Spectral Power Distribution
The Building Block of Applied Lighting

DOE Technology Development Workshop
November 16, 2016

Dr. Michael Royer
Pacific Northwest National Laboratory
Are LED lights ruining Van Gogh's Sunflowers?

EUROPE TRAVEL | JANUARY 20, 2013 | BY: LESLEY PETERSON | + Subscribe
The Dark Side of LED Lightbulbs

LIGHTBULB FRENZY IN THE 21ST CENTURY

1. Why My Parents Have a Closet Full of Lightbulbs
2. Blinded by the Light: Wrecked Up by Our Juice, Another Citizen of the Night [Slide Show]
3. Does Turning Fluorescent Lights Off Use More Energy Than Leaving Them On?
4. How to Green Your Office
LED Lights May Damage Eyes, Researcher Says

By Marc Lallanilla, Live Science Contributor | May 13, 2013 12:02pm ET

The retinas of the eye may be especially sensitive to radiation from LED lights.
AMA Adopts Community Guidance to Reduce the Harmful Human and Environmental Effects of High Intensity Street Lighting

For immediate release:
June 14, 2016

CHICAGO - Strong arguments exist for overhauling the lighting systems on U.S. roadways with light emitting diodes (LED), but conversions to improper LED technology can have adverse consequences. In response, physicians at the Annual Meeting of the American Medical Association (AMA) today adopted guidance for communities on selecting among LED lighting options to minimize potential harmful human and environmental effects.

Converting conventional street light to energy efficient LED lighting leads to cost and energy savings, and a lower reliance on fossil-based fuels. Approximately 10 percent of existing U.S. street lighting has been converted to solid state LED technology, with efforts underway to accelerate this conversion.

"Despite the energy efficiency benefits, some LED lights are harmful when used as street lighting," AMA Board Member Maya A. Babu, M.D., M.B.A. "The new AMA guidance encourages proper attention to optimal design and engineering features when converting to LED lighting that minimize detrimental health and environmental effects."

High-intensity LED lighting designs emit a large amount of blue light that appears white to the naked eye and create worse nighttime glare than conventional lighting. Discomfort and disability from intense, blue-rich LED lighting can decrease visual acuity and safety, resulting in concerns and creating a road hazard.

In addition to its impact on drivers, blue-rich LED streetlights operate at a wavelength that most adversely suppresses melatonin during night. It is estimated that white LED lamps have five times greater impact on circadian sleep rhythms than conventional street lamps. Recent large surveys found that brighter residential nighttime lighting is associated with reduced sleep times, dissatisfaction with sleep quality, excessive sleepiness, impaired daytime functioning and obesity.

The detrimental effects of high-intensity LED lighting are not limited to humans. Excessive outdoor lighting disrupts...
Doctors issue warning about LED streetlights

By Richard G. "Bugs" Stevens, The Conversation

Updated 2:00 PM ET, Tue June 21, 2016

Photos: Los Angeles LED streetlights

The Sixth Street bridge over the Los Angeles River looks a bit different with old, left, and new streetlights.
What is this about?

1. Basics of light and vision
2. Types of light sources
3. Displaying spectral data
4. Weighting functions: use and meaning
5. Spectral tuning
Electromagnetic Spectrum

https://sites.google.com/site/mochebiologysite/online-textbook/light
What is a Spectral Power Distribution?

https://people.rit.edu/andpph/photofile-c/spectrum_8664.jpg
Plotting a Spectral Power Distribution
Sensing Radiant Energy – The Human Eye

Photoreceptor Variation
Visual System: It’s Complex!

And that’s not even talking about non-visual photoreception.
Spectral Power Distributions
Spectral Power Distributions

CAUTION: Light sources technologies are not homogenous!
Phosphor-Coated LEDs
Color Mixed LEDs

[Graph showing the spectral power distribution of various LED colors across different wavelengths (nm)].

- Red
- Lime
- Amber
- Green
- Cyan
- Blue
- Indigo

[Spectral power (W/nm) vs. Wavelength (nm)]
Color-Mixed LEDs

SPDs from: Royer MP, Wilkerson AM, Wei M, Houser KW, Davis RG. 2016. Human Perceptions of Color Rendition Vary with Average Fidelity, Average Gamut, and Gamut Shape. Lighting Research and Technology. Online before print. DOI: 10.1177/1477153516663615
Color-Mixed LEDs
Comparing Spectral Power Distributions

![Graph comparing spectral power distributions with Wavelength (nm) on the x-axis and Relative Power on the y-axis.](image-url)
Comparing Spectral Power Distributions

Absolute SPD
(Normalized for equal lumen output)
Spectral Weighting Functions

- Also known as Action Spectra, (Spectral) Efficiency Functions
- Assign a weight to each wavelength, based on a given effect or perception
- Based on human subjects experiments, then standardized
- Weighting functions are often a simplification
- Effects assumed to be additive
- Various effects:
  - (Relative) Brightness perception
  - Viewing colored light
  - Melatonin suppression/circadian effects
  - Retinal damage
  - Material damage
- Other spectrum-related effects, such as color rendering or CS, are not weighting functions
Luminous (Visual) Efficiency Function, $V(\lambda)$

$$\Phi = 683 \int P_\lambda V_\lambda d\lambda$$
Luminous (Visual) Efficiency Function, $V(\lambda)$

- Adopted by CIE in 1924
- Informed by five experiments using three different methods
  - Minimum flicker
  - Step-by-step brightness matching
  - Direct brightness matching
- All experiments used a 2° field of view, surround of same brightness
- Official version combines three experiments across different parts of the spectrum
- Large individual differences standardized to a single function
- Later refinements made, but change is difficult!
- Relative brightness, or “brightness-based”
Luminous (Visual) Efficiency Function, $V(\lambda)$

[Graph showing the luminous efficiency function $V(\lambda)$ with different sensitivity curves for various types of cones and rods.]
Calculating Weighted Values
Luminous Efficacy of Radiation (LER) = \frac{\text{Luminous Flux (Im)}}{\text{Radiant Flux (W)}}

LER = \frac{683^* \text{ Area}}{\text{Area}} = 315 \text{ lm/W}_{\text{radiant}}

LER = \frac{683^* \text{ Area}}{\text{Area}} = 154 \text{ lm/W}_{\text{radiant}}

Radiant Watts, Not Electrical Watts
Maximizing lumens requires tradeoffs with light color, color rendering, nonvisual stimulation, etc.!

Max LER = 683 lm/W
Metamerism

Area = Z

Area = Y

Area = X
Metamerism

\[ \text{Area} = X \]

\[ \text{Area} = Y \]

\[ \text{Area} = Z \]
**Metamerism / Light Color**

\[
x = \frac{X}{X + Y + Z} = 0.4507 \\
y = \frac{Y}{X + Y + Z} = 0.4080
\]

<table>
<thead>
<tr>
<th></th>
<th>LED</th>
<th>Incandescent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$</td>
<td>0.4507</td>
<td>0.4515</td>
</tr>
<tr>
<td>$Y$</td>
<td>0.4080</td>
<td>0.4067</td>
</tr>
</tbody>
</table>

$(u, v)$ and $(u', v')$ are just linear transformations of $(x, y)$
## Metamerism / Light Color

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$x = \frac{X}{X + Y + Z}$</td>
<td>0.4507</td>
<td>0.4515</td>
</tr>
<tr>
<td>$y = \frac{Y}{X + Y + Z}$</td>
<td>0.4080</td>
<td>0.4067</td>
</tr>
</tbody>
</table>

**Correlated Color Temperature (CCT)**

- Closest point on the blackbody curve (in CIE 1960 chromaticity diagram)
  - **LED**: 2789 K
  - **Incandescent**: 2812 K
CCT: An Approximation of Spectral Content
CCT: An Approximation of Spectral Content

CIE 1960 (u, v) Chromaticity Diagram

- 570
- 575
- 580
- 585

- 4000 K
- 5000 K
- 6000 K
- 7000 K
- 10000 K
- 20000 K
- 3000 K
- 2500 K
CCT: An Approximation of Spectral Content

Normalized for Equal Lumens

Nominal CCT
- 2700 K
- 3000 K
- 3500 K
- 4000 K
- 5000 K
- 6500 K
- 3000 K VP

Spectral Power (W/nm)

Wavelength (nm)
CCT: An Approximation of Spectral Content

PC LED

Linear Fluorescent

Planckian Radiation

Increasing CCT
<table>
<thead>
<tr>
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<th>Incandescent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>x</strong> = ( \frac{X}{X+Y+Z} )</td>
<td>0.4507</td>
<td>0.4515</td>
</tr>
<tr>
<td><strong>y</strong> = ( \frac{Y}{X+Y+Z} )</td>
<td>0.4080</td>
<td>0.4067</td>
</tr>
<tr>
<td><strong>CCT</strong> = Closest point on the blackbody curve (in CIE 1960 chromaticity diagram)</td>
<td>2789 K</td>
<td>2812 K</td>
</tr>
<tr>
<td><strong>D_{uv}</strong> = Distance between source and blackbody curve (in CIE 1960)</td>
<td>-0.0007</td>
<td>-0.0001</td>
</tr>
</tbody>
</table>
CCT and $D_{uv}$
CCT Has Limitations!

Spectral Power (W/nm) vs. Wavelength (nm)

3598 K
3577 K

$D_{uv} = 0.0173$

$D_{uv} = 0.0003$
Revisiting LER: Tradeoffs

Using ETC D22 Lustr+

LER (lm/W\text{radiant})

<table>
<thead>
<tr>
<th>Condition</th>
<th>LER (lm/W\text{radiant})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Maximum</td>
<td>700</td>
</tr>
<tr>
<td>Max LER</td>
<td>600</td>
</tr>
<tr>
<td>Max LER</td>
<td>300</td>
</tr>
<tr>
<td>Max LER</td>
<td>300</td>
</tr>
<tr>
<td>Max LER</td>
<td>300</td>
</tr>
</tbody>
</table>

- $D_{uv} \leq 0.007$
- $R_f \geq 80$
“Blue” Light Special!

ipRGCs and Nonvisual Photoreception (i.e., Light and Health)

- Big picture, nonvisual photoreception is a new phenomenon
- The photosensitivity of melanopsin is known and agreed upon (peak in the “blue”), but the overall sensitivity of various elements of the human body (e.g., circadian system) are still under investigation.
  - Other photoreceptors likely contribute
  - Response may be non-linear/non-additive
  - Response may change based on other factors

Blue light Hazard

- “Blue” light can case damage to the retina under the right circumstances

Material Damage

- “Blue” light can damage materials, like artwork
Blue Light Considerations

- Percent Blue
- Blue Light Hazard
- Color Matching (CCT)
- Melanopsin
- Scotopic
- Luminous Efficiency
Comparing Spectral Power Distributions

(Values shown are relative M/P ratio)
## Compare with numbers!

<table>
<thead>
<tr>
<th>Row</th>
<th>Light source</th>
<th>Luminous Flux (lm)</th>
<th>CCT (K)</th>
<th>% Blue*</th>
<th>Relative Scotopic Potential</th>
<th>Relative Melanopic Potential**</th>
<th>Relative BLH Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>PC White LED</td>
<td>1000</td>
<td>2700</td>
<td>17% - 20%</td>
<td>0.80 - 0.99</td>
<td>0.70 - 0.99</td>
<td>0.79 - 1.05</td>
</tr>
<tr>
<td>B</td>
<td>PC White LED</td>
<td>1000</td>
<td>3000</td>
<td>18% - 25%</td>
<td>0.85 - 1.08</td>
<td>0.77 - 1.10</td>
<td>0.67 - 1.35</td>
</tr>
<tr>
<td>C</td>
<td>PC White LED</td>
<td>1000</td>
<td>3500</td>
<td>22% - 27%</td>
<td>0.92 - 1.24</td>
<td>0.86 - 1.31</td>
<td>1.21 - 1.70</td>
</tr>
<tr>
<td>D</td>
<td>PC White LED</td>
<td>1000</td>
<td>4000</td>
<td>27% - 32%</td>
<td>0.95 - 1.20</td>
<td>0.86 - 1.25</td>
<td>1.38 - 1.94</td>
</tr>
<tr>
<td>E</td>
<td>PC White LED</td>
<td>1000</td>
<td>4500</td>
<td>31% - 35%</td>
<td>1.06 - 1.29</td>
<td>1.01 - 1.40</td>
<td>1.77 - 2.11</td>
</tr>
<tr>
<td>F</td>
<td>PC White LED</td>
<td>1000</td>
<td>5000</td>
<td>34% - 39%</td>
<td>1.17 - 1.31</td>
<td>1.17 - 1.38</td>
<td>1.91 - 2.46</td>
</tr>
<tr>
<td>G</td>
<td>PC White LED</td>
<td>1000</td>
<td>5700</td>
<td>39% - 43%</td>
<td>1.25 - 1.50</td>
<td>1.27 - 1.66</td>
<td>2.22 - 2.74</td>
</tr>
<tr>
<td>H</td>
<td>PC White LED</td>
<td>1000</td>
<td>6500</td>
<td>43% - 48%</td>
<td>1.48 - 1.79</td>
<td>1.61 - 2.15</td>
<td>2.52 - 2.84</td>
</tr>
<tr>
<td>I</td>
<td>Narrowband Amber LED</td>
<td>1000</td>
<td>1606</td>
<td>0%</td>
<td>0.16</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>J</td>
<td>Low Pressure Sodium</td>
<td>1000</td>
<td>1718</td>
<td>0%</td>
<td>0.16</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>K</td>
<td>PC Amber LED</td>
<td>1000</td>
<td>1872</td>
<td>1%</td>
<td>0.32</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>L</td>
<td>High Pressure Sodium</td>
<td>1000</td>
<td>1959</td>
<td>9%</td>
<td>0.40</td>
<td>0.32</td>
<td>0.36</td>
</tr>
<tr>
<td>M</td>
<td>High Pressure Sodium</td>
<td>1000</td>
<td>2041</td>
<td>10%</td>
<td>0.45</td>
<td>0.37</td>
<td>0.42</td>
</tr>
<tr>
<td>N</td>
<td>Mercury Vapor</td>
<td>1000</td>
<td>6924</td>
<td>36%</td>
<td>1.05</td>
<td>0.91</td>
<td>2.58</td>
</tr>
<tr>
<td>O</td>
<td>Mercury Vapor</td>
<td>1000</td>
<td>4037</td>
<td>35%</td>
<td>0.96</td>
<td>0.92</td>
<td>3.36</td>
</tr>
<tr>
<td>P</td>
<td>Metal Halide</td>
<td>1000</td>
<td>3145</td>
<td>24%</td>
<td>0.98</td>
<td>0.94</td>
<td>1.28</td>
</tr>
<tr>
<td>Q</td>
<td>Metal Halide</td>
<td>1000</td>
<td>4002</td>
<td>33%</td>
<td>1.14</td>
<td>1.16</td>
<td>2.15</td>
</tr>
<tr>
<td>R</td>
<td>Metal Halide</td>
<td>1000</td>
<td>4041</td>
<td>35%</td>
<td>1.28</td>
<td>1.38</td>
<td>2.14</td>
</tr>
<tr>
<td>S</td>
<td>Moonlight***</td>
<td>1000</td>
<td>4681</td>
<td>29%</td>
<td>1.50</td>
<td>1.68</td>
<td>2.26</td>
</tr>
<tr>
<td>T</td>
<td>Incandescent</td>
<td>1000</td>
<td>2812</td>
<td>11%</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>U</td>
<td>Halogen</td>
<td>1000</td>
<td>2934</td>
<td>13%</td>
<td>1.03</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>V</td>
<td>F32T8/830 Fluorescent</td>
<td>1000</td>
<td>2940</td>
<td>20%</td>
<td>0.91</td>
<td>0.84</td>
<td>1.08</td>
</tr>
<tr>
<td>W</td>
<td>F32T8/835 Fluorescent</td>
<td>1000</td>
<td>3480</td>
<td>26%</td>
<td>1.07</td>
<td>1.05</td>
<td>1.50</td>
</tr>
<tr>
<td>X</td>
<td>F32T8/841 Fluorescent</td>
<td>1000</td>
<td>3969</td>
<td>30%</td>
<td>1.17</td>
<td>1.17</td>
<td>1.68</td>
</tr>
</tbody>
</table>


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

*** Measurement by Telelumen. Moonlight does not have a constant CCT.
Comparing Blue Measures
Compare with numbers!

Spectral Power (W/nm)

- 3598 K: 0.0173
- 3577 K: 0.0003

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>S/P</th>
<th>M/P</th>
<th>B/P</th>
<th>%B</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>1.15</td>
<td>1.14</td>
<td>0.92</td>
<td>3%</td>
</tr>
<tr>
<td>430</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>480</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>530</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>580</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>630</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>680</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>730</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>780</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Maximizing and minimizing melanopic content at same chromaticity:

CCT = 4133 K  \(D_{uv} = -0.0094\)  Rf = 57  Rg = 92  \(m/p = 2.27\)

CCT = 3838 K  \(D_{uv} = 0.01\)  Rf = 75  Rg = 96  \(m/p = 1.00\)

CCT = 3900 K  \(D_{uv} = 0.005\)  Rf = 80  Rg = 99  \(m/p = 1.11\)

CCT = 4101 K  \(D_{uv} = -0.005\)  Rf = 80  Rg = 95  \(m/p = 1.83\)

\(m/p\) normalized to incandescent = 1
Maximizing and minimizing melanopic content at same chromaticity:

CCT = 3900 K
$D_{uv} = 0.005$
Rf = 80
Rg = 99
m/p = 1.11

CCT = 4101 K
$D_{uv} = -0.005$
Rf = 80
Rg = 95
m/p = 1.83
Don’t Forget! Material Damage Function, $S(\lambda)$

Where $b$ is an average value calculated from measured reference samples for a specific medium. For example, $b = 0.012$ for watercolors, or $b = 0.038$ for newspapers.

$$s_{df}(\lambda) = \exp[b(300-\lambda)]$$
Don’t Forget! Plants and Animals

![Graph showing absorbance and wavelength for Chlorophyll a and Chlorophyll b. The x-axis represents Wavelength [nm] ranging from 400 to 700, and the y-axis represents Absorbance. The graph highlights peaks at different wavelengths for each pigment.]
Don’t Forget! Color Rendition
Conclusions

- LEDs offer unprecedented ability for spectral engineering.
- LED is not a homogenous technology!
- LEDs do not pose an unusual hazard for any undesirable consequence of lighting.
- Measures of blue are correlated, but not substitutes. Sources can be carefully tuned to minimize or maximize various effects.
- One action spectrum can’t be used to quantify another. Illuminance doesn’t characterize melanopic response.
- When designing a spectrum, there are inevitably tradeoffs.
- Understand how SPDs are measured and reported.
- Understand how SPDs can be represented in charts.
- Use numbers, rather than visual evaluations.

Other warnings:
Never use two weighting functions at once.
Watch out for scaling factors and know when they are/aren’t used.
Always use absolute SPDs when calculating weighted values.
Understand the dλ term and how SPDs are measured/reported.