, photon intensity, S/P ratios, melanopic lumens, color rendition metrics … the list goes on and on.

The LM-63 and EULUMDAT file formats are clearly incapable of characterizing light sources and luminaires for these applications. It is therefore time, indeed well past time, to rethink the photometric data file format.

Standards Development

In September 2016, the IESCC initiated a project to develop a new photometric data format from first principles. As is often the case with such projects, one or two members write an initial draft based on their expertise and knowledge. This draft document is reviewed, edited numerous times, and voted upon by the committee members. If approved as a project, the proposed project is again reviewed and voted upon by the IES Board of Directors. In January 2017, technical committee project IES TM-xx, Standard Format for the Electronic Transfer of Luminaire Optical Data, was officially approved (FIG. 3).



Title:	**IES TM-xx Standard Format for the Electronic Transfer of Luminaire Optical Data**
Purpose:	**To provide a data exchange specification that subsumes IES LM-63-xx, CIBSE TM14, and ELUMDATA photometric and IES TM-27-14 spectral data formats in a single document that supports most lighting applications, including color-changing luminaires and horticultural luminaires.**
Scope:	**This technical memorandum will provide an international standard for most lighting applications.**

FIG. 3 – IESCC project summary

Luminaire Component Data

Some readers may recognize this proposed standard from a previous incarnation known as IESNA LM-74-05, Standard File Format for the Electronic Transfer of Luminaire Component Data[8]. The IESCC worked on the development of this document for nearly a decade prior to its publication in 2005. It was ambitious effort to combine all aspects of luminaires into a single file, including far-field photometry, lamp and ballast information, physical geometry, construction materials and finishes, CAD drawings and photographs, and more.

Unfortunately, it was too ambitious. Despite the first release being focused on lamp data, the standard was never adopted by its intended audience of luminaire manufacturers, architects and engineers, lighting product specifiers, photometric testing laboratories, and lighting software developers. To the frustration of the IESCC members, the lighting industry at the time did not see a need for such a standard.

Today, we might look upon LM-74-05 as being an early example of a specialized building information management (BIM) schema, one that focused on a small subset of typically much larger datasets. (A document schema is conceptually equivalent to a file format.) The Green Building XML Schema (gbXML) for BIM applications provides an excellent example. Quoting from the gbXML Web site: "The Green Building XML schema, or 'gbXML,' was developed to facilitate the transfer of building information stored in CAD-based building information models, enabling interoperability between disparate building design and engineering analysis software tools. This is all in the name of helping architects, engineers, and energy modelers to design more energy efficient buildings."

Unfortunately for lighting design professionals, the gbXML schema has an XML "element" (see below) called "Photometry," whose description reads:

> "This element has been left open for use with other photometry definitions. Photometric data is required for various forms of lighting analysis. This tag provides a way for the photometric data to be passed. Since this can be done in a variety of ways (iesna LM-63, cibse TM14, ELUMDAT, etc.) a specific format is not being specified."

Defining a new luminaire optical data format that is compatible with the gbXML schema therefore serves a clear and present need.

Understanding XML

The advantage of gbXML is that it is based on the international data exchange standard XML (eXtensible Markup Language)[15]. The details of this standard are complex and exhausting, but basically every XML document consists of text strings called "elements" such as:

```
<name>Alfred E. Neuman</name>
```

where the data is surrounded by begin and end "tags."
These elements can be arranged in a hierarchy, such as:

```
<person>
  <name>Alfred E. Neuman</name>
  <employer>MAD Magazine</employer>
</person>
```

In this example, the <person> element is the "parent," and any elements within it are its "children."

Building on this simplest of representations, virtually any type of data can be unambiguously represented within an XML document. If a person or computer program reading an XML document encounters an unknown element tag, the element and its children (if any) can simply be ignored.

This, of course, is the problem with including LM-63 or EULUMDAT text files verbatim (i.e., as a multiline text string) within gbXML or similar BIM documents. Yes, it can be done, but the computer program reading the document needs to be able to somehow identify and read these files. Designing IES TM-xx as an XML document resolves this problem.

Having chosen a suitable representation for TM-xx, we can now consider what it needs to represent.

Luminaire Optical Data

IES TM-xx represents the luminaire optical data in four sections:

1. Header
2. Luminaire
3. Equipment
4. Light source

Header

The header section includes information that is currently available in LM-63 and EULUMDAT files:

- Manufacturer
- Catalog number
- Description
- Test laboratory
- Report number
- Report date
- Document creator
- Document creation date
- Unique identifier
- Comments

Most of these elements are self-explanatory, with the exception of the "unique identifier" element. One of the problems with current photometric data files is that there is no version control. If a company reissues photometric data for a product, there is no way of distinguishing between files other than their file creation dates. If the files are copied for any reason, these dates can change.

The unique identifier element is a "Universally Unique IDentifier" (UUID) that uniquely identifies the TM-xx document, regardless of whether it has been copied as a file. While it does not prevent someone from intentionally modifying the document data, it at least solves the problem of multiple files with the same name.

The IESCC is currently considering the addition of search terms and possibly CAD symbols to the header section. These and other details may therefore result in changes to the draft release of TM-xx, but the basic structure discussed here will remain.

Luminaire

TM-xx represents the luminaire as a rectangular box or cylinder. The luminaire section therefore lists the dimensions of these geometric objects as length, width, and height. In addition, each face may include an emission area. These areas are useful for calculating visual glare metrics such as the CIE Unified Glare Rating (UGR)[5], and also for modeling the luminaire as one or more area sources or arrays of point sources for lighting calculations and visualization.

The luminaire section also includes the light center position with respect to the geometric center of the luminaire. (The light center represents the fixed position about which the goniometer rotates while performing intensity distribution measurements.)

Equipment

The equipment section describes the laboratory equipment used to perform the luminaire optical data measurements. These can include:

- Goniometer (intensity measurements)
- Integrating sphere (flux measurements)
- Spectroradiometer (spectral power distribution measurements)

and detailed information specific to these instruments.

Light Source

Photometric data files assume that the luminaire includes one or more removable lamps, but this concept does not apply to solid state lighting, which may have removable LED modules or non-removable LED arrays. For the purposes of TM-xx, these are collectively referred to as “light sources.” Following LM-63 and EULUMDAT, the information pertaining to them may include (as applicable):

- Quantity
- Description
- Catalog number
- Rated lumens
- Input wattage
- Tilt angle

In addition, the information may include correlated color temperature (CCT) values, color rendering metric values (Ra and R9 for CIE Colour Rendering[3] and Rf and Rg for IES Color Rendition[11]), and scotopic-to-photopic lumens (S/P) ratios[9]. (Note that these values may need to be expressed as ranges for variable color temperature light sources.)
There are actually 14 CIE Colour Rendering Special Indices (R1 to R14), which may be required for special purposes. These can either be calculated by the user from the measured spectroradiometric data for the light source (see below), or represented by custom XML elements.

Spectroradiometric Data

A key requirement of the light source section is to represent the spectral power distribution (SPD) of the light source. Following IES TM-27-14, IES Standard Format for the Electronic Transfer of Spectral Data[10], the measured spectral radiant flux is reported for each wavelength.

Most SPDs are reported with constant wavelength intervals (e.g., 5 nm), but TM-xx does not impose such a restriction. Consequently, both continuous and line emission spectral features can be represented with arbitrary wavelength precision.

Intensity Data

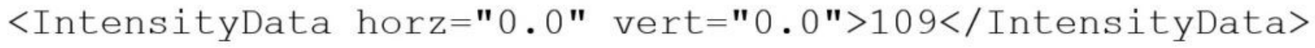
With photometric data files, most of the data represents the luminous intensity measurements for vertical and horizontal angles. The same is true for TM-xx documents in the light source section except that, depending on the application, the intensity measurements may be based on luminous flux, radiant flux, photon flux[ß], or spectral radiant flux.

Luminous intensity distributions are expressed in lumens per steradian (i.e., candela), and are most useful for architectural and roadway lighting applications.
Radiant intensity distributions are expressed in watts per steradian, and are most useful in characterizing ultraviolet and infrared radiation sources for applications such as UV sterilization and radiant heating.

Photon intensity distributions are expressed in micromoles per steradian per second, and are most useful for horticultural lighting applications[1].
Both radiant and photon intensity are measured over a specified range of wavelengths. When photon intensity is measured over the range of 400 nm to 700 nm, it is equivalent to photosynthetically active radiation (PAR)[1].

Spectral radiant intensity distributions assign an SPD to each measurement for vertical and horizontal angles. Expressed in watts per steradian per nanometer, they are useful for representing the variation in color over viewing angle, such as occurs with phosphor-coated white light LEDs.

Finally, each intensity measurement is expressed as (for example):



```
<IntensityData horz="0.0" vert="0.0">109</IntensityData>
```

By explicitly expressing the vertical and horizontal angles for each measurement, there is no requirement for the data to be organized as a two-dimensional array of vertical angles and horizontal planes. This is important because some robotic goniometers are capable of measuring angular positions on a geodesic sphere and other complex angular patterns.

Exclusions

IES TM-xx differs from its predecessor LM-74-05 in that it focuses exclusively on luminaire optical data. This necessarily excludes other luminaire components and characteristics, including:

- Detailed physical dimensions
- Mechanical and structural data
- Materials and finishes
- Building code certifications
- CAD drawings
- Photographs and renderings
- Electronic ballasts and drivers
- Lighting controls and sensors

It would certainly be possible to include this information, but it comes at a price. Every time a component option is added to a product, it increases the number of product variations exponentially. If, for example, a lighting control has four ordering options, this potentially results in 16 different TM-xx documents.

With this, the design philosophy for TM-xx follows what Albert Einstein purportedly once said: "Everything should be made as simple as possible, but no simpler." Given the purposeful extensibility of XML, it is always possible to add elements with custom tags for specific purposes. To avoid conflicts with identical tag names being used by other companies, an XML namespace can be used to uniquely identify the custom tags. With this, TM-xx is being designed to be "as simple as possible but no simpler."

This design philosophy also extends to the intensity data. TM-xx optionally reports luminous, radiant, photon, and spectral radiant intensity, but not, for example, *MELANOPIC* intensity that is useful in human centric lighting applications[13].

The reason is that if you report melanopic intensity, you should arguably also report *CYANOPIC*, *CHLOROPIC*, *ERYTHROPIC*, and *RHODOPIC* intensity to represent to the responsivity of short-wavelength, (blue), medium-wavelength (green), and long-wavelength (red) cones and rods respectively in the human retina. (Melanopic intensity represents the responsivity of intrinsic retinal ganglion cells, or ipRGCs, to retinal irradiance.) This is, of course, an extreme example, but it illustrates the complexities that can arise in trying to satisfy every requirement.

Luminous, radiant, photon, and spectral radiant intensity are optionally reported because they are the most commonly used metrics in architectural, roadway, and horticultural lighting applications. All other intensity metrics can be calculated, if necessary, by appropriately weighting the spectral radiant intensity data.

Files versus Documents

Thirty years ago, almost all data was stored on magnetic media — floppy disks, hard disks, and magnetic tape. Data, whatever its form, was organized in the form of files. It therefore made sense to refer to photometric data files and file formats.

Today, data is stored on a variety of media, including magnetic, optical, solid state, and holographic devices. Long-term storage of data still requires data files and file formats, such as the default NTFS file system used by Microsoft Windows operating systems.

However, the data itself has become somewhat more amorphous. How it is organized better described as a document, a symbolic representation of the data.

Using gbXML as an example, an architect or engineer may assemble a temporary BIM document by linking together information from various manufacturers. The BIM program sends requests to the manufacturers' servers, which may in turn assemble BIM documents to be returned as XML documents. The documents are compressed for transmission, so that the document format is converted into a more compact representation. More to the point, the document may never exist as a physical file.

With this, TM-xx defines a standard format for XML *DOCUMENTS*. The term “file” is properly relegated to the era of floppy disks and acoustic modems.

Why Not JSON?

Computer-savvy readers may well ask, “Why XML and not JSON?” After all, JSON is an alternative computer markup language that is widely used to exchange data between browsers and servers[12]. Compared to XML, it is a much simpler and less verbose language that typically results in smaller documents. It also natively supports two-dimensional data (i.e., matrices) such as luminous intensity distributions, which are more difficult to represent in XML.

The answer is that the electronic exchange of data between computer systems typically involves compressed documents, often with the ZIP file format. In the compression process, the element tags are represented by single symbols, which typically results in document compression ratios of 10:1. More to the point, compressed XML and JSON documents representing the same data are typically the same size. With this, the ability to embed TM-xx documents in XML-based BIM documents outweighs any advantages of JSON.

International Standards

Referring once again to FIG. 3, note the phrase “international standard.” There have been several attempts in the past to develop an international standard for photometric data formats, including CIE 102-1993, Recommended File Format for the Electronic Transfer of Luminaire Photometric Data[4] and EN 13032-1:2004+A1:2012, Light and Lighting — Measurement and Presentation of Photometric Data of Lamps and Luminaires — Part 1[6]. Despite being an explicitly international file format developed by representatives of eleven countries, CIE 102 was never adopted for commercial use.

Sadly, the same fate seems to have befallen EN 13032-1.

This is, unfortunately, the fate of many standards. Companies and individuals volunteer their time and expertise to develop standards that meet perceived industry needs, but the industry in question is the final arbiter of what its needs are. If existing standards are sufficient, it is often difficult to convince manufacturers to abandon them in favor of a new and untried standard. Good examples of this are CIE 102-1993, EN 13032-1, and IES LM-74-05, but there are many others.

Recognizing this problem, the IES Computer Committee has chosen to work directly with its international colleagues, including lighting software companies, luminaire manufacturers, testing laboratories, lighting professionals, and academia with expertise in both architectural and horticultural lighting. It is further using social media to communicate its activities and invite feedback from several thousand lighting professionals. More than any other standard, TM-xx is being designed by those who will most benefit from its adoption and use.

Finally — and this is perhaps a key point — IES TM-xx has been explicitly designed to be forward compatible with IES LM-63, EULUMDAT, and CIBSE TM14. That is, it will be possible to automatically batch convert previous photometric data files into TM-xx documents with insignificant loss of information. Lighting software companies, luminaire manufacturers, and testing laboratories will therefore be encouraged but not required to transition their workflow and photometric data to TM-xx. In the meantime, lighting design software will be able to seamlessly support both photometric data files and TM-xx documents.

Summary

The intent of this article has been to: 1) review the history of photometric data file formats; 2) describe the ongoing efforts of the IES Computer Committee and its partners to develop an international standard for architectural, roadway, and horticultural lighting; and 3) describe both the design philosophy and the international effort behind the development of IES Technical Memorandum TM-xx, Standard Format of the Electronic Transfer of Luminaire Optical Data.

Simply put, the lighting industry currently relies on photometric data file formats that were developed three decades ago. IES TM-xx is being designed for today and the future.

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W3C Extensible Markup Language (XML) 1.0, Fifth Edition (http://www.w3.org/TR/REC-xml).

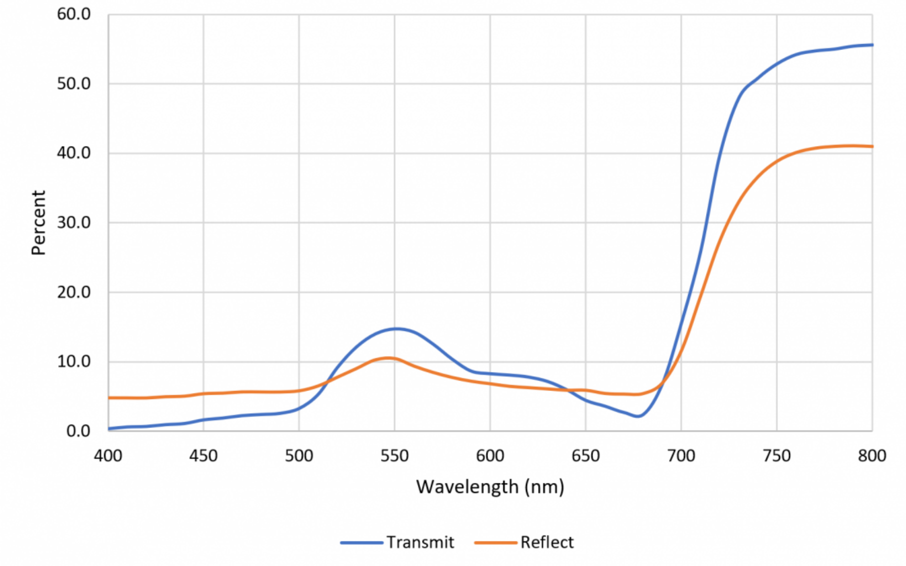
[á] The EULUMDAT file format specification is available from http://www.helios32.com/Eulumdat.htm.

[ß] Photon flux, also commonly referred to as quantum flux, is the rate of flow of photons. Radiant flux, by comparison, is the rate of flow of energy. The energy of a photon is inversely proportional to its wavelength, so quantum flux is not directly comparable to radiant flux.

HORTICULTURAL INFORMATION

FAR-RED LIGHTING AND THE PHYTOCHROMES

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published 18/06/04.
2018 Maximum Yield 20(7):60-66 (October).



Most LED grow lights feature blue and red LEDs whose peak wavelengths – approximately 450 nm for blue and 660 nm for red – have been chosen to coincide with the spectral absorption peaks of chlorophyll A and B molecules. In doing so, they optimize the conversion of electrical energy into plant photosynthesis.

Some manufacturers, however, are now offering grow lights with “far-red” LEDs that feature peak wavelengths of approximately 735 nm. Unfortunately, they offer little if any information on why these LEDs are useful.

In order to make an informed choice when purchasing these grow lights, it is necessary to understand some of the science behind far-red radiation and how plants perceive and respond to it.

Red and Far-Red Radiation

What we call “visible light” is electromagnetic radiation with wavelengths ranging from 400 to 700 nanometers (nm). We perceive this radiation as ranging from very deep blue (400 nm), bordering on ultraviolet radiation, to very deep red (700 nm), bordering on infrared radiation. Coincidentally, this is also the range of wavelengths that plants can utilize for photosynthesis (PAR = Photosynthetically Active Radiation).

There is no formal definition of “red” in terms of wavelength, but it is often considered to consist of wavelengths ranging from 600 nm (bordering on orange) to 700 nm. The term “far-red,” on the other hand, has been formally defined to consist of wavelengths between 700 nm and 800 nm. We can barely see this radiation as a very deep red if the radiation is intense enough, but it is for practical purposes invisible to the human eye. Plants, on the other hand, readily perceive and respond to far-red radiation.

We see vegetation as being green because the chlorophyll A and B molecules strongly absorb blue and red light. A typical green leaf absorbs 90 percent of incident red light; the remainder is reflected and transmitted (FIG. 1). Beyond 700 nm, however, chlorophyll is basically transparent. This means that beyond approximately 750 nm, green vegetation reflects 40 percent and transmits 55 percent of far-red radiation. The region of rapid change in spectral reflectance between 700 and 750 nm is called the "red edge," and is used to monitor vegetation coverage from space using remote imaging.

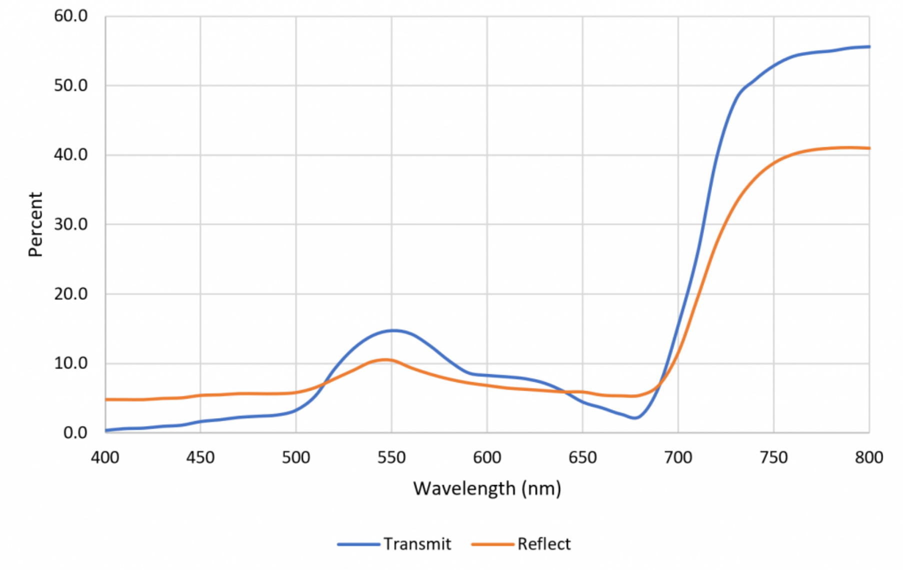


FIG. 1 – Typical Vegetation Spectral Properties.

The Phytochromes

Angiosperms – flowering plants – also take advantage of the red edge using a family of photoreceptor molecules called *PHYTOCHROMES* (Latin for "plant color"). They have been doing so since they first appeared in the fossil record some 160 million years ago. It is not an exaggeration to say that without these molecules, we would still be living in a world of conifers, cycads, and ginkgoes.

The number of different phytochromes varies by plant species – rice has three, thale cress (*ARABIDOPSIS THALANIA*) has five, maize has six, and so on. Each type serves different (and often multiple) functions in each species, but they all absorb red and far-red light in exactly the same manner.

Each phytochrome molecule has two states called *ISOFORMS*. Left in the dark for several hours, it reverts to a state called P_r, where it strongly absorbs red light (FIG. 2). If a phytochrome molecule in this state absorbs a red photon, it changes to its P_{fr} state, where it absorbs far-red radiation. If the molecule absorbs a far-red photon, it reverts back to its P_r state. When in its P_{fr} state, the molecule is biologically active, and may interact with the plant's molecular machinery. Given this, phytochrome can be seen as a reversible biological switch that can enable or inhibit various plant functions. One such important function is the detection of neighboring plants.

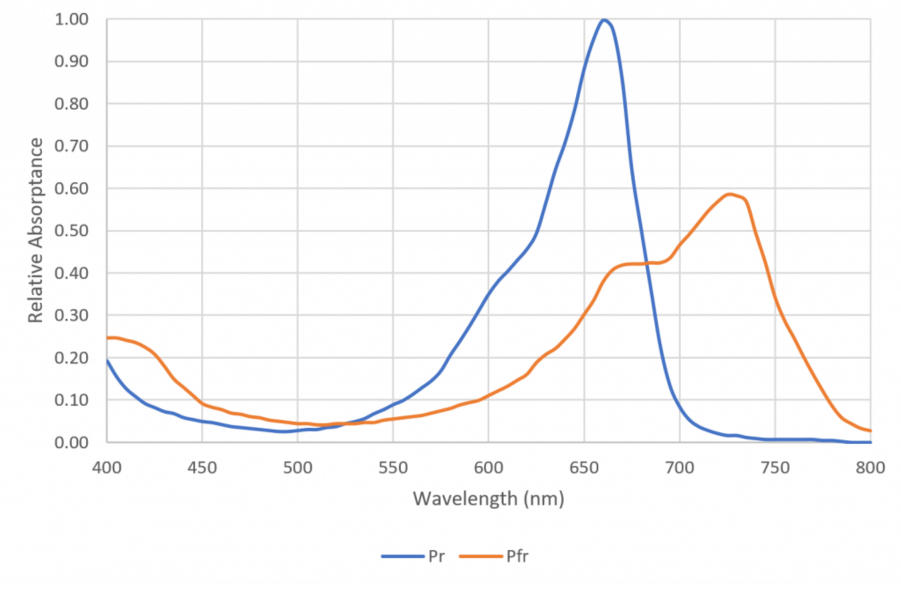


FIG. 2 – Phytochrome Spectral Absorptance.

Shade-Avoidance Syndrome

Flowering plants that tolerate full or partial sun need to gain access for their leaves to direct sunlight in order to photosynthesize. The problem is that they often have competition from other plants for the same resource. That is, the leaves of other plants may block access, either at present or in the future. In response, the plant may elongate its stem (*APICAL DOMINANCE*) and decrease branching in order to tower above the competition. In doing so, it necessarily diverts resources from other priorities, including producing secondary metabolites for pathogen resistance and insect herbivore deterrence, improving drought tolerance, and reducing root biomass. Together, these responses are called the *SHADE-AVOIDANCE SYNDROME* (SAS).

If the plant realizes or predicts that it cannot avoid being shaded, it responds by growing in a more compact form and flowering early. Being crowded by other plants, it is more susceptible to pathogen and herbivore predation. The best strategy is therefore to build chemical and defenses and stay close to the ground while producing seeds as soon as possible in order to survive into the next generation.

Shade-loving flowering plants, on the other hand, may not exhibit any of the SAS responses, at least to the same degree. The daylight they receive has likely been diffused by the forest canopy, and so there is less advantage in devoting resources to avoid being blocked by the leaves of neighboring plants.

Red/Far-Red Ratio

On a clear day, direct sunlight has a ratio of red light to far-red radiation (R:FR) of about 1.3. That is, there is about 30 percent more red light than far-red radiation that is received by the plant leaves. Even daylight reflected from natural inorganic materials such as rock and soil exhibits roughly the same R:FR ratio.

When the direct sunlight is being blocked by the leaves of neighboring plants, however, the "red edge" effect takes hold. A single layer of leaves can change the R:FR ratio from 1.3 to 0.2 or less. That is, there is now about six times *LESS* red light than far-red radiation incident on the plant leaves. Two layers of leaves and the difference becomes thirty times or more.

Flowering plants use phytochrome to detect the R:FR ratio and so decide whether SAS responses are necessary. In addition to detecting whether the direct sunlight is being directly blocked, the plants can determine from the R:FR ratio whether there are neighboring plants that might pose a future threat and so initiate appropriate SAS responses.

End of Day

The R:FR ratio of direct sunlight is about 1.3 during most of the day, but it approaches 0.6 or so during twilight when the atmosphere preferentially scatters blue light and the sky turns yellow and red. This only lasts for half an hour or less, but it is important because plants use these changes to synchronize their internal circadian clocks both with the 24-hour day and the seasons. This involves a burst of gene expression activity that is controlled by phytochrome.

Blackout curtains can be used in greenhouses to eliminate twilight, and both red and far-red LEDs can be used to simulate twilight for vertical farms at the end of the daily photoperiod. Interestingly, low PAR values are required, on the order of one $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{sec}^{-1}$, for this purpose. Various SAS responses to red and far-red pulses have been recorded for different species, including stem elongation and changes in leaf area. End-of-day pulses of far-red radiation, for example, have been shown to result in useful hypocotyl elongation of tomato rootstocks for grafting.

Night Breaks

Floriculturists have long used incandescent lighting at night to disrupt the photoperiod of short-day plants such as poinsettias and chrysanthemums. During the night, the phytochrome molecules revert to their biologically inactive P_r state. If the plants are exposed to incandescent lighting (which has an R:FR ratio of 0.7) during the night, the phytochrome molecules are re-activated, which results in their circadian clocks being reset. Repeated nightly exposure ("night breaks") in the middle of the night prevents the plants from stopping vegetative growth and setting their flower buds.

For long-day plants, night break lighting may have the opposite effect of advancing rather than delaying flowering. The operative here is "may," as different species and even cultivars respond differently to night breaks.

It is important to note that only red light can be used for night breaks; when phytochrome is in its P_r state, it cannot absorb far-red photons. Red LEDs with their 660 nm peak wavelengths are thus ideal for night break lighting, whereas far-red LEDs will have no effect (FIG. 2).

Far-Red Radiation Sources

Given that plants are subjected to an R:FR ratio of 1.3 in direct sunlight and much lower ratios when shaded by neighbouring plants, it is interesting to consider what we subject them to with various electric light sources. Incandescent lamps have an R:FR ratio of 0.7, which is what plants would perceive when they are adjacent to neighboring plants but not directly shaded.

High-pressure sodium (HPS) lamps, on the other hand, have an R:FR ratio of about 4.8, metal halide lamps have R:FR ratios varying from 2.6 to 3.4. and white light LEDs (regardless of color temperature) have R:FR ratios varying from 3.6 to 4.0. Various fluorescent lamps have R:FR ratios varying from 5.5 to 13.0 and above.

The common reason for these high R:FR ratios is that, putting aside technology limitations, the lamps are designed for visual applications – there is no reason for them to generate invisible far-red radiation. If they did, it would simply lower their luminous efficacy (lumens per electrical watt) values.

With only blue and red LEDs, the R:FR ratio is essentially infinite. SAS responses can sometimes be elicited by blue light alone, but the likelihood is that many plants will not recognize the presence of neighboring competitors when irradiated by most grow lights.

Far-Red Applications

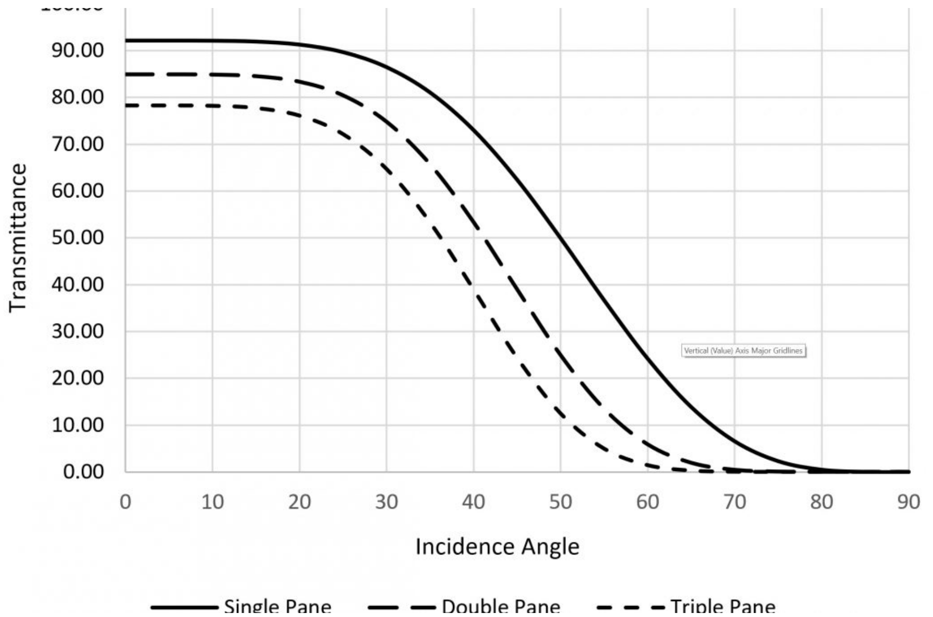
This leaves open many questions regarding the possible applications of far-red LEDs. While various species and cultivars may grow well (or not) under the familiar blue and red (“blurple”) LEDs, they may not exhibit any shade avoidance syndrome responses. In some situations, these responses may actually be desirable. For instances, sun-loving plants that are grown in shade may be more compact, but they may also exhibit greater pathogen and drought resistance, and they may generate desirable secondary metabolites as defense mechanisms. Their flowering may be advanced or delayed, the number of buds may change … the list goes on.

It is also possible that end-of-day far-red pulses of radiation at low irradiance levels may have a greater effect on plant growth than during the day, as this is when gene expression is particularly active. (Blue light pulses at dawn have also been shown to change plant morphology.) One advantage is that this requires less energy than having the far-red LEDs continuously on during the day.

For horticulturalists and floriculturists, experimentation with far-red LEDs offers opportunities for developing species- and cultivar-specific light recipes as trade secrets. If horticultural luminaire manufacturers have not yet said why far-red LEDs are useful, it is because there is much that still needs to be researched and discovered. With a basic knowledge of the science behind far-red radiation and the phytochromes, it becomes practical to experiment with light recipes and photoperiods, and to understand why the plants respond the way they do.

LIGHT TRANSMITTANCE THROUGH GREENHOUSE GLAZING

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 18/10/01.



Look at a greenhouse manufacturer's product specifications and you will see that the light transmittance of single-pane clear glass is typically 88 to 91 percent. Compared to double-wall polycarbonate with a transmittance of 80 percent, it would seem that glass is the better choice. However, if you measure the photosynthetically active radiation (PAR) at the leaf canopy within the greenhouse, it is often only 40 to 60 percent of that measured outside the greenhouse. Why is this?

The answer is that these transmittance values were based on standard test procedures developed by the American Society of Testing Materials (ASTM), which require the incident light to be perpendicular to the glazing material. For greenhouses however, the incident light comes from direct sunlight, diffuse daylight, and daylight reflected from the ground and other exterior surfaces. In other words, light is incident upon the glazing material from all angles.

To better understand the issue, look at a sheet of clear glass. When it is perpendicular to your line of sight, it is essentially transparent. However, as you tilt the glass, you begin to notice reflections. These reflections increase in brightness until you are looking at the glass at a grazing angle, at which point it behaves essentially like a mirror.

This also happens, of course, with daylight entering the greenhouse. On a clear day, this is mostly direct sunlight, and so the amount of sunlight entering the greenhouse depends on the incidence angle θ (Fig. 1).

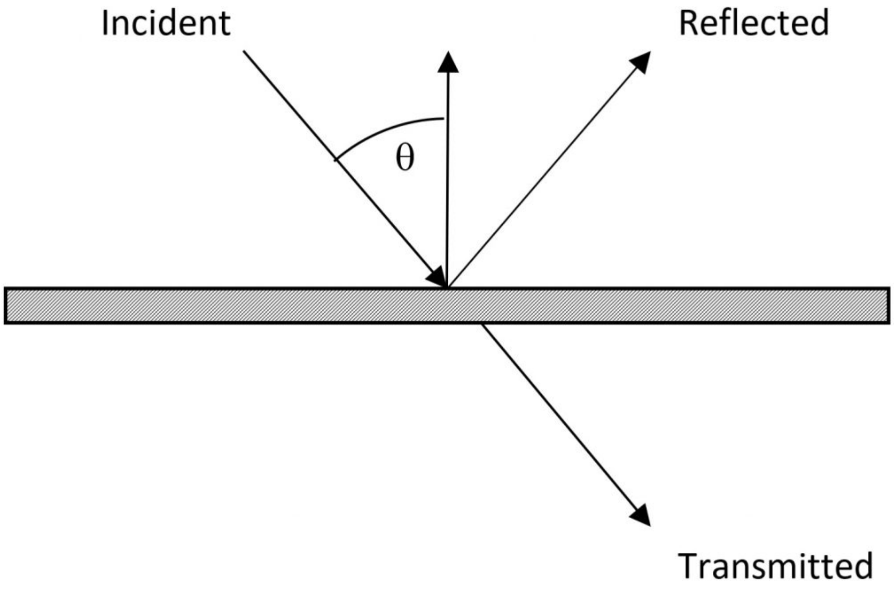


FIG. 1 – Incidence angle.

Assuming that the glazing material is perfectly transparent (that is, it does not absorb any light), the PAR light transmittance varies with the incidence angle as shown in FIG. 2.

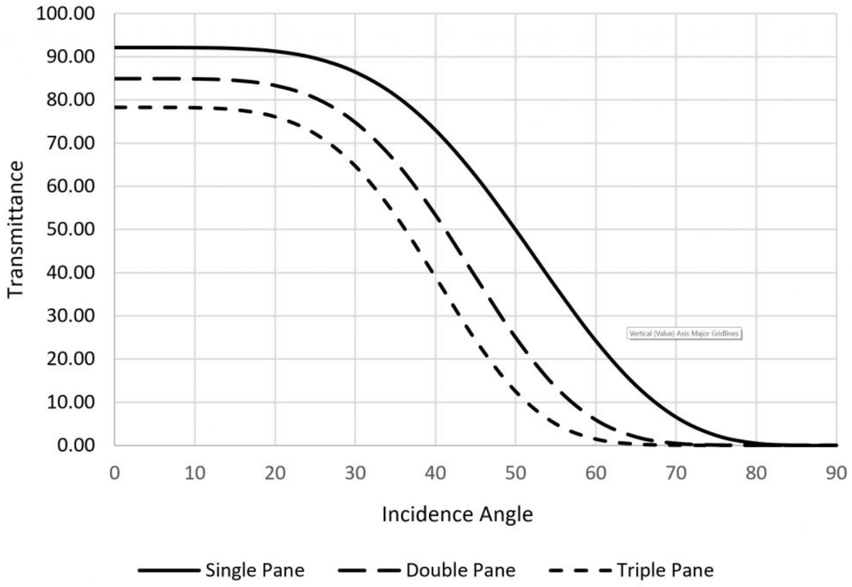


FIG. 2 – Transmittance of direct sunlight through clear glazing.

To put this into perspective, consider a gutter-connected greenhouse with a 1:2 (30-degree) roof pitch and double-pane glass glazing that is located in Vancouver, Canada at a latitude of 49 degrees and oriented on an east-west axis. The solar elevation at noon on December 21st will be 18 degrees. The incidence angle will be 42 degrees, and so the transmittance of the south-facing roof panels will be 48 percent. We can now see where the “40 to 60 percent” figure come from.

It is important to note that these results apply only to clear glazing materials with smooth surfaces, such as glass and acrylic. For materials such as polyethylene and polycarbonate with rough or striated surfaces that tend to diffuse the incident light, it becomes more difficult to predict their optical characteristics. A better approach is to measure their transmittance for various incidence angles in a test laboratory.

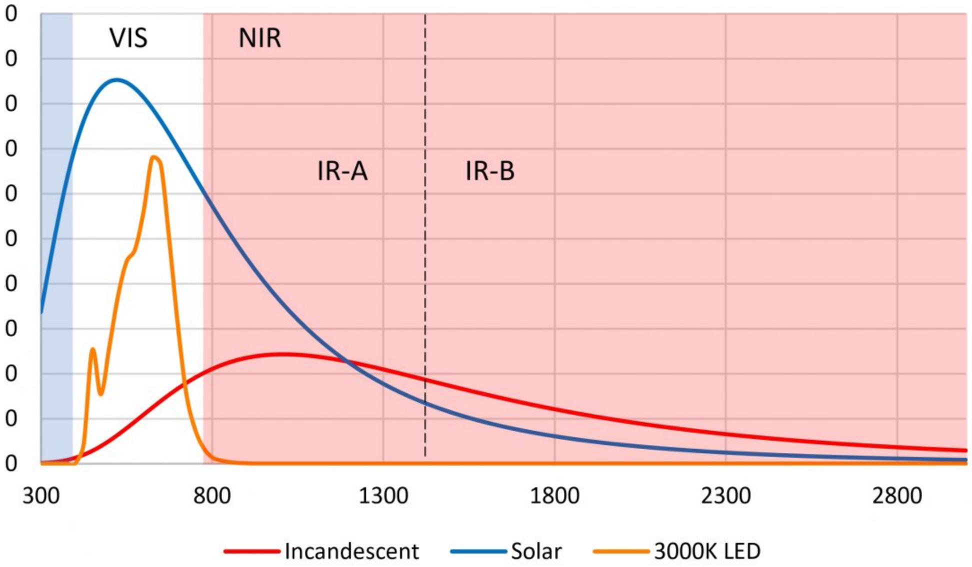
Predicting the precise amount of daylight that will be incident upon the leaf canopy in a greenhouse can be done, but it requires a horticultural lighting design program that considers building latitude and orientation, building layout and dimensions, glazing materials, date and time, weather conditions, and more. For now, however, it is sufficient to see why the measured light at the leaf canopy is considerably less than what is measured outside.

HEALTH INFORMATION

THE SCIENCE OF NEAR-INFRARED LIGHTING

Ian Ashdown, P. Eng., FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 18/07/13

IES FIRES blog June 28, 2018



There is a common-sense argument being presented in the popular media that since humans evolved under sunlight, our bodies must surely make use of all the solar energy available to us. Given that more than 50 percent of this energy is due to near-infrared radiation, we are clearly risking our health and well-being by using LED lighting that emits no near-infrared radiation whatsoever.

Fact or Fiction?

To examine this issue, we begin with a few definitions. There are several schemes used to partition the infrared spectrum. ISO 20473, for example, defines near-infrared radiation as electromagnetic radiation with wavelengths ranging from 780 nm to 3.0 mm (ISO 2007). Meanwhile, the CIE divides this into IR-A (780 nm to 1.4 mm) and IR-B (1.4 mm to 3.0 m), while noting that the borders of near-infrared "necessarily vary with the application (e.g., including meteorology, photochemistry, optical design, thermal physics, etc.)" (CIE 2016).

The terrestrial solar spectrum that we are exposed to on a clear day is shown in Figure 1. This varies somewhat depending on the solar elevation, which is in turn dependent on the latitude, time of day, and date. However, Figure 1 is sufficient for discussion purposes.

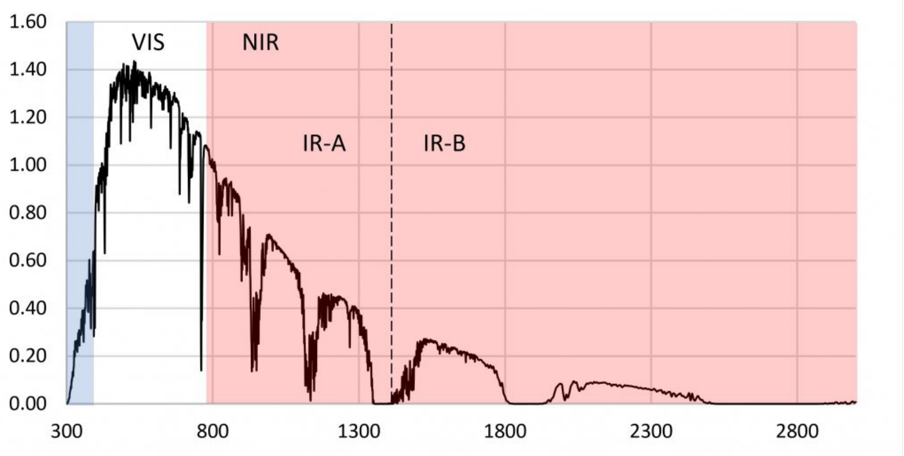


Figure 1 – Terrestrial solar spectrum. (ASTM G173-03).

Compared to sunlight, modern-day electric lighting, and in particular LED lighting, is sorely deficient in near-infrared radiation. Figure 2 illustrates the problem, where the terrestrial solar spectrum has been approximated by a blackbody radiator with a color temperature of 5500 K. Look at the spectrum of incandescent lights – they clearly provide the near-infrared radiation that we need. By comparison, 3000-K LEDs (and indeed, any white light LEDs) provide no near-infrared radiation whatsoever.

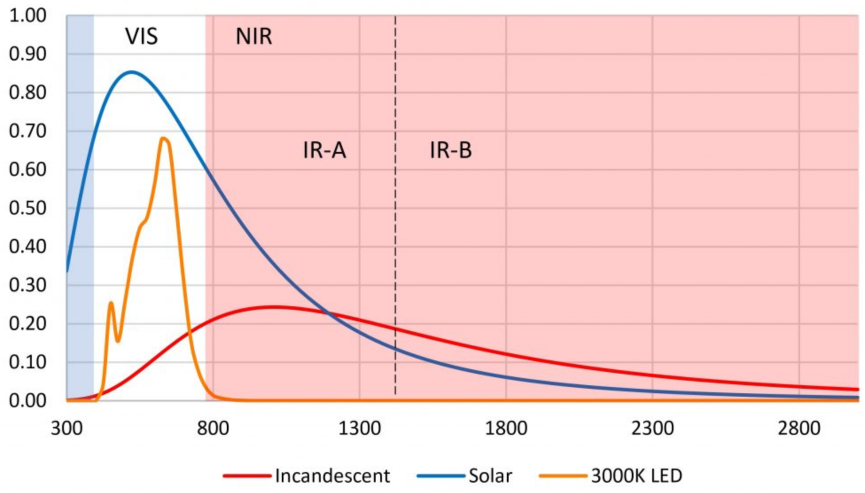


Figure 2 – Spectrum comparisons.

The same is true, of course, for fluorescent lamps. Given how much time most people spend indoors, we have been depriving ourselves of near-infrared radiation since the introduction of fluorescent lamps in the 1950s!

This is only common sense, but it was also common sense that led Werner von Siemens to proclaim, “Electric light will never take the place of gas!” Common sense notwithstanding, the above two paragraphs are patent nonsense.

A Sense of Scale

Figure 2 is deliberately misleading, even though it was recently published in a trade journal elsewhere without comment. The problem is one of scale. If we go back to the early 1950s with its predominantly incandescent lighting in homes and offices, illuminance levels were on the order of 50 to 200 lux. Meanwhile, outdoor illuminance levels are on the order of 1000 lux for overcast days, and 10,000 to 100,000 lux for clear days.

Even on an overcast day, we would have received roughly five to ten times as much near-infrared radiation outdoors as we would have indoors. On a clear day, it would have been five hundred to one thousand times. Given this, properly scaled incandescent and 3000-K LED plots in Figure 2 would *BOTH* be no more than smudges on the abscissa.

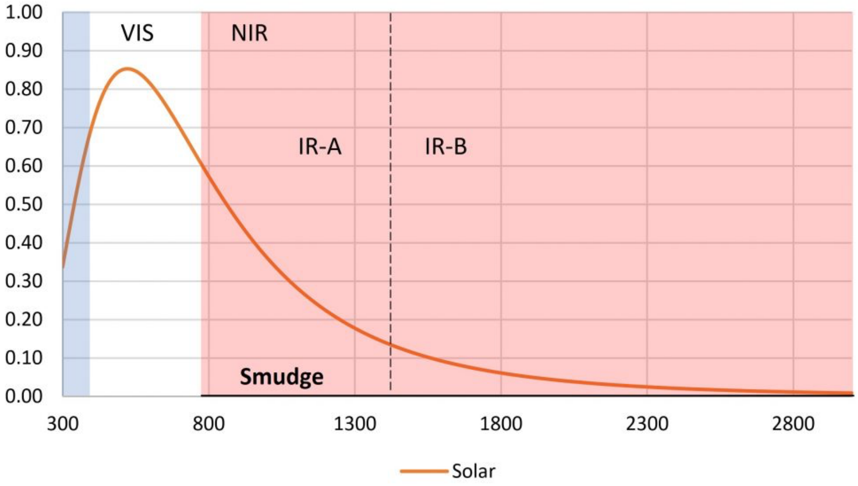


Figure 3 – Infrared “smudge” (see text for explanation).

Common sense should also tell us that we have survived quite nicely without near-infrared radiation in our daily lives ever since we began spending our time in offices and factories rather than working in the fields during the day. It does not matter whether the electric light sources are incandescent, fluorescent, or LED – the amount of near-infrared radiation they produce compared to solar radiation is inconsequential.

This does not mean, however, that near-infrared radiation has no effect on our bodies. There are hundreds, if not thousands, of medical studies that indicate otherwise. For lighting professionals, it is therefore important to understand these effects and how they relate to lighting design.

Low Level Light Therapy

Many of the medical studies involving near-infrared radiation concern *LOW LEVEL LIGHT THERAPY* (LLLT), also known as “low level laser therapy,” “cold laser therapy,” “laser biostimulation,” and most generally, “photobiomodulation.” Using devices with lasers or LEDs that emit visible light or near-infrared radiation, these therapies promise to reduce pain, inflammation, and edema; promote healing of wounds, deeper tissues, and nerves; and prevent tissue damage.

Laser therapy is often referred to as a form of "alternative medicine," mostly because it is often difficult to quantify its beneficial effects in medical studies. Unfortunately, the popular literature, including magazine articles, personal blogs, product testimonials, and self-help medical websites, often reference these studies as evidence that near-infrared radiation is essential to our health and well-being. In doing so, they overlook two key points: irradiance and dosage.

Irradiance

The adjective "low level" is somewhat of a misnomer, as it is used to distinguish LLLT medical devices from high-power medical lasers used for tissue ablation, cutting, and cauterization. The radiation level (that is, irradiance) is less than that needed to heat the tissue, which is about 100 mW/cm^2. By comparison, the average solar IR-A irradiance is around 20 mW/cm^2 during the day, with a peak irradiance reaching 40 mW/cm^2 (Piazena and Kelleher 2010).

This is not a fair comparison, however. In designing studies to test LLLT hypotheses, there are many parameters that must be considered, including whether to use coherent (laser) or incoherent (LED) radiation, the laser wavelength (or peak wavelength for LEDs), whether to use continuous or pulsed radiation, and the irradiance, target area, and pulse shape. Tsai and Hamblin (2017) correctly noted that if any of these parameters are changed, it may not be possible to compare otherwise similar studies.

Solar near-infrared radiation has its own complexities. In Figure 1, the valleys in the spectral distribution are mostly due to atmospheric absorption by water and carbon dioxide. Further, the spectral distribution itself varies over the course of the day, with relatively more of the visible light being absorbed near sunrise and sunset. Simply saying "solar near-infrared" is not enough when comparing daylight exposure to LLLT study results.

Complicating matters even further is the fact that near-infrared radiation can penetrate from a few millimeters to a centimeter or so through the epidermis and into the dermis, where it is both absorbed and scattered. The radiation is strongly absorbed by water at wavelengths longer than 1150 nm, so there is an "optical window" between approximately 600 nm and 1200 nm where low level light therapy devices operate.

The biochemical details of how near-infrared radiation interacts with the human body are fascinating, with the primary chromophores hemoglobin and melanin absorbing the photons and then undergoing radiationless de-excitation, fluorescence, and other photochemical processes. For our purposes, however, these details are well beyond the focus of this article.

What is of interest, however, is that whatever positive results may be attributed to a given medical study, because of the differences elucidated above it is difficult to compare them with exposure to solar near-infrared radiation. Further, the irradiance levels are considerably higher than what we would experience outdoors on a clear day, and much higher than we would experience indoors, even with incandescent light sources. Given this, it is generally inappropriate to consider LLLT studies as evidence that near-infrared radiation is essential to our health and well-being.

Dosage

The Bunsen-Roscoe law, also known as the “law of reciprocity,” is one of the fundamental laws of photobiology and photochemistry. It states that the biological effect of electromagnetic radiation is dependent only on the radiant energy (stated in joules), and so is independent of the duration over which the exposure occurs. That is, one short pulse of high irradiance is equal one or more long pulses at low irradiance, as long as the energy (duration times irradiance) is the same.

Unfortunately, human tissue does not obey this law. Instead, it exhibits a “biphasic dose response,” where larger doses (i.e., greater irradiance) are often less effective than smaller doses. At higher levels (greater than approximately 100 mW/cm^2), the radiant power induces skin hyperthermia (that is, overheating), while at lower levels, there is a threshold below which no beneficial effects are observed (Huang et al. 2009). This is presumably due to various repair mechanisms in response to photo-induced cellular damage.

This is not to say that solar near-infrared radiation may not have a beneficial effect. As an example, a study of wound healing in mice using 670-nm red LEDs demonstrated significant increases in wound closure rates beginning at 8 mW/cm^2 irradiance (Lanzafame et al. 2007). This is comparable with an average 20 mW/cm^2 solar IR-A irradiance on a clear day. However, this is also orders of magnitude greater than the average irradiance that might be expected indoors from incandescent light sources.

As an aside, it should be noted that treatment of dermatological conditions with sunlight, or *HELIOTHERAPY*, was practiced by ancient Egyptian and Indian healers more than 3,500 years ago (Hönigsmann 2013). However, this involved the entire solar spectrum from 300 nm (UV-B) to 2500 nm (IR-B); it is impossible to relate the effects of such treatments to near-infrared radiation alone.

Near-Infrared Radiation Risks

Based on the evidence of low-level light therapy studies, there appears to be scant evidence – if any – that a lack of near-infrared radiation in indoor environments is deleterious to our health and well-being. If anything, the minimum required irradiances and the biphasic dose response argue against it.

There are, in fact, known risks to near-infrared radiation exposure. Erythema ab igne, for example, is a disorder characterized by a patchy discoloration of the skin and other clinical symptoms. It is caused by prolonged exposure to hearth fires, and it is an occupational hazard of glass blowers and bakers exposed to furnaces and hot ovens (e.g., Tsai and Hamblin 2017). It is not a risk to the general population, however, in that the irradiance is usually many times that of solar near-infrared irradiance.

More worryingly, IR-A radiation can penetrate deeply into the skin and cause tissue damage, resulting in photoaging of the skin (Schroeder et al. 2008, Robert et al. 2015), and at worst, possibly skin cancers (e.g., Schroeder et al. 2010, Tanaka 2012). Sunscreen lotions may block ultraviolet radiation that similarly causes photoaging and skin cancers, but they have no effect on near-infrared radiation.

Evolutionary Adaptation

Excess amounts of ultraviolet radiation can cause erythema (sunburn) in the short term, and photoaging and skin cancers in the long term. Curiously, pre-exposure to IR-A radiation preconditions the skin, making it less susceptible to UV-B radiation damage (Menezes et al. 1998). This is probably an evolutionary adaptation, as the atmosphere absorbs and scatters ultraviolet and blue light in the morning hours shortly after sunrise (Barolet et al. 2016). This morning exposure to IR-A radiation is likely taken as a cue to ready the skin for the coming mid-day exposure to more intense ultraviolet and near-infrared radiation. Late afternoon exposure to decreased amounts of ultraviolet radiation may further be taken as a cue to initiate cellular repair of the UV-damaged skin. In this sense then, solar near-infrared radiation is an identified benefit.

Conclusion

So, are we risking our health and well-being by using LED lighting that emits no near-infrared radiation, or is this patent nonsense as stated above? Perhaps surprisingly, the answer is that we do not know.

The above discussion has focused on the effects of near-infrared radiation on the skin and low-level light therapy. Given that the irradiances and dosages of LLLT are *MUCH* greater than those experienced from indoor lighting (including incandescent), it is inappropriate to cite LLLT medical studies in support of near-infrared lighting.

This does not mean, however, that there are not benefits to long-term exposure to near-infrared radiation, or risks from the lack thereof. The problem is in identifying these possible benefits and risks. Without obvious medical consequences, epidemiological studies would need to be designed that eliminate a long list of confounding factors, from light and radiation exposure to diet and circadian rhythms. They would also need to be performed with laboratory animals, as human volunteers are unlikely to agree to completely avoid exposure to daylight for months to years at a time.

In the meantime, we as lighting professionals must work with the best available knowledge. Lacking any credible evidence that very low levels of near-infrared radiation is necessary for our health and well-being, there appears to be no reason not to continue with LED and fluorescent light sources.

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MELANOPIC GREEN: THE OTHER SIDE OF BLUE

Ian Ashdown, P. Eng. FIES, Senior Scientist, SunTracker Technologies Ltd. Published: 18/09/03

IES FIRES blog August 23, 2018

Numerous medical studies have shown that exposure to blue light at night suppresses the production of melatonin by the pineal gland in our brains and so disrupts our circadian rhythms. As a result, we may have difficulty sleeping. It is therefore only common sense that we should specify warm white (3000 K) light sources wherever possible, especially for street lighting.

True or false?

To answer this question, we first need to define what we mean by "blue light." Neither the Illuminating Engineering Society (IES) nor the Commission Internationale d'Eclairage (CIE) define the term in their online vocabularies. However, UL, LLC (formerly Underwriters Laboratories Inc.) has recently introduced its UL Verified Mark , a "third-party product claims verification program." One such Verified Mark is shown in **Figure 1**:

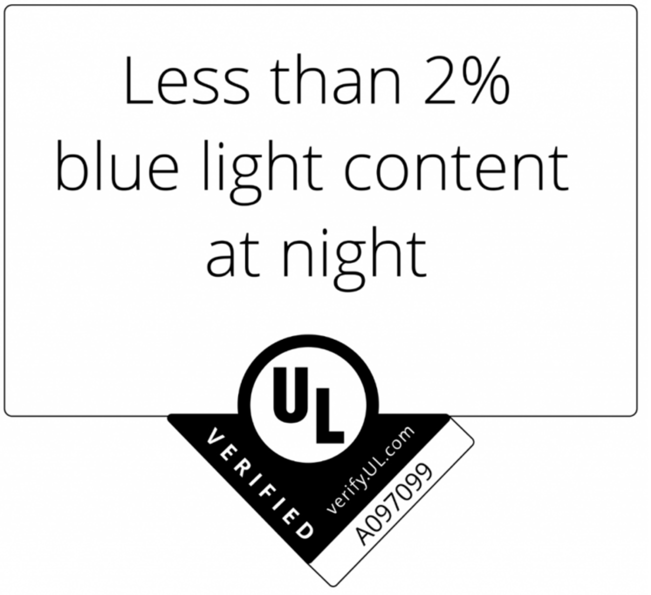

FIG. 1 – UL Verified Mark example.

The verification process for this mark is described thus:

> *"IN ACCORDANCE WITH LM-79-08, SECTION 9.1, MEASURE THE RADIATION EMITTED BY THE PRODUCT ACROSS THE VISIBLE SPECTRUM OF 380 – 780 NM. FROM THE VISIBLE SPECTRUM RADIATION MEASUREMENT, DETERMINE THE AMOUNT OF 'BLUE LIGHT' RADIATION EMITTED BETWEEN 440 – 490 NM. TO CALCULATE THE PERCENT OF BLUE LIGHT EMITTED, DIVIDE THE AMOUNT OF BLUE LIGHT RADIATION BY THE AMOUNT OF RADIATION MEASURED ACROSS THE COMPLETE VISIBLE SPECTRUM."*

The lower wavelength limit of 440 nm seems somewhat arbitrary unless you also define "violet light," but the upper wavelength limit of 490 nm makes sense; wavelengths in the region of 490 to 570 nm appear to be varying hues of green. This makes it easy – if we eliminate light of all wavelengths below 490 nm, we should not have any concerns about suppressing the production of melatonin and possible sleep disruption.

True or false?

To answer this question, we need to take a closer look at those medical studies. The human retina has a smattering of *INTRINSICALLY PHOTOSENSITIVE RETINAL GANGLION CELLS*, or ipRGCs. Similar to the more familiar rods and cones, these ipRGCs contain a photosensitive protein called melanopsin. The sensitivity of melanopsin varies with wavelength, as shown in Figure 2.

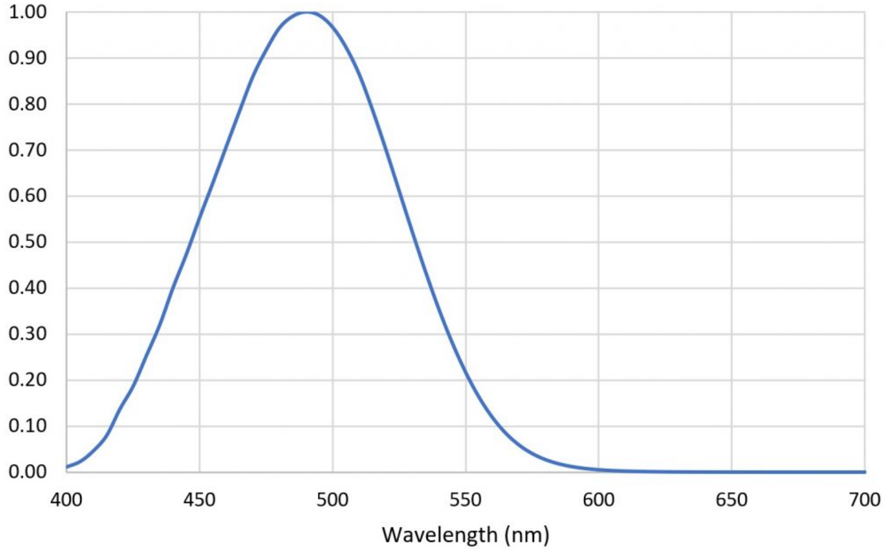

FIG. 2 – Relative melanopic sensitivity (from CIE 2015).

It is these ipRGCs that sense "blue light" and send signals to the suprachiasmatic nucleus (SCN), a tiny region of some 20,000 neurons in the brain that is responsible for instructing the pineal gland when to produce melatonin.

Looking more closely at Figure 2, however, it is evident that the ipRGCs' spectral sensitivity peaks at 490 nm, as well as extending to the ultraviolet edge of the visible spectrum at 380 nm. Most important, fully half the the spectral sensitivity of melanopsin is to green light.

Common sense is starting to look rather nervous …

The spectral sensitivity shown in Figure 2 is interesting enough, but it becomes even more so when we consider what it means for how we respond to the radiation emitted by white light LEDs. Figure 3 shows the relative spectral power distributions (SPDs) of typical white light LEDs with correlated color temperatures (CCTs) of 3000 K and 4000 K, scaled such that both LEDs produce equal amounts of luminous flux.

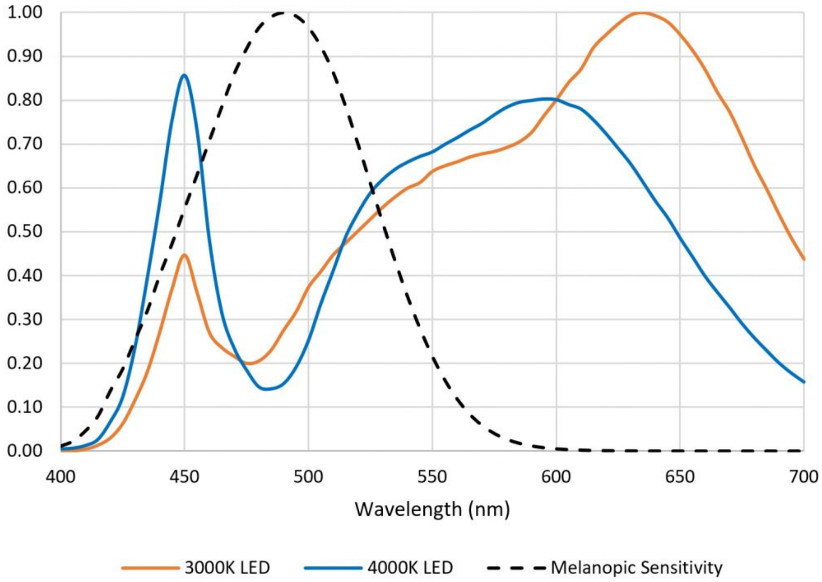

FIG. 3 – White light LED spectral power distributions.

Determining the relative response of ipRGCs to these LEDS is easy – we simply multiply their SPDs by the melanopic sensitivity function on a per-wavelength basis, as shown in Figure 4.

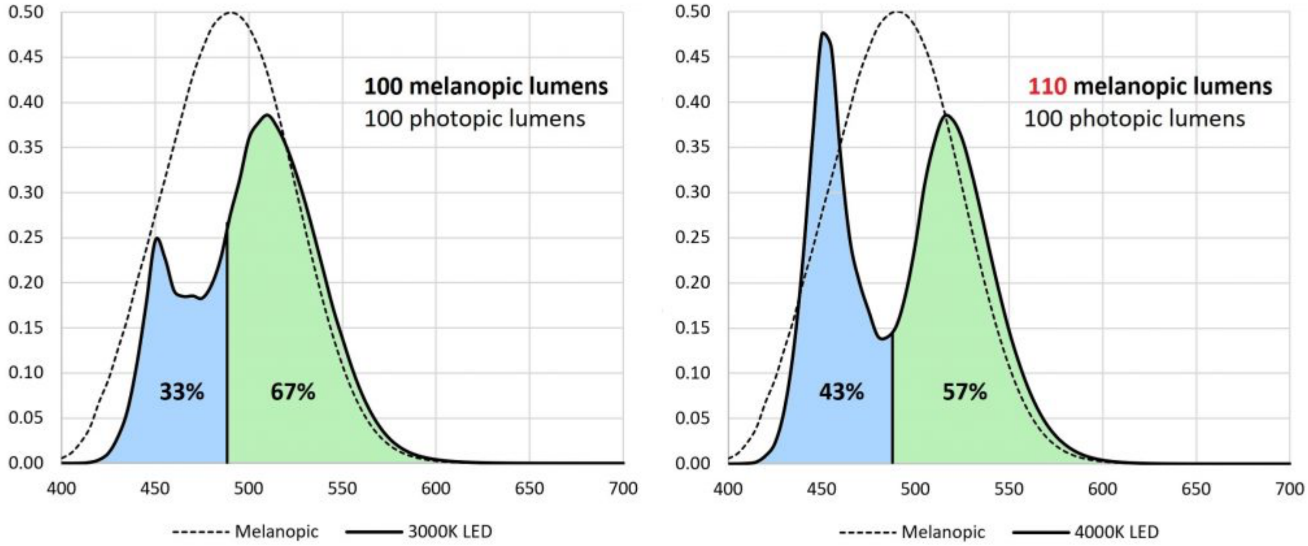

FIG. 4 – Examples of LED melanopic lumens. Left: 3000 K; right: 4000 K.

Common sense, it would seem, has good reason to be nervous. Yes, 3000-K LEDs produce less melanopic flux than 4000-K LEDs when they produce equal luminous flux. However, *THE DIFFERENCE IS ONLY TEN PERCENT*. This is within the tolerance of architectural and roadway lighting design practices. As such, it should not be argued that 3000-K LEDs are required for nighttime lighting in order to minimize circadian rhythm disruption – the difference in melanopic flux does not support this. Rather, it is simply one of several factors that must be considered when designing and specifying lighting systems.

Blue-Blocking Glasses

Figure 4 highlights another issue: the efficacy of blue-blocking glasses, which are often marketed as promoting better sleep (Figure 5).

FIG. 5 – Blue-blocking glasses. (Source: www.swanwicksleep.com).

If we assume that the yellow filters provide a perfect cutoff at 490 nm, they are only 33% effective in blocking melanopic flux from 3000-K (warm white) LEDs and 43% effective with 4000-K (neutral white) LEDs. In reality, the filters likely let through some amount of blue light in the region of 470 nm to 490 nm, and so they may be even less effective.

Simply put, we cannot prevent melanopic flux emitted by white light sources from impacting our circadian rhythms unless we use deep-red filters. This is not to say that blue-blocking filters on eyeglasses or light sources do not work – they inarguably block blue light. However, *MELANOPIC FLUX INCLUDES BOTH BLUE AND GREEN LIGHT*.

From a marketing perspective, it is fair to say that blocking blue light may alleviate circadian rhythm disruption and loss-of-sleep issues, even if it is due to the placebo effect. (There are many other psychophysiological and environmental parameters involved in circadian rhythm entrainment that are not discussed here.) However, it is incorrect to claim that blocking blue light will eliminate melatonin suppression and so prevent circadian rhythm disruption. The facts state otherwise.

Electronic Devices

Finally, what about those evil electronic devices that threaten our sleep? **Figure 6** shows the spectral power distribution of an Apple iPadÔ and the resultant melanopic flux when the display is set to full white (which has a CCT of 6700 K, somewhat higher than the 6500-K white point of most computer monitors).

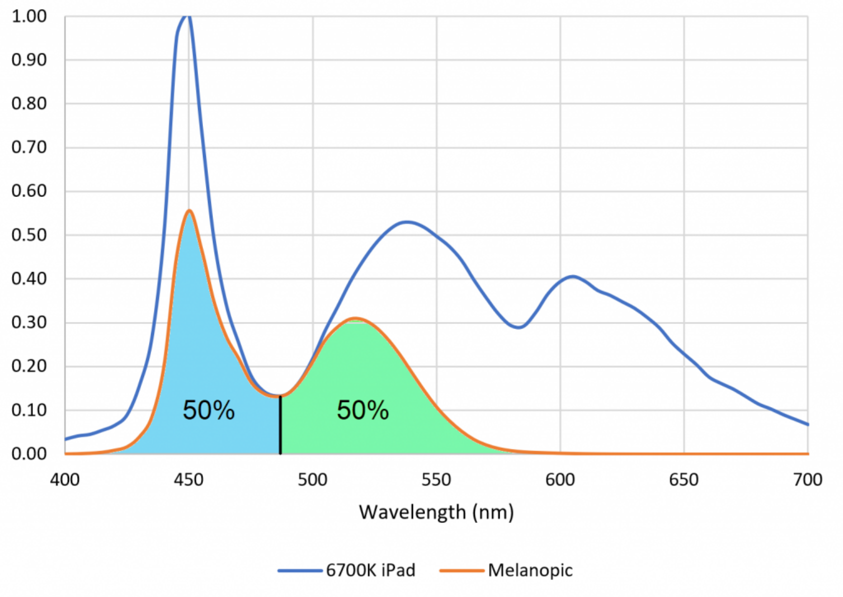

FIG. 6 – Apple iPad melanopic flux.

As shown by Figure 6, the best any optical filter or software-based change in the device white point (that is, a change in color temperature) can hope to achieve is a 50 percent reduction in melanopic flux.

What is more important, however, is that iPad screen luminance is approximately 400 cd/m^2 (nits). This is on the order of 50 to 100 times the light levels recommended for residential street lighting. If we are to complain about light trespass from residential street lighting into our bedrooms causing sleep deprivation, we cannot ignore the influence of the televisions, computer monitors, and tablets that we often stare at for hours before going to bed, and in much closer proximity.

Conclusions

Research into the influence of spectral content and retinal illuminance on circadian rhythms is ongoing (e.g., Nagare et al., 2015). As such, this article should not be taken as evidence (or lack thereof) for the effect of "blue light" on our sleep patterns. Rather, it is a reminder to look beyond the marketing claims of "blue-light blocking" products and ask what this really means.

To answer the question of whether we should specify warm white (3000 K) light sources for street lighting, the answer is, "it depends." All things being equal, the difference in melanopic flux between 3000-K and 4000-K LEDs is only ten percent. This is within the uncertainty of light design practices, and so more weight should be given to residents' concerns, aesthetics, color discrimination, and energy savings when making design and specification decisions.

To answer the question of whether eliminating light of all wavelengths below 490 nm (that is, “blue light”) will eliminate any concerns about melatonin suppression and possible sleep disruption, the answer is clear: FALSE!

References

CIE. 2015. Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013. CIE Technical Note TN 003:2015.

Nagare, R., et al. 2017. “Does the iPad Night Shift Mode Reduce Melatonin Suppression?” Lighting Research and Technology.

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