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Light Spectrum and Color Quality

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Color Rendering of Light Source
Light Color vs. Object Color

Chromaticity diagrams such as $(x,y)$, $(u',v')$ are two-dimensional and are only for light color. These are not for object color.

No black, grey, or brown

Object color needs another axis: black—white

so, 3-dimensional color space.
Three attributes of object color are hue, chroma (saturation), and lightness, and are expressed in a three dimensional space.

CIE standard object color spaces:
- CIELAB
- CIELUV
published in 1976.
CIE 1976 (L*a* b*) color space
(CIELAB color space)

\[ X, Y, Z \]: for object surface
\[ X_n, Y_n, Z_n \]: white reference
(perfect diffuser)

\[ L^* = 116 \left( \frac{Y}{Y_n} \right)^{1/3} - 16 \]
\[ a^* = 500 \left[ \left( \frac{X}{X_n} \right)^{1/3} - \left( \frac{Y}{Y_n} \right)^{1/3} \right] \]
\[ b^* = 200 \left[ \left( \frac{Y}{Y_n} \right)^{1/3} - \left( \frac{Z}{Z_n} \right)^{1/3} \right] \]

(when \( X / X_n, Y / Y_n, Z / Z_n > 0.008856 \))

Color difference

\[ \Delta E_{ab}^* = \left[ (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{1/2} \]

Ref. CIE 15:2004
CIELAB \((a^*, b^*)\) plots: Hue-Chroma plot

1200 Munsell color samples

15 saturated Munsell color samples

Ref. D65
## Color Rendering Index (CRI)

### CIE 13.3

**Test source**

- Same CCT [K]

**Reference source**

- Planckian (CCT < 5000 K)
- Standard Daylight (CCT > 5000 K)

### Table

<table>
<thead>
<tr>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Color Sample 1" /></td>
<td><img src="image2.png" alt="Color Sample 2" /></td>
<td><img src="image3.png" alt="Color Sample 3" /></td>
<td><img src="image4.png" alt="Color Sample 4" /></td>
<td><img src="image5.png" alt="Color Sample 5" /></td>
<td><img src="image6.png" alt="Color Sample 6" /></td>
<td><img src="image7.png" alt="Color Sample 7" /></td>
<td><img src="image8.png" alt="Color Sample 8" /></td>
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</tbody>
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<thead>
<tr>
<th>#9</th>
<th>#10</th>
<th>#11</th>
<th>#12</th>
<th>#13</th>
<th>#14</th>
</tr>
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<tbody>
<tr>
<td><img src="image9.png" alt="Color Sample 9" /></td>
<td><img src="image10.png" alt="Color Sample 10" /></td>
<td><img src="image11.png" alt="Color Sample 11" /></td>
<td><img src="image12.png" alt="Color Sample 12" /></td>
<td><img src="image13.png" alt="Color Sample 13" /></td>
<td><img src="image14.png" alt="Color Sample 14" /></td>
</tr>
</tbody>
</table>
**$R_9$ for red object rendering**

$R_9$ : Good indication for rendering of red objects and skin tone (very important). Useful information to supplement $R_a$.

**Why $R9$ scores go negative?**
The red region in color space ($W^*U^*V^*$) used in CRI is extremely stretched (by a factor of 3 or 4). Color difference ($\Delta E$) in red is calculated to be much larger than other colors and its score gets low: $R_9 = 100 - 4.6 \times \Delta E_9$.

To convert $R_9$ value to the similar scale as $R_a$ (for 2700 to 3000 K),

$$R_9' = 100 - (100 - R_9)/4$$

So,

$R_9 > 0 \Rightarrow R_9' > 75$ (acceptable)

$R_9 > 50 \Rightarrow R_9' > 88$ (very good)
Fixes the problems of CRI for SSL sources
Produce one number score that correlates well with visual perception of color rendering for real objects

- 15 saturated test color samples
- Update the old formulae in CRI
  - CIELAB color space
  - CMCCAT2000 chromatic adaptation
  - 0 to 100 scale
  - RMS averaging of color differences
- Saturation factor (address the Hunt effect)
- Discussed in CIE TC1-69. Next action..

W. Davis and Y. Ohno, Color Quality Scale, Optical Engineering 49 (3), 033602 March 2010
Color Rendering Simulation (CQS 9.0 EXCEL sheet)

Color quality and energy efficiency

Optimize spectrum for intended applications.
Trade-off between efficacy and color rendering

Daylight (400-700 nm)  
White light source  
Low pressure sodium lamp

LER (theoretical maximum)  
~ 250 lm/W  300 ~ 400 lm/W  520 lm/W

Excellent color rendering  (CRI=100)  
color rendering  ??  
No color rendering  (CRI= -47)

There are some ways to enhance both color quality and energy efficiency
Luminous Efficacy of a Source

Theoretical maximum lm/W of a given source.
Determined only by the spectrum of the source.

Example: \( 200 \text{ lm/W} \times 50\% = 100 \text{ lm/W} \)

\[
\text{Luminous Efficacy of a Source [lm/W]} = \frac{\text{Luminous flux [lm]}}{\text{Electrical power [W]}} \times \text{Radiant Efficiency (External Q.E.)} \times \frac{\text{Luminous flux [lm]}}{\text{Optical power [W]}}
\]

\[
400 \text{ lm/W}
\]

\[
\begin{array}{c}
400 \\
500 \\
600 \\
700 \\
\end{array}
\]

\[
\text{Example: } 200 \text{ lm/W} \times 50\% = 100 \text{ lm/W}
\]

\[
\text{Luminous Efficacy of Radiation [lm/W]} = \frac{\text{Luminous flux [lm]}}{\text{Optical power [W]}}
\]

\[
\text{Theoretical maximum lm/W of a given source.}
\]

\[
\text{Determined only by the spectrum of the source.}
\]
Luminous Efficacy of Radiation - LER (lm/W)

Theoretical lm/W for a given spectrum

\[ K_m \int \frac{S(\lambda)V(\lambda)d\lambda}{\int S(\lambda)d\lambda} \quad [\text{lm/W}] \]

(\( K_m = 683 \text{ lm/W} \))

<Examples of LER>
Tri-p FL (3300 K) \( \sim \) 350 lm/W
CW FL (4300 K) \( \sim \) 340 lm/W
MH (4300 K) \( \sim \) 300 lm/W
HPS (2100 K) \( \sim \) 380 lm/W
B-Y phosphor LED \( \sim \) 310 lm/W
What we can learn from fluorescent lamps

Cool White

- CCT: 4196
- Duv: 0.008
- CRI Ra: 59
- R9: -106
- LER (lm/W): 356
  - CQS: 61

Cool White improved for color

- CCT: 4030
- Duv: -0.006
- CRI Ra: 87
- R9: -1
- LER (lm/W): 311
  - CQS: 84

Tri-phosphor

- CCT: 3969
- Duv: 0.005
- CRI Ra: 85
- R9: 17
- LER (lm/W): 349
  - CQS: 83

Narrow-band may be the solution for both high efficacy and high color rendering.
Examples of real LED lamps (sold in USA)

Phosphor-type white LEDs are meeting current needs, but . . . .
Narrowband can be more efficient (available LEDs)

Narrow-band: + 20% higher theoretical lm/W, plus another + 20 % gain from no Stokes loss
Simulation of RGB/RGBA (not limited to available LEDs)

<table>
<thead>
<tr>
<th>LED Model</th>
<th>CCT</th>
<th>Duv</th>
<th>CRI Ra</th>
<th>R9</th>
<th>LER (lm/W)</th>
<th>CQS Qa</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB model (457/546/619)</td>
<td>3000</td>
<td>0.000</td>
<td>85</td>
<td>90</td>
<td>378</td>
<td>86</td>
</tr>
<tr>
<td>RGBA-1 (457/526/576/619)</td>
<td>3000</td>
<td>0.000</td>
<td>91</td>
<td>32</td>
<td>382</td>
<td>90</td>
</tr>
<tr>
<td>RGBA-2 (457/526/576/626)</td>
<td>3000</td>
<td>0.000</td>
<td>96</td>
<td>95</td>
<td>364</td>
<td>92</td>
</tr>
<tr>
<td>RGBA-3 (R-G enhanced)</td>
<td>3000</td>
<td>0.000</td>
<td>87</td>
<td>64</td>
<td>352</td>
<td>93</td>
</tr>
</tbody>
</table>

- **378 lm/W**
  - $R_a = 85$
  - $R_g = 90$

- **382 lm/W**
  - $R_a = 91$

- **364 lm/W**
  - $R_a = 96$

- **352 lm/W**
  - $Q_a = 93$
All the numbers look good.

How about real color quality?
NIST Spectrally Tunable Lighting Facility
NIST Spectrally Tunable Lighting Facility

- Real-size room (2.5 m x 2.5 m cubicle)
- 2 cubicles side by side.
- 1800 high power LEDs in 22 channels of LED spectra.
- > 500 lx illumination with many simulated white light spectra
Broadband Reference light (4000 K)

4000 K
CRI Ra=98
Duv=0.000
RGBA 4 Peaks light (4000 K)

4000 K  
CRI Ra=95  
Duv=0.001
Broadband Reference light (3000 K)

3000 K
CRI Ra=96
Duv=0.000
RGBA 4 Peaks light (3000 K)

3000 K
CRI Ra=95
Duv=0.000
Typical WW LED lamp (phosphor)

3000 K
CRI Ra=78
Duv=0.000
Broadband Reference light (3000 K)

3000 K
CRI Ra=98
Duv=-0.001
RGBA Color-enhanced

3000 K
CRI Ra=81
CQS=88
Duv=0.000
Current broadband phosphor white LEDs meet current urgent needs for energy saving, but color quality and theoretical efficacy of most of them are not great.

Narrowbands can be theoretically more energy efficient.

Narrowbands can create as good color rendering as smooth broadband sources.

Narrowbands can make color-enhanced sources (preferred in many applications.)

Thank you for your attention.
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