Color Quality Metrics and Spectral Design of SSL Sources

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Topics

- Color Quality Metrics update (TM-30 Rf, CIE Rf)
- Color fidelity and color preference
- Broadband and narrowband
- New research at NIST on color quality
- White light chromaticity
Color Quality metrics

Standards / documents from standardizing bodies

- **CRI**
  - CIE 13.2 (1974)
  - CRI CIE 13.3 (1995)
  - Editorial revision

- **IES TM-30**
  - IES Fidelity Index Rf
  - IES Gamut Index Rg

- **CIE 224**
  - CIE 2017 Color Fidelity Index Rf

Research / proposals

- **CQS**
- **GAI**
- **CRI-2012**
- **Memory color-CRI**
- **Gamut shape**
- **Red saturation**

- **CIE TC 1-91**
  - Technical Report
  - Summary of published metrics beyond fidelity
IES TM-30-15 IES Method for Evaluating Light Source Color Rendition

- Two-metric system
  - Fidelity index $R_f$
  - Gamut index $R_g$

- 99 test samples

- Latest color space and formula

- Color shift graphics

Color fidelity: Improvement of CRI $R_a$

Information related to preference

Works accurately for “all colors of objects” and all kinds of spectra

Provide details beyond $R_f$ and $R_g$. 
TM-30 cannot replace CRI. Why?

• A regional standard cannot replace an international standard (unless it is adopted internationally).
• TM-30 is not a standard. It is issued for evaluation (IES position statement PS0815 Color Rendering Index)

Technically,
• TM-30 has two numbers, $R_f$ and $R_g$. One number is needed to replace CRI $R_a$.
• Can Fidelity Index $R_f$ (only) replace CRI $R_a$?
CIE 2017 Colour Fidelity Index
for Accurate Scientific Use

- CIE TC1-90 (started in 2012) was developing an improved color fidelity metric (with original intention to replace CRI)
- TC1-90 examined and adopted IES TM-30 Fidelity Index $R_f$ with small modifications. The 99 test samples and color space, calculation formulae are the same.

“The general colour fidelity index $R_f$ is not a replacement of the CRI ($R_a$) for the purpose of rating and specification of products nor for regulatory or other minimum performance requirements”
Average scores of Ra and Rf are equal \((R_a=R_f=75.1)\) for F1 to F12 (fluorescent lamp illuminants) in CIE 15:2004.
A modification of TM-30 $R_f$ (scaling factor)

Average scores of $R_a$ and $R_f$ are equal ($R_a = R_f = 80.8$) for 187 lamp spectra ($Ra>60$) in the SPD Library of IES TM-30-15 calculation tool, consisting of

- 36 fluorescent lamps,
- 14 HID lamps,
- 129 LED phosphor type,
- 8 LED hybrid lamps
(not including RGB(A))

$$R'_f = 100 - 6.73 \left( \frac{1}{99} \sum_{i=1}^{99} (\Delta E_{Jab,i}) \right)$$

CIE 224 Scaling Factor
Color Fidelity and Color Preference

Color fidelity: How close a light source renders object colors to the reference light (blackbody / daylight).

Color preference: There are perception effects beyond fidelity. Slight over-saturation of colors is often preferred.

**Scientists:** Color fidelity is the fundamental color quality. It should be the color quality measure for products.

**Industry:** Color preference is important. Color quality metric should consider both.
2014 Vision Experiment at NIST on preferred chroma saturation level

- 20 subjects
- 2700 K, 3500 K, 5000 K
- $D_{uv} = 0$, -0.015 (3500 K only)
- Illuminance 300 lx

Most saturated

Most de-saturated
2014 Vision Experiment at NIST on preferred chroma saturation level

- 20 subjects
- 2700 K, 3500 K, 5000 K
- \( D_{uv}=0, -0.015 \) (3500 K only)
- Illuminance 300 lx

\[
\Delta C^*_{ab} = 16
\]

\[
\Delta C^*_{ab} = -16
\]

Results (average of all CCTs)

- Over-saturation
- De-saturation
- CRI \( Ra \)
- (for 3500K)

- Fruits/Vegetable
- Skin tone
- Red fruits
- Green fruits

Subjects' preference

Chroma difference \( \Delta C^*_{ab} \) (CQS red sample)

Broadband and Narrowband

* Narrowband spectrum is theoretically more energy efficient

**p-c White + Red phosphor**
- CCT: 3000
- Duv: 0.000
- CRI Ra: 90
- R9: 45
- LER (lm/W): 310
- CQS: 89

**p-c White + Red chip**
- CCT: 3000
- Duv: 0.000
- CRI Ra: 90
- R9: 30
- LER (lm/W): 375
- CQS: 88

**RGBA simulation**
- (457/526/576/619)
- CCT: 3000
- Duv: 0.000
- CRI Ra: 91
- R9: 32
- LER (lm/W): 382
- CQS Qa: 90

Lot of developments for narrow-band emitters
- narrow-band phosphors
- Quantum dots
- Nano crystals
Differences between CIE $R_f$ and CRI $R_a$ scores

Over-saturation in red penalized by CRI

Narrow-band sources penalized by $R_f$

These differences not well understood

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Narrow-band sources penalized by $R_f$

These differences not well understood
Broadband and Narrowband

- **Narrow-band sources are penalized** under new color fidelity index (IES or CIE).
- To get the same score on new fidelity index, **more energy is needed**.

99 test color samples (TM-30) represent all kinds of object colors. New fidelity index requires **broader band spectra and deeper red** than in CRI.

CRI 8 samples represent typical daily life objects: less sensitive to spectra in deep red region.
Industry opposes replacing CRI by TM-30 Rf


NEMA opposes any mandatory reporting or performance requirements for IES-Rf or IES-Rg. Characterizing color quality is difficult because there are many aspects to be considered.

Global Lighting Association (GLA) position statement on CRI
http://www.globallightingassociation.org/library

The GLA supports the need for an additional colour quality metric - for example, a colour saturation metric, in conjunction with the well-established fidelity metric Ra.

LightingEurope Position Paper on Color Quality (Oct. 2014)

JLMA Position Paper on Colour Rendering Index
What we need – Evaluation of overall color quality

Overall Color Quality

Color Fidelity (CIE 224)

Color perception/preference

CRI

Inaccuracies of CRI as fidelity metric

A formula to replace CRI Ra

CIE’s goal
Develop a set of color quality metrics that allow evaluation of overall color quality of light sources, which can replace CRI.
Differences in Color Space

Plots of 15 CQS samples.

- **W*U*V*** used in CRI
- **CAM02UCS** used in CIE and IES $R_f$
- **CIELAB** (Current CIE standard) Used in CQS

2700 K Planck

D65 (6500 K)
Gamut area is not sufficient

Different gamut shapes with same gamut area

Perceived color quality of these two lights are significantly different.

2016 NIST Experiment on color saturation preference in different hues

(Collaboration with Ulsan National Institute of Science and Technology, Korea)

11 different gamut shapes

Red $\Delta C^*_{ab} = -5$  $\Delta C^*_{ab} = 5$  $\Delta C^*_{ab} = 10$  $\Delta C^*_{ab} = 15$

Green $\Delta C^*_{ab} = -5$  $\Delta C^*_{ab} = 10$  $\Delta C^*_{ab} = 15$

Yellow $\Delta C^*_{ab} = -5$  $\Delta C^*_{ab} = 5$  $\Delta C^*_{ab} = 10$

19 subjects evaluate preference in light pairs

Hunt Effect

Under low light levels, perceived chroma (color saturation) of objects decreases (Hunt, 1950).

If so, oversaturating colors at low light levels can bring color appearance of objects closer to outdoor daylight? (Brings higher fidelity?)
2017 NIST Experiment on Hunt Effect

- 24 subjects
- Saturation preference experiment at 100 lx and 1000 lx
- Which light looks “more natural”

Results: Perceived naturalness compared to Neutral

NIST Spectrally Tunable Lighting Facility

Presented at CIE USNC CNC Joint meeting, NIST, Oct 3-4, 2017.
White Light Chromaticity – Preference to below blackbody –

Experiment on perceived white point by LRC (2013)


Experiment on preferred lighting by NRC, Canada (2013)


NIST vision experiment in 2013 & 2015


Experiment of whiteness done by Philips Eindhoven

Experiment of whiteness done by Philips Eindhoven
ANCI C78.377-2017 revision published, July, 2017

Figure E2
Graphical Representation of the Chromaticity Specification of Table 2, Extended Nominal CCT Specification, on the CIE ($u'$, $v'$) chromaticity diagram
ANCI C78.377-2017 revision published, July, 2017

Flexible Duv Specification

Figure E3
An example of Extended Flexible CCT/Duv specification (at 3200 K, Duv = -0.006) on the CIE (u', v') chromaticity diagram
Summary

• CRI’s biggest problem: penalizing preferred light sources.
• Pure color fidelity metric is not supported by the industry (issues on preference, narrow-band spectra).
• Additional metric for color preference/perception is needed in addition to color fidelity index.
• Gamut area is not sufficient for preference metric.
• More research is needed to develop preference/perception metrics suitable for lighting products.
• White light below Planckian locus is a possibility for new color quality design.
• TM-30 Rf, Rg, CIE Rf, CQS, .. are useful design/research tools.
Thank you for your attention.

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