IES TM-30-15:
A New Tool for Evaluating Light Source Color Rendition

AATCC LED Summit
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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.” (CIE)

The effect of Light on Objects’ appearance, as judged by a Human observer based on their expectations.
Color Rendering Metrics Help Us To...

Understand.
Communicate.
Engineer.
Compare.
Predict.

Object Colors

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<tr>
<th>Source Spectrum</th>
<th>Object Reflection</th>
<th>Stimulus</th>
</tr>
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<tbody>
<tr>
<td><img src="source_spectrum_graph.png" alt="Graph" /></td>
<td><img src="object_reflection_graph.png" alt="Graph" /></td>
<td><img src="stimulus_graph.png" alt="Graph" /></td>
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Wavelength (nm)
A stimulus is reduced to three “numbers” by the three cone sensors in our eyes (similar to an RGB digital camera).

A color space is a 3-dimensional coordinate system that corresponds to visual stimuli. It is a mathematical model of our visual system.

“Source color space” – characterizes the color of a light source (Chromaticity Diagram)

“Object color space” – characterizes the color of objects under a light source

CIEXYZ

CAM02-UCS
Color Space

Interaction of “Colors” and Light
Interaction of “Colors” and Light

Desaturating (more dull)

Saturating (more vivid)

Reference color

Hue shift (more orange)

Hue shift (more pink)
Characterizing Color Shifts

- Reference colors for a series of objects
- Colors under a test source

Saturating for yellow objects
Desaturating for red objects

CIE CRI
Determine the CCT of the test source.

Calculate a reference source at the same CCT

Calculate the color of test samples under the test and reference sources

Determine the average difference in color for the two sets.

• What does “reference color” mean?
  • It is the color of an object illuminated by a reference light source.

• Ok then... what does a “reference light source” mean?
  • By convention, we use daylight for CCT > 5000K and Planckian radiation (heated mass) for CCT < 5000K. We use a reference at the same CCT as the test source.
CIE CRI ($R_a$)

Test Source

Reference Illuminant

Radiant Power

Wavelength (nm)

SAME CRI

Radiant Power

Wavelength (nm)

CIE CRI ($R_a$)

Color Samples for $R_a$

TCS 01
TCS 02
TCS 03
TCS 04
TCS 05
TCS 06
TCS 07
TCS 08

Color Samples for $R_{9-14}$

TCS 09
TCS 10
TCS 11
TCS 12
TCS 13
TCS 14
Each "color error" lowers the CRI score. The longer the arrow, the lower the CRI score.

The CRI tells us whether a light source renders colors "naturally" (like the reference), on average.
Technical Limitations of CRI

Some of the color science used in the CRI is outdated / inaccurate:

- **Non-uniform color space.** Color distortions are not all weighted equally.
- **Incorrect chromatic adaptation transformation.**
- **Limited number of test colors.** Fine-tuning of spectral peaks can lead to several points difference in CRI score that is not representative of what we see.
- **Samples have limited features.** Do pastels tell us about all colors?

IES TM-30-15
IES TM-30 versus CIE CRI

CRI Calculation Engine  
Outdated Color Science  
Limited Color Samples

TM-30 Calculation Engine  
Modern Color Science  
New Color Samples

Average Fidelity  
$R_a$ (CRI)

Specific Sample Fidelity  
$R_s$, etc.

High Level Average Values  
Fidelity Index ($R_f$)  
Gamut Index ($R_g$)

Graphical Representations  
Color Vector Graphic  
Color Distortion Graphic

Detailed Values  
Skin Fidelity ($R_{f,skin}$)  
Fidelity by Hue ($R_{f,h}$)  
Chroma Shift by Hue ($R_{cs,h}$)  
Fidelity by Sample ($R_{f,CES}$)

CRI Calculation Engine  
Outdated Color Science  
Limited Color Samples

CIE CRI (1965/1974)  
CIE 1964 U*V*W*  
8 color samples  
Medium chroma/lightness  
Spectral sensitivity varies  
Munsell samples only  
Ref Illuminant Step Function  
No lower limit for scores and inconsistent scales

IES TM-30 (2015)  
CAM02-UCS (CIE CAM02)  
99 color samples  
Uniform color space coverage  
Spectral sensitivity neutral  
Variety of real objects  
Ref Illuminant Continuous  
(Uses same reference sources, but blended between 4500 K and 5500 K)  
0 to 100 scale (fidelity)
Color Fidelity
The accurate rendition of color so that they appear as they would under familiar (reference) illuminants.
Fidelity Index ($R_f$) (0-100)

Color Gamut
The average level of saturation relative to familiar (reference) illuminants.
Gamut Index ($R_g$) ~60-140 when $R_f > 60$

Gamut Shape
Changes over different hues

Color Vector Graphic
Hue Bin Chroma Shift

Is TM-30 $R_f$ Different from CRI?

~16 point spread in $R_f$ scores at $R_a = ~80$
Is TM-30 $R_f$ Different from CRI?

5,000 Real and Modelled* SPDs
*All modelled SPDs composed of combinations of Gaussian primaries; chromaticity on Planckian locus between 2700 K and 7000 K

Adding Average Gamut Area

- Evaluate tradeoffs between fidelity and saturation.
- When disparate fidelity and gamut measures are used together, the tradeoffs are less apparent.
- But average values don’t tell the whole story...
TM-30 Color Vector Graphics

COLOR VECTOR GRAPHIC

CES CHROMATICITY COMPARISON

- Reference Source
- Test Source

TM-30 Color Vector Graphics
TM-30 Color Vector Graphics

COLOR VECTOR GRAPHIC

CES CHROMATICITY COMPARISON

- Reference Source
- Test Source

Decreased Saturation
Hue Shift

Increased Saturation
Decreased Saturation
Why are Color Vector Graphics Important?

Same red fidelity, shift in opposite directions.
Light Sources

A Fundamental Relationship

We can make sources like the reference, but they’re not very efficient.
Halogen (MR16)
TM-30 Library Source No. 80

\[ R_f = 99 \]
\[ R_g = 99 \]
\[ R_{f,\text{skin}} = 99 \]
\[ R_{f,h1} = 98 \]
\[ R_{cs,h1} = -1\% \]
\[ R_a = 99 \]
\[ R_g = 93 \]
\[ \text{CCT} = 2988 K \]
\[ D_{uv} = 0.0010 \]
\[ \text{LER} = 180 \]
Neodymium Incandescent
TM-30 Library Source No. 88

$R_f = 86$
$R_g = 109$
$R_{f,skin} = 84$
$R_{f,h1} = 78$
$R_{cs,h1} = 11\%$
$R_a = 77$
$R_g = 15$

CCT = 2756 K
$D_{uv} = -0.0048$
LER = 136

Linear Fluorescent F32T8/835
TM-30 Library Source No. 38

$R_f = 75$
$R_g = 99$
$R_{f,skin} = 84$
$R_{f,h1} = 74$
$R_{cs,h1} = -12\%$
$R_a = 79$
$R_g = -5$

CCT = 3563 K
$D_{uv} = -0.0002$
LER = 349
Ceramic Metal Halide 835
TM-30 Library Source No. 62

\[ R_f = 79 \]
\[ R_g = 100 \]
\[ R_{f,\text{skin}} = 78 \]
\[ R_{f,h1} = 74 \]
\[ R_{cs,h1} = -12\% \]
\[ R_a = 84 \]
\[ R_g = -29 \]
\[ \text{CCT} = 3083 \text{ K} \]
\[ D_{uv} = -0.0024 \]
\[ \text{LER} = 294 \]

PC White LED
TM-30 Library Source No. 184

\[ R_f = 81 \]
\[ R_g = 94 \]
\[ R_{f,\text{skin}} = 86 \]
\[ R_{f,h1} = 75 \]
\[ R_{cs,h1} = -13\% \]
\[ R_a = 81 \]
\[ R_g = 0 \]
\[ \text{CCT} = 3429 \text{ K} \]
\[ D_{uv} = 0.0001 \]
\[ \text{LER} = 332 \]
### Hybrid LED (PC+Red)

TM-30 Library Source No. 92

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$R_f$</td>
<td>89</td>
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<tr>
<td>$R_g$</td>
<td>105</td>
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<tr>
<td>$R_{f,\text{skin}}$</td>
<td>97</td>
</tr>
<tr>
<td>$R_{f,h1}$</td>
<td>91</td>
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<tr>
<td>$R_{cs,h1}$</td>
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<tr>
<td>$R_a$</td>
<td>94</td>
</tr>
<tr>
<td>$R_g$</td>
<td>89</td>
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<tr>
<td>CCT</td>
<td>2776 K</td>
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<tr>
<td>$D_{uv}$</td>
<td>0.0011</td>
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<tr>
<td>LER</td>
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### RGB LED

TM-30 Library Source No. 108

<table>
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<td>$R_f$</td>
<td>80</td>
</tr>
<tr>
<td>$R_g$</td>
<td>114</td>
</tr>
<tr>
<td>$R_{f,\text{skin}}$</td>
<td>81</td>
</tr>
<tr>
<td>$R_{f,h1}$</td>
<td>70</td>
</tr>
<tr>
<td>$R_{cs,h1}$</td>
<td>15%</td>
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<tr>
<td>$R_a$</td>
<td>71</td>
</tr>
<tr>
<td>$R_g$</td>
<td>-27</td>
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<tr>
<td>CCT</td>
<td>3906 K</td>
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<tr>
<td>$D_{uv}$</td>
<td>0.0027</td>
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<tr>
<td>LER</td>
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PC White LED
TM-30 Library Source No. 175

<table>
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<th>Parameter</th>
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<td>$R_f$</td>
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<tr>
<td>$R_g$</td>
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<td>$R_{f,skin}$</td>
<td>98</td>
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<tr>
<td>$R_{f,h_1}$</td>
<td>97</td>
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<tr>
<td>$R_{c_s,h_1}$</td>
<td>0%</td>
</tr>
<tr>
<td>$R_a$</td>
<td>97</td>
</tr>
<tr>
<td>$R_g$</td>
<td>98</td>
</tr>
<tr>
<td>CCT</td>
<td>2733 K</td>
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<tr>
<td>$D_{uv}$</td>
<td>-0.0031</td>
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<tr>
<td>LER</td>
<td>252</td>
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What Color Distortions Do We Prefer?
Experiment Context

Lighting Conditions: 26
Illuminance: ~20 fc
CCT: 3500 K
Objects: Generic Consumer, balanced hues
Application: Undefined
Participants: 18-65, 16 females 12 males
Rating Questions: Normal-Shifted, Saturated-Dull, Like-Dislike
Preferrency vs. Fidelity

\[ R^2 = 0.06 \]

Dislike

Like

Fidelity Index \( R_f \)

Mean Preference Rating

\( R_f \rightarrow 80 \quad \frac{115}{R_f} \)

CCT = 2501 K

\( R_f \rightarrow 140 \quad \frac{115}{R_f} \)

\( \frac{140}{115} \quad \frac{115}{R_f} \)

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\( \frac{140}{115} \quad \frac{115}{R_f} \)

\( \frac{140}{115} \quad \frac{115}{R_f} \)

\( \frac{140}{115} \quad \frac{115}{R_f} \)
### Preference vs. Fidelity/Gamut

![Preference vs. Fidelity/Gamut Diagram]

- Model $\eta = 0.68$

### Gamut Shape/Red Rendering

![Gamut Shape/Red Rendering Diagram]

- 21, 5.0, More Favorable
- 22, 3.1, More Improved

Same Fidelity, Same Gamut, Significantly Different Rating.
Preference for Increased Red Saturation...with limits.

Best Model for Preference:
Like-Dislike = 7.396 - 0.0408(R_f) + 103.4(R_{cs,h16}^2) - 9.949(R_{cs,h16})

Preference Model for this Experiment
Summary

Normalness = Fidelity + Red Fidelity/Saturation
\[ R_f > 80 \quad R_{f,h1} > 80 \quad 0\% < R_{cs,h1} < 8\% \]

Saturation = Red Saturation
Maximize \( R_{cs,h16}, R_{cs,h1} \)

Preference = Fidelity + Red Saturation
\[ R_f > 74 \quad 0\% < R_{cs,h16} < 15\% \quad (R_g > 100) \]
\[ 0\% < R_{cs,h1} < 15\% \]

Context =

[Image of a room with various items]

[Image of a store front with 'Celtic Football Club']
A Look at Existing Sources vs. Preference

- Phosphor LED
- Color Mixed LED
- Hybrid LED
- Standard Halogen
- Filtered Halogen
- Triphosphor Fluorescent, 7XX
- Triphosphor Fluorescent, 8XX
- Triphosphor Fluorescent, 9XX
- Metal Halide
A Look at Existing Sources

Why so Few Preferred Sources?
Why so Few Preferred Sources?

Common Commercially Available Sources

(Developed for CRI $R_a$):

F32T8/735

F32T8/835

Blue-Pump Phosphor LED (81 CRI)

$R_a$ 74, LER 348

$R_a$ 83, LER 343

$R_a$ 83, LER 309
Enhanced Sources?
(Developed for CRI $R_a$ and/or Gamut Area)

LED (Patent Application)

- Projected Rank: 2 of 26
- $R_a 80$, LER 272

LED (Available Product)

- Projected Rank: 17 of 26
- $R_a 87$, LER 295

Sources Designed for Preference
(Developed based on research and/or TM-30)

Neodymium Incandescent

- $R_a 85$, LER 2756 K

LED (Available Product)

- $R_a 78$, LER 3000 K
Efficiency vs. Preference

High Preference, High LER

- CRI: 82, R\textsubscript{9}: 43
- CRI: 88, R\textsubscript{9}: 78

Relative Power vs. Wavelength (nm)
Evaluation of new color metrics: Guidelines for developing narrow-band red phosphors for WLEDs†

Ji Hyun Oh,†† Han Joo Eun,†† Hwee Chang Yoon,†† Young-Ouk Huh,† and Young Reg Oh††

Phosphor-converted white-light-emitting diodes (pc-WLEDs) are rapidly becoming more popular in the lighting industry due to their energy savings, long lifetimes, and environmentally friendly characteristics. The color rendering index (CRI, R9) and the visual energy efficiency (luminous efficacy of radiation, Eo) are the critical metrics to be considered when developing novel red phosphors for use in white pc-WLEDs to replace incandescent and fluorescent lamps. In this regard, narrow-band red-emitting materials have been intensively developed in terms of the CRI and L90 in an effort to complement the red deficiency of the widely commercialized red phosphors based on YAG:Ce3+ and YAG:Eu2+. However, CRI and L90 are limited in their ability to guarantee good structural colors of illuminated objects under a warm white color. Instead of using CRI and L90 alone, a more comprehensive system, such as the CIE quality factor (Qq), was developed and adapted by the Illuminating Engineering Society (IES) technical memorandum TM-30-2013 for correct evaluations of the color rendition and to guide the optimization of LED light sources. In this review, we summarize the recent findings on next-generation red phosphors, the improved color and visual energy properties of these phosphors, and their ability to impress the structural properties of corresponding warm-white pc-WLED lightings. To address the complex problem of overestimation of high CRI values, we discuss the cases in which the narrow-band red phosphor affects the new color metrics (90, R9, and color lumen) and the UCLs of similar pc-WLEDs with varying the narrow scale structure. The illustrative peak position of red phosphors. These new color metrics and CIE criteria provide guidelines with which many research and industry researchers can develop new red phosphors by optimizing the crystal structure, crystal rigidity, band symmetry, the number of available sites for activators, the selection of the host and activator, and other factors.
Summary

• TM-30 offers substantial improvement over CRI, both in terms of technical accuracy and in providing a more complete representation of color rendering.
• TM-30 can be as simple or as complicated as you want it to be; it’s more than just two average measures.
• TM-30 provides benefits for manufacturers, specifiers, researchers, and energy efficiency programs.
• TM-30 is a tool, not an answer. You must understand it to be able to use it effectively.
• Color quality is more than just TM-30. Keep an eye on other metrics.
• How will the relationship between lighting and textiles change?

Additional Resources

IES Technical Memorandum (TM) 30-15 (Includes Excel Calculators):
IES Method for Evaluating Light Source Color Rendition
http://bit.ly/1MWZvUo

Optics Express journal article that provides overview of the IES method:
Development of the IES method for evaluating the color rendition of light sources

Application webinar co-sponsored by US Department of Energy and Illuminating Engineering Society:
http://1.usa.gov/1YDsBZ

Technical webinar co-sponsored by US Department of Energy and Illuminating Engineering Society:
A Technical Discussion of TM-30-15: Why and How it Advances Color Rendition Metrics
http://1.usa.gov/Mn15LG

LEUKOS journal article supporting TM-30’s technical foundations:
http://dx.doi.org/10.1080/15502724.2015.1091386

LEUKOS editorial discussing next steps:
http://dx.doi.org/10.1080/15502724.2015.1093752

Lighting Research and Technology, Open Letter:
Correspondence: In support of the IES method of evaluating light source colour rendition
(More than 30 authors)
http://dx.doi.org/10.1177/1477153515617392

DOE Fact Sheet on TM-30

DOE TM-30 FAQs Page:
http://energy.gov/ees/tm-30-frequently-asked-questions