Color Quality Metrics and Spectral Design of SSL Sources

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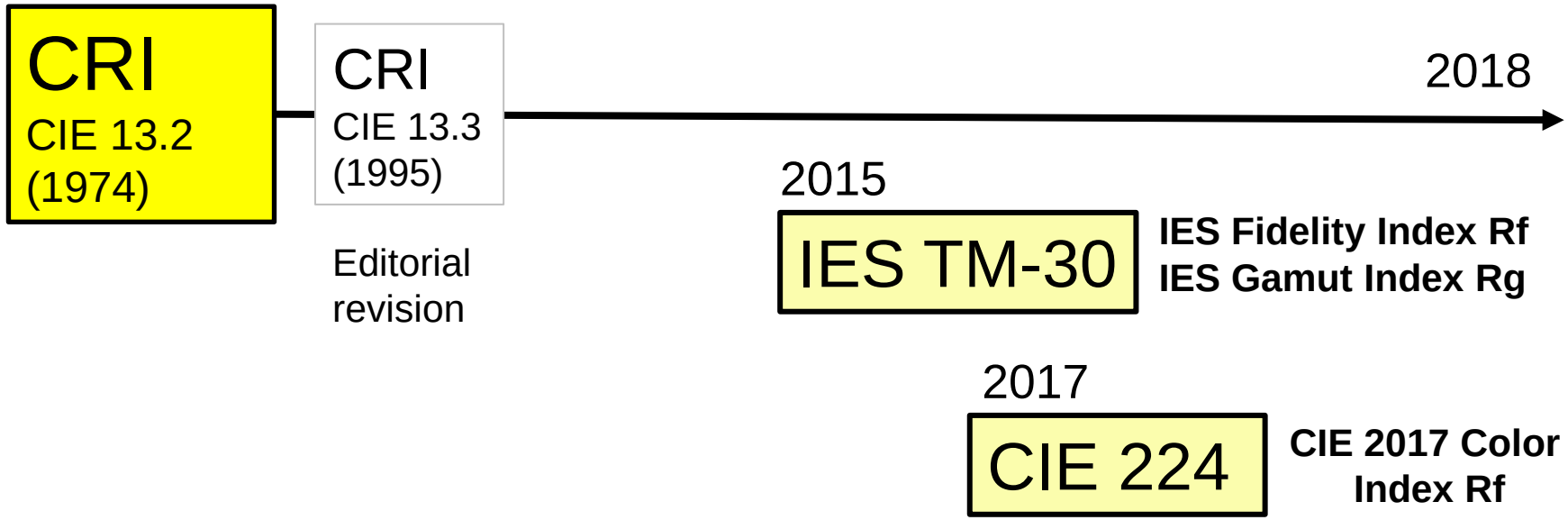
Topics

- 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



Research / proposals

CQS

GAI

CRI-2012

Memory color-CRI

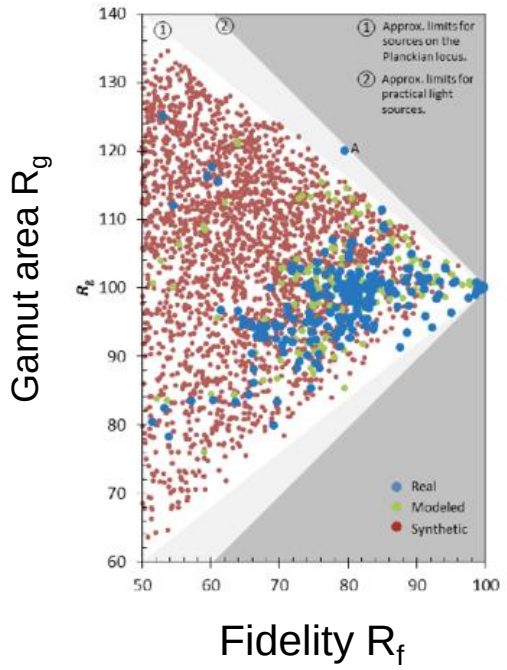
Gamut shape

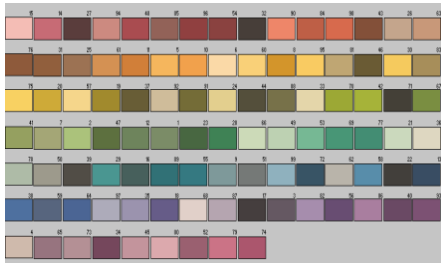
Red saturation

CIE TC 1-91 → Technical Report

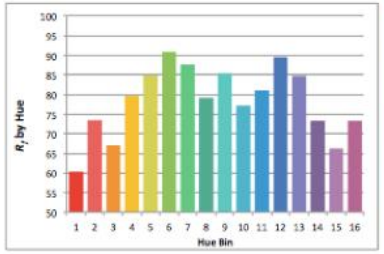
Summary of published metrics beyond fidelity

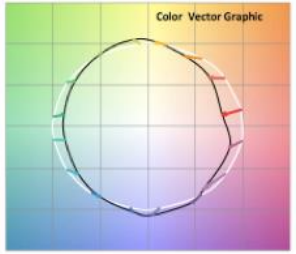
IES TM-30-15 IES Method for Evaluating Light Source Color Rendition





- ❑ 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)

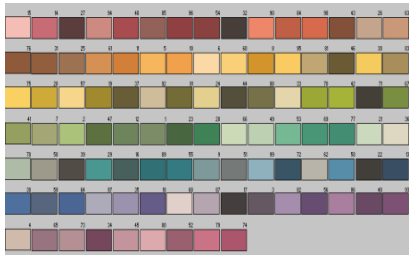
Technically,

- 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

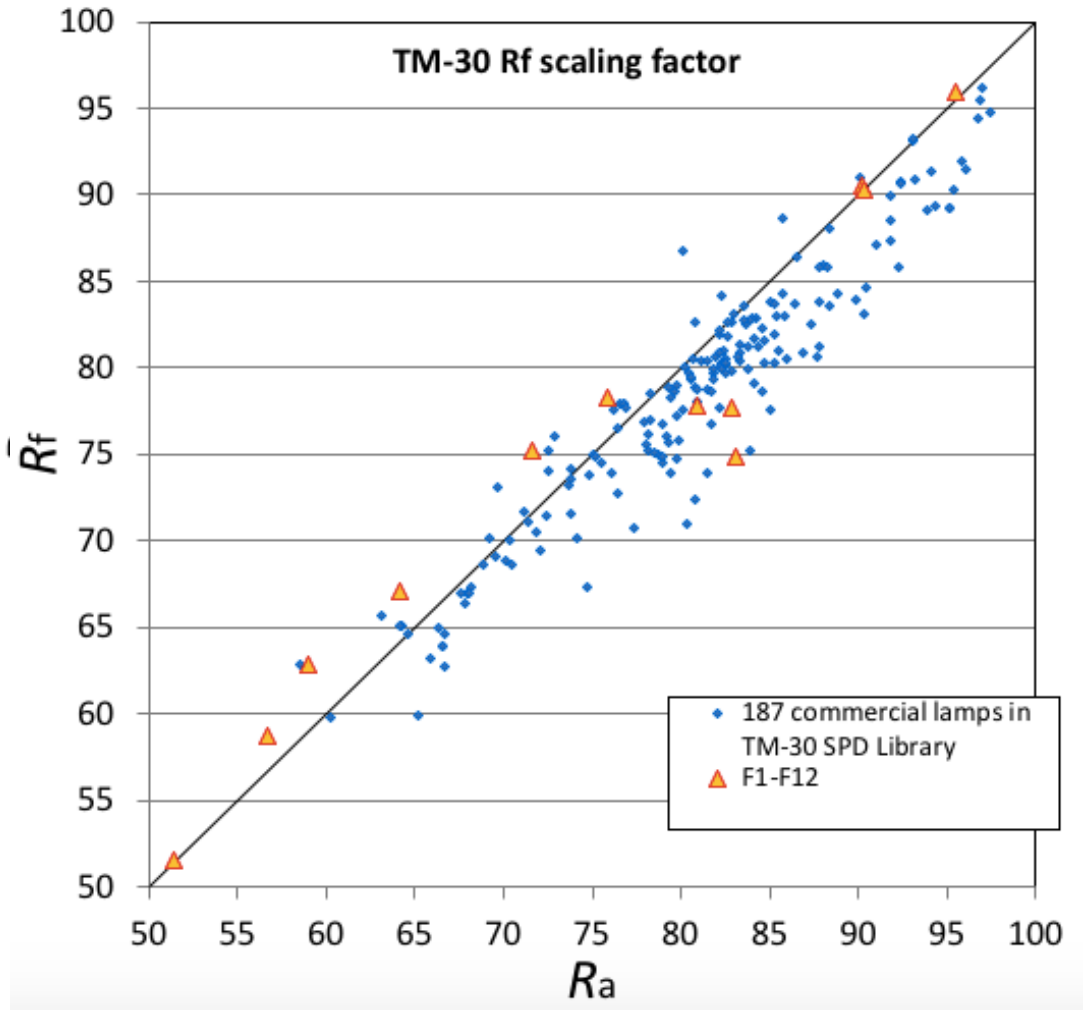
for Accurate Scientific Use

- 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"

A modification of TM-30 Rf (scaling factor)

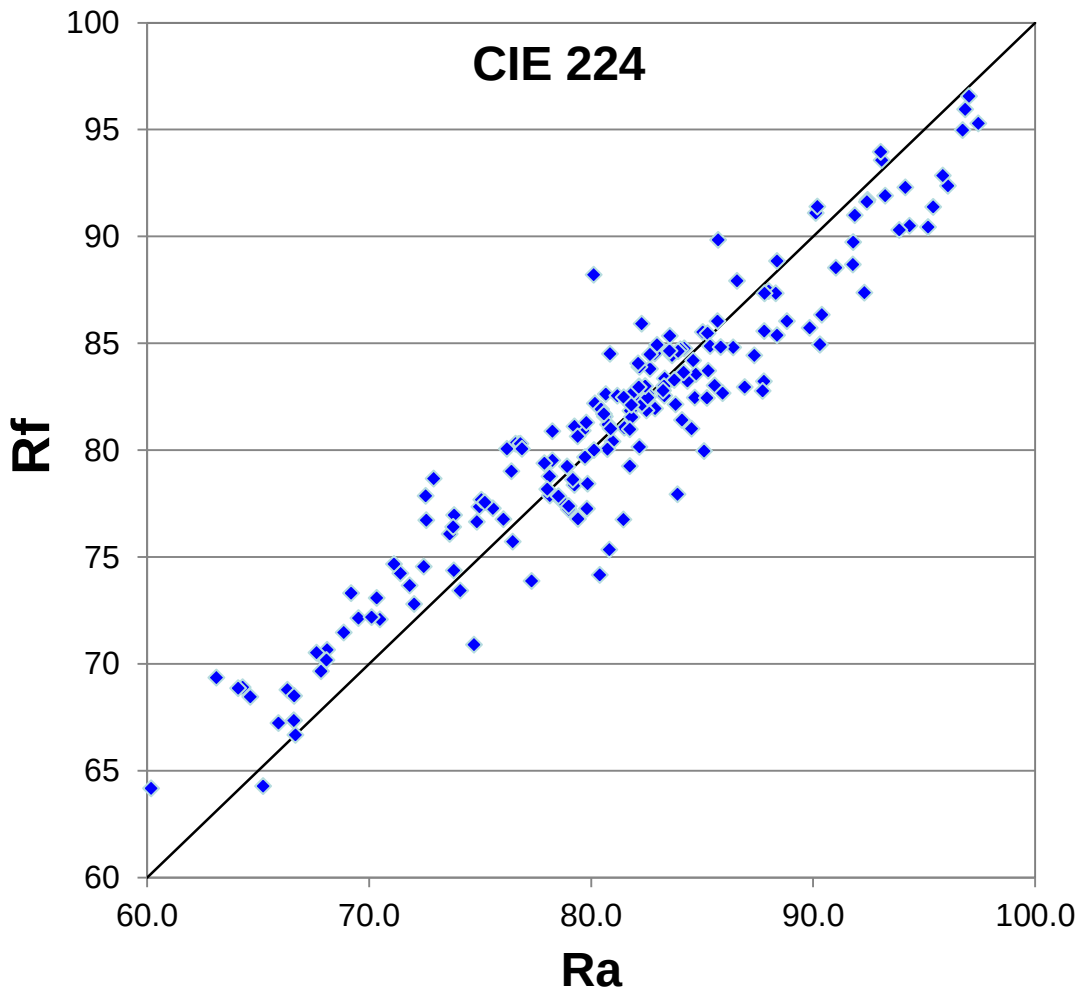


TM-30: Scaling factor

$$R'_f = 100 - 7.54\left(\frac{1}{99}\sum_{i=1}^{99}(\Delta E_{Jab,i})\right)$$

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 Rf (scaling factor)



CIE 224 Scaling Factor

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

Average scores of Ra and Rf 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))

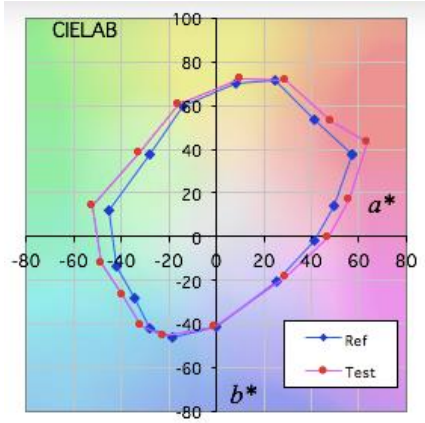
Color Fidelity and Color Preference

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.

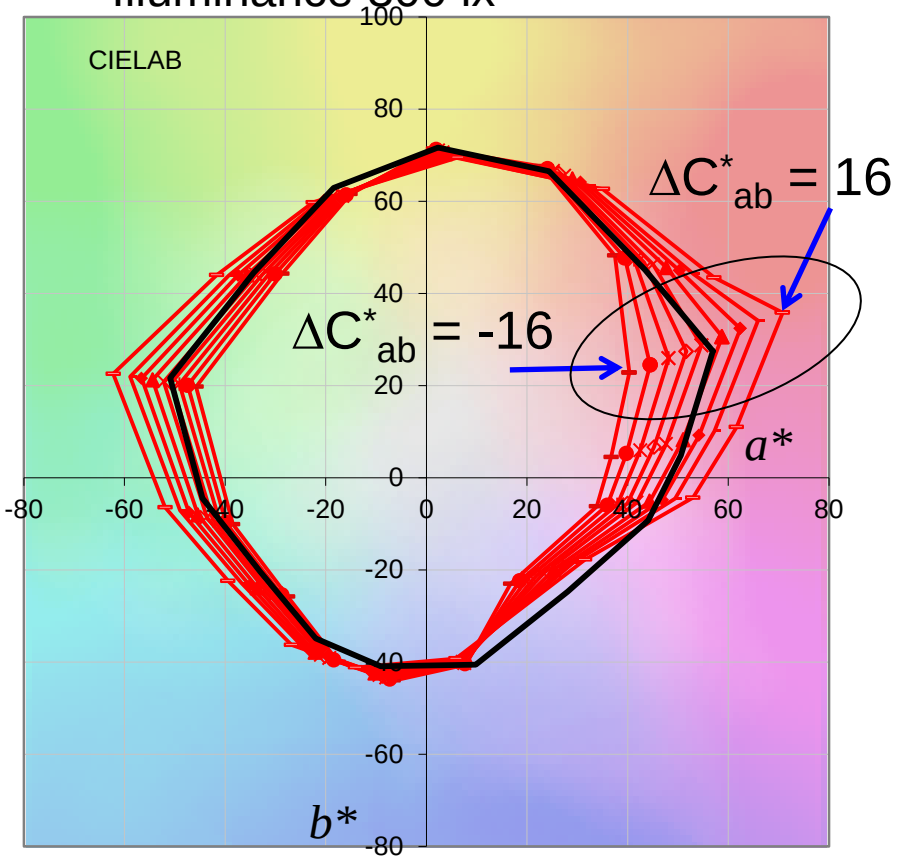
Scientists: Color fidelity is the fundamental color quality. It should be the color quality measure for products.

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

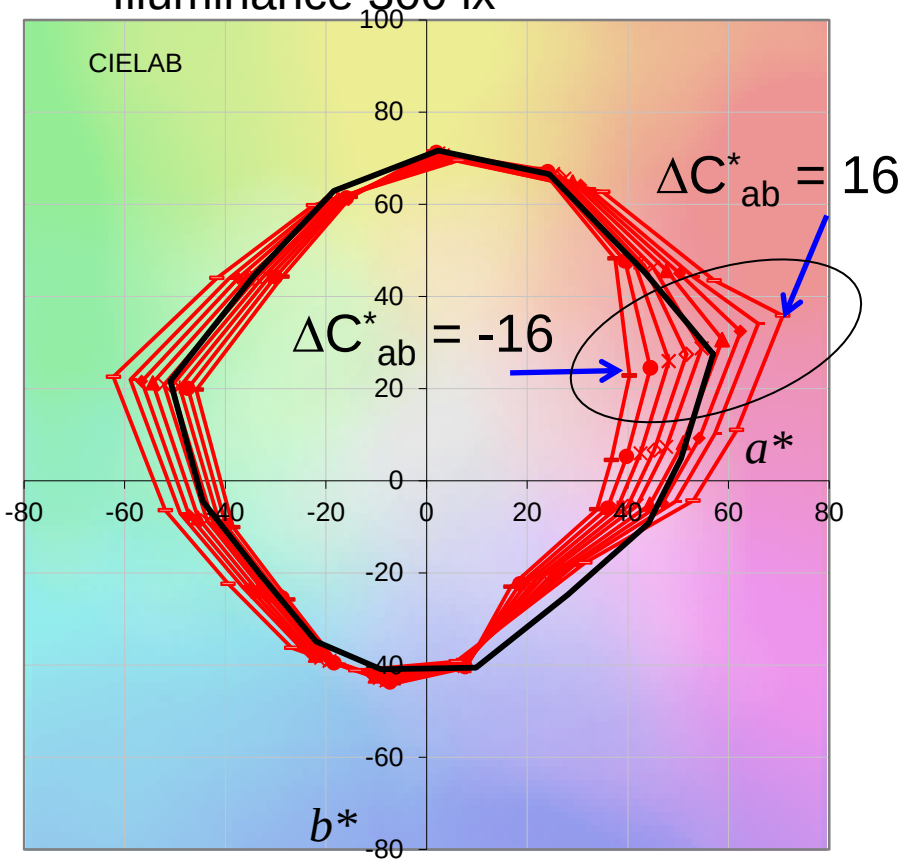


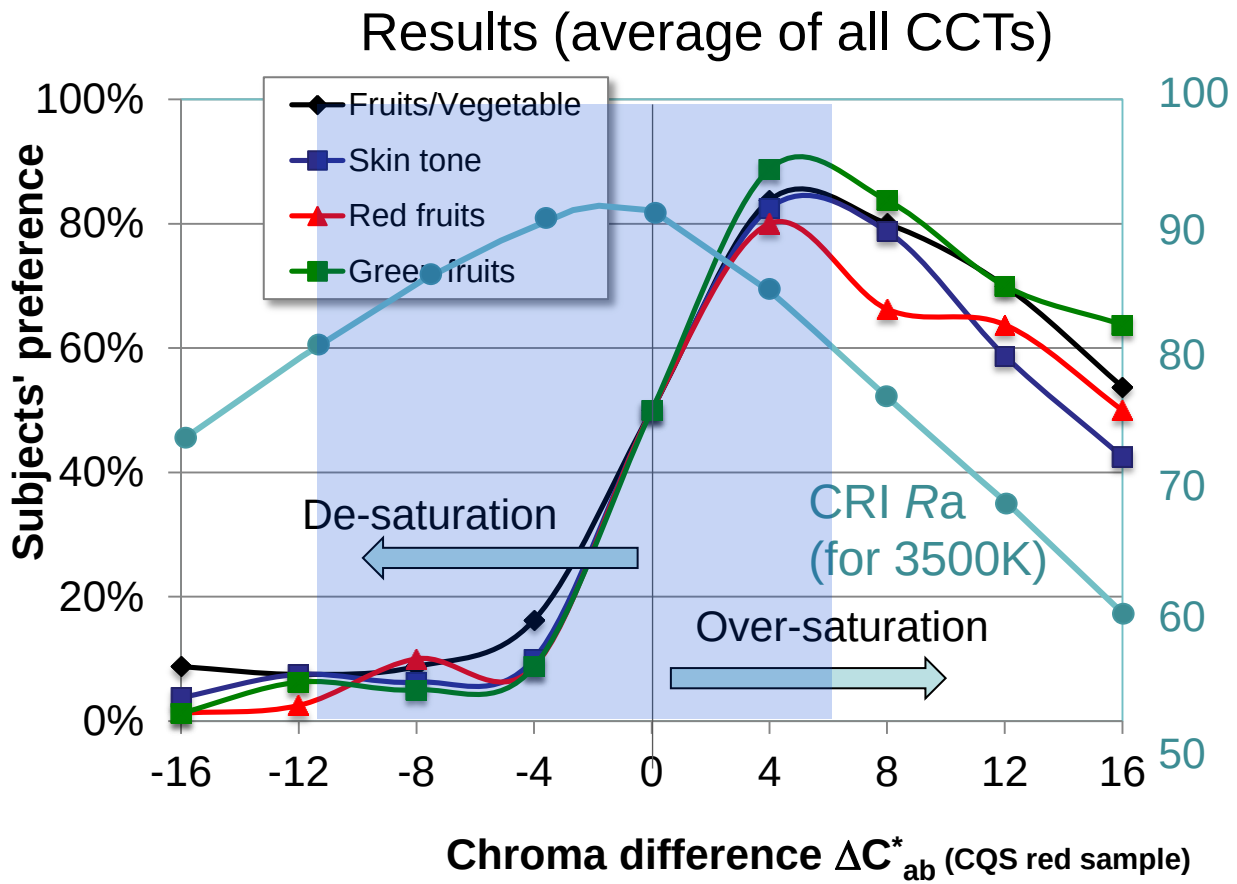
Most saturated

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





Y. Ohno, M. Fein, C. Miller, Vision Experiment on Chroma Saturation for Color Quality Preference, CIE 216 :2015, pp. 60 – 69 (2015)

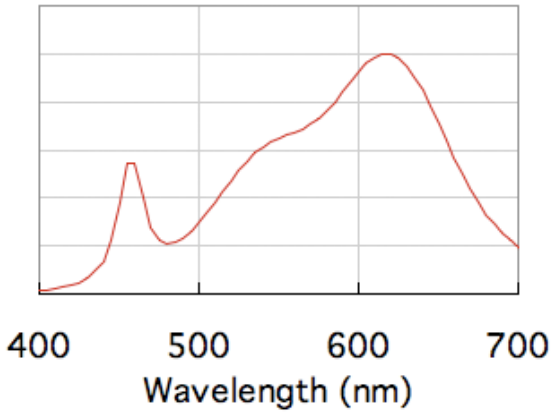
Broadband and Narrowband

* 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

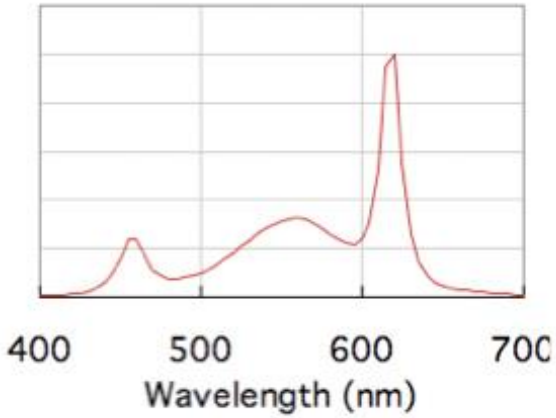


LER= 310 lm/W

p-c White
+ Red chip

CCT: 3000
Duv: 0.000
CRI Ra: 90
R9: 30

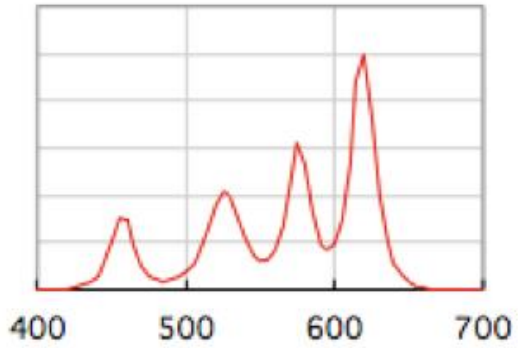
LER (lm/W): 375
CQS 88



LER= 375 lm/W

RGBA simulation
(457/526/576/619)

CCT: 3000
Duv: 0.000
CRI Ra: 91
R9: 32
LER (lm/W): 382
CQS Qa: 90



LER= 382 lm/W

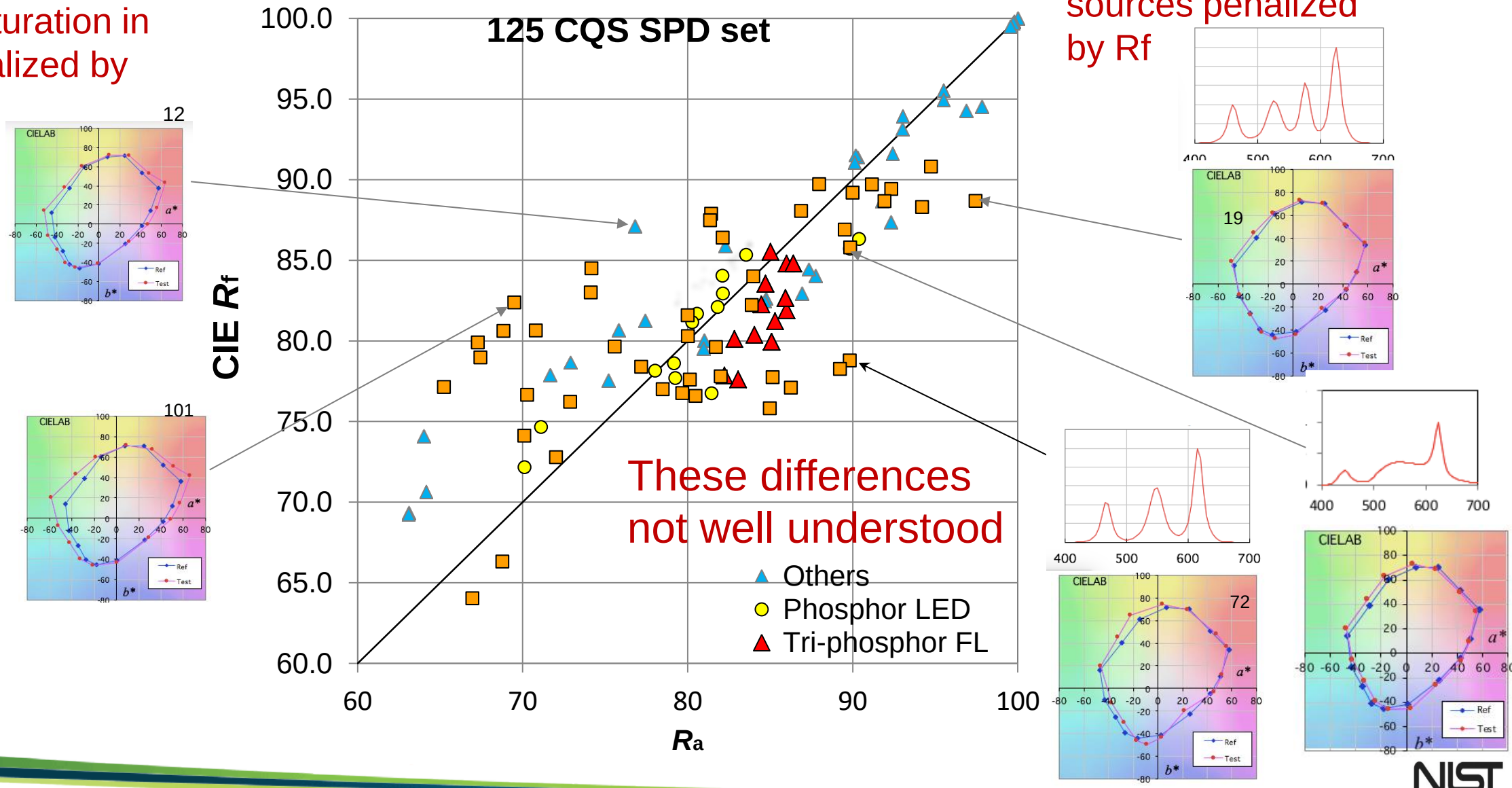
Lot of developments for narrow-band emitters

- 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 Rf



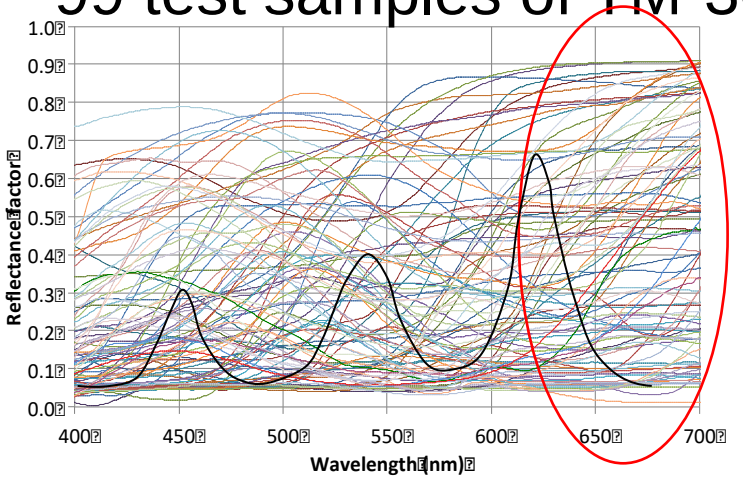
Broadband and Narrowband

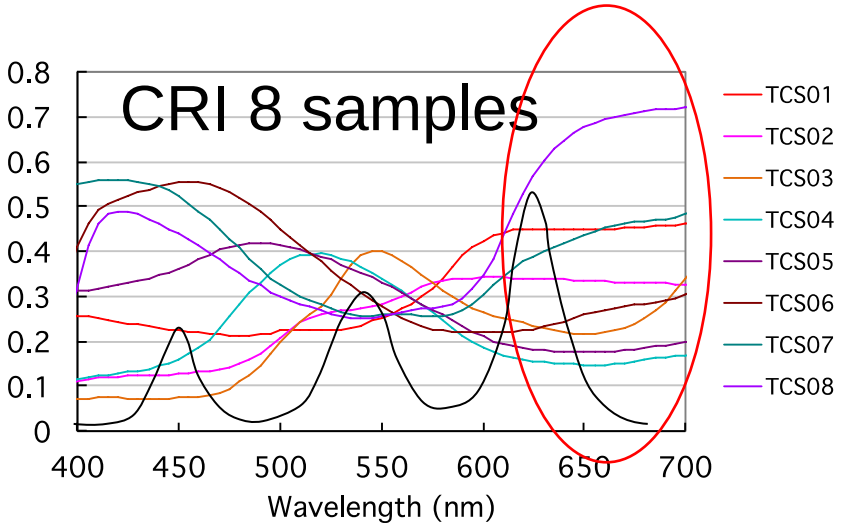
- Narrow-band sources are penalized under new color fidelity index (IES or CIE).
- To get the same score on new fidelity index, more energy is needed.

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.

99 test samples of TM-30





Industry opposes replacing CRI by TM-30 Rf

NEMA Lighting Systems Division Position Paper on IES TM-30-15 LSCR-PP 1-2015

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.

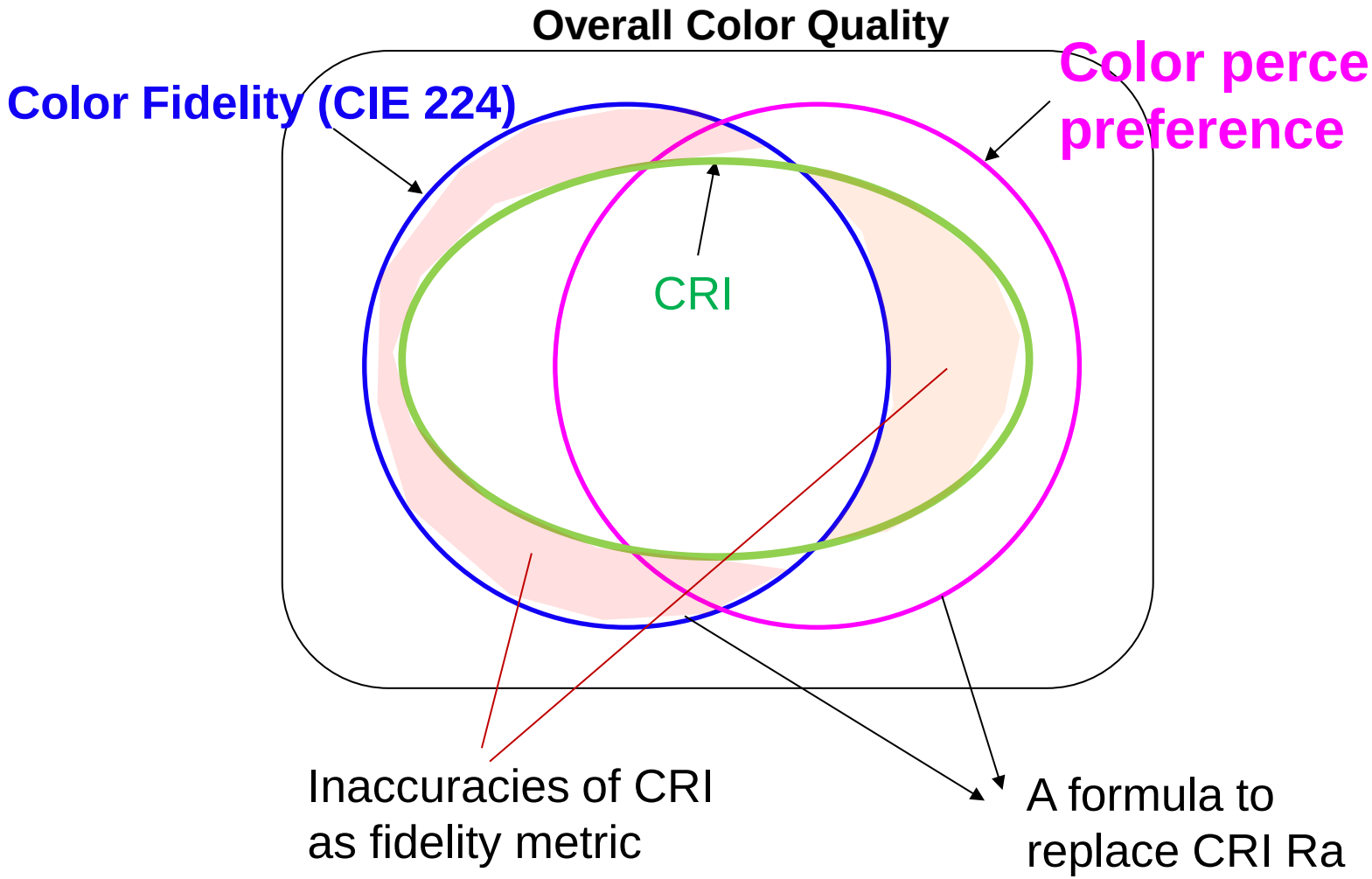
Global Lighting Association (GLA) position statement on CRI
http://www.globallightingassociation.org/library

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



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

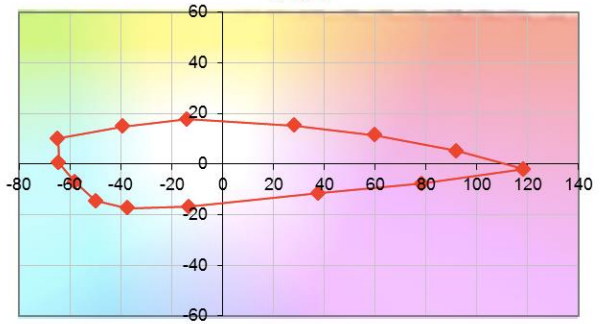
Plots of 15 CQS samples.

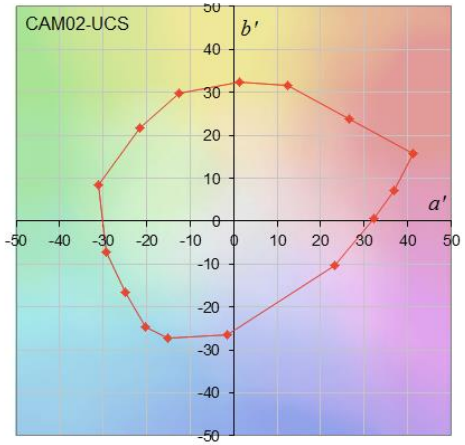
W*U*V* used in CRI

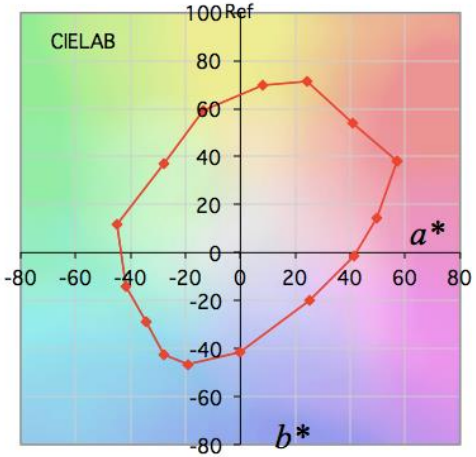
CAM02UCS used in CIE and IES R_f

CIELAB (Current CIE standard) Used in CQS

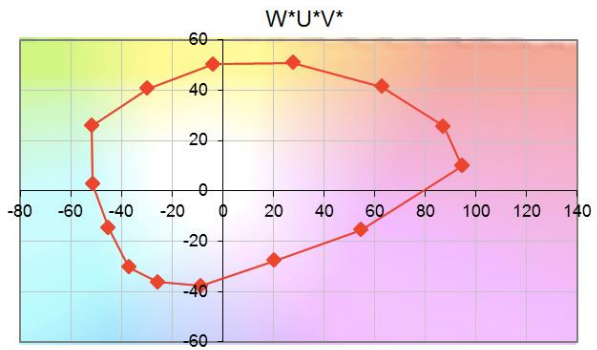
2700 K Planck

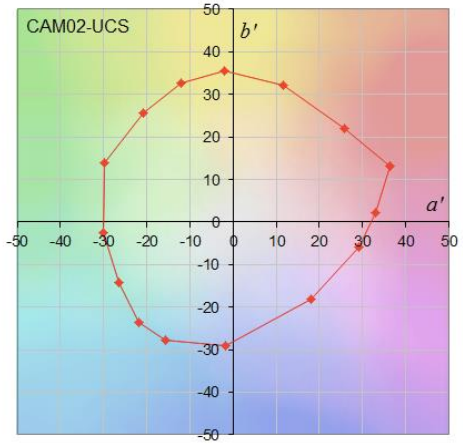


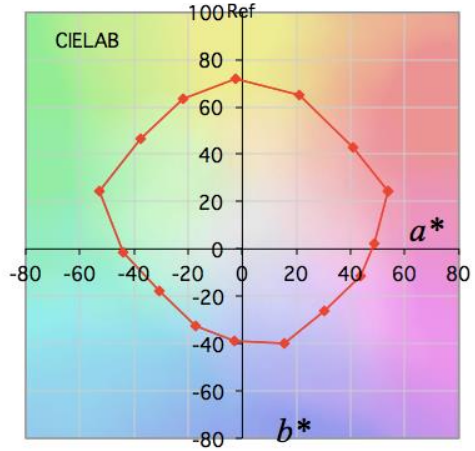




D65 (6500 K)

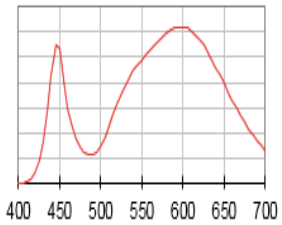


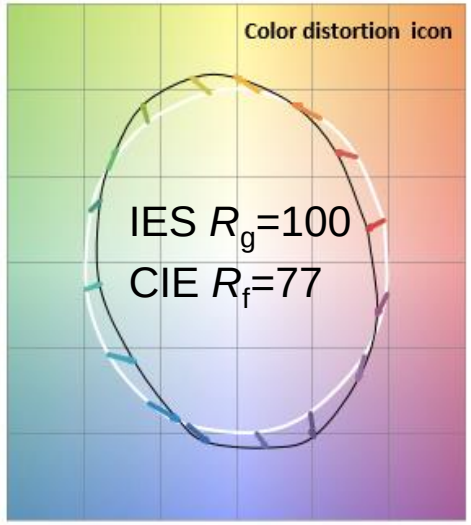


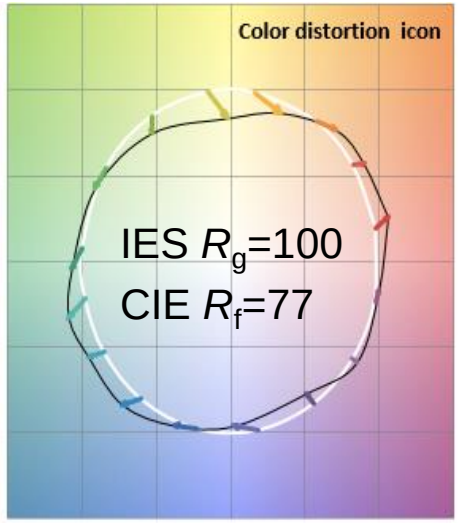


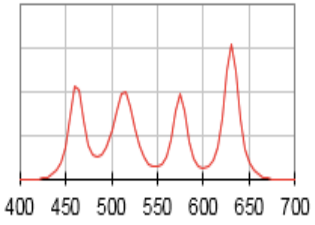
Gamut area is not sufficient

Different gamut shapes with same gamut area









This looks better

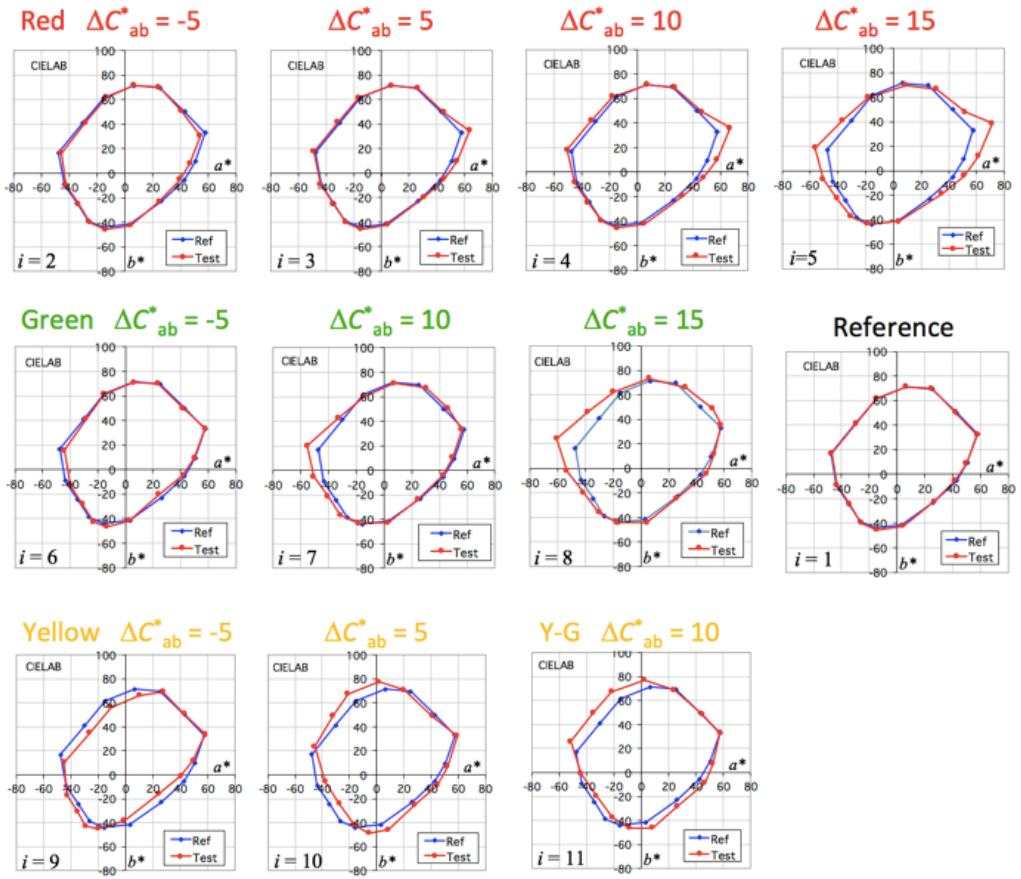
Perceived color quality of these two lights are significantly different.

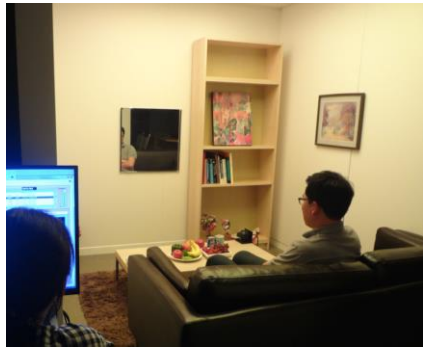
Also available:
Royer M et al, Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape. Light Res. Technol. 2016.

2016 NIST Experiment on color saturation preference in different hues

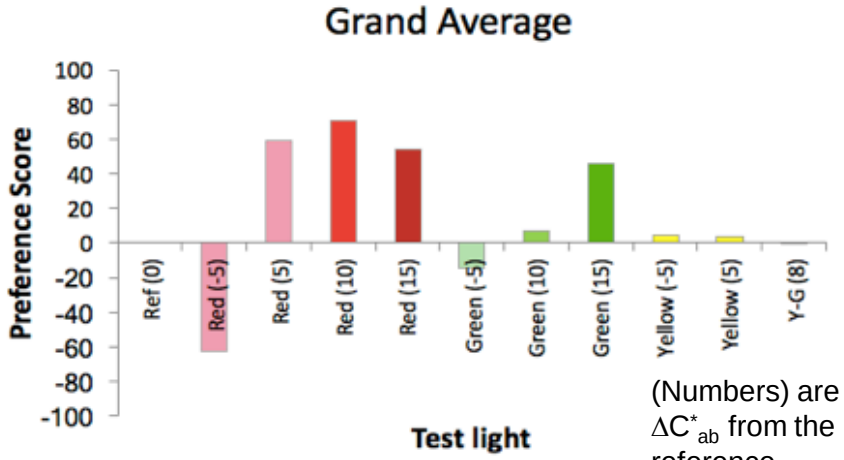
(Collaboration with Ulsan National Institute of Science and Technology, Korea)

11 different gamut shapes





19 subjects evaluate preference in light pairs



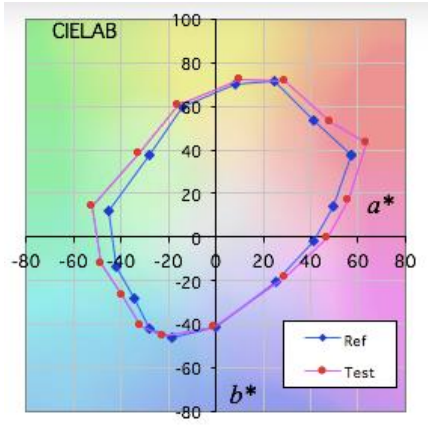
(Numbers) are ΔC^*_{ab} from the reference.

Y. Ohno, S. Oh, Y. Kwak, Vision Experiment on Chroma Saturation Preference in Different Hues, Proc. CIE 2017 Midterm Jeju, Korea (2017)

Hunt Effect

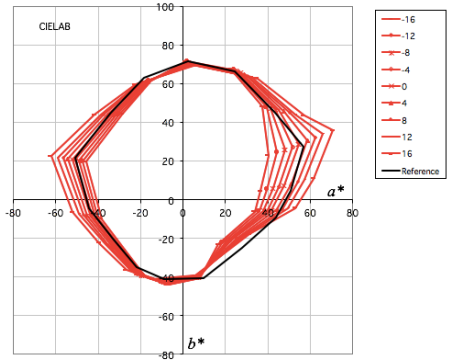
Under low light levels, perceived chroma (color saturation) of objects decreases (Hunt, 1950).

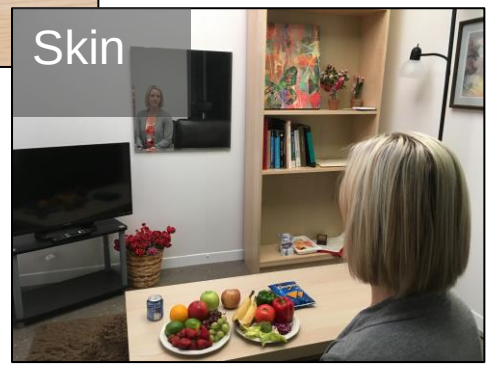
If so, oversaturating colors at low light levels can bring color appearance of objects closer to outdoor daylight? (Brings higher fidelity?)



2017 NIST Experiment on Hunt Effect

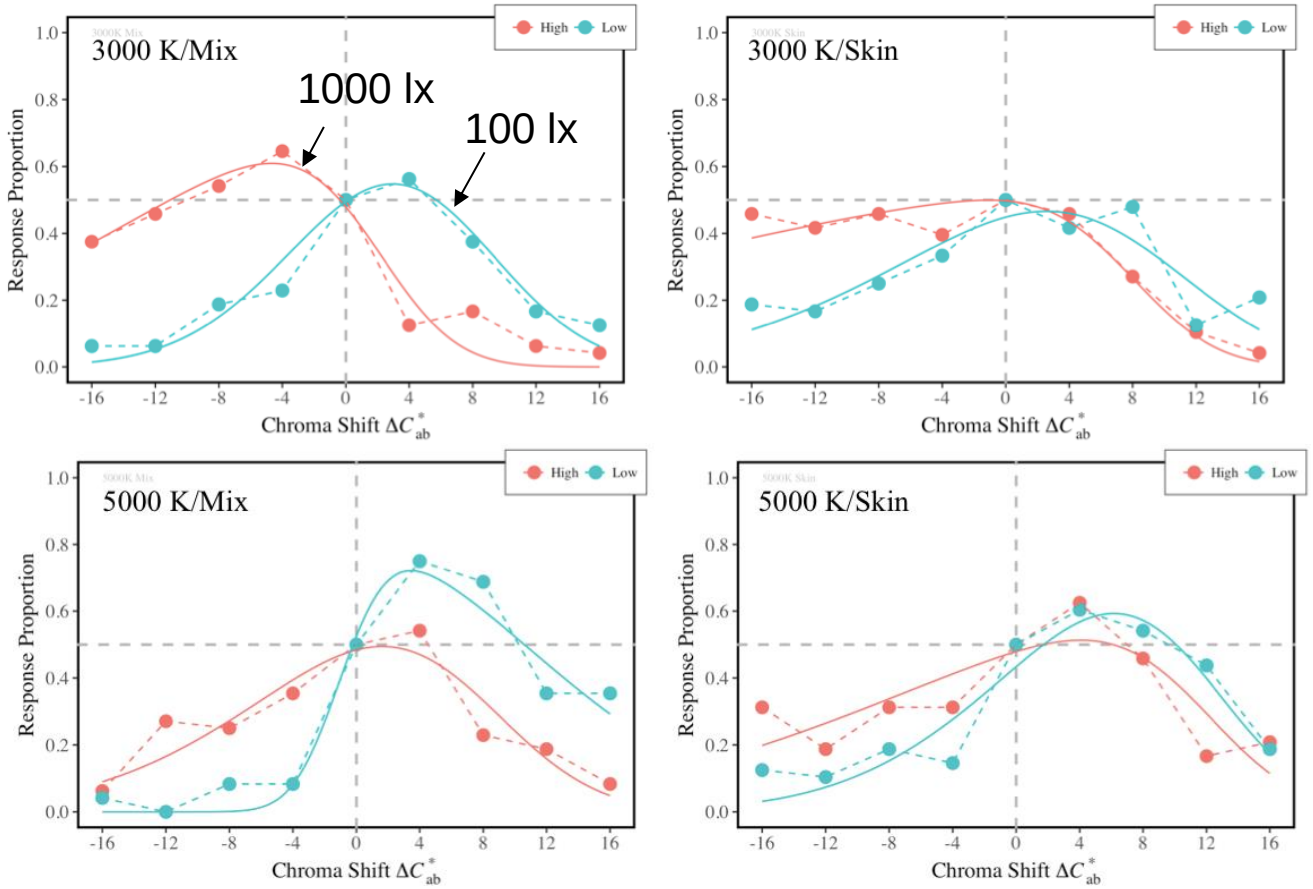
- 24 subjects
- Saturation preference experiment at 100 lx and 1000 lx
- Which light looks “more natural”





NIST Spectrally Tunable Lighting Facility

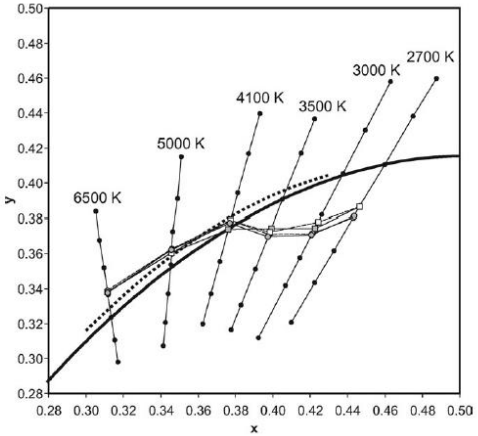
Results: Perceived naturalness compared to Neutral



Presented at CIE USNC CNC Joint meeting, NIST, Oct 3-4, 2017.

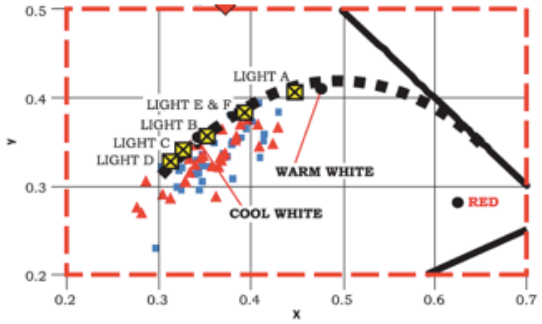
White Light Chromaticity
– Preference to below blackbody–

Experiment on perceived white point by LRC (2013)



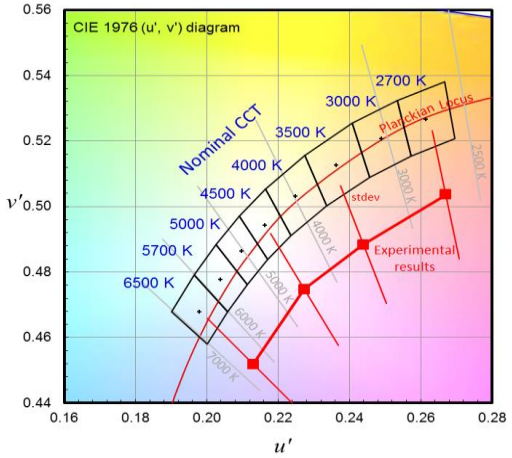
M. S. Rea,* J. P. Freyssinier, “White Lighting”, CR&A**, 30-2**, 82-92, 2013.

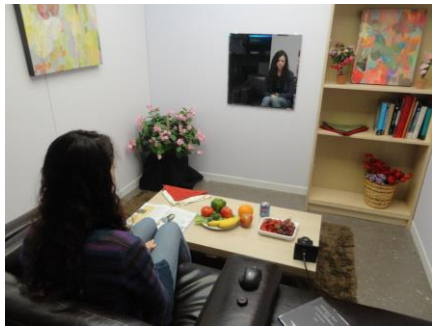
Experiment on preferred lighting by NRC, Canada (2013)



Dikel et al, ”Preferred Chromaticity of Color-Tunable LED Lighting”, LEUKOS, 10:2, 101-115, DOI: 10.1080/15502724.2013.855614 (2013).

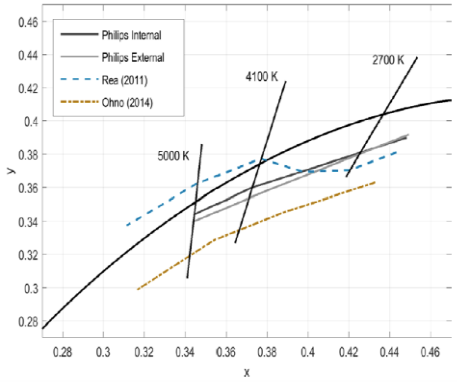
NIST vision experiment in 2013 & 2015





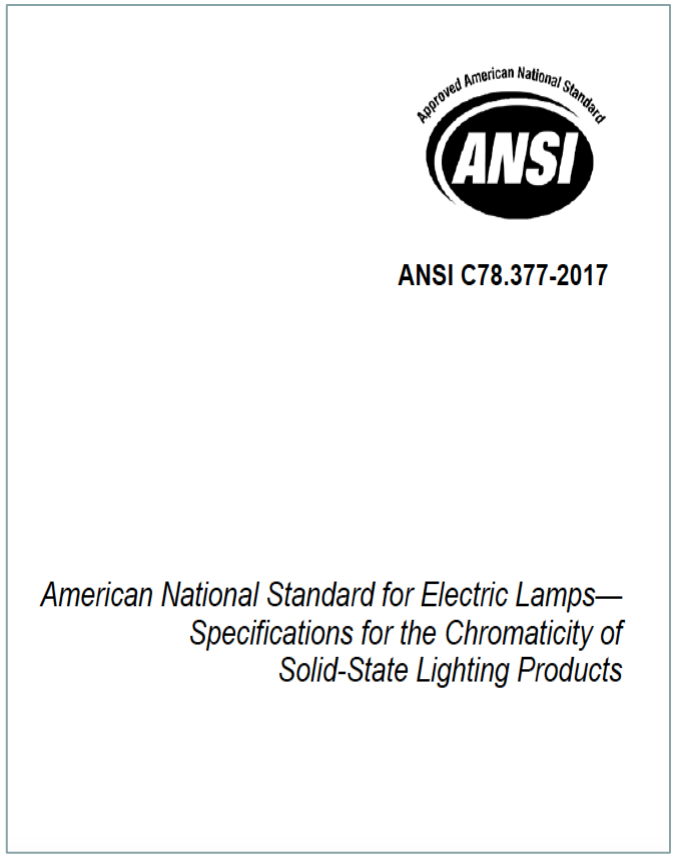
Ohno, Y., Fein, M., Vision Experiment on Acceptable and Preferred White Light Chromaticity for Lighting, CIE x039:2014, pp. 192-199 (2014).

Experiment of whiteness done by Philips Eindhoven



Perz, M.1, Baselmans, R.1, Sekulovski, Perception of Illumination Whiteness, CIE x043:2017, pp.1-7 (2017)

ANCI C78.377-2017 revision published, July, 2017



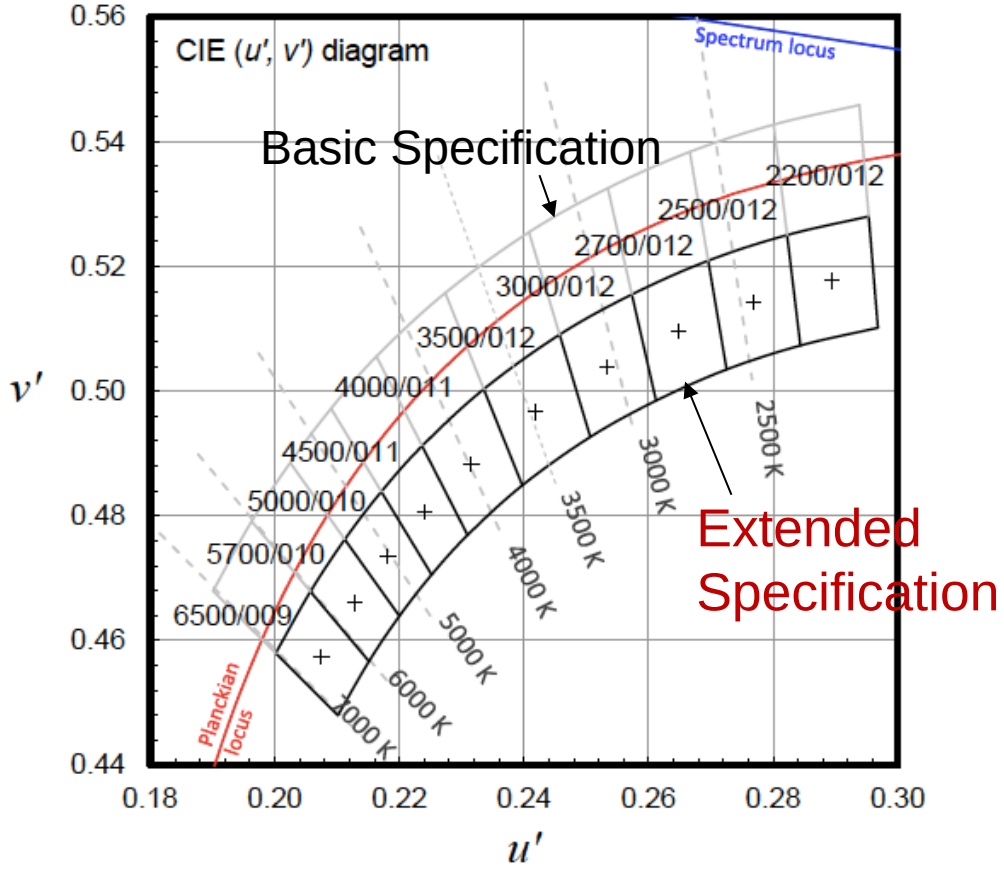


Figure E2
Graphical Representation of the Chromaticity Specification of Table 2,
Extended Nominal CCT Specification, on the CIE (*u′, v′*) chromaticity diagram

ANCI C78.377-2017 revision published, July, 2017

Approved American National Standard

ANSI

ANSI C78.377-2017

American National Standard for Electric Lamps—
Specifications for the Chromaticity of
Solid-State Lighting Products

Flexible Duv Specification

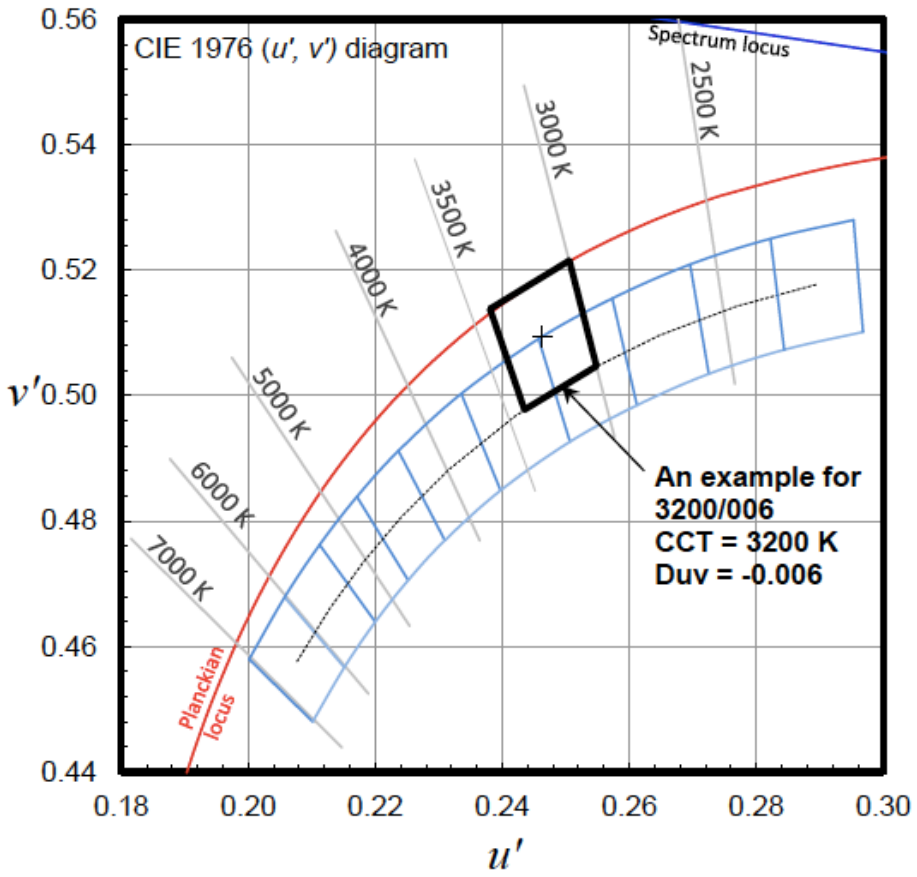


Figure E3
An example of Extended Flexible CCT/Duv specification
(at 3200 K, D_{uv}= −0.006) on the CIE (*u′*, *v′*) chromaticity diagram

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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