U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

TM-30: What have we learned in the past two years?

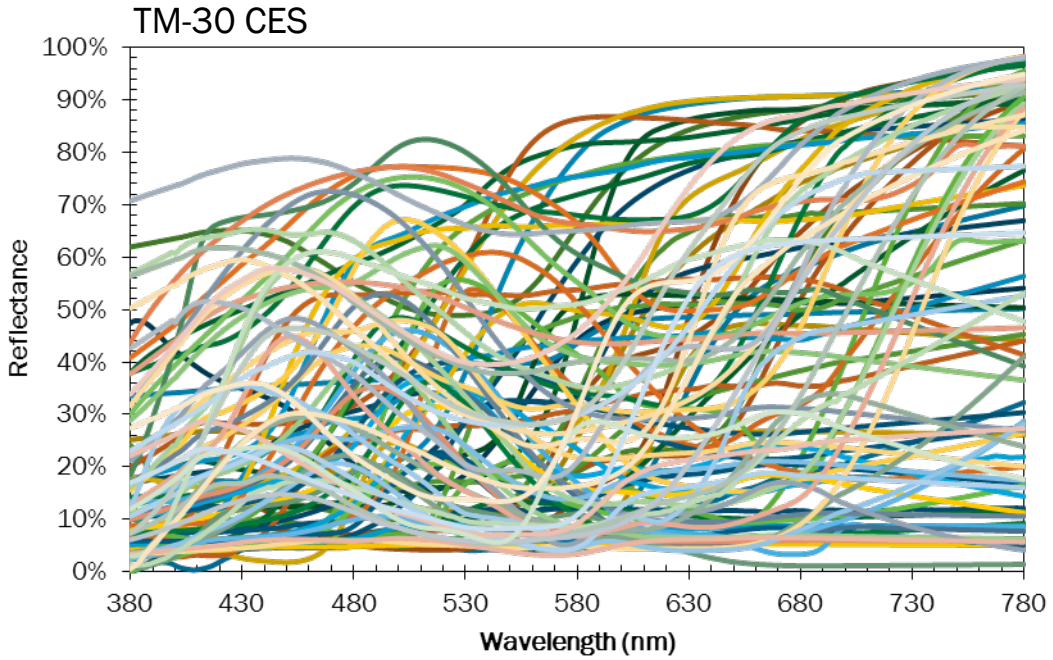
Michael Royer, PhD | Pacific Northwest National Laboratory

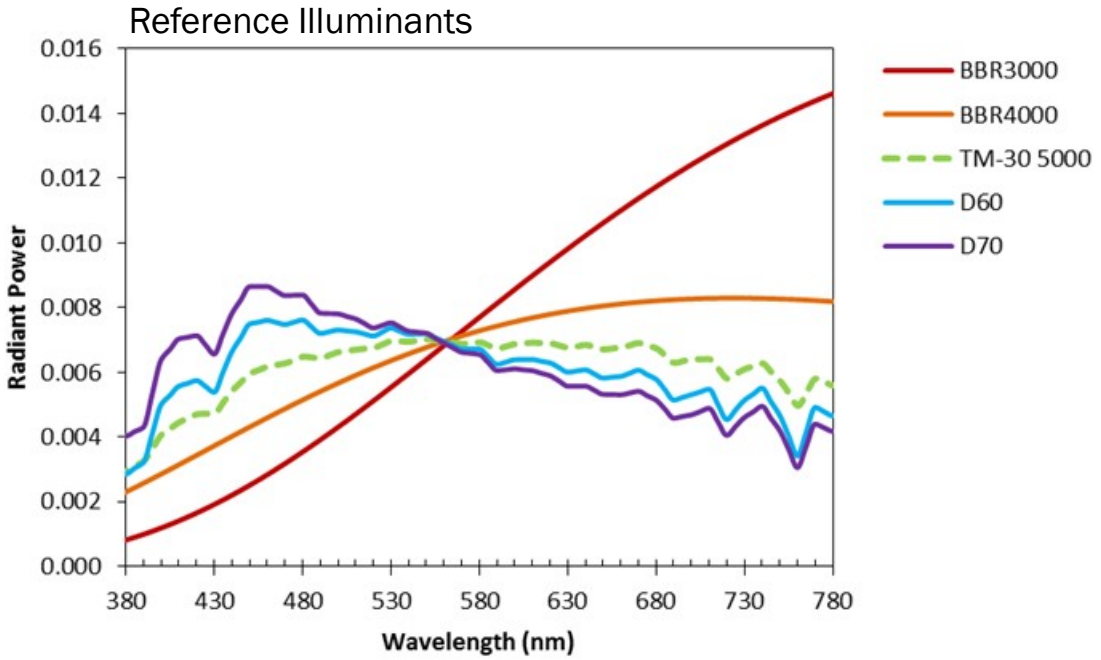
https://energy.gov/eere/ssl/color-rendition

12 September 2017

IES TM-30-15: What is it?

1. **A method for evaluating light source color rendition, with a core system comprised of:**
   - An accurate model of human color vision: CAM02-UCS
   - A standardized set of color samples: 99 color evaluation samples
   - A system to establish a reference baseline: Planckian radiation/D Series illuminant





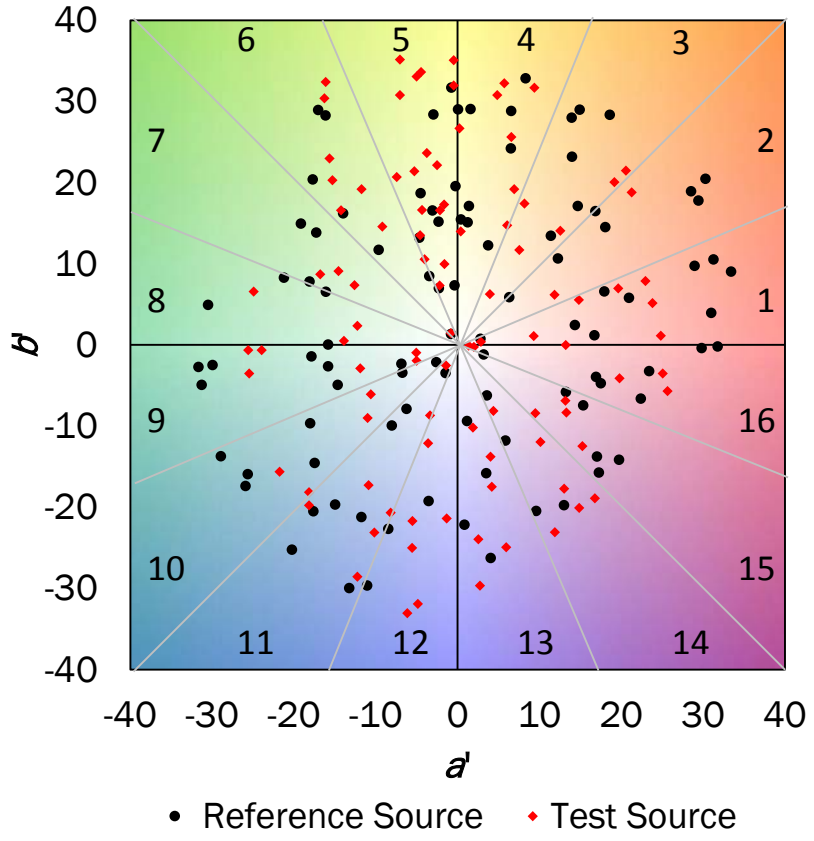
IES TM-30-15: What is it?

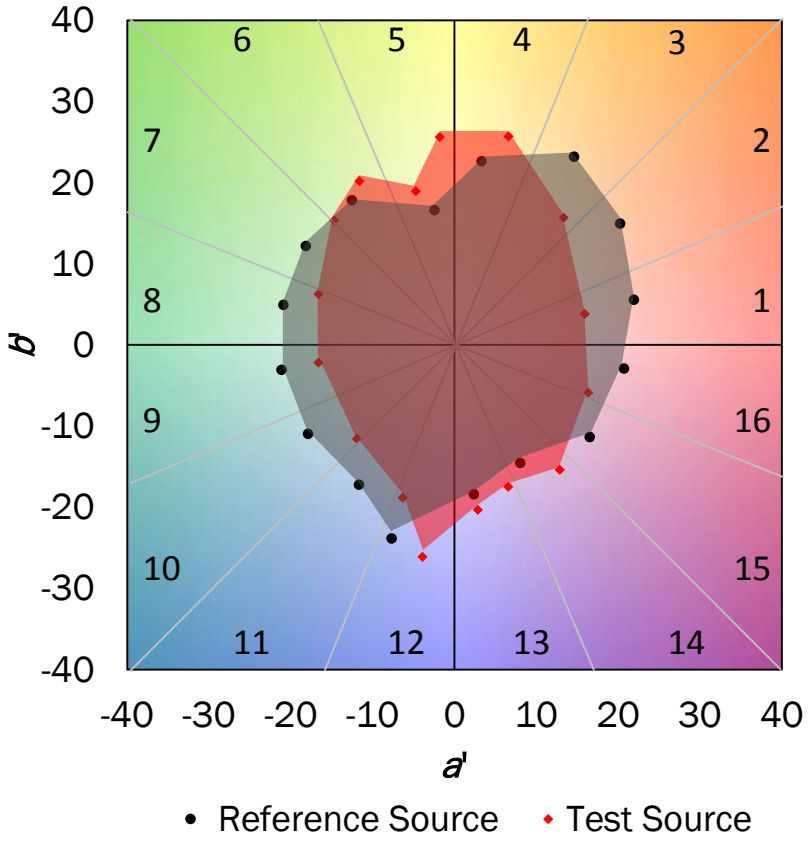
2. **From this system, a suite of objective characterizations of light source color rendition can be calculated, including:**
   - the Fidelity Index (R_f), a characterization of average color fidelity for all 99 CES
   - the Gamut Index (R_g), a characterization of gamut area using all 99 CES
   - 16 Local Chroma Shift values (R_{cs,h_j}), which characterize changes in chroma for the CES within each of 16 hue-angle ranges
   - 16 Local Color Fidelity values (R_{f,h_j}), which characterize average color difference for the CES within each of 16 hue-angle ranges
   - the Color Vector Graphic, which provides a visual representation of hue and chroma shifts versus the reference for the 16 hue-angle ranges

IES TM-30-15: What is it?

3. **The objective characterizations are intended to be used in various combinations to predict perceptual outcomes** (preference, normalness, naturalness, vividness, saturation, acceptability, etc.) **based on the context of the architectural environment** (color palette, application, design intent, adaptation, duration, culture, etc.).

TM-30: More than average color fidelity



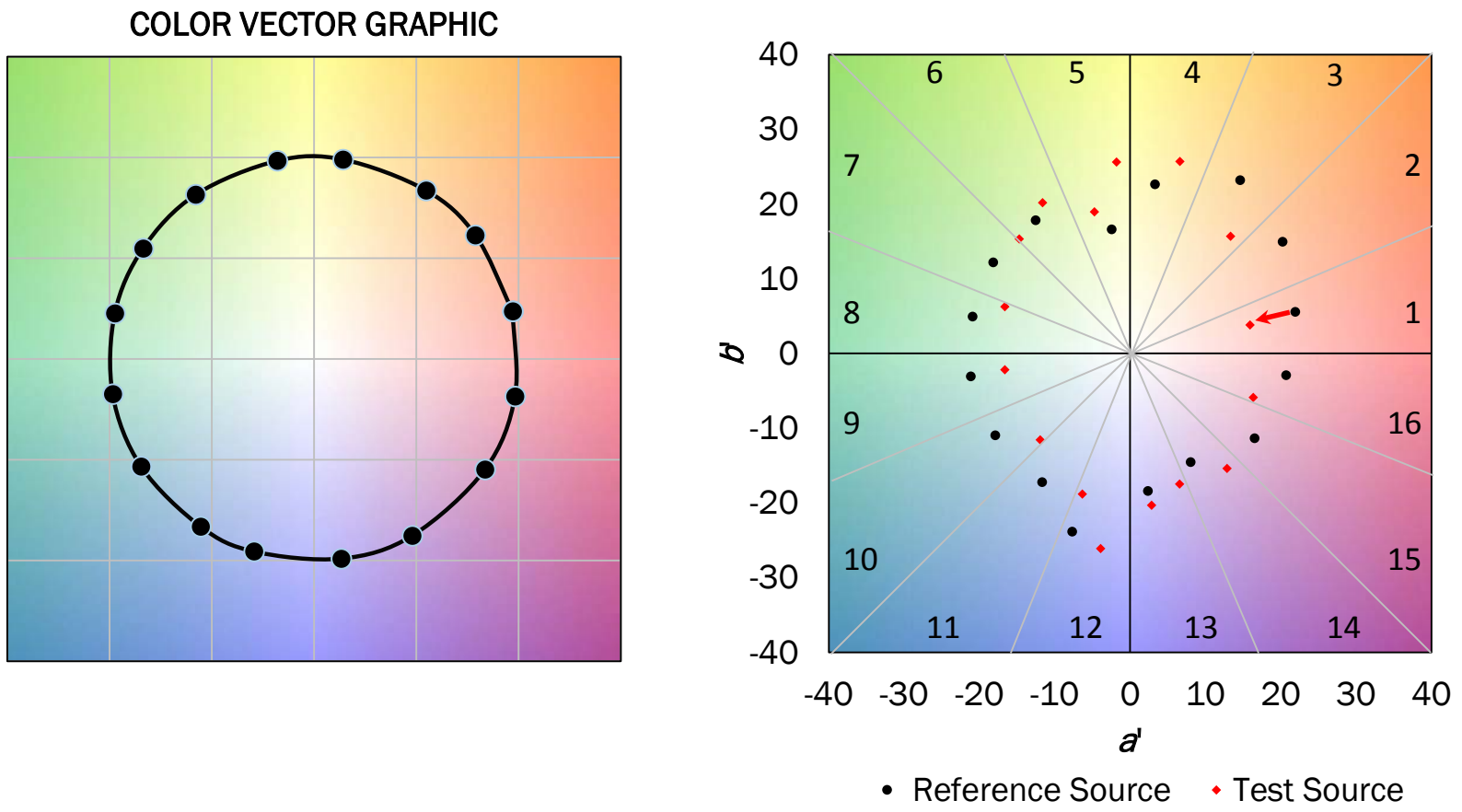


Average (a', b') coordinates in each hue-angle bin (sorted by reference condition).

***Average Color Fidelity* (IES R_f):**
Average magnitude of difference between test and reference.

***Gamut Area* (IES R_g):**
Area enclosed by hue-angle-bin average coordinates.

Gamut Shape: Color Vector Graphic (CVG)



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*Gamut Shape (*IES CVG*;* IES R_{cs,h_i}*):*
Pattern of average hue and chroma shifts across different nominal hues.

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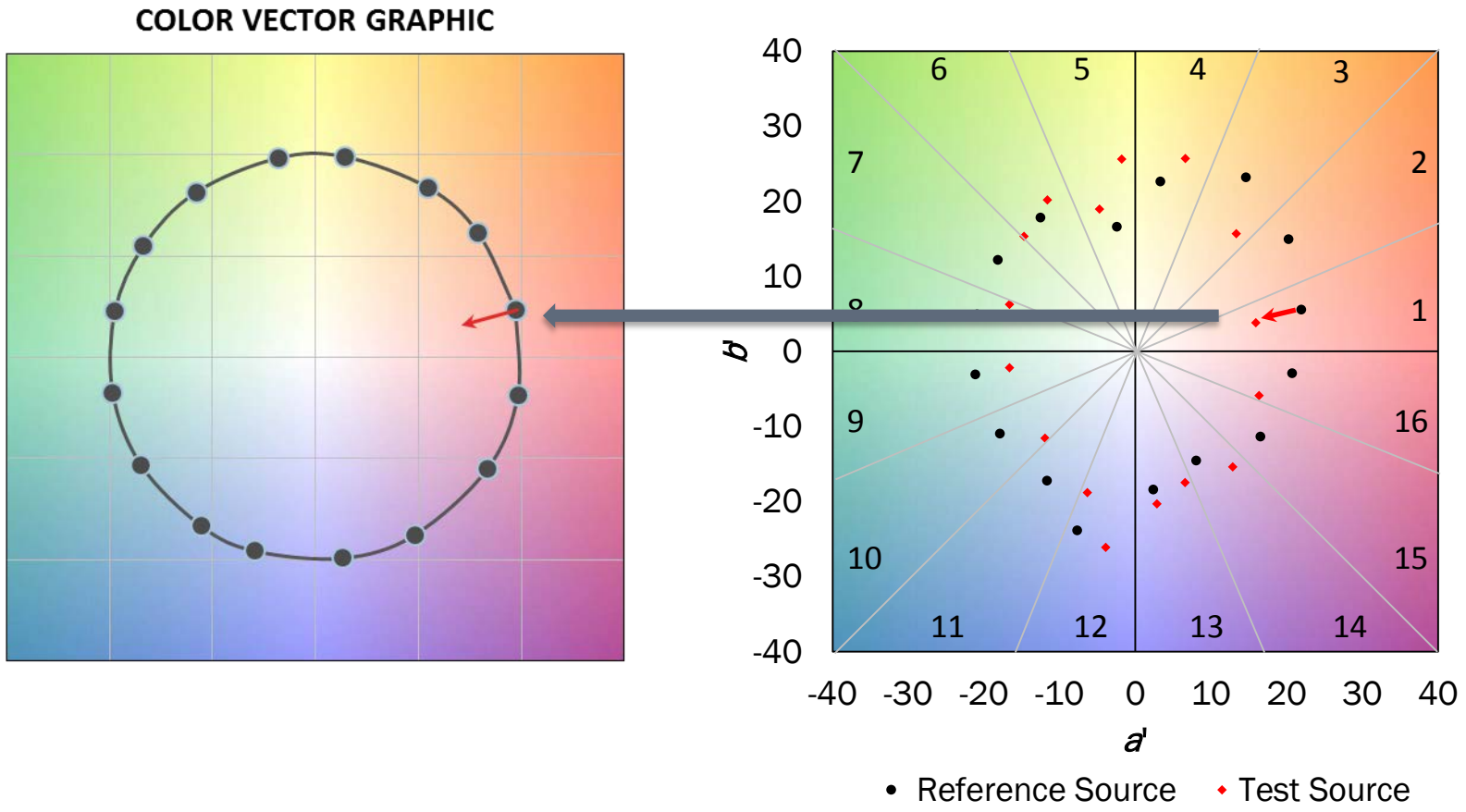

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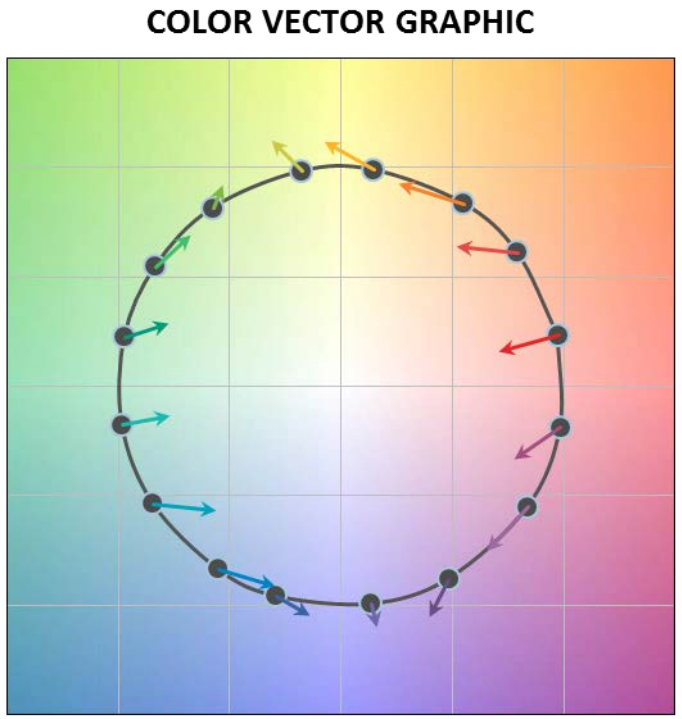

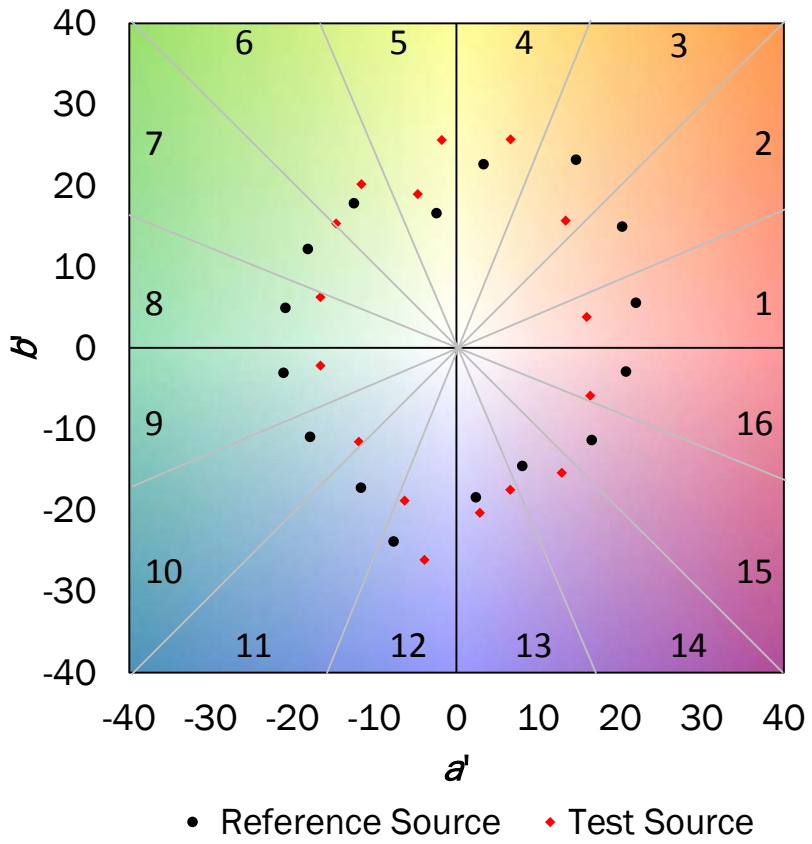

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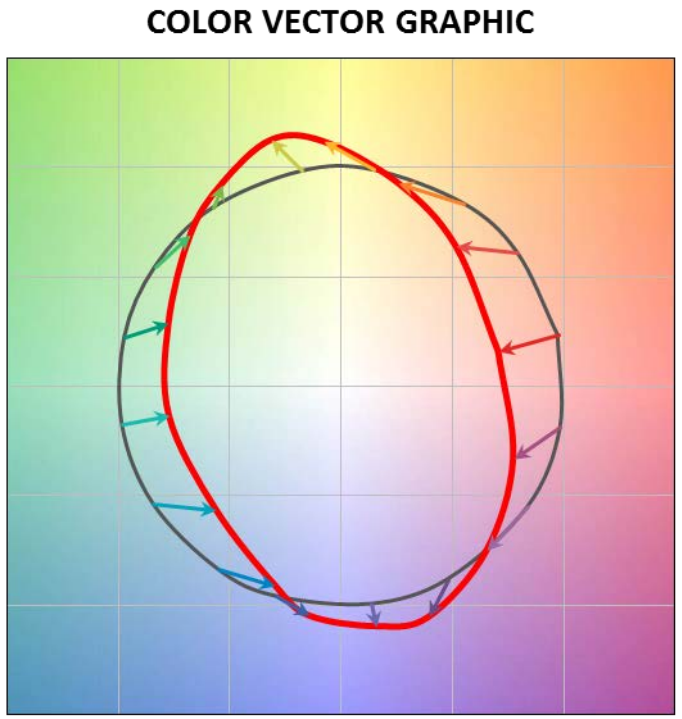

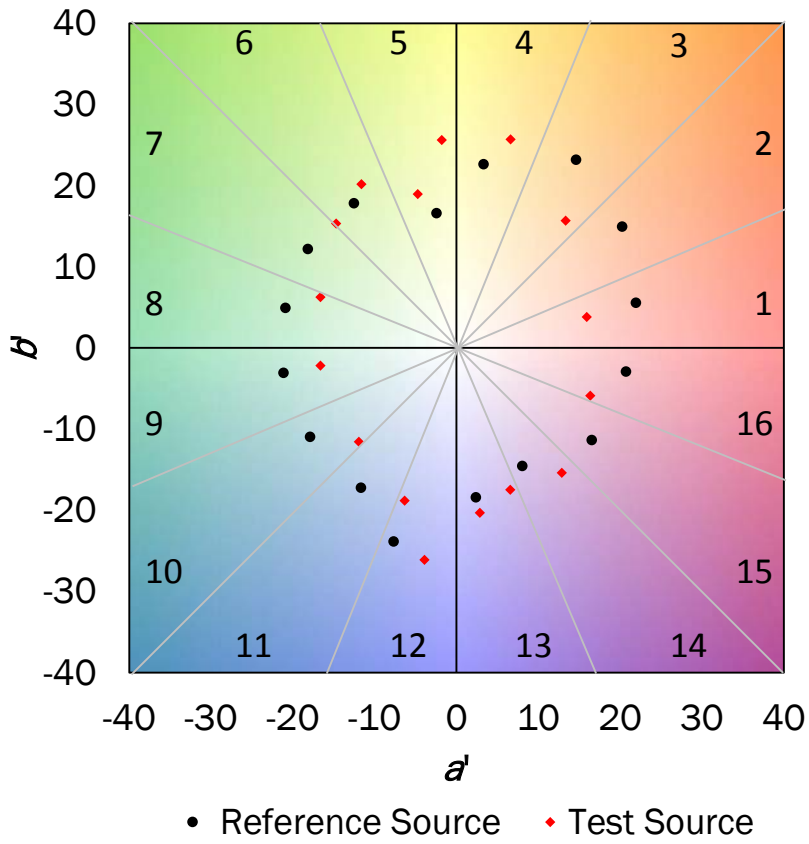

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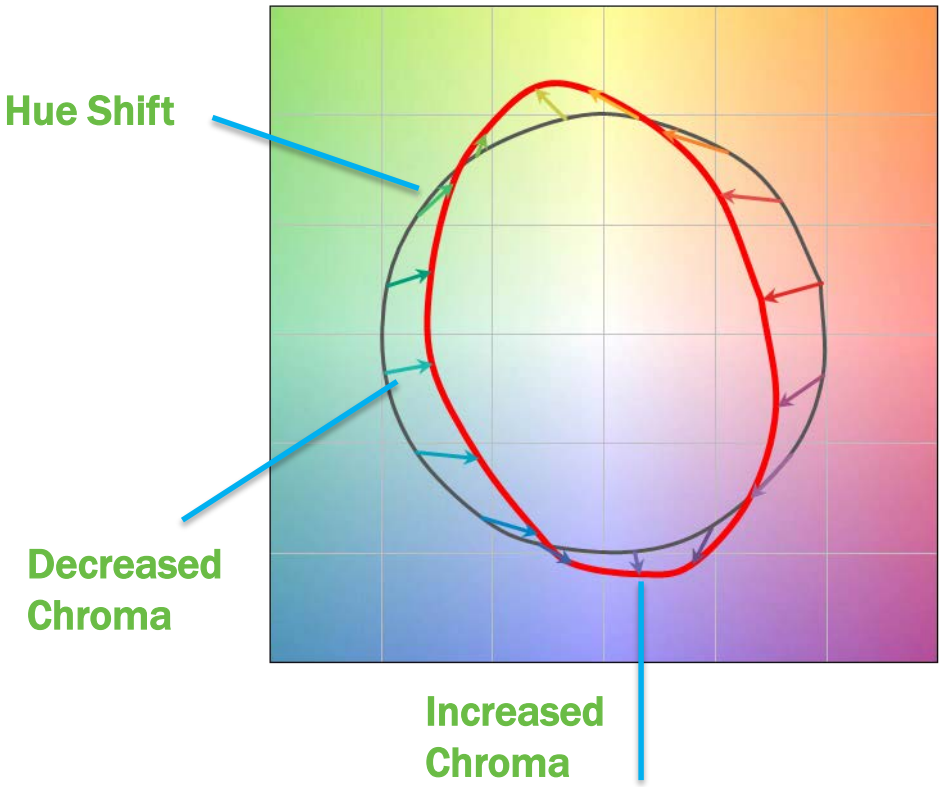
Gamut Shape: CVG and Local Chroma Shift

COLOR VECTOR GRAPHIC



LOCAL CHROMA SHIFT

$$R_{\mathrm{cs,h}j} = \frac{(a'_{test} - a'_{ref})}{\sqrt{({a'_{ref}}^2 + {b'_{ref}}^2)}} \cos\theta_j + \frac{(b'_{test} - b'_{ref})}{\sqrt{({a'_{ref}}^2 + {b'_{ref}}^2)}} \sin\theta_j$$

The purely radial difference versus the reference.

(Equivalent to colorfulness)

Represented as a percentage.
(Can be applied to samples of any chroma level)

Average Color Fidelity (IES R_f):
Average magnitude of difference between test and reference.

Gamut Area (IES R_g):
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Gamut Shape (IES CVG; IES $R_{cs,hj}$):
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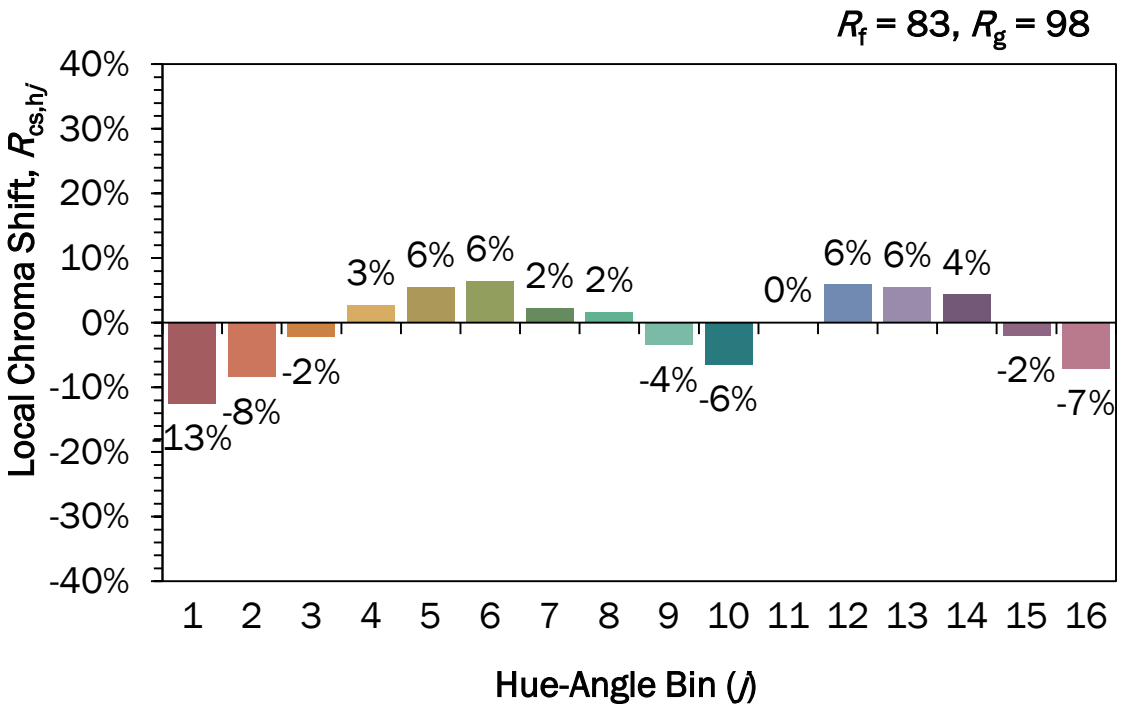
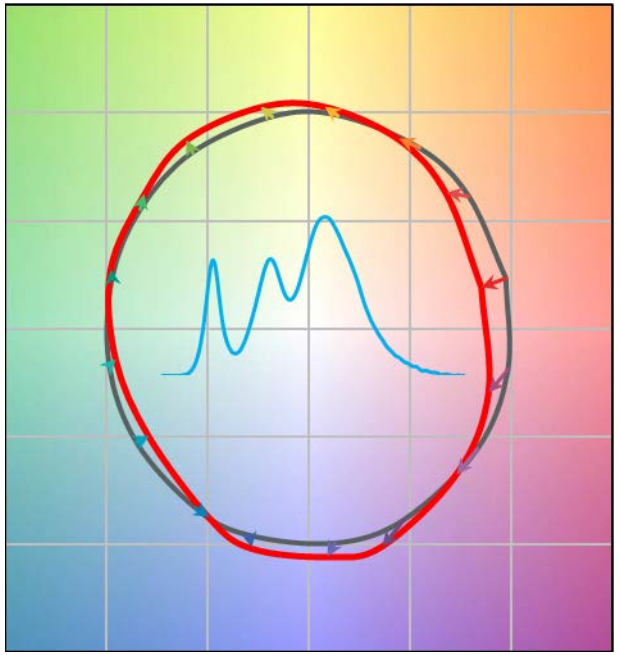
Gamut Shape Importance





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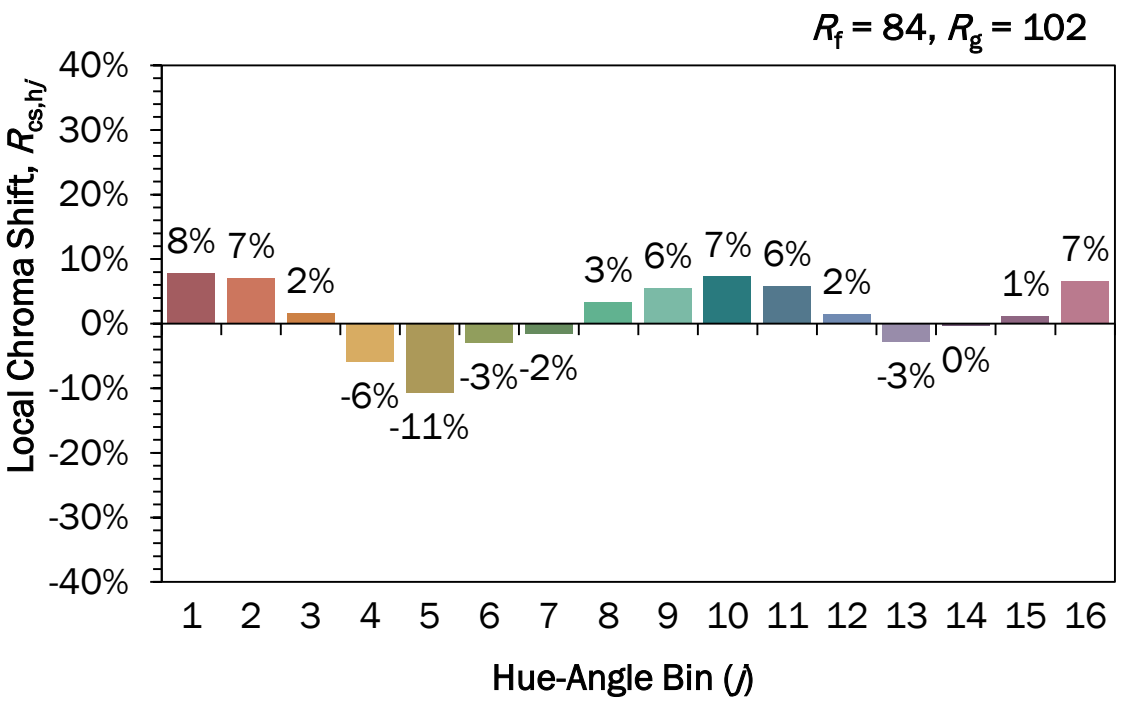

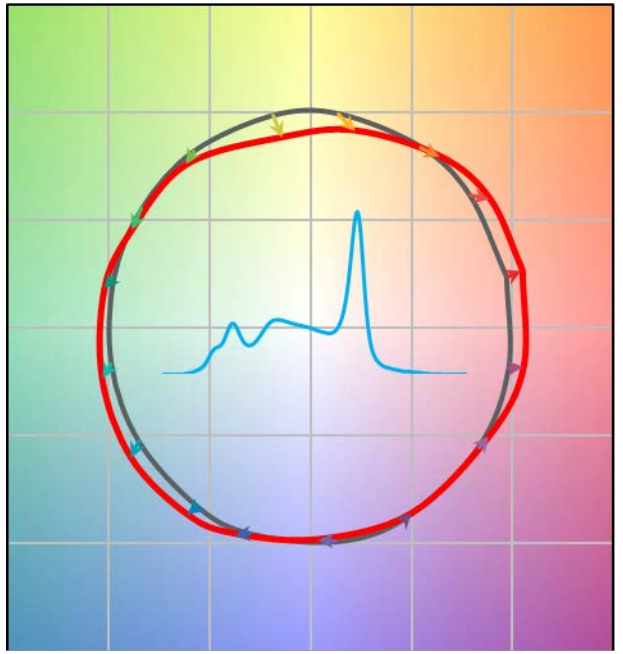

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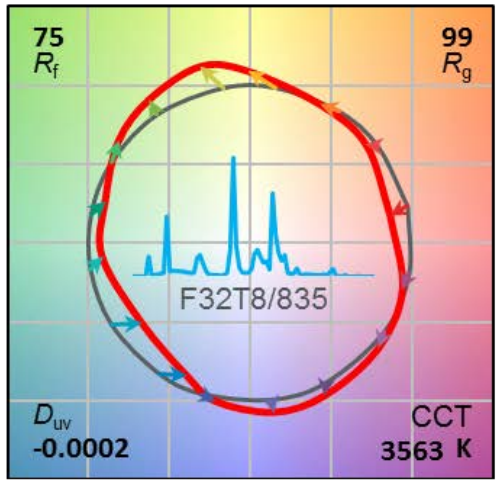
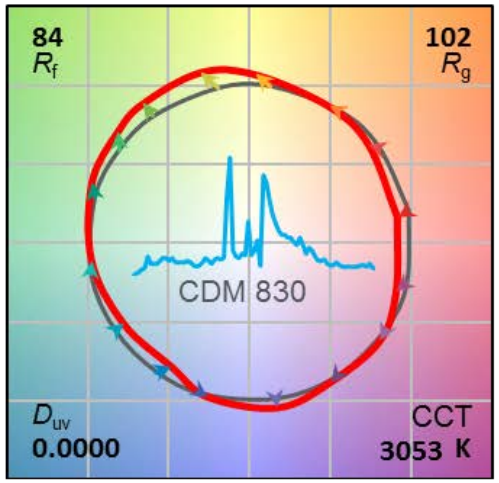
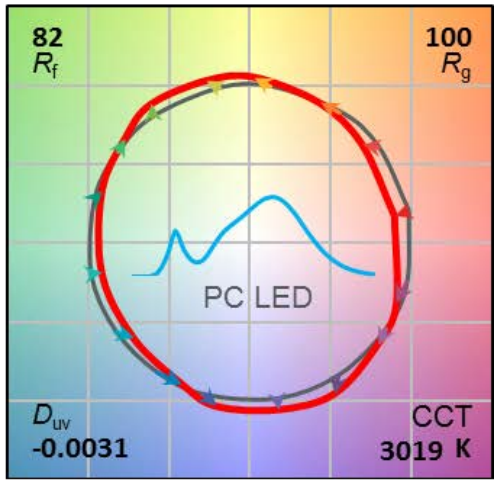
Gamut Shape Possibilities

Commercially Available Sources







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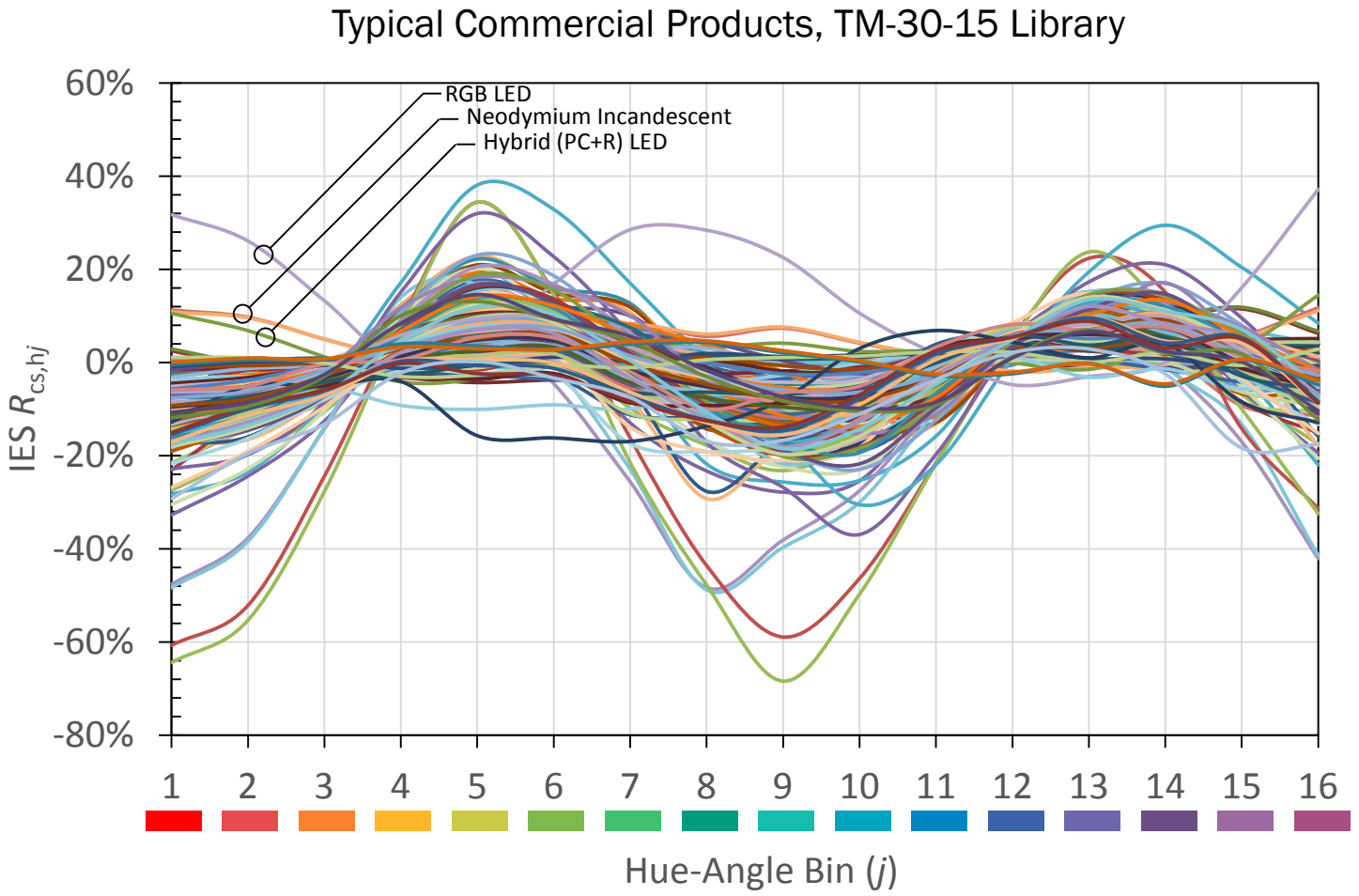

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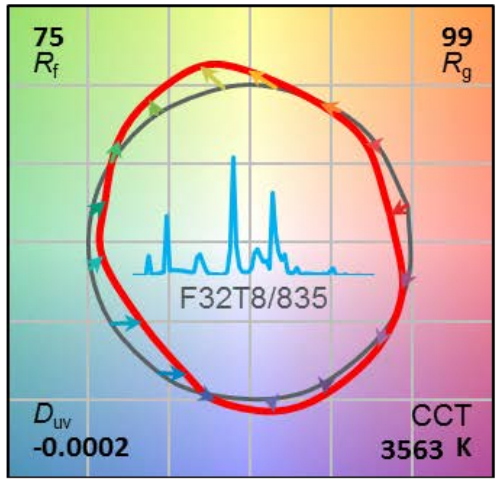
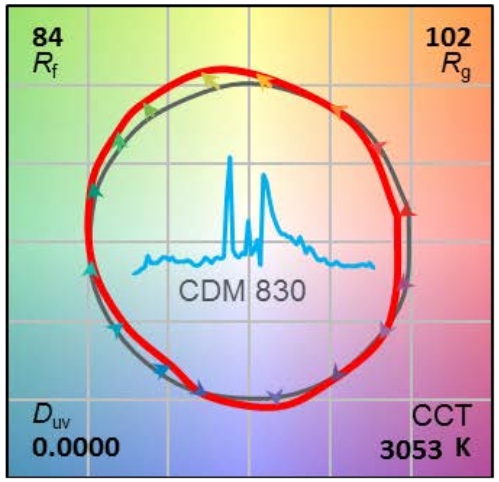
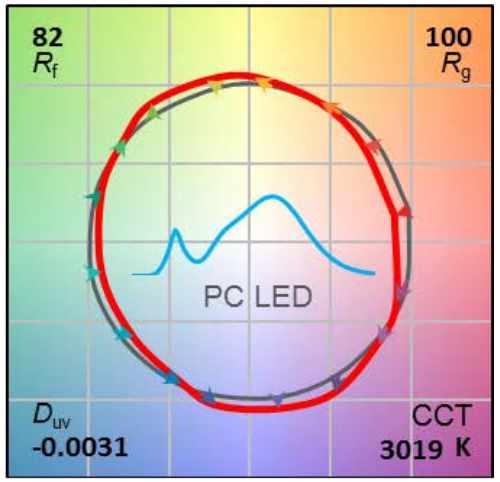
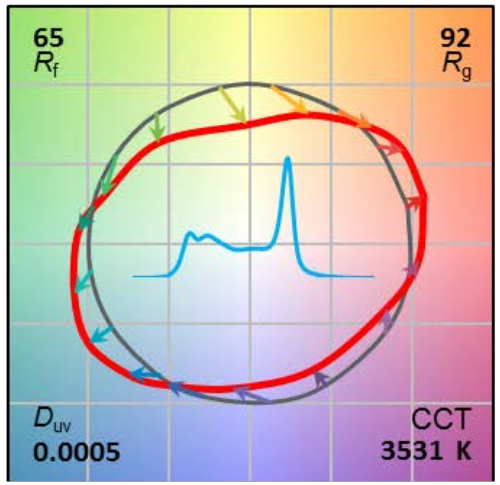
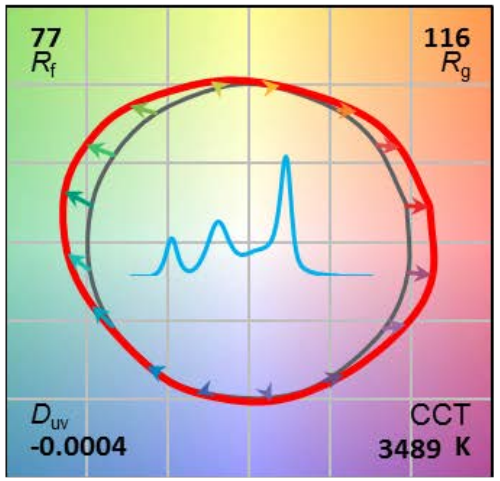


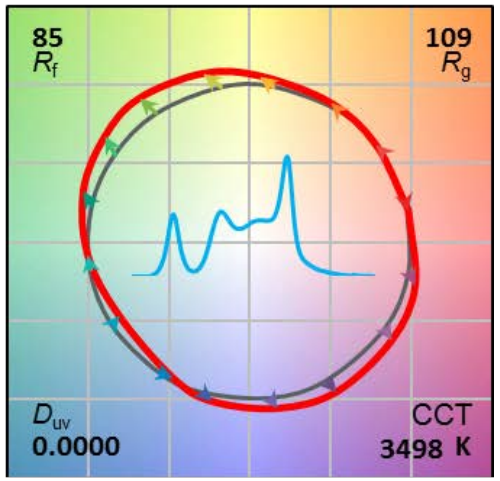




Experimental LED Sources







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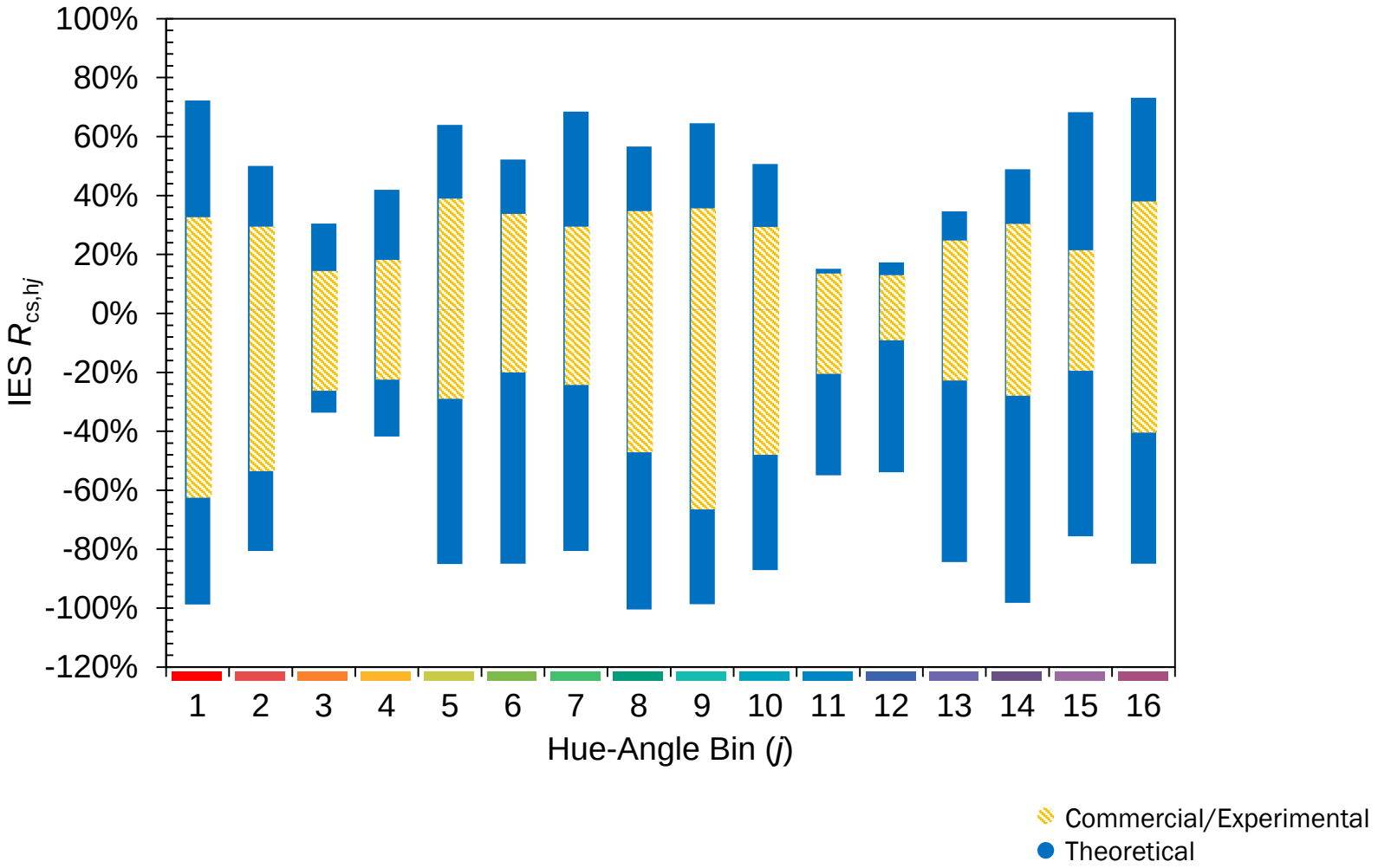
Range of Potential Local Chroma Shift values



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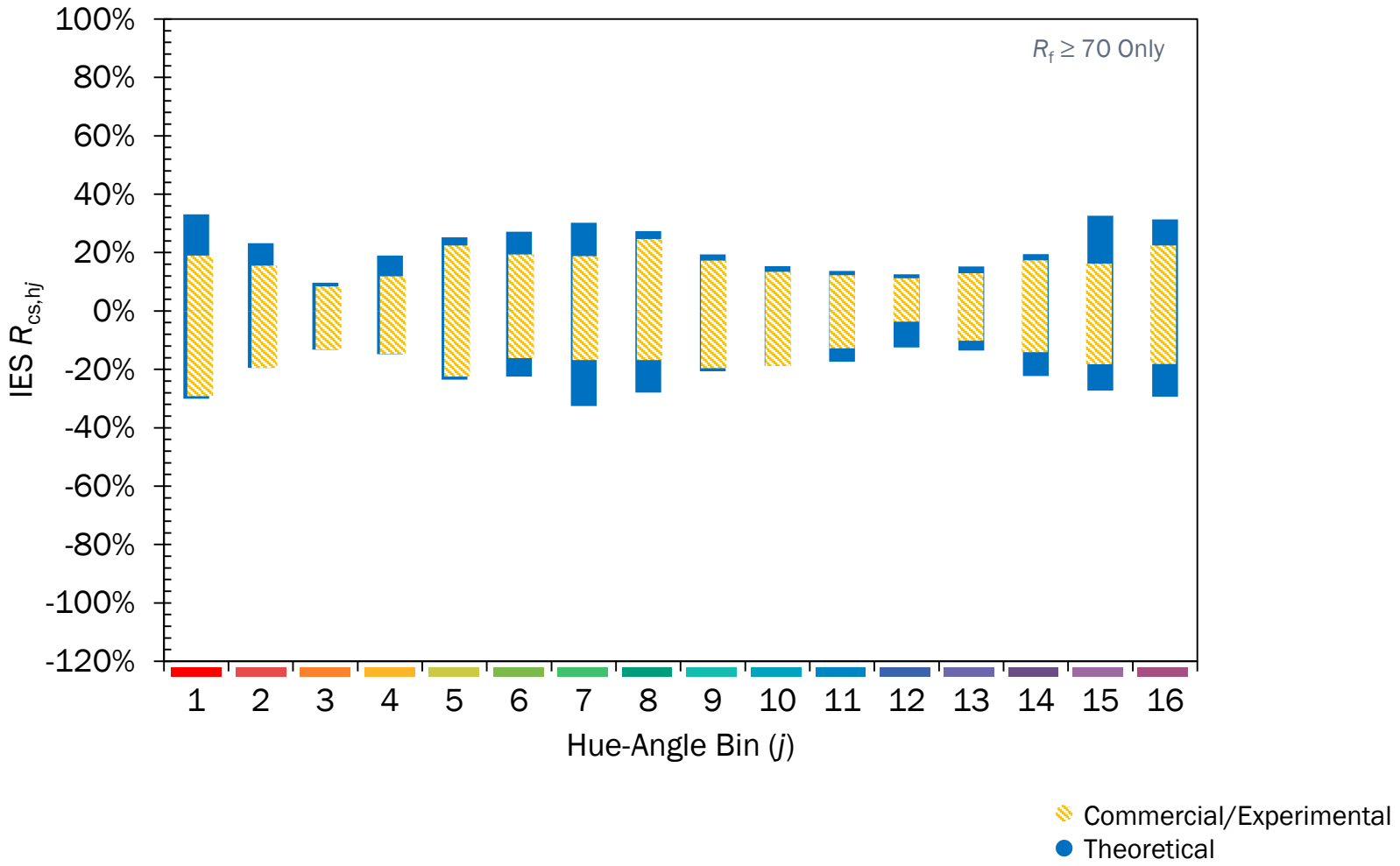

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Perceptions of Color Rendition

CREX1 PARAMETERS [2015]

CHROMATICITY
3500 K
0.000 D_{uv}

4 LEVELS R_f
5 LEVELS R_g
MIN or MAX $R_{cs,h1}$

26 TOTAL LIGHTING SCENES

3 RATING QUESTIONS
Dull or Saturated
Normal or Shifted
Like or Dislike

16 AGE 19-61

12 AGE 30-65

30 SECONDS
Minimum View Time
Per Scene

Royer M, Wilkerson A, Wei M, Houser K, Davis R. 2016. Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape. Lighting Research and Technology. Online Before Print. DOI: 10.1177/1477153516663615.

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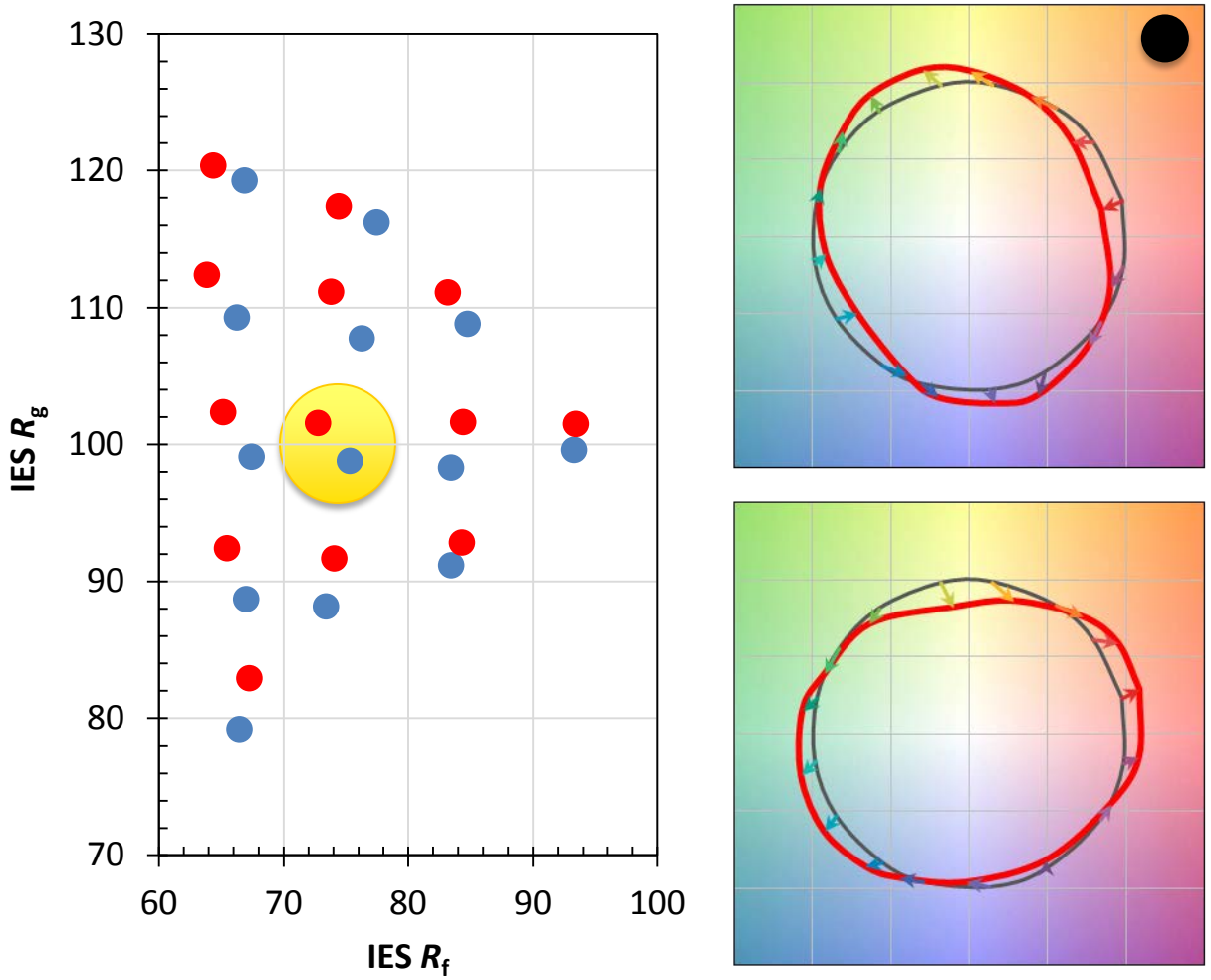

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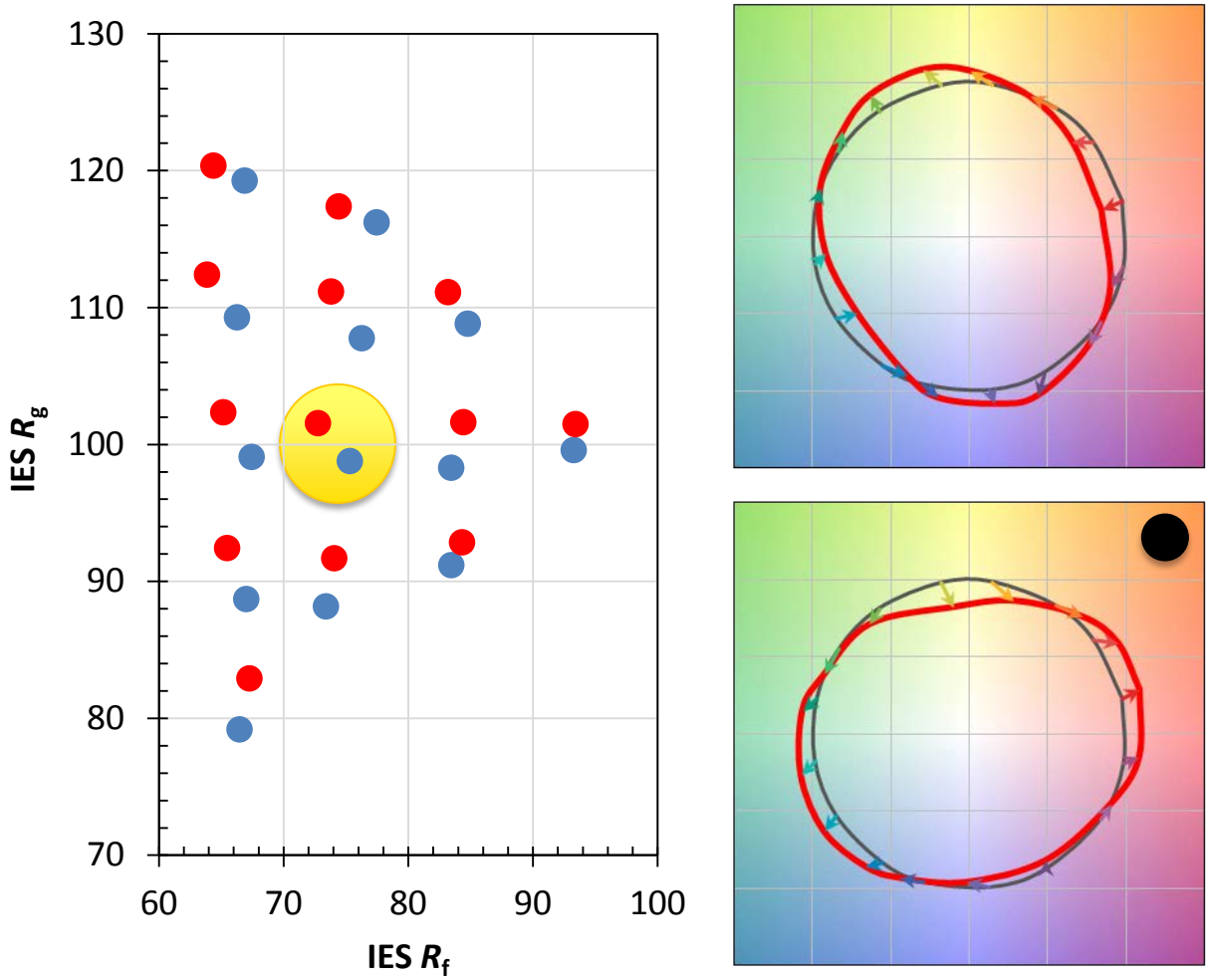

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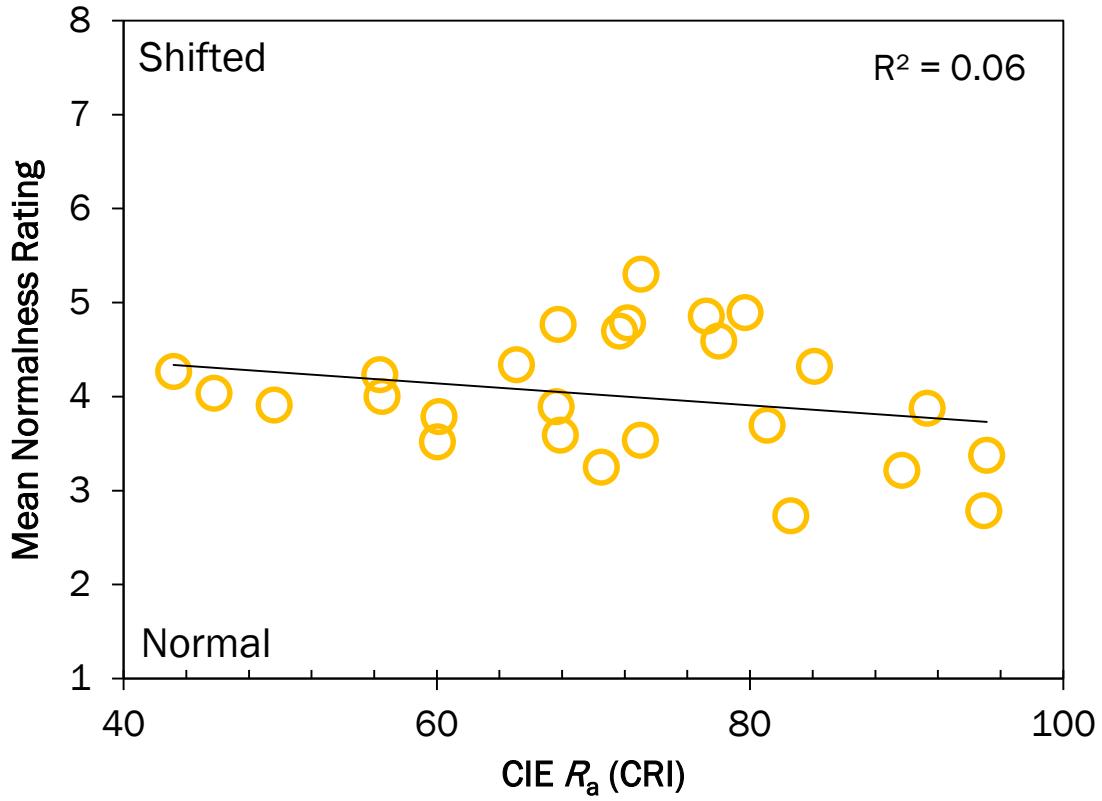
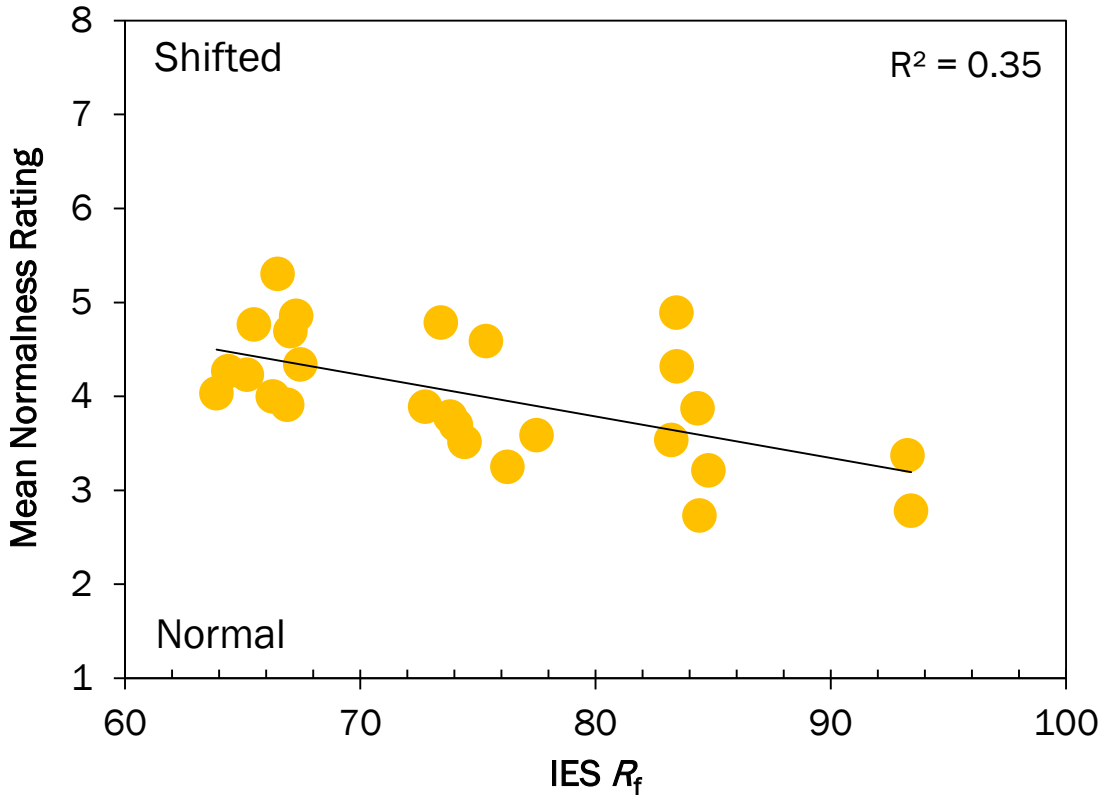
Perceptions of Normalness (Naturalness)





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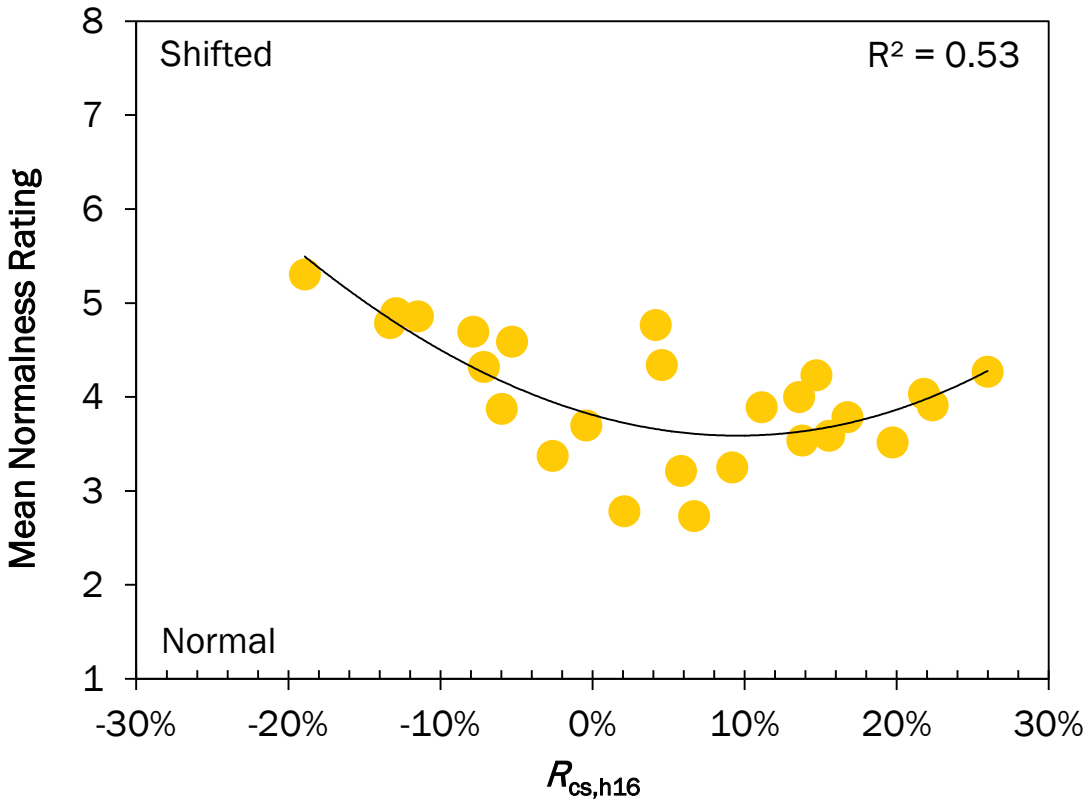

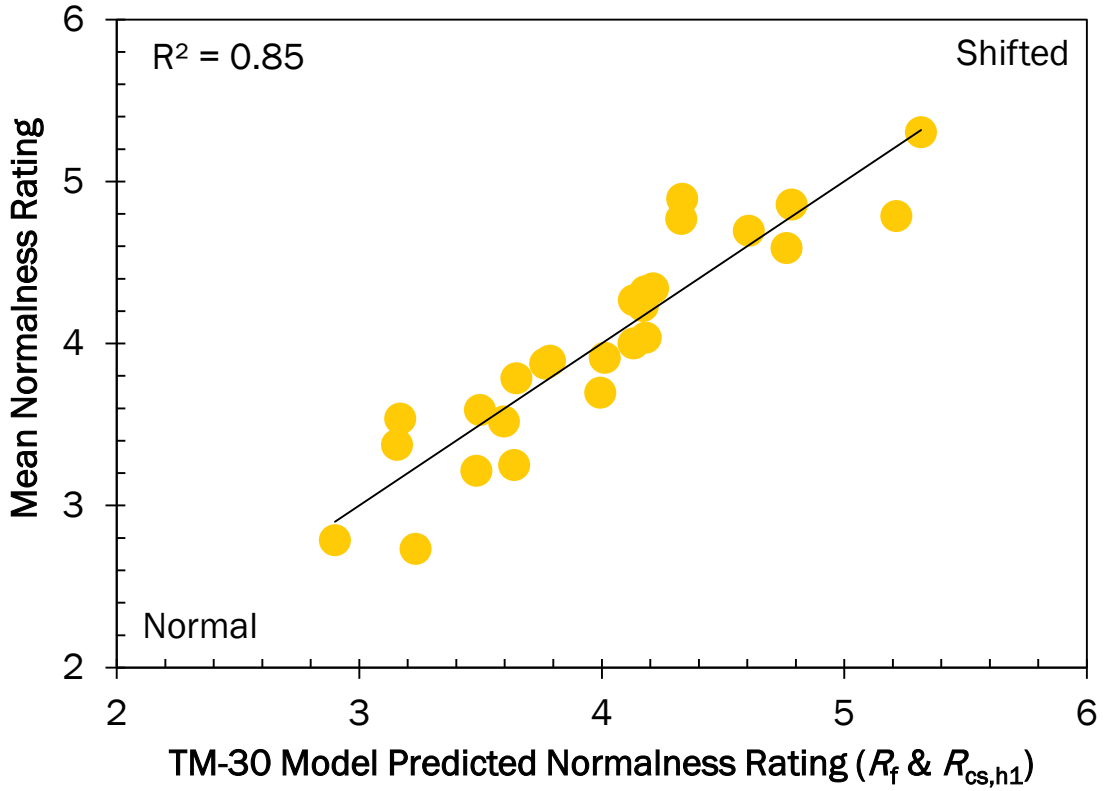

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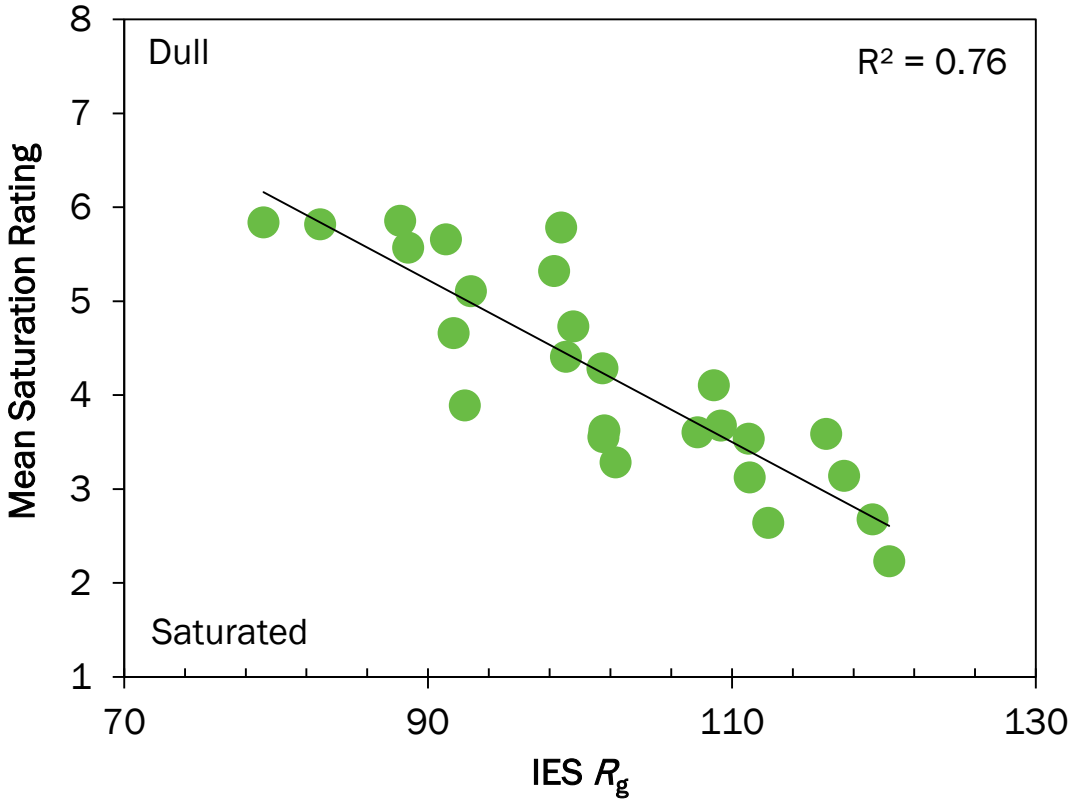
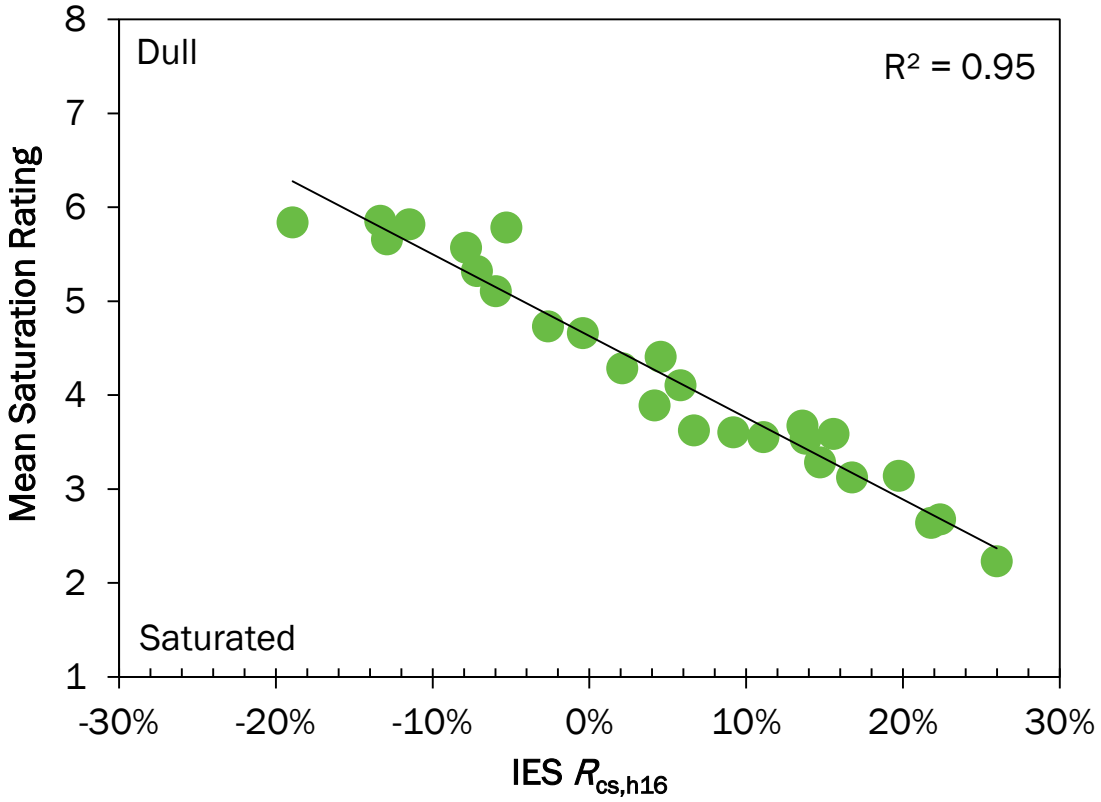
Perceptions of Saturation (Vividness)





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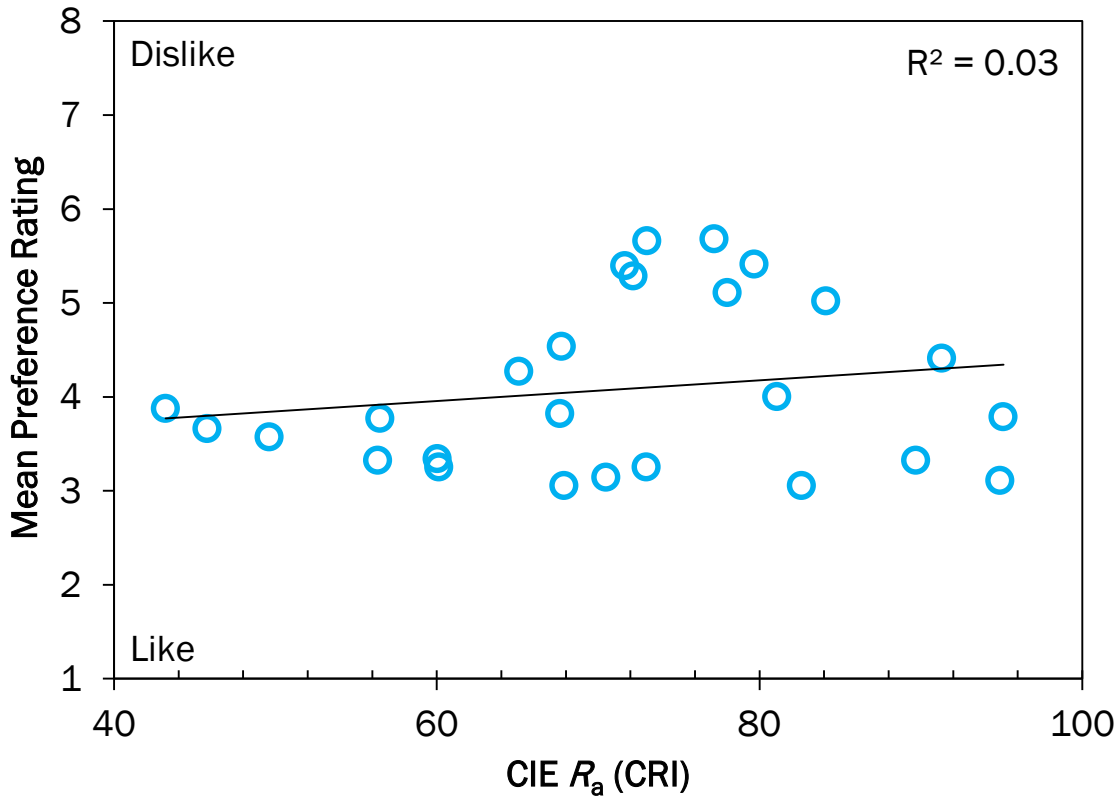
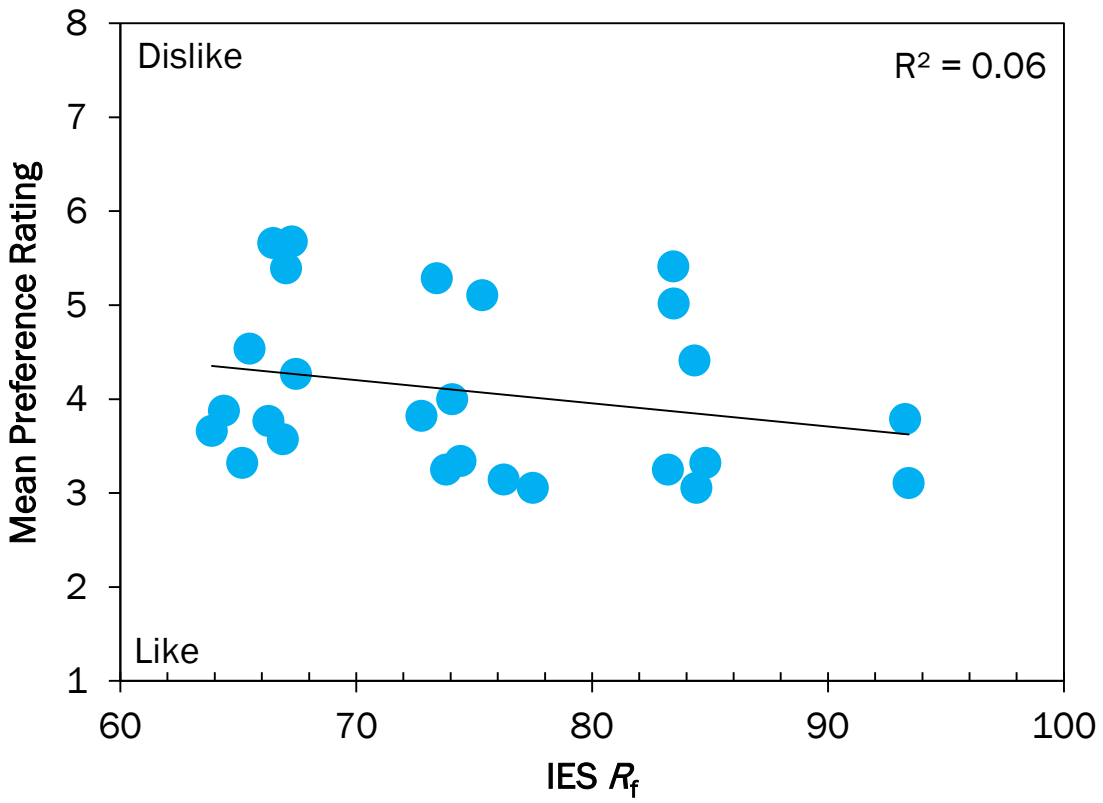
Color Rendition Preferences





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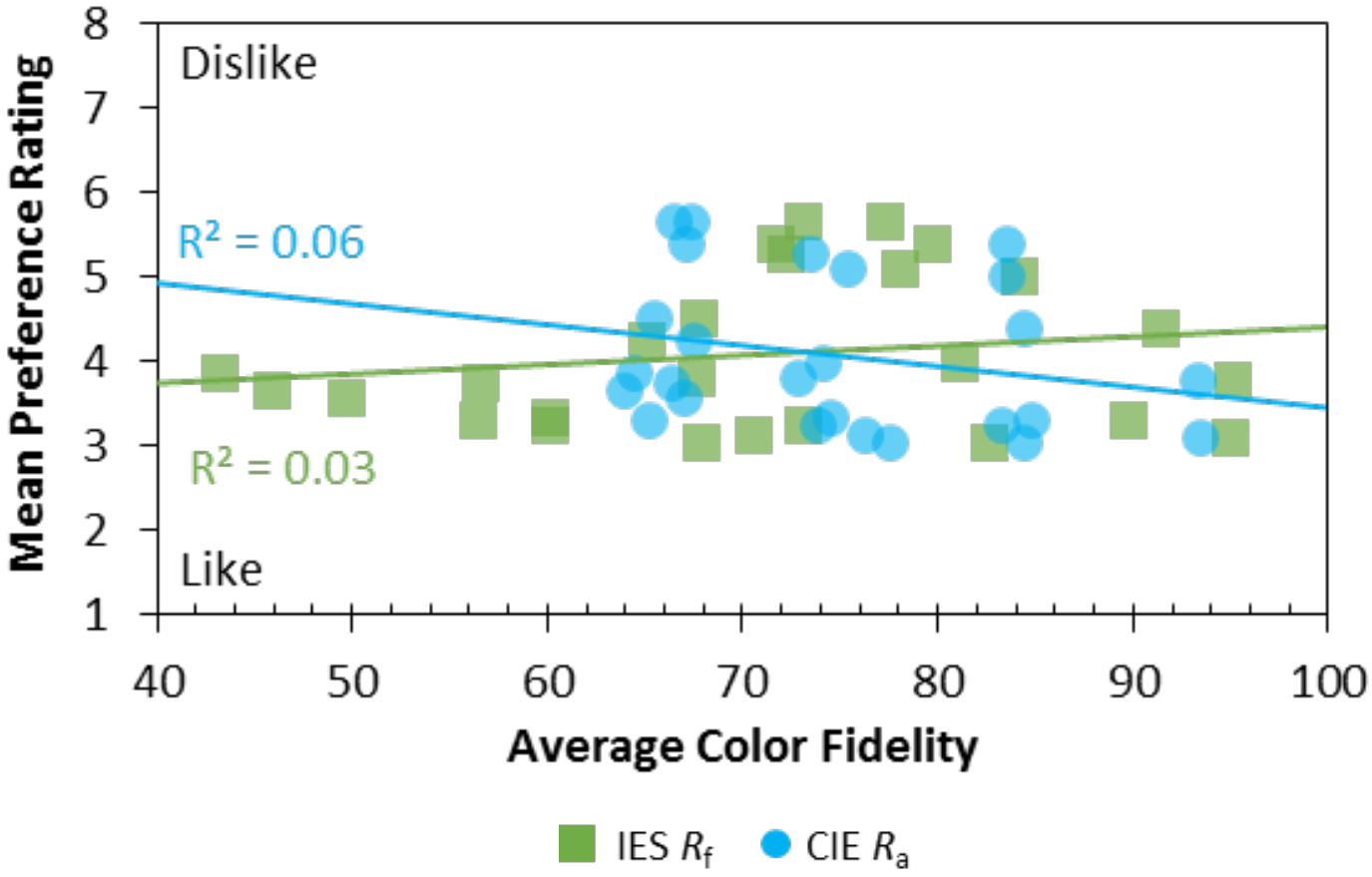
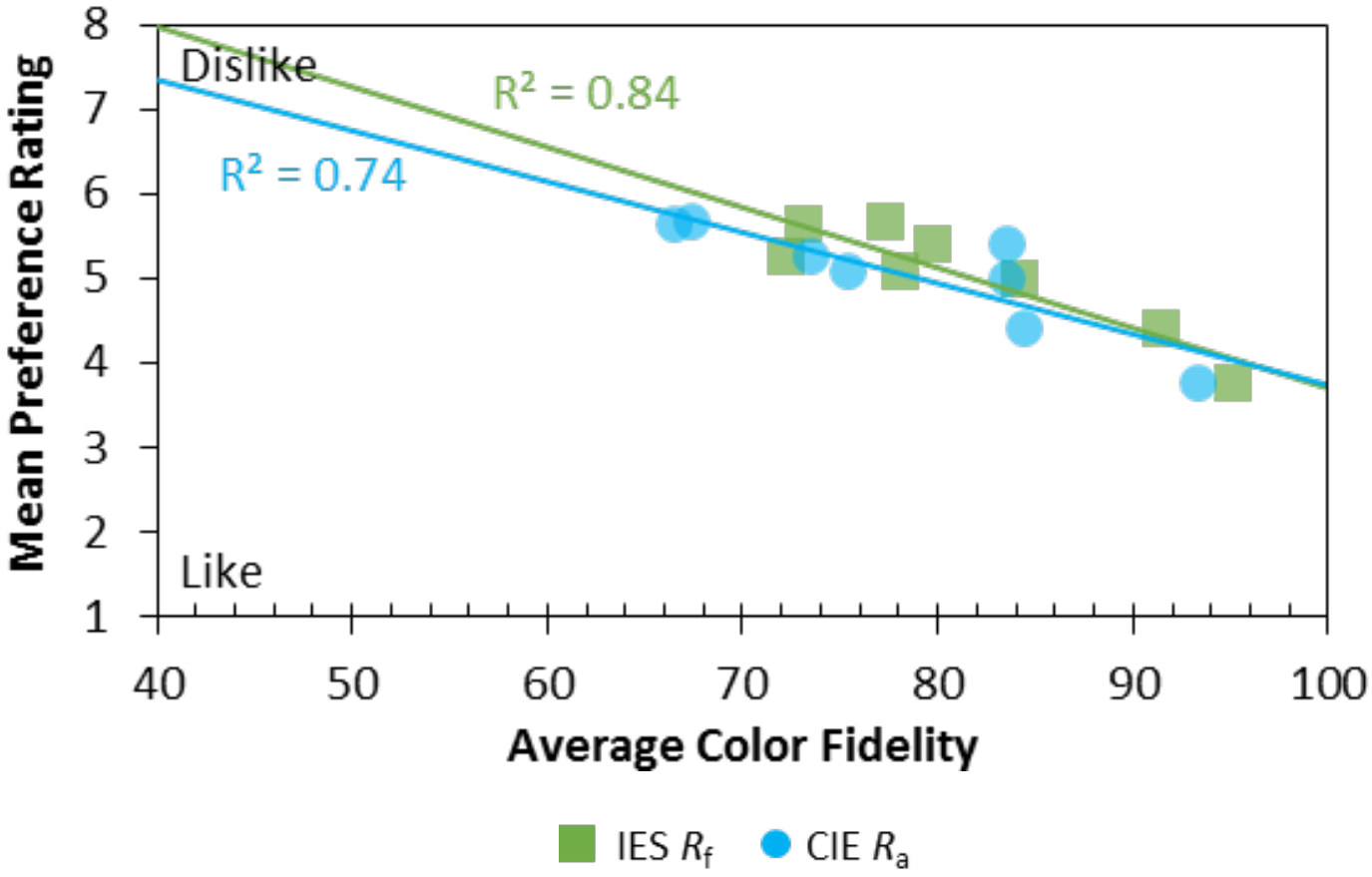
Aside: R_f versus R_a (CRI)



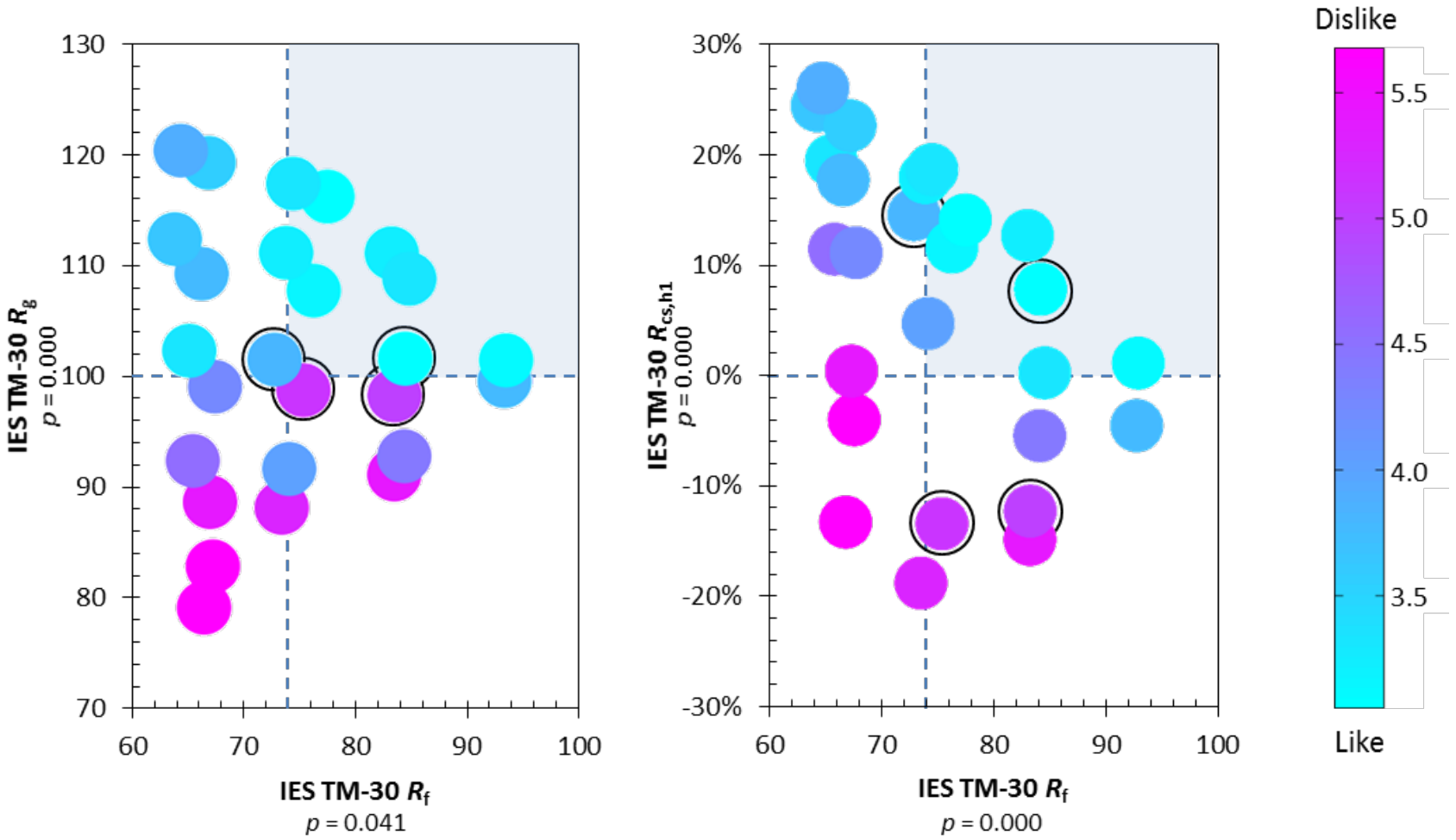
[All 26 SPDs from CREX1]

Aside: R_f versus R_a (CRI)



[8 SPDs with $R_{cs,h1}$ < 0%]

Color Rendition Preferences



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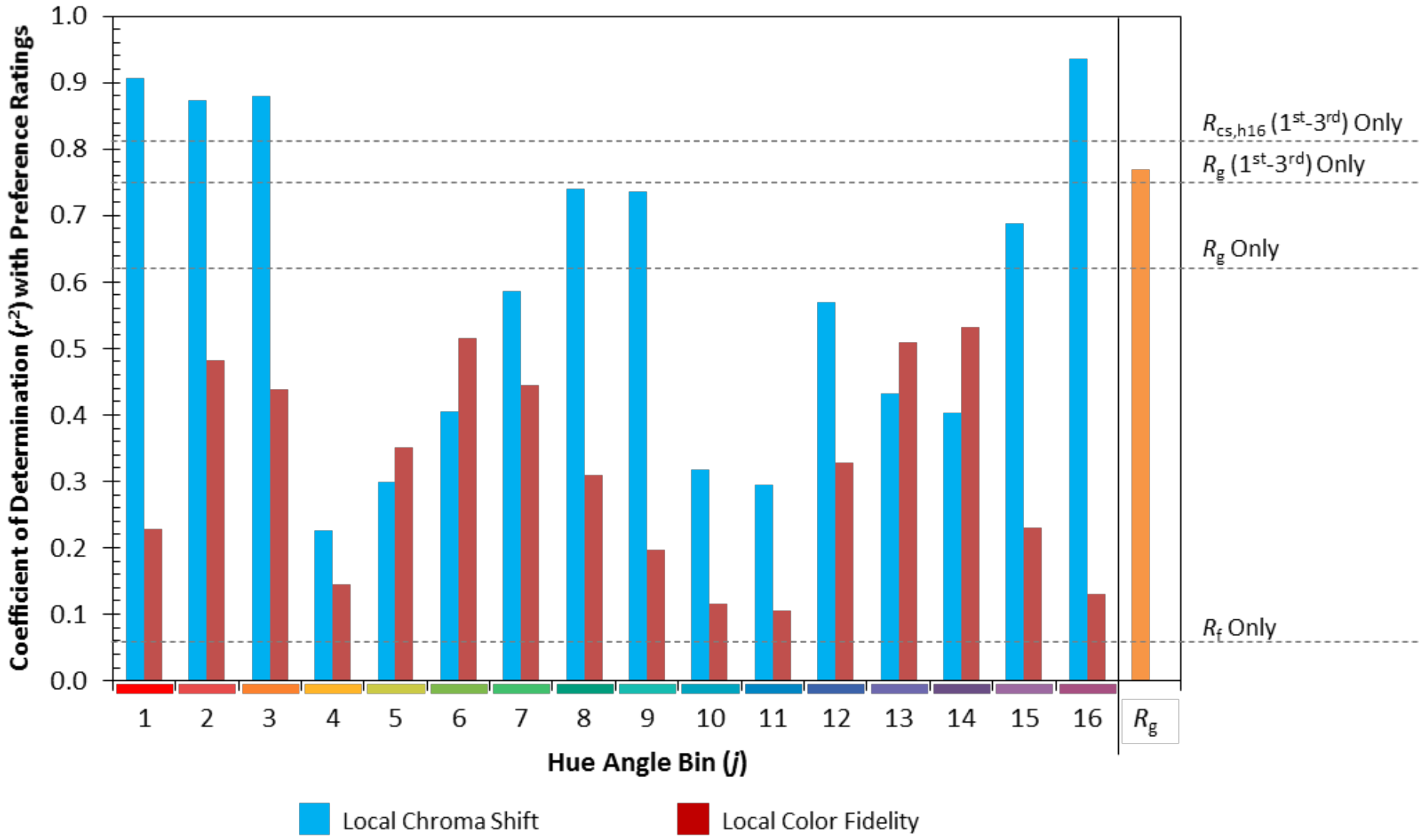

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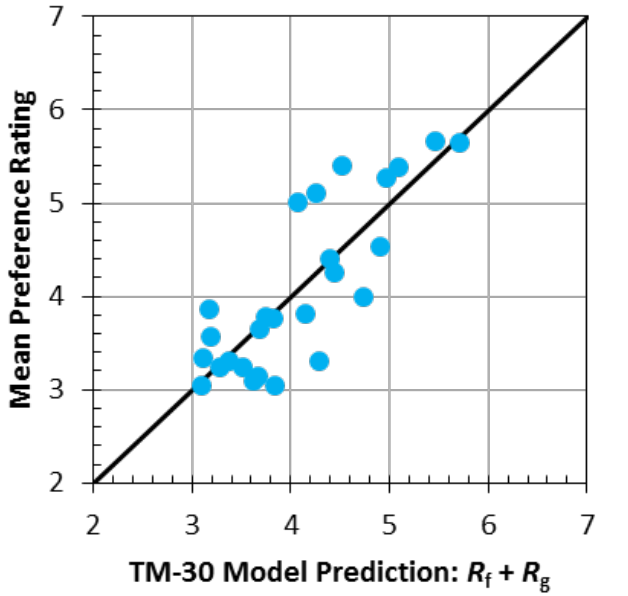
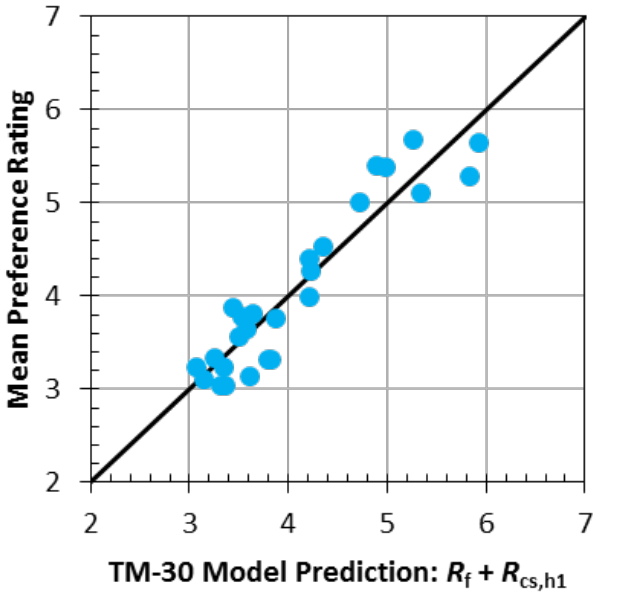


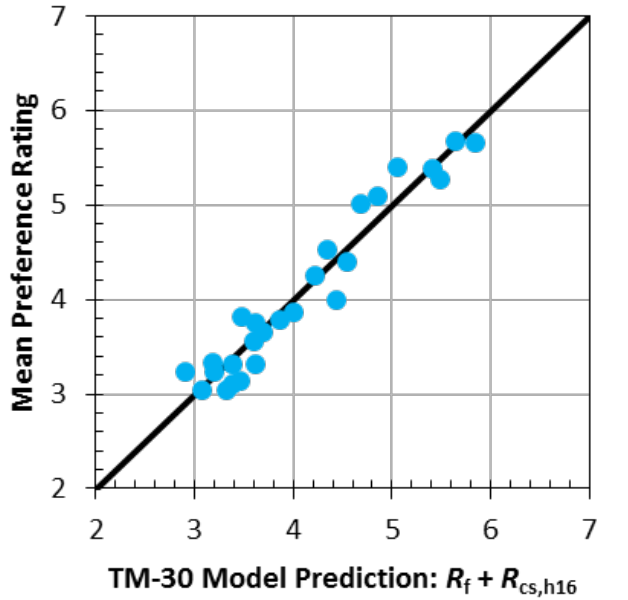
Preference = $12.37 - 0.026\,R_f - 0.063\,R_g$

$r^2 = 0.68$



Preference = $9.52 - 0.067\,R_f - 6.59\,R_{cs,h1}$

$r^2 = 0.88$



Preference = $7.45 - 0.041\,R_f - 9.99\,R_{cs,h16} - 0.90\,R_{cs,h16}^2 + 106.6\,R_{cs,h16}^3$

$r^2 = 0.94$

Royer M, Wilkerson A, Wei M, Houser K, Davis R. 2016. Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape. Lighting Research and Technology. Online Before Print. DOI: 10.1177/1477153516663615.

Specification Criteria?

Normalness = Red Chroma + Average Color Fidelity

$0\% \le R_{cs,h1} \le 8\%$ $R_f \ge 80$

Saturation = Red Chroma

Maximize $R_{cs,h16}$, $R_{cs,h1}$

Preference = Red Chroma + Average Color Fidelity

$0\% \le R_{cs,h16} \le 15\%$ $R_f \ge 74$ $(R_g \ge 100)$

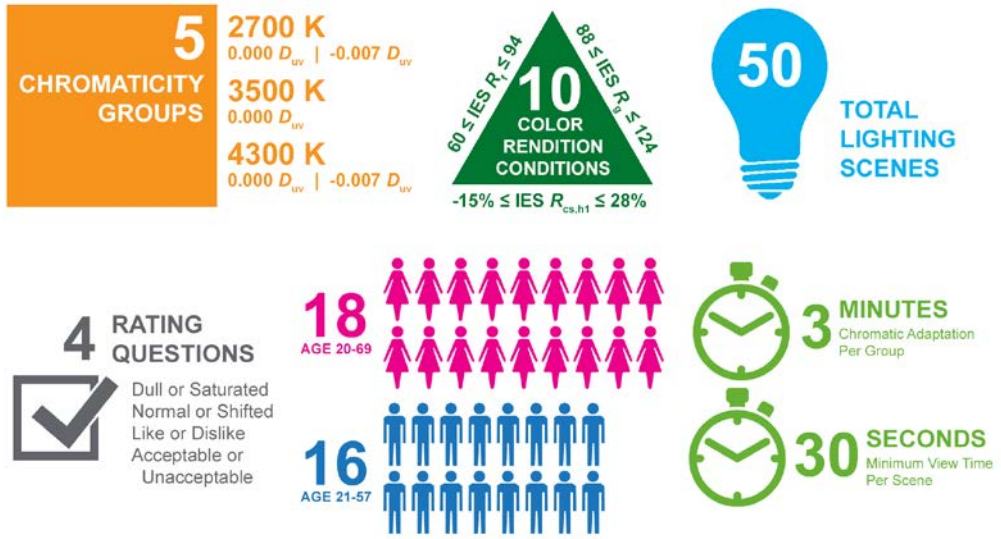
or $0\% \le R_{cs,h1} \le 15\%$

More on specification criteria later…

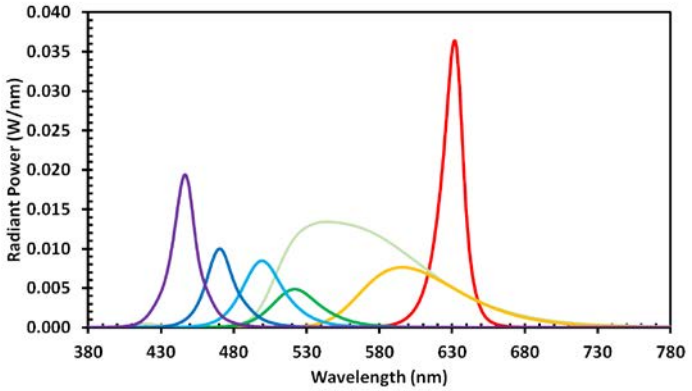
Royer M, Wilkerson A, Wei M, Houser K, Davis R. 2016. Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape. Lighting Research and Technology. Online Before Print. DOI: 10.1177/1477153516663615.

What about other Chromaticities?

CREX2 PARAMETERS [2016]

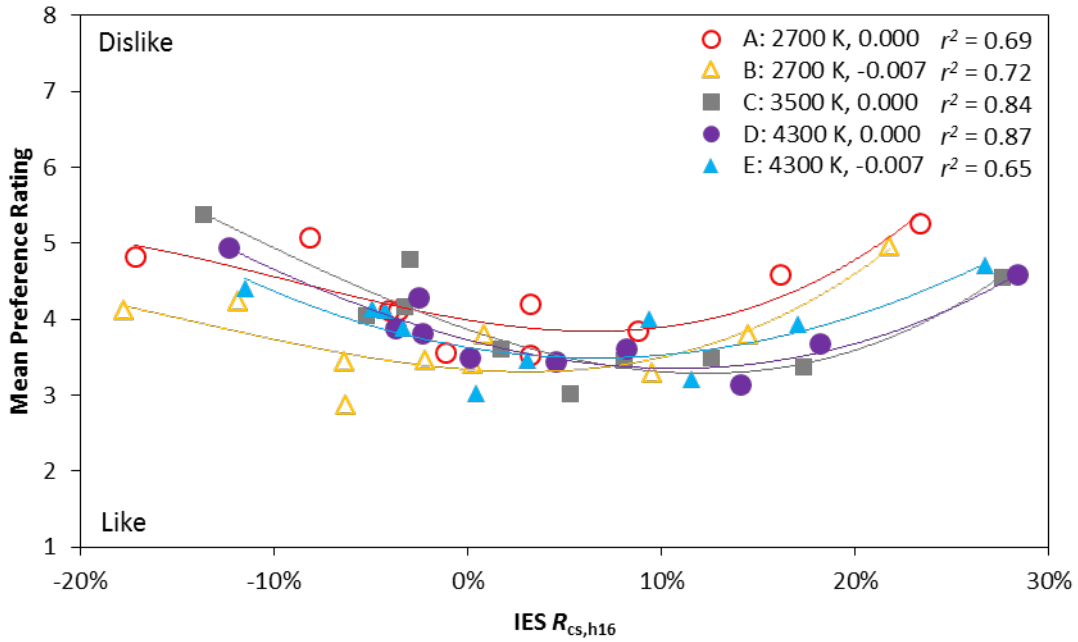


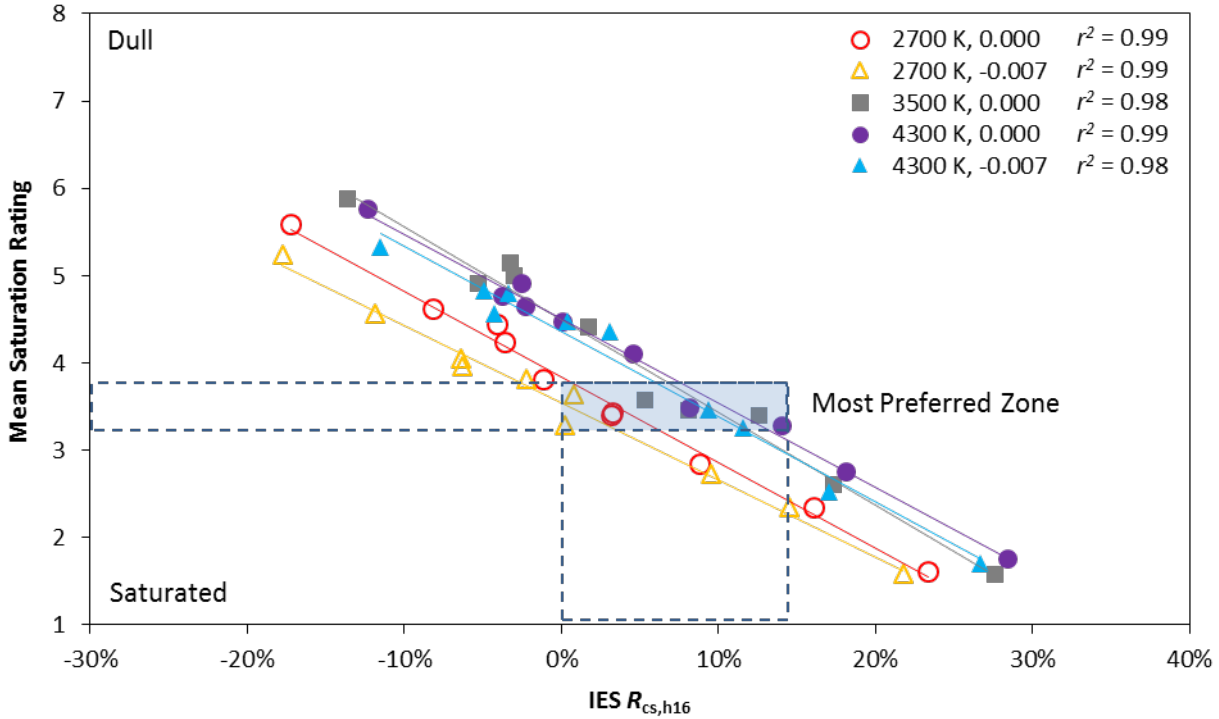
ETC Source 4 Series 2 Lustr



Royer M, Wilkerson A, Wei M. 2017b. Human Perceptions of Color Rendition at Different Chromaticities. Lighting Research & Technology. Online before print. DOI: 10.1177/1477153517725974.

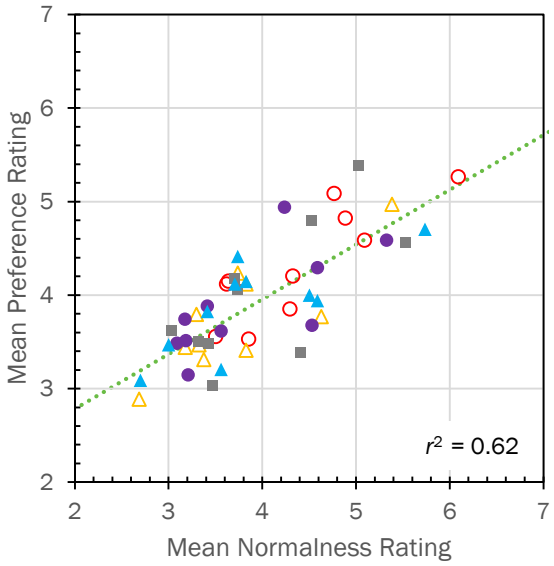
Same Driving Influence: Red Chroma

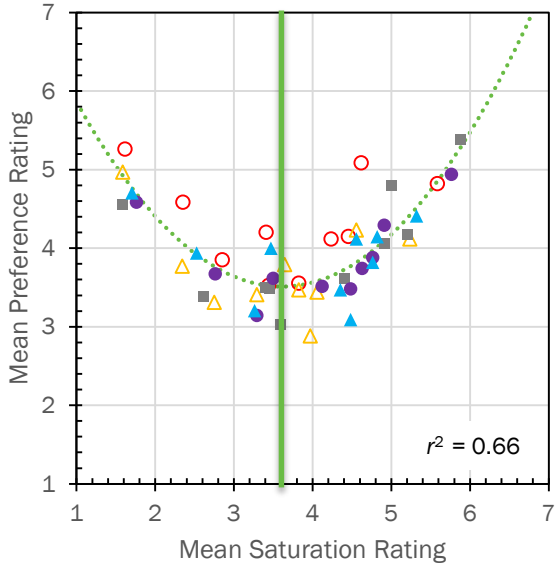


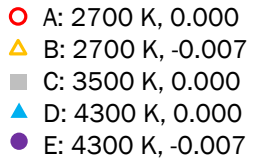


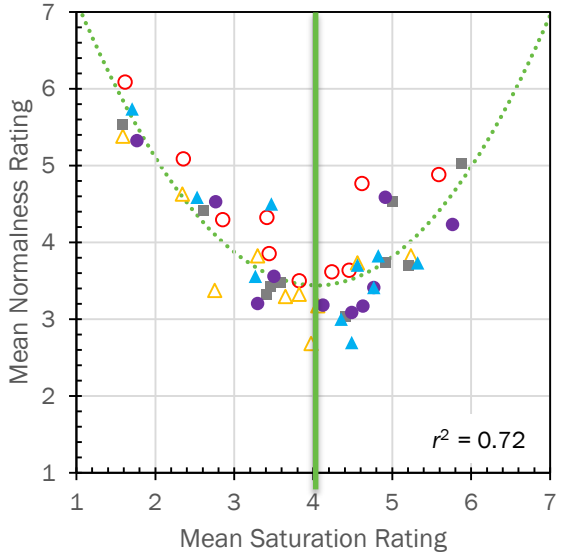
Royer M, Wilkerson A, Wei M. 2017b. Human Perceptions of Color Rendition at Different Chromaticities. Lighting Research & Technology. Online before print. DOI: 10.1177/1477153517725974.

Saturation vs. Preference vs. Normalness



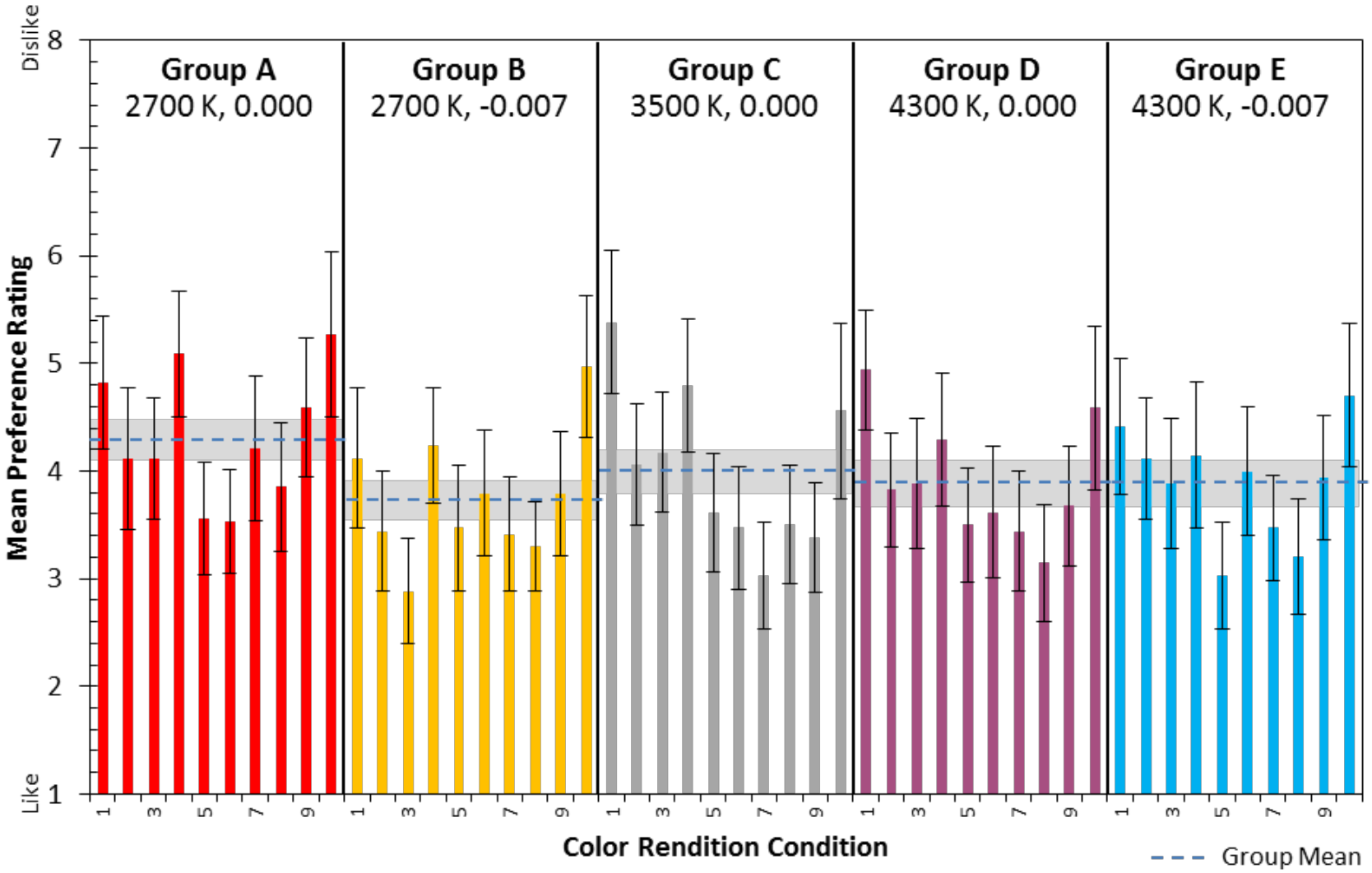






Royer M, Wilkerson A, Wei M. 2017b. Human Perceptions of Color Rendition at Different Chromaticities. Lighting Research & Technology. Online before print. DOI: 10.1177/1477153517725974.

Chromaticity Effects?

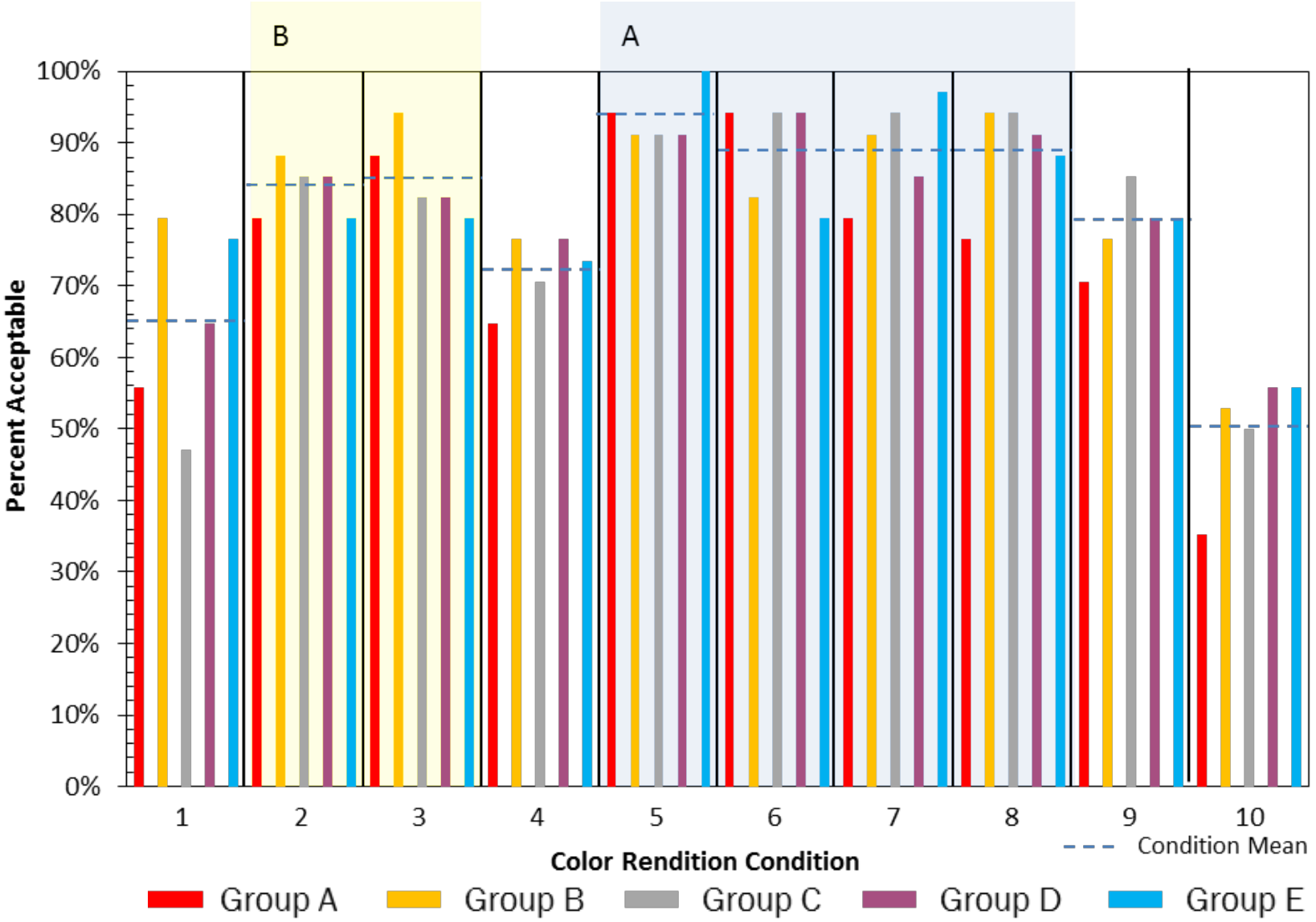


D_{uv} mattered overall at 2700 K, but not at 4300 K.

Color rendition had a larger effect than chromaticity.

Royer M, Wilkerson A, Wei M. 2017b. Human Perceptions of Color Rendition at Different Chromaticities. Lighting Research & Technology. Online before print. DOI: 10.1177/1477153517725974.

Specification Criteria



Composite Specification Criteria:

A: (> 89% acceptable)
IES $R_f \geq 75$
IES $R_g \geq 100$
$-1\% \leq$ IES $R_{cs,h1} \leq 15\%$

B: (> 84% acceptable)
IES $R_f \geq 75$
IES $R_g \geq 98$
$-7\% \leq$ IES $R_{cs,h1} \leq 15\%$

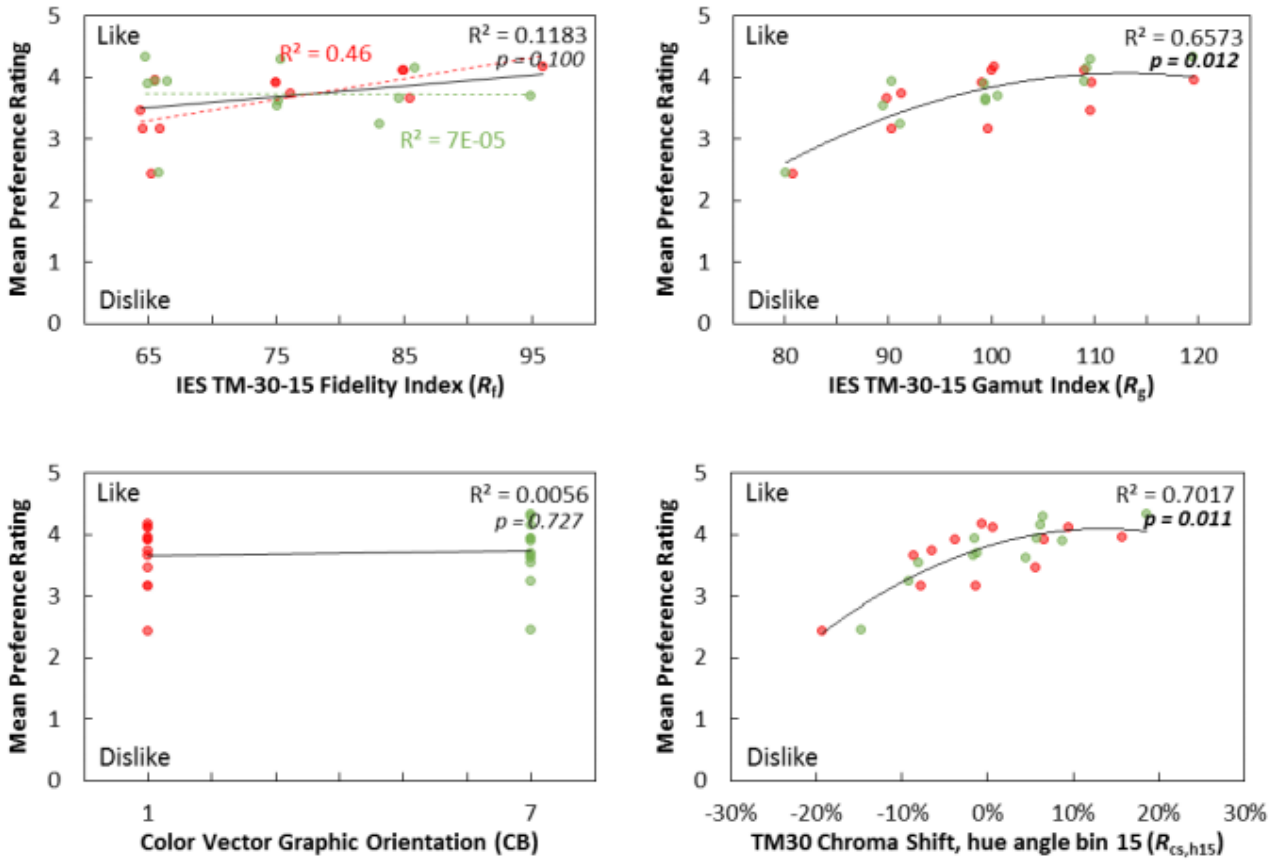
Royer M, Wilkerson A, Wei M. 2017b. Human Perceptions of Color Rendition at Different Chromaticities. Lighting Research & Technology. Online before print. DOI: 10.1177/1477153517725974.

PNNL Next Steps

- **Experiment 3: Further Exploration of Chromaticity Effects**
  - Refine understanding of how CCT and D_{uv} interact with color rendition
  - Focus on transition between 2700 K and 3500 K
- **Experiment 4: Investigation of Illuminance Effects**
  - Preference for increased red chroma versus the reference at interior illuminance levels counters the Hunt effect?

Other Important TM-30 Experiments

Esposito 2016 (Dissertation)



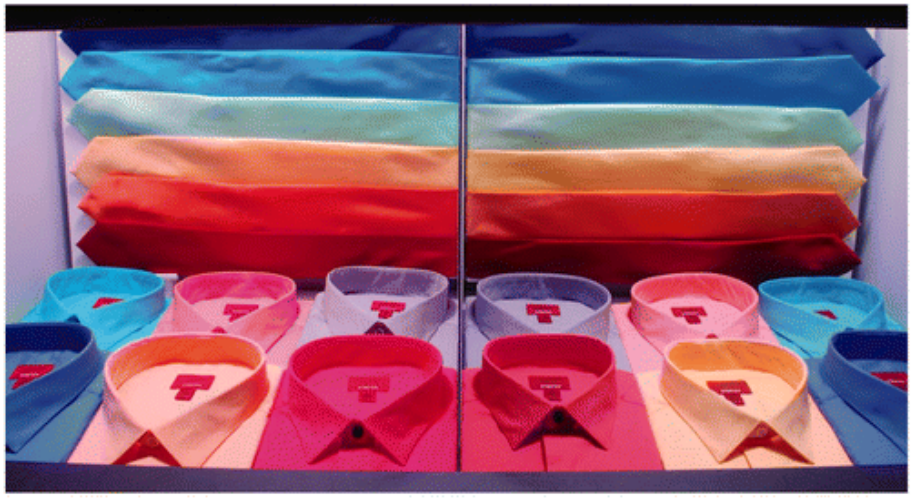
$$LIKE = 1.629 + 0.02686\ R_f + 3.423\ R_{cs,h16} - 10.01\ R_{cs,h16}^2 - 0.04866\ \psi + 0.000566\ R_f{*}\psi$$

Esposito T. 2016. Modeling color rendition and color discrimination with average fidelity, average gamut, and gamut shape [Doctoral]. [University Park, PA]: Penn State University.

Other Important TM-30 Experiments

Wei et al. 2016

> "When objects were unfamiliar, as with the fabrics, all chroma-enhancing spectra were preferred to the fixed reference regardless of the gamut shapes. When familiar objects were present, such as food, observers were more discerning about changes in chroma and hue. We conclude that a graphic of gamut shape is an important adjunct to average measures of colour fidelity and gamut."

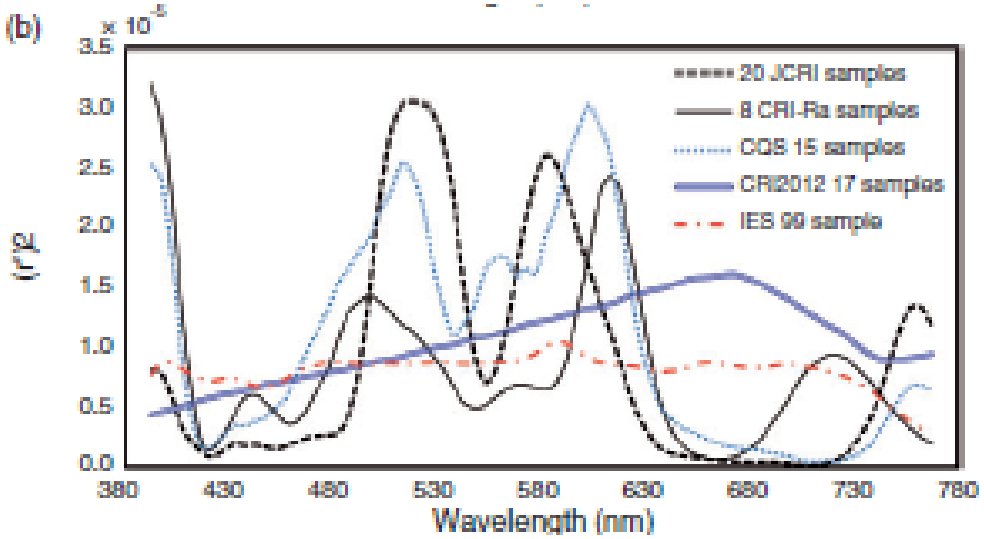


Wei M, Houser K, David A, Krames M. 2016. Colour gamut size and shape influence colour preference. Lighting Research and Technology. Online before print. DOI: 10.1177/1477153516651472.

Other Important TM-30 Research

Xu et al. 2016

"A psychophysical experiment was conducted to investigate perceived colour differences of 20 colour samples under 11 pairs of light settings. It was found that the CIE 1964 10-dgree CMFs together with CAM02-UCS correlated better than other tested measures to the perceived colour difference assessments made by the observers. The better performance of CAM02-UCS was also suggested by the improved correlation between the visual assessments and IES-R_f with the replacement of colour samples."



Xu W, Wei M, Smet K, Lin Y. 2016. The prediction of perceived colour differences by colour fidelity metrics. Lighting Research and Technology Online before print. DOI: 10.1177/1477153516653650.

TM-30: What's the Status?

Known use to date:

- **Manufacturers (LED Lighting Facts and/or Web Search):**
  Alphabet, Axis, Beta-Calco, Cree, Dongguan Kingsun Optoelectronic, Eaton, Energy Planning Associates, Engineered Products, ETC, EYE, Finelite, Hawaii LED Star, Horner, Intense, Juno, Kenall, Landscape Forms, LF Illumination, LSI, Lumenetix, Nicor, PLANLED, RAB, Selux, Shat-R-Shield, Silescent, SLP, Soraa, L.C. Doane, Lighting Quotient, Visa, Xicato
- **Meters/Calculation Software (Web Search):**
  Labsphere, UPRtek, Lighting Passport, BabelColor, Gossen, Osram LED Color Calculator

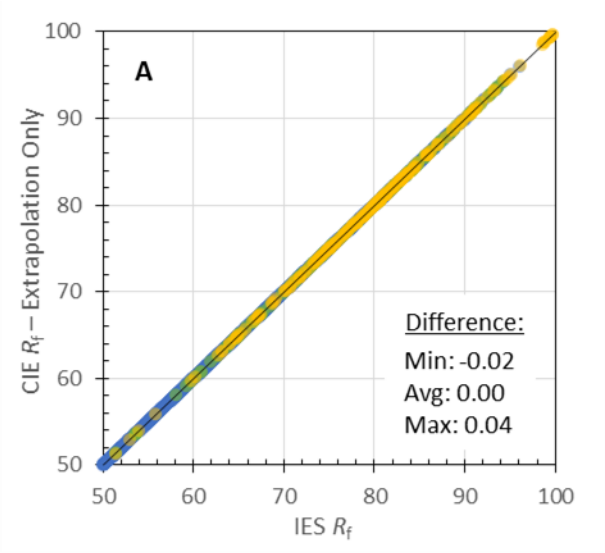
  (Any measured SPD can be used to calculate TM-30 values!)

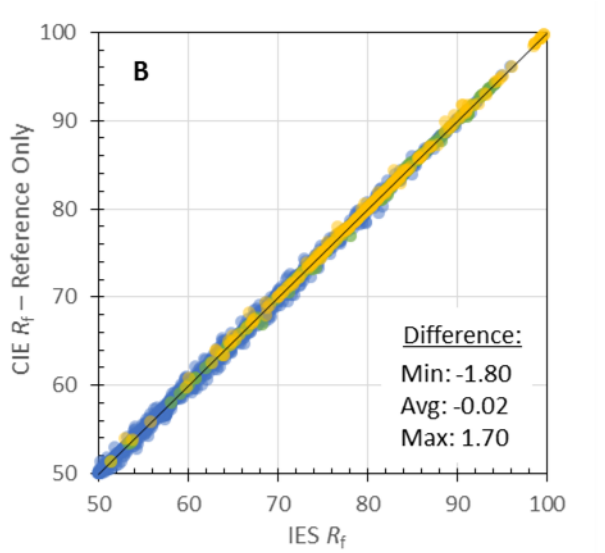
TM-30: What's the Status?

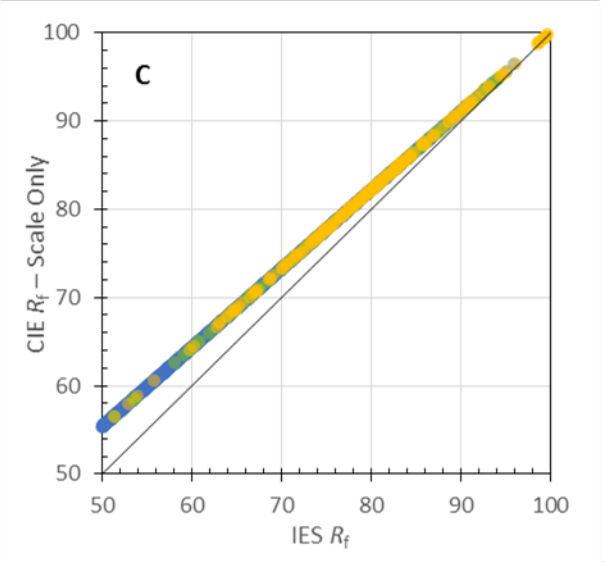
- **CIE TC1-90: Issued Report 224:2017, "*Colour Fidelity Index for accurate scientific use.*"**
  - Essentially adopts IES TM-30-15 R_f with minor tweaks
  - CIE still supports simultaneous use of R_a (CRI)
- **CIE TC1-91: Focus on issues other than color fidelity. No recent progress.**
  - May includes other IES TM-30-15 measures, among others, in report
- **CIE TC?: New TC expected to convene this year for continued investigation of color preference.**

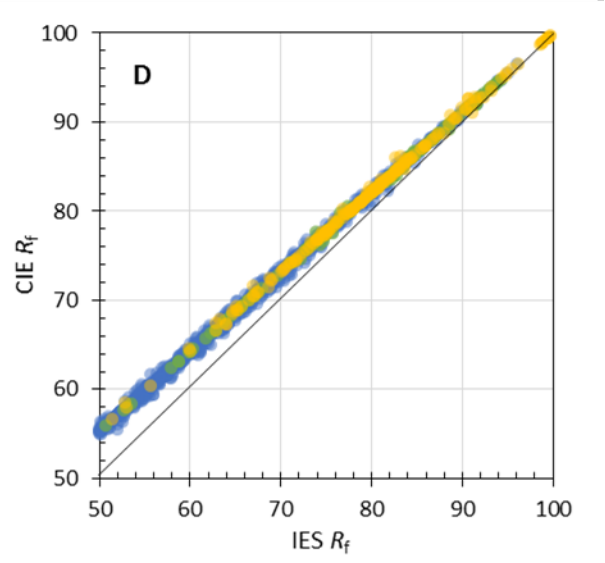
- **IES Color Committee considering changes to harmonize IES TM-30 with CIE R_f.**
- **IES Color Committee working on recommended practices, specification sheet guidance.**

Comparing Measures of Average Color Fidelity: IES R_f vs. CIE R_f vs. CIE R_a









A: Change extrapolation method for CES outside the range of 400 to 700 nm.

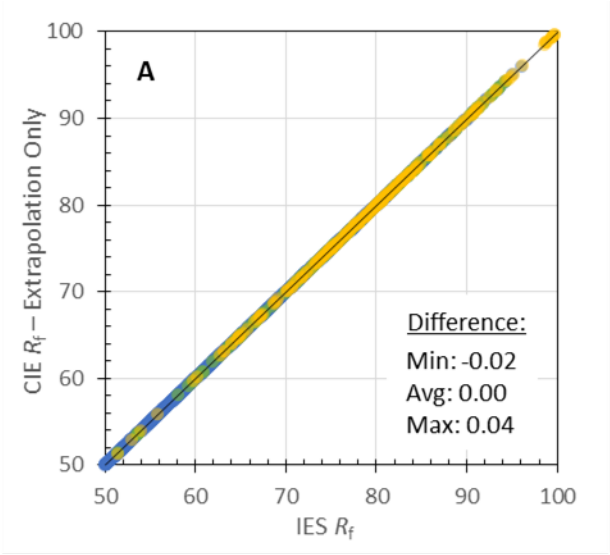
B: Change the reference blending region from 4500-5500 K to 4000-5000 K.

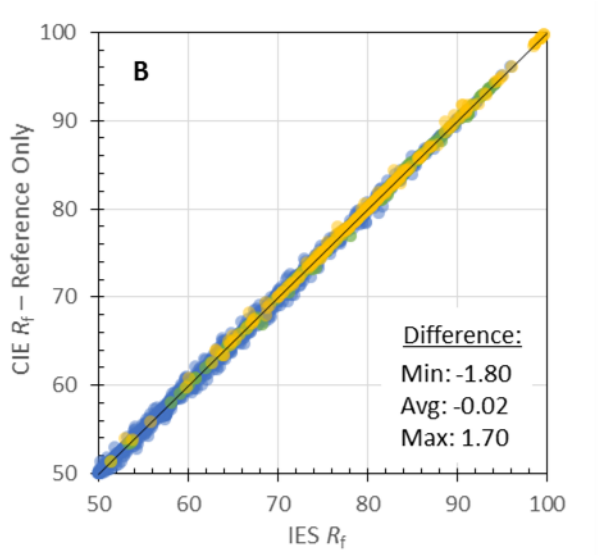
C: Change the scaling factor.

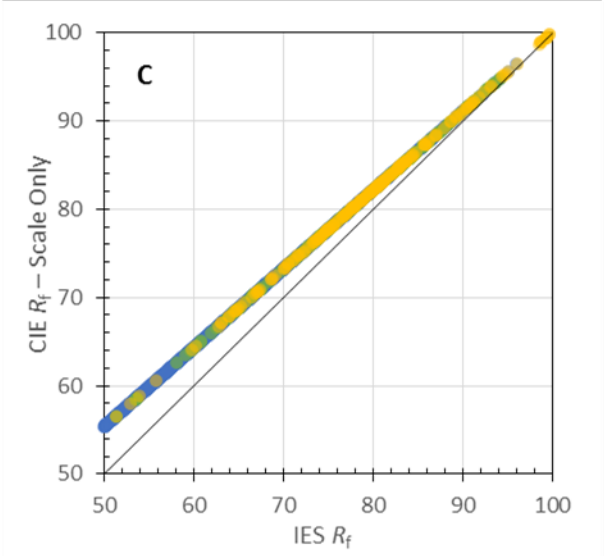
D: Composite effect of changes.

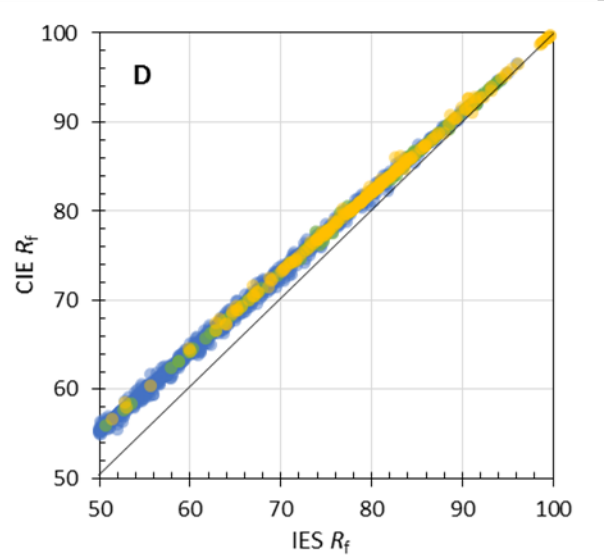
- Commercially Available (n = 211)
- Experimental (n = 152)
- Theoretical (n = 4,582)

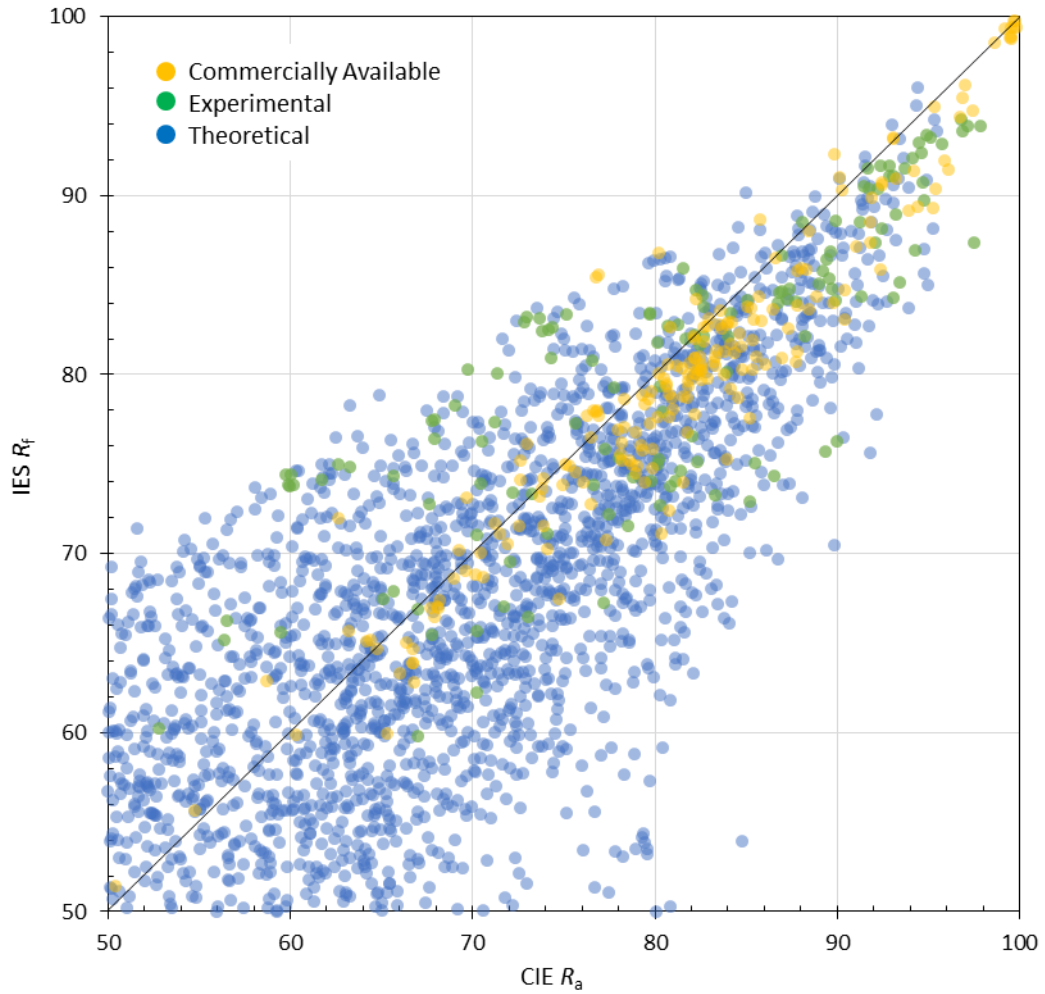
Comparing Measures of Average Color Fidelity: IES R_f vs. CIE R_f vs. CIE R_a





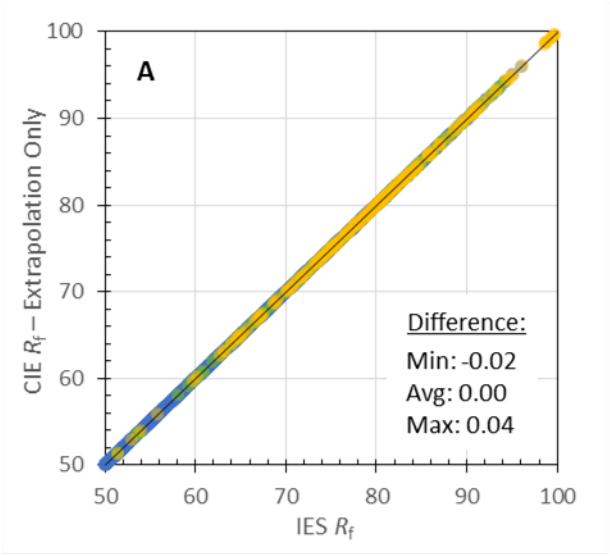


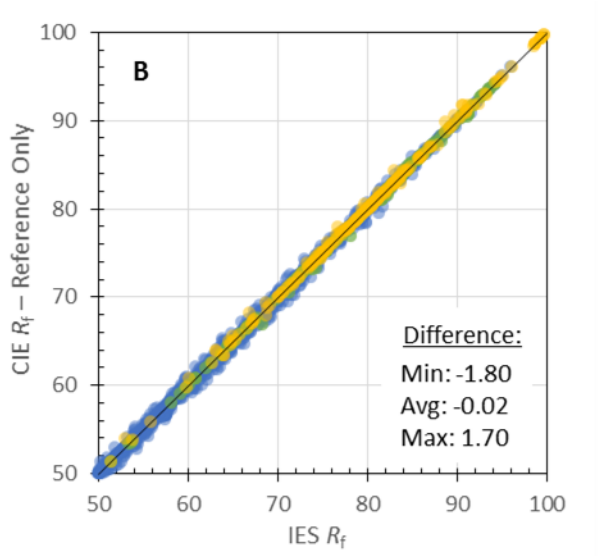


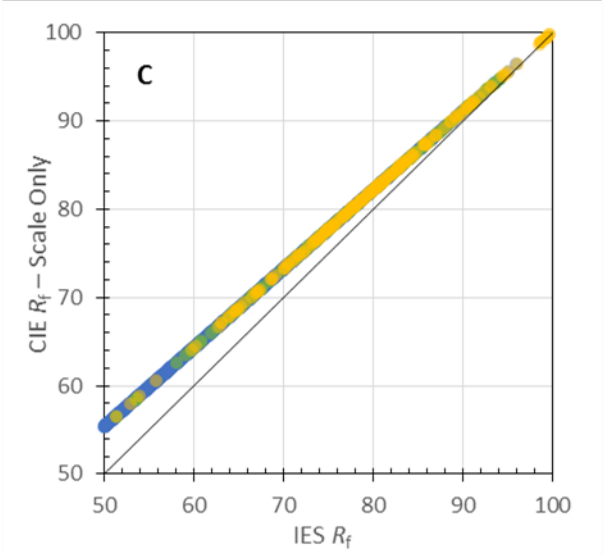


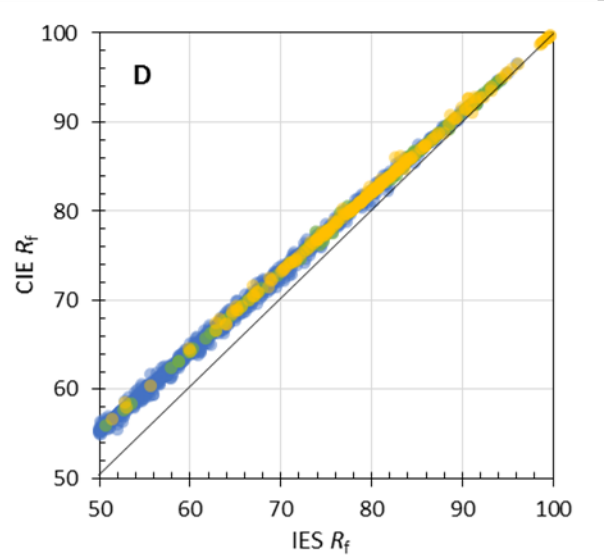
Royer M. 2017. Comparing Measures of Average Color Fidelity. Leukos. Submitted for publication.

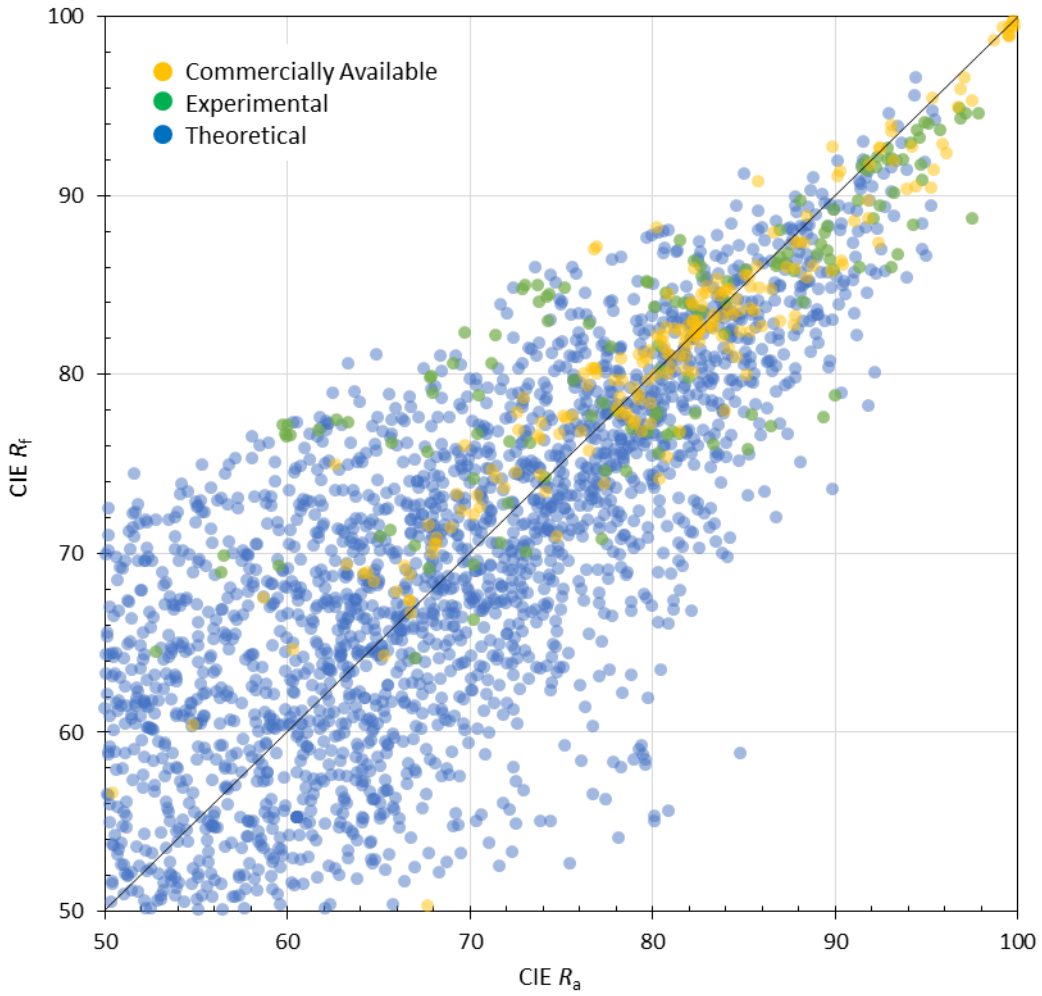
Comparing Measures of Average Color Fidelity: IES R_f vs. CIE R_f vs. CIE R_a







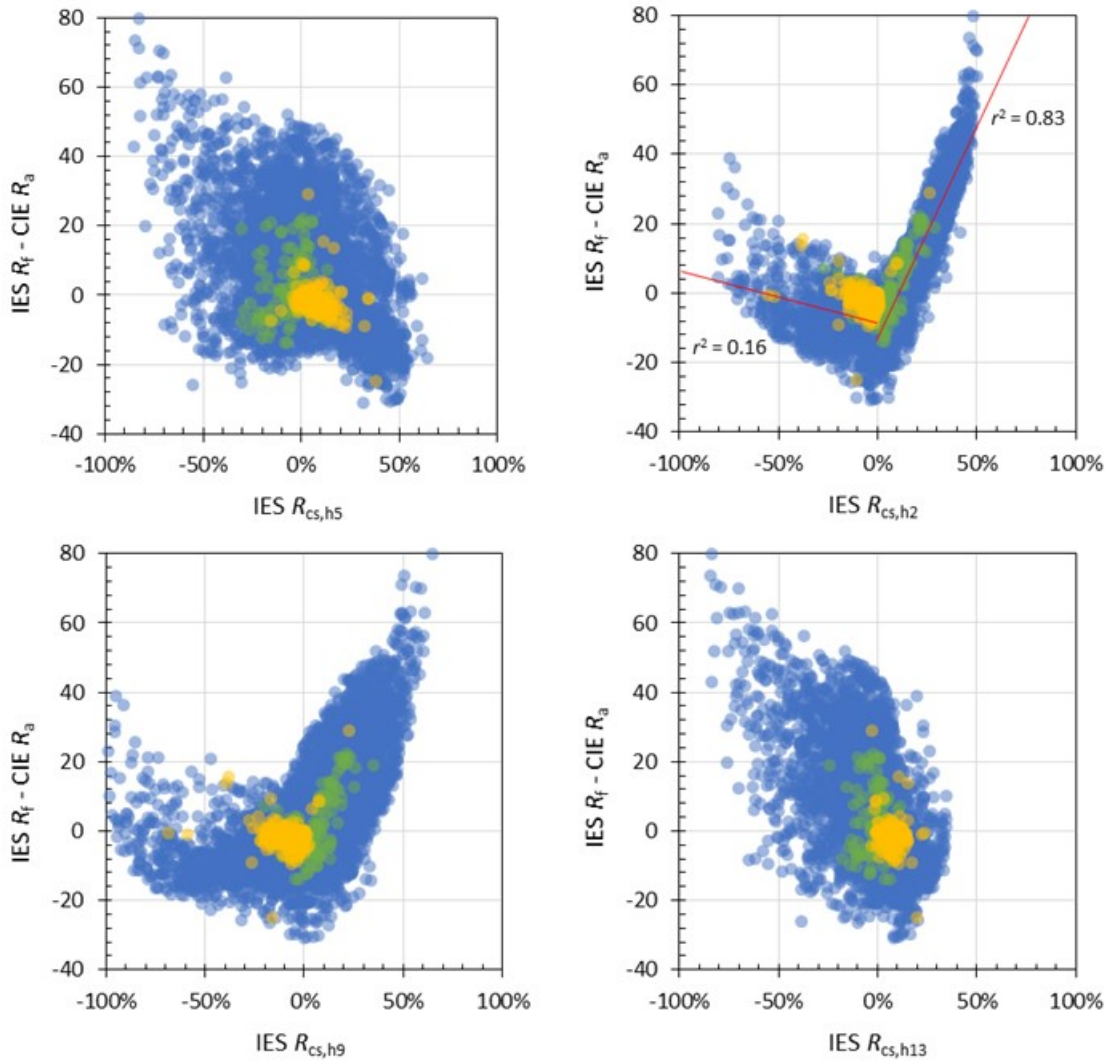




Royer M. 2017. Comparing Measures of Average Color Fidelity. Leukos. Submitted for publication.

Comparing Measures of Average Color Fidelity: IES R_f vs. CIE R_f vs. CIE R_a

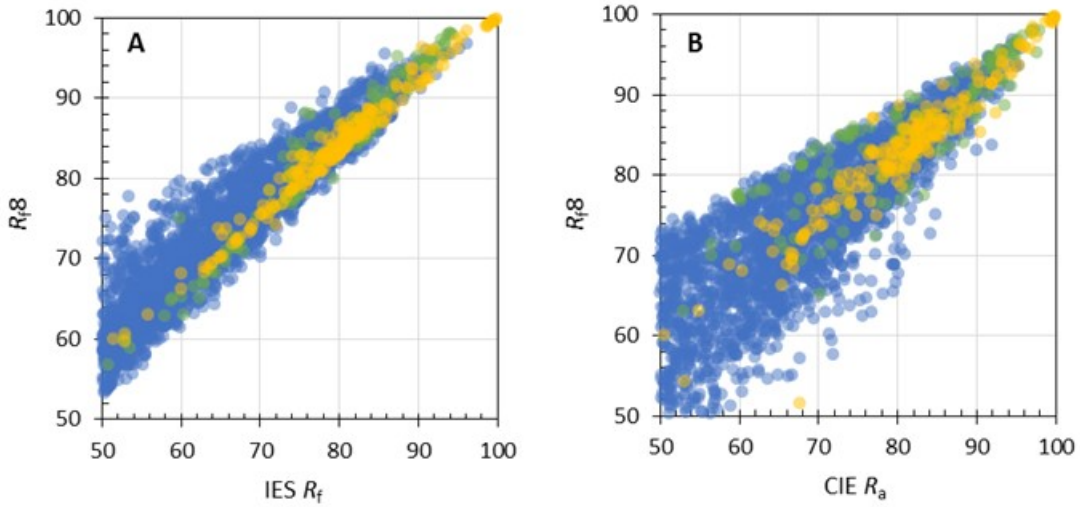
- Differences between IES (or CIE) R_f and CIE R_a are dependent on the type of shifts that occur.
- Increases in red chroma are penalized more strongly by CIE R_a.

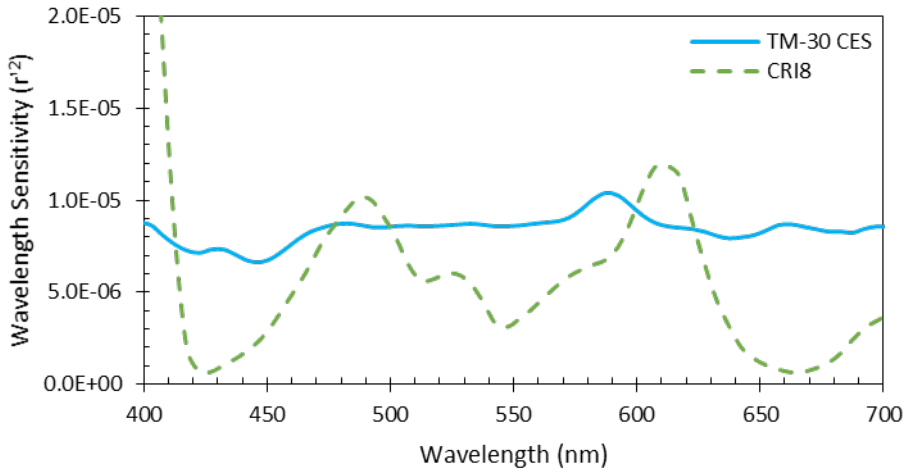


Royer M. 2017. Comparing Measures of Average Color Fidelity. Leukos. Submitted for publication.

Comparing Measures of Average Color Fidelity: IES R_f vs. CIE R_f vs. CIE R_a

- Differences between IES (or CIE) R_f and CIE R_a are dependent on the type of shifts that occur.
- Increases in red chroma are penalized more strongly by CIE R_a.
- Differences are due to
  A. Different sample sets (can't score better on 99 than on 8)
  B. Non-uniformity of the CIE 1964 U*V*W* color space (think R_9 scale issues). Differences based on gamut shape.
- **Differences mean CIE R_a discourages development of sources that are perceived as more natural and preferred (especially if used alone).**





Should the Lighting Industry Make the Effort?

- CRI: the anti-preference/naturalness measure
- Using average fidelity alone is…mostly useless. It is unrelated to any perceptual attribute.
- More research is available today to support specifications based on IES TM-30-15 than there ever was to support CRI ≥ 80 (or 90)
- It's not more complicated: IES TM-30-15 can be boiled down to 2 (or 3) numbers for an effective specification
- We can have preferred AND efficient lighting if fidelity is not the only consideration
- International agreement?
- Reporting IES TM-30-15 requires no additional testing or measurements
- The science is there…ultimately, color quality is a choice of specifiers, manufacturers, EE programs, consumers, etc.

More Information

https://energy.gov/eere/ssl/color-rendition