U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Human Perceptions of Color Rendition
Experiments, Analysis, and Steps Forward

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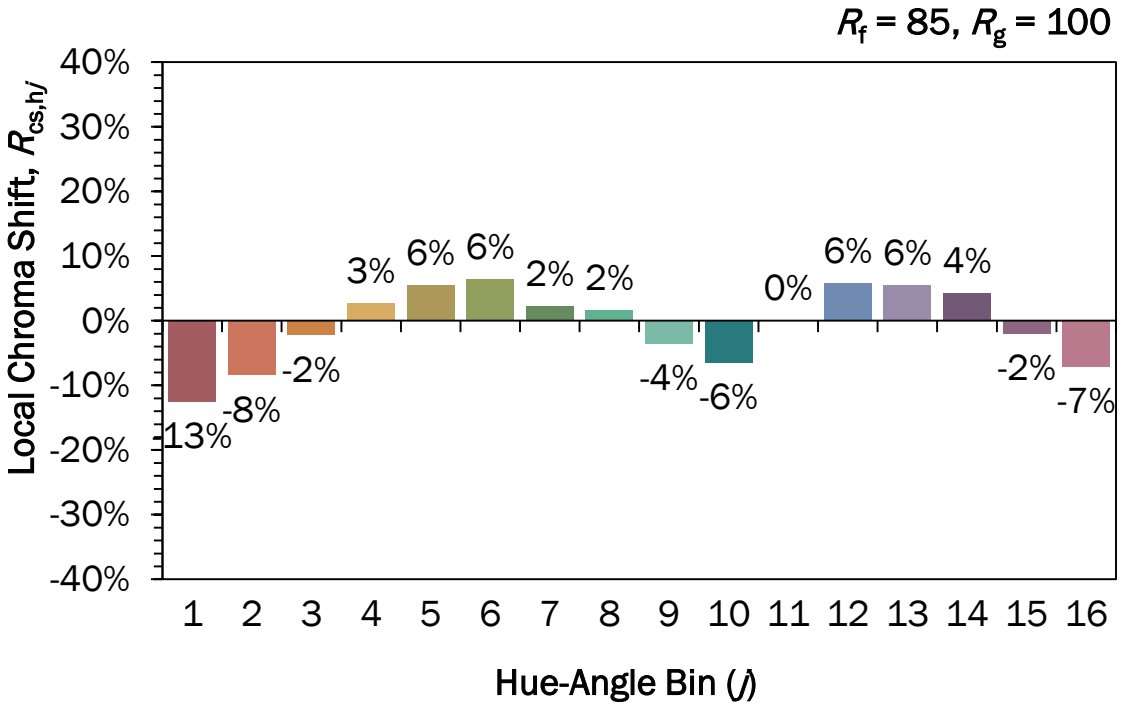
https://energy.gov/eere/ssl/color-rendition

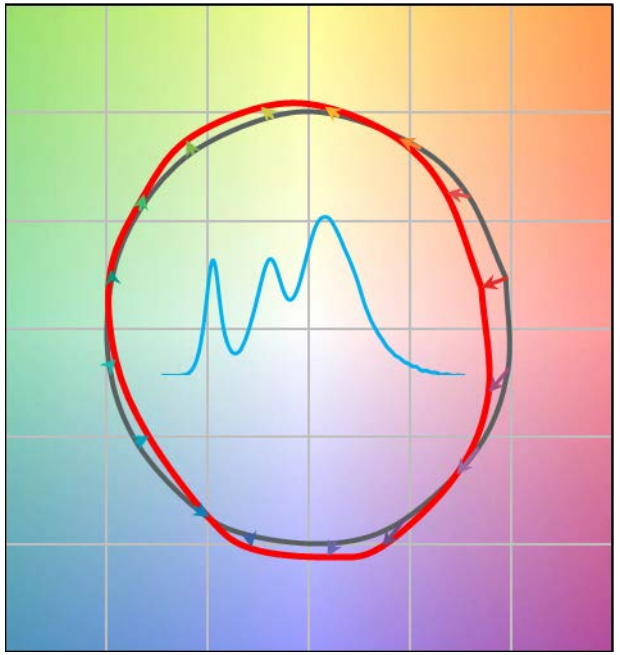
8 November 2017

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
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_i}), which characterize changes in chroma for the CES within each of 16 hue-angle ranges
   - 16 Local Hue Shift values (R_{hs,h_i}), which characterize changes in hue for the CES within each of 16 hue-angle ranges
   - 16 Local Color Fidelity values (R_{f,h_i}), 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
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.).

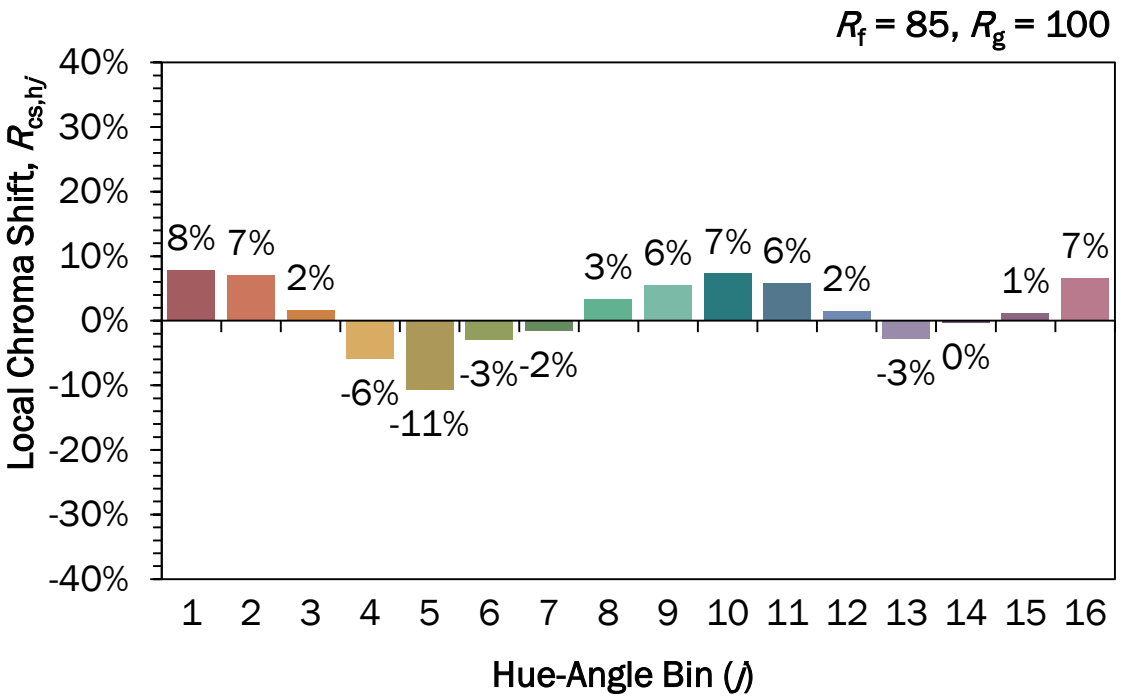
Gamut Shape Importance

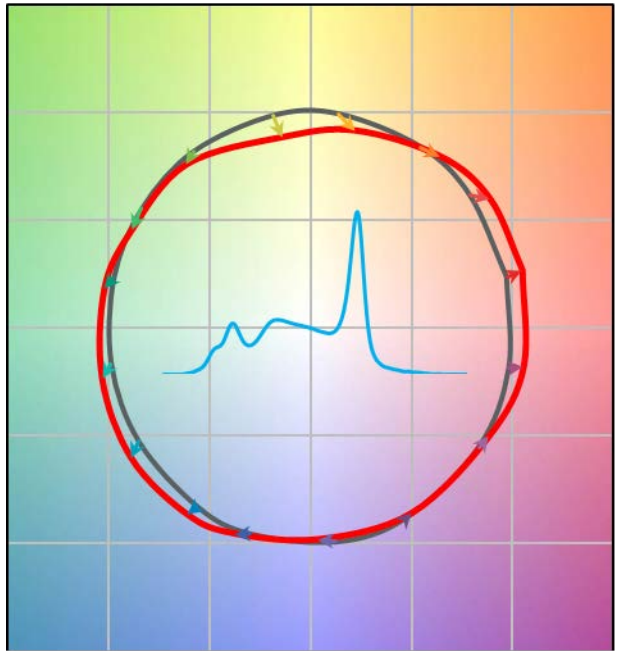




Royer M, Houser K, David A. 2017. Chroma Shift and Gamut Shape: Going Beyond Average Color Fidelity and Gamut Area. Leukos. Accepted .

Gamut Shape Importance





Royer M, Houser K, David A. 2017. Chroma Shift and Gamut Shape: Going Beyond Average Color Fidelity and Gamut Area. Leukos. Accepted .

Understanding Objective Measures of Color Rendition

- **Methods:**
  1. Experimental
     - Pros: Direct response from users; can vary light source properties in many ways
     - Cons: Does apparatus reflect real-world applications?
  2. Experience
     - Pros: Real-world applications
     - Cons: Takes a long time to build; chicken and the egg; limited light sources
  3. Benchmarking
     - Pros: Fast; cheap; relatively straightforward
     - Cons: Dependent on existing sources/those used for benchmarking; any limitations may be carried forward
- **Criteria:**
  - Minimum acceptability versus top performers

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

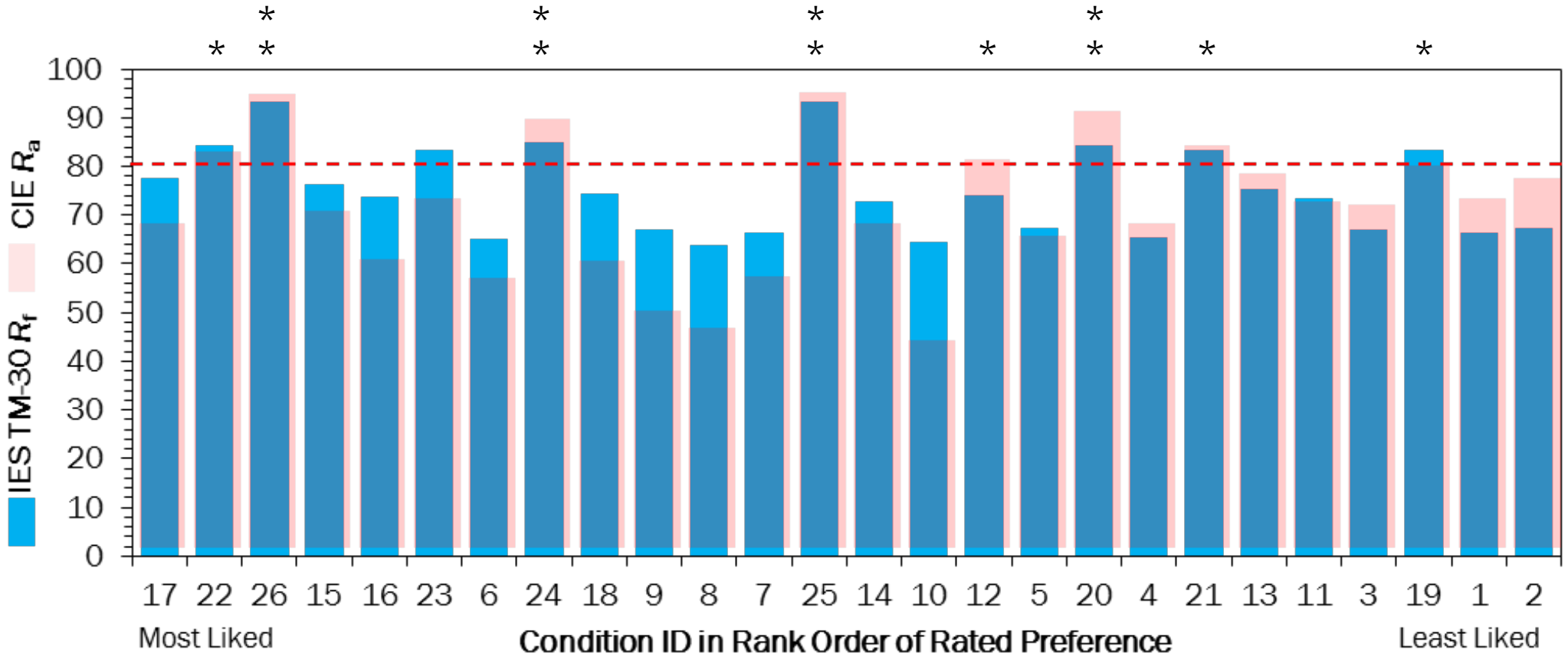
16 AGE 19-61

12 AGE 30-65

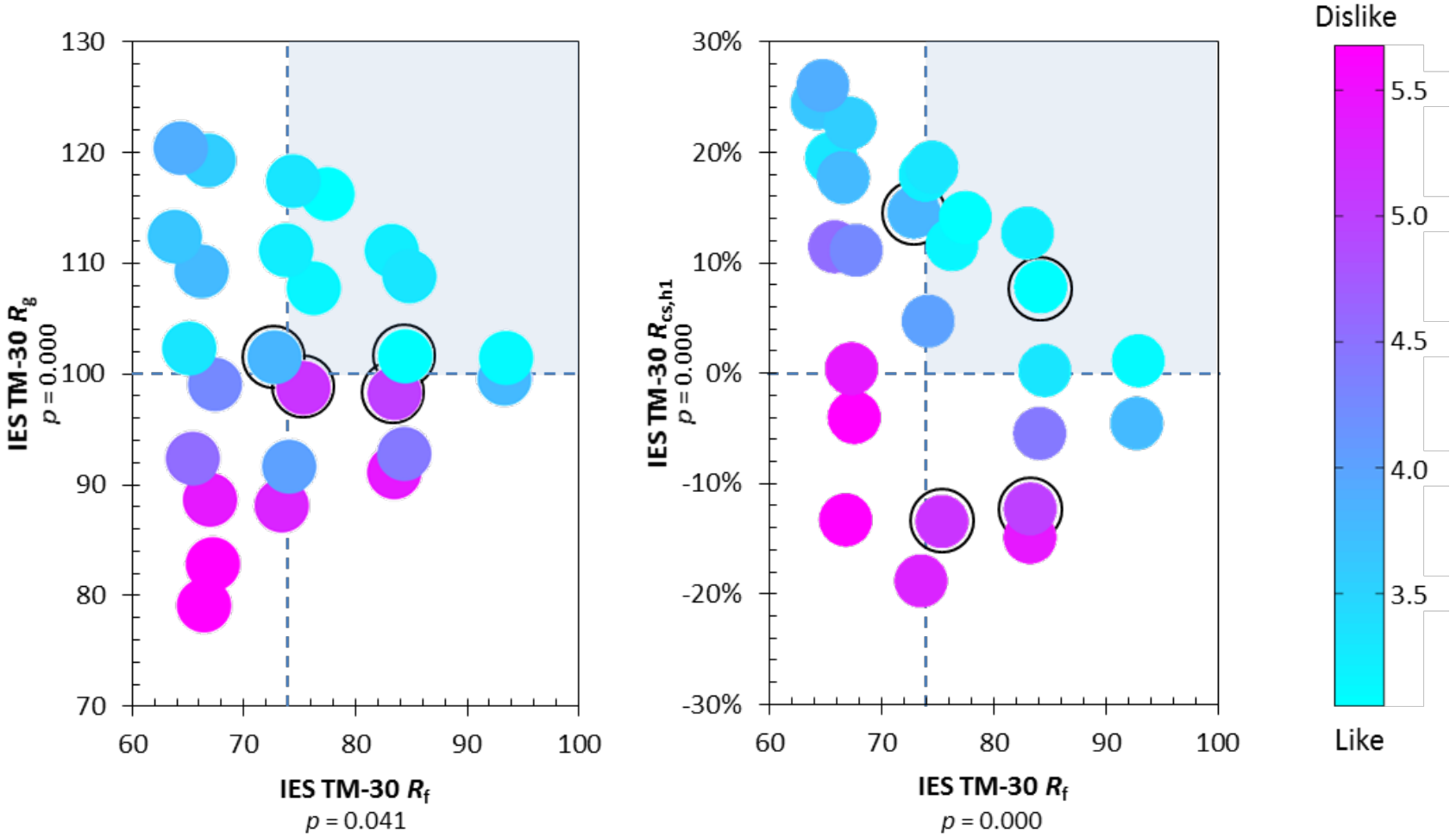
30 SECONDS
Minimum View Time Per Scene

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.

Existing Specs – CRI ≥ 80 (*), CRI ≥ 90 (**)



Color Rendition Preferences



Specification Criteria?

Normalness = Red Chroma + Average Color Fidelity

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

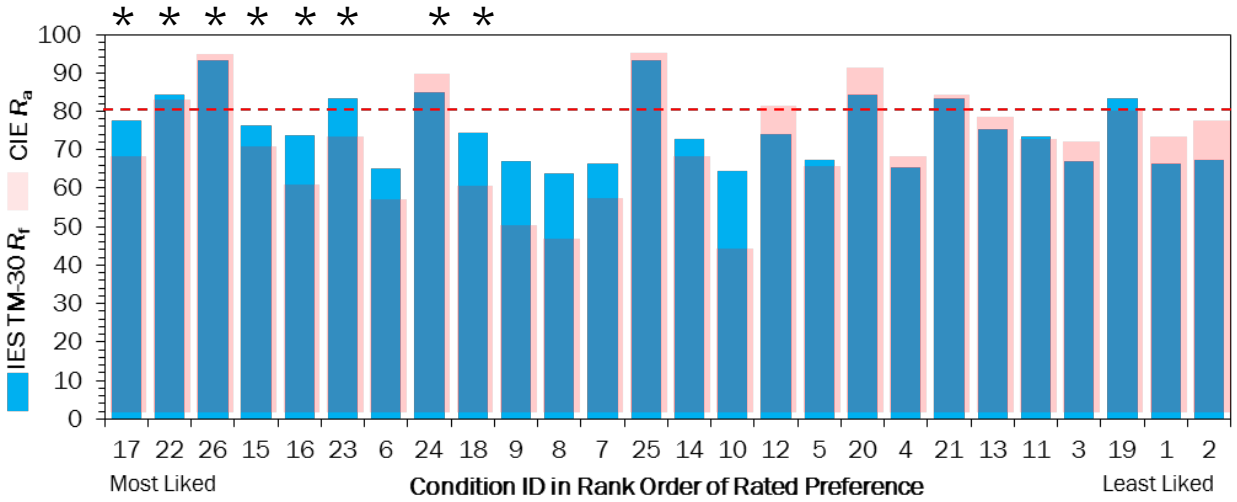
Saturation = Red Chroma

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

Preference = Red Chroma + Average Color Fidelity

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

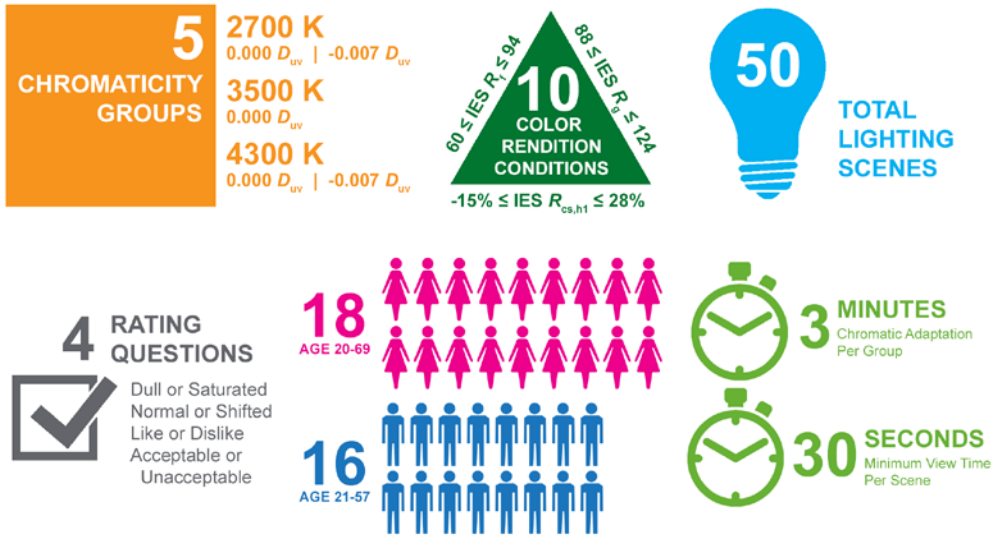
or $0\% \le R_{cs,h1} \le 15\%$



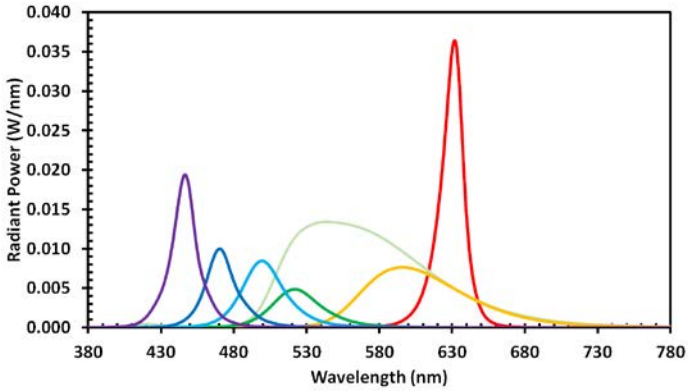
(Values based on IES TM-30-15)

What about other Chromaticities?

CREX2 PARAMETERS [2016]

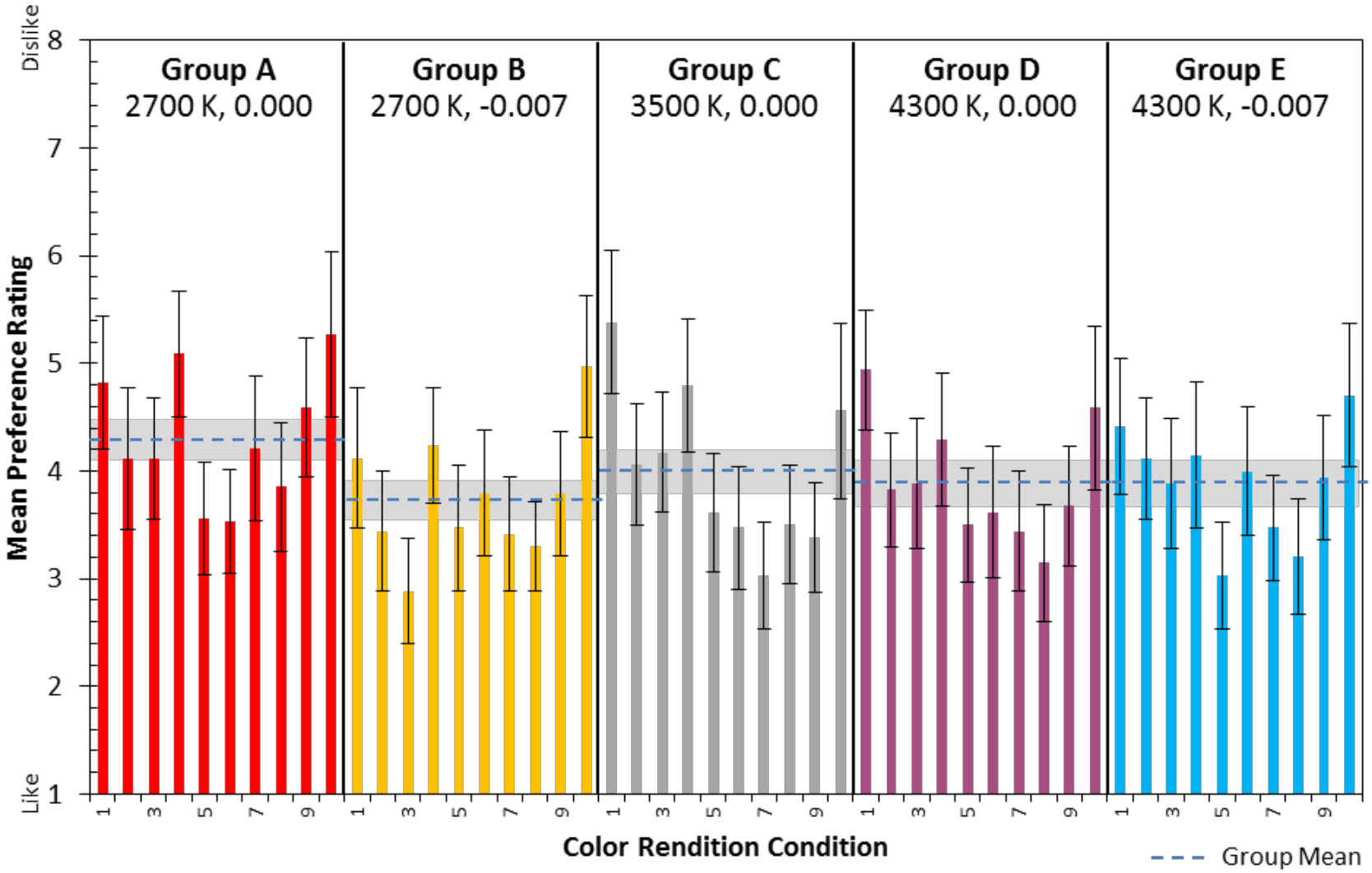


ETC Source 4 Series 2 Lustr



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.

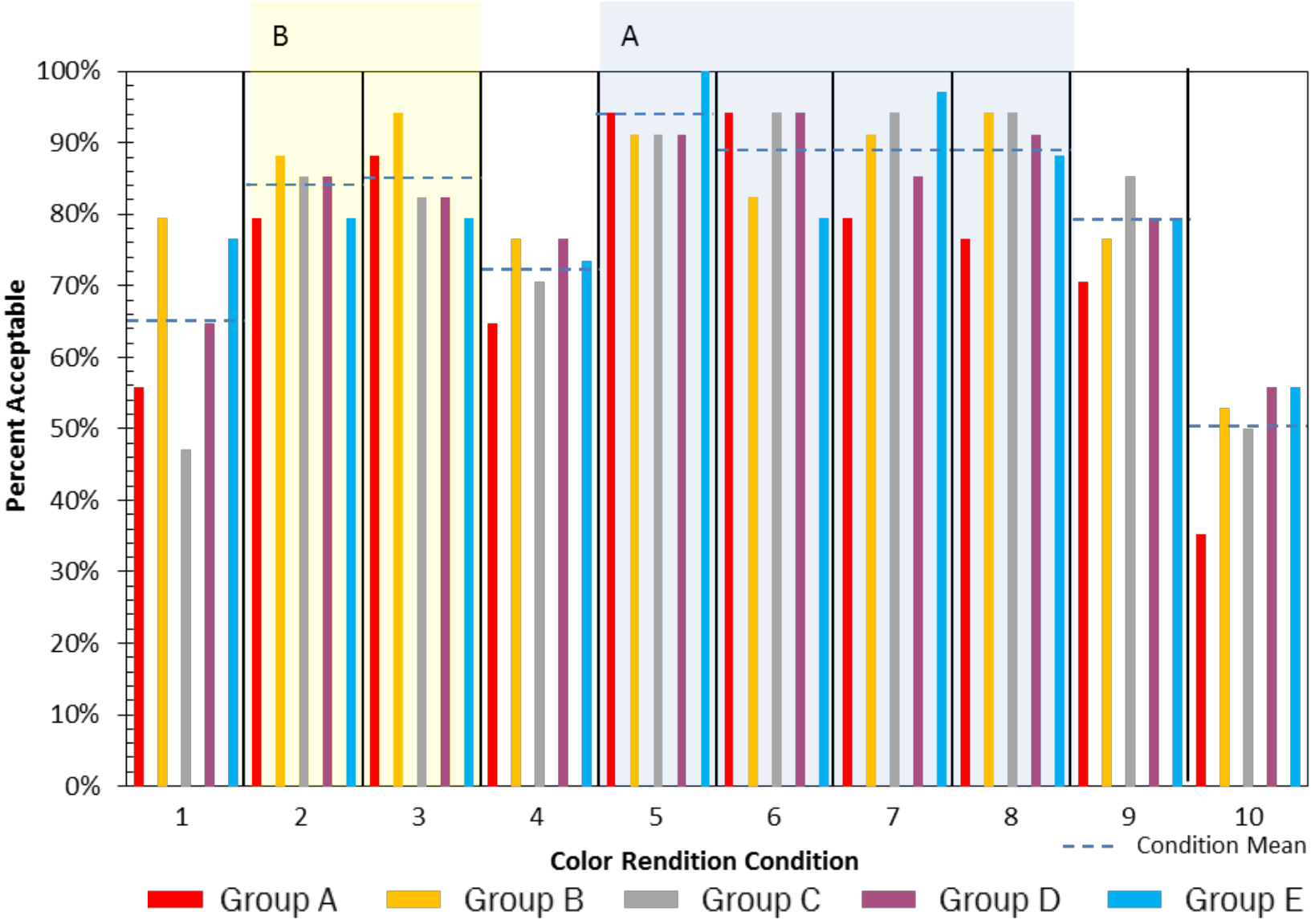
Effect of Chromaticity and Color Rendition



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

Color rendition had a larger effect than chromaticity.

Specification Criteria?



Composite Specification Criteria:

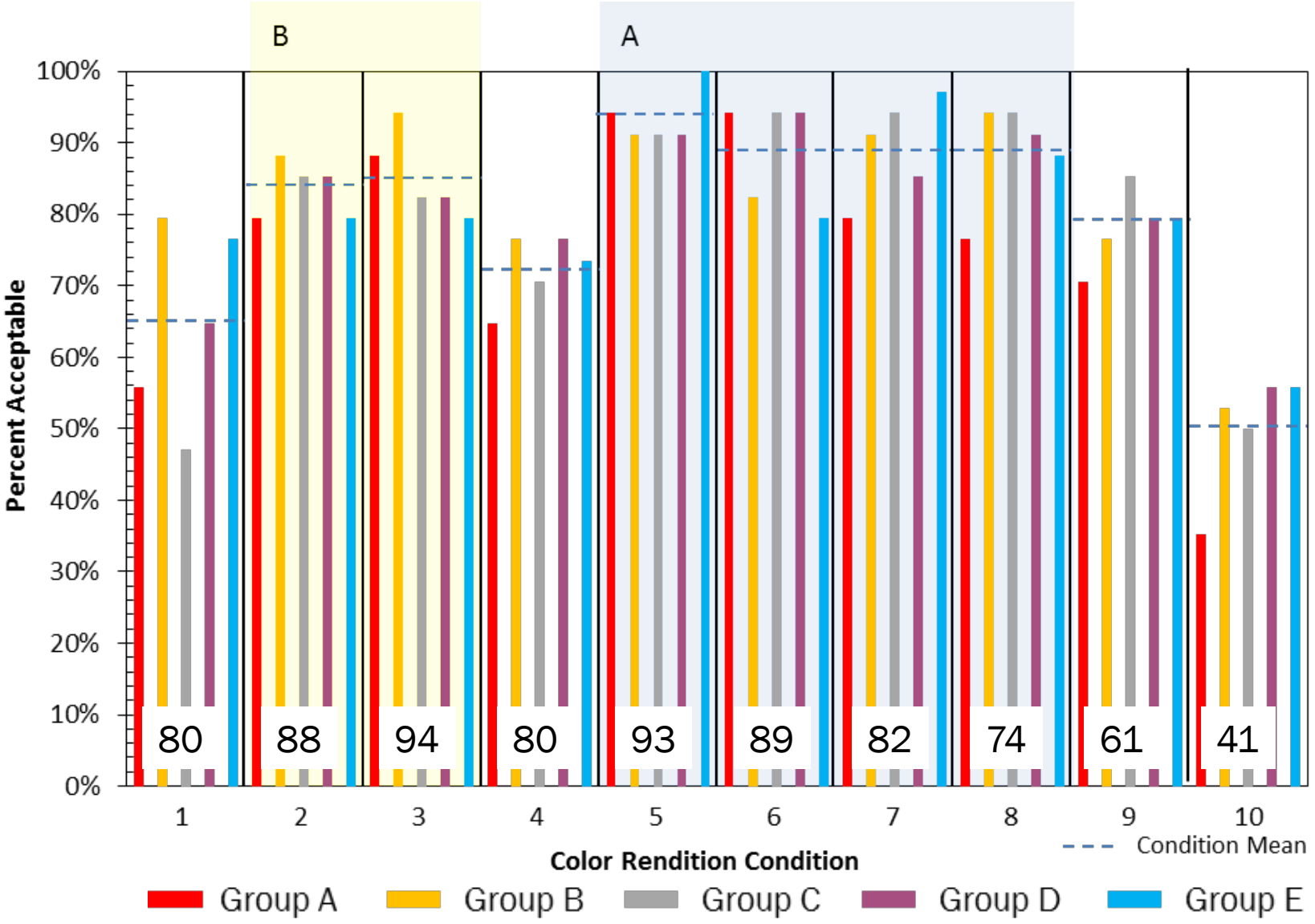
A: (> 89% acceptable)
IES $R_f \geq 75$
IES $R_g \geq 100$
$-1\% \leq$ IES $R_{cs,h1} \leq 15\%$

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

(Values based on IES TM-30-15)

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.

Specification Criteria?



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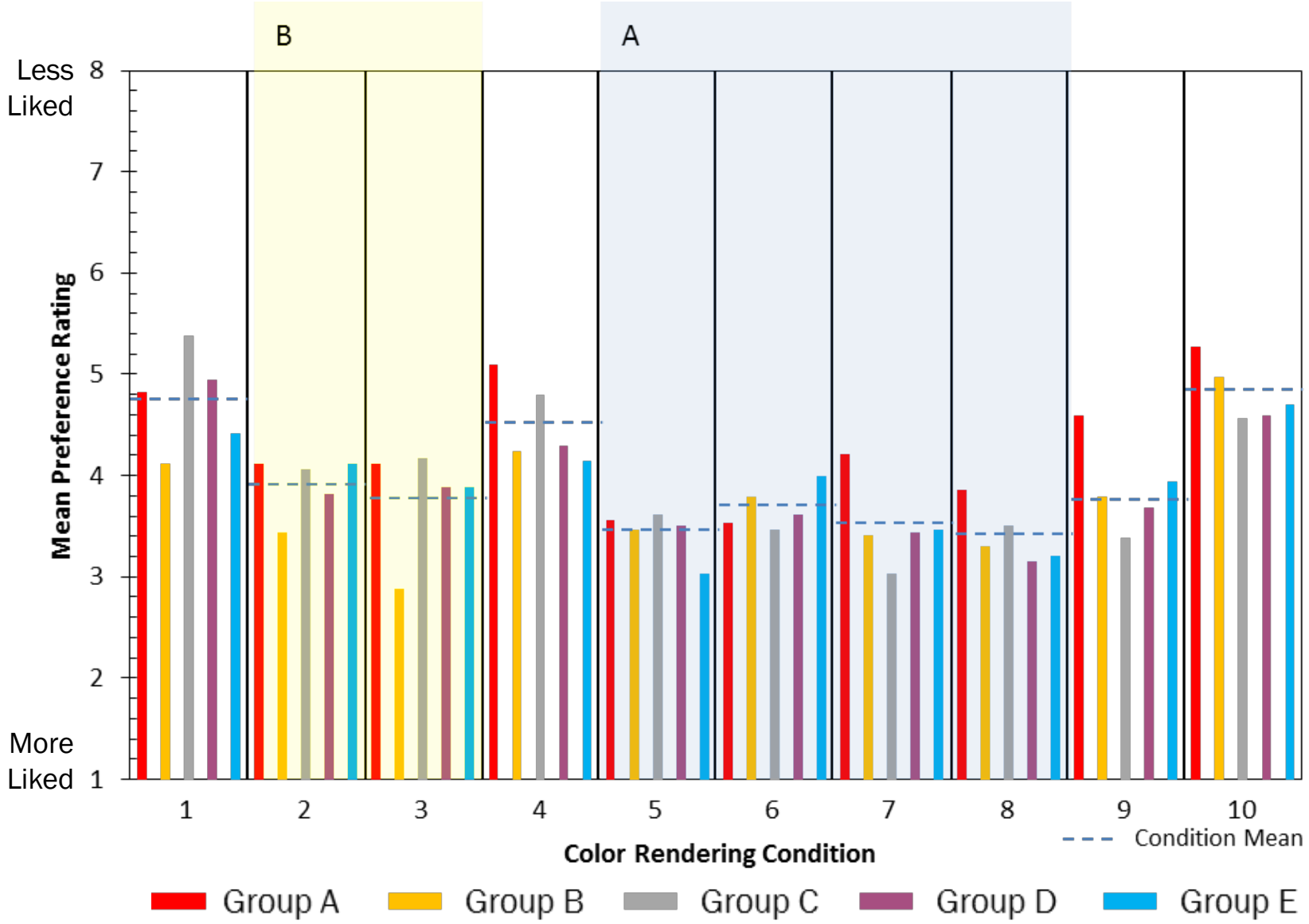
[CRI]

(Values based on IES TM-30-15)

Specification Criteria



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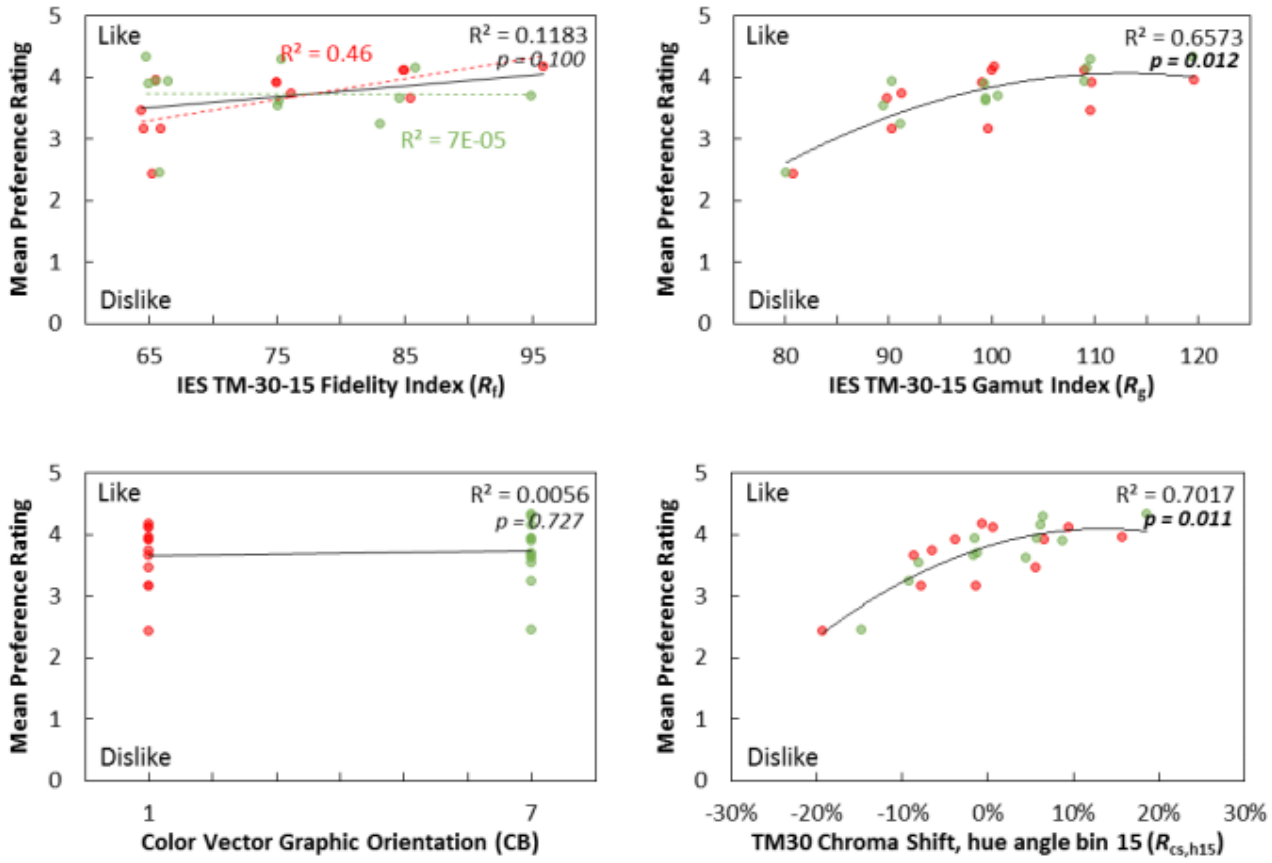
(Values based on IES TM-30-15)

Penn State University

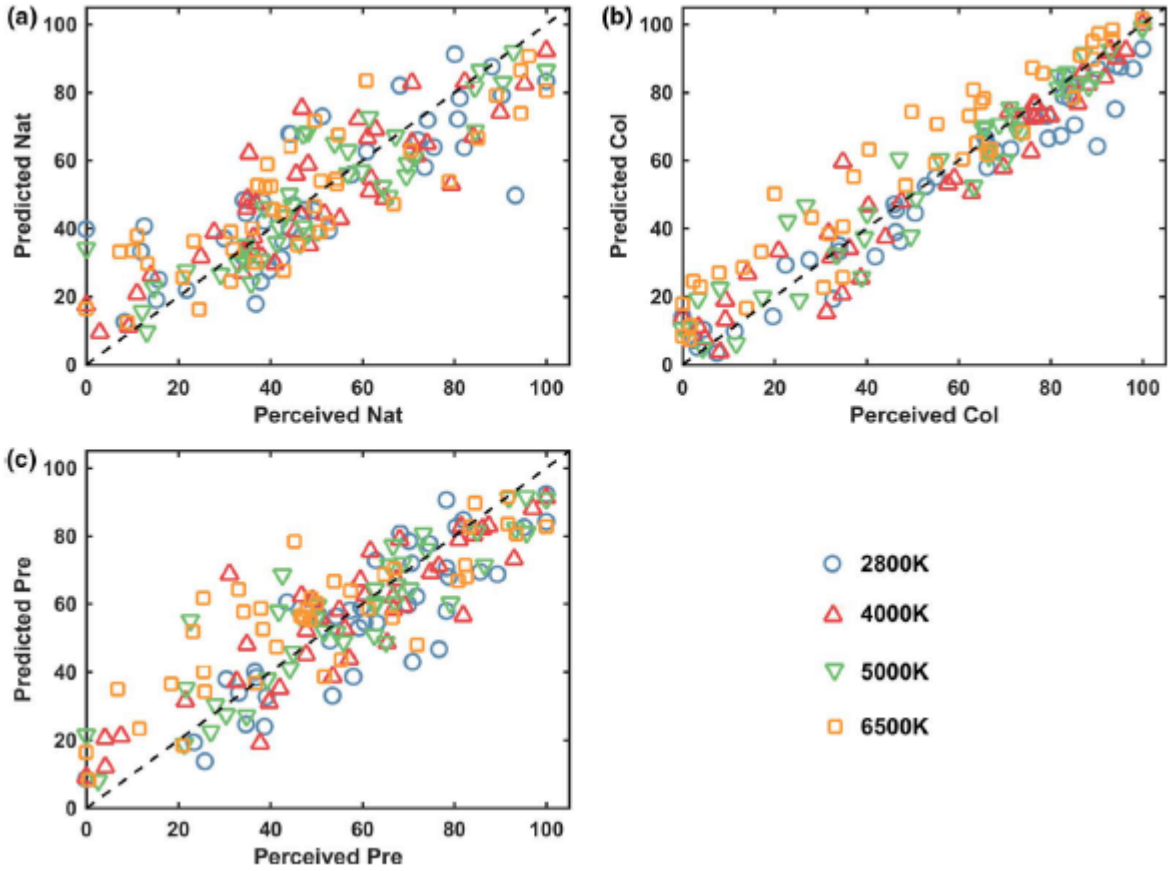


$$\text{LIKE} = 1.629 + 0.02686\ R_f + 3.423\ R_{cs,h16} - 10.01\ R_{cs,h16}^2 - 0.04866\ \psi + 0.000566\ R_f{*}\psi$$

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

Zhejiang University

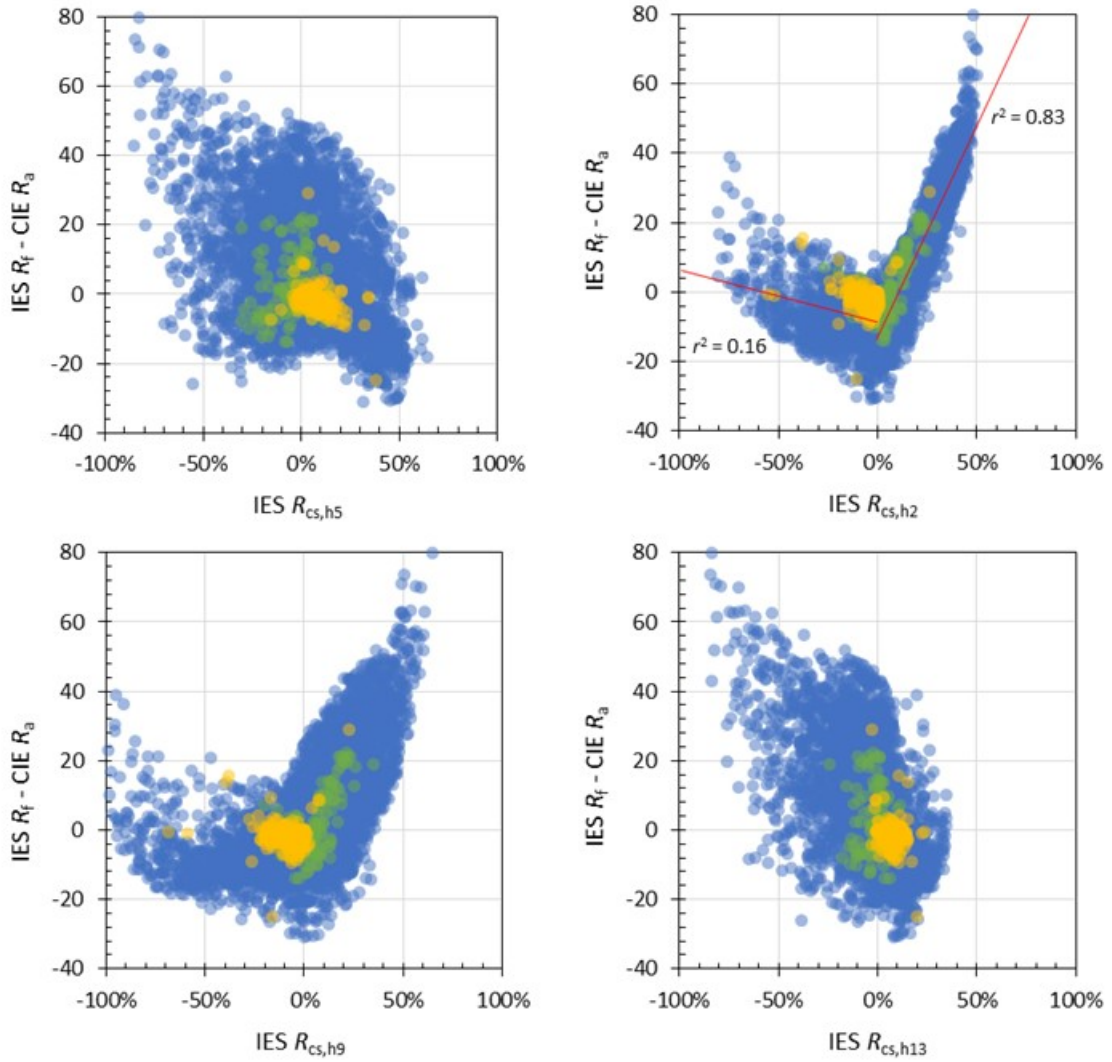
$$Q_{i,0} = C_0 + C_f R_f + C_g R_g + C_s R_{cs,b1} + C_{gs} R_g R_{cs,b1},$$



Zhang F, Xu H and Feng H. Toward a unified model for predicting color quality of light sources. *Applied Optics*. 2017; 56: 8186-95.

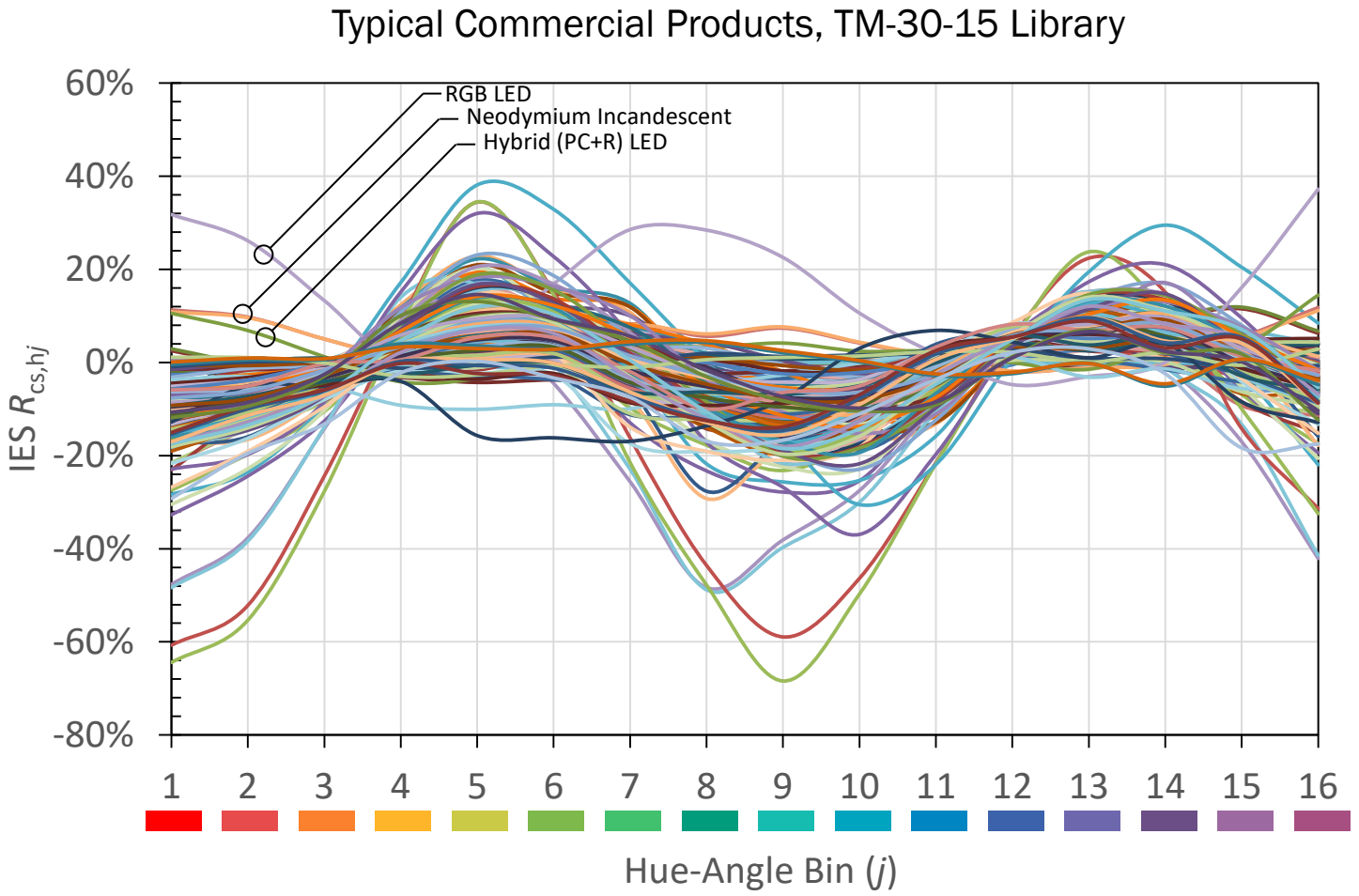
Influence of Measures on Product Development?

- 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, MP. 2017. Comparing Measures of Average Color Fidelity. Leukos. Accepted for Publication.

Typical Products



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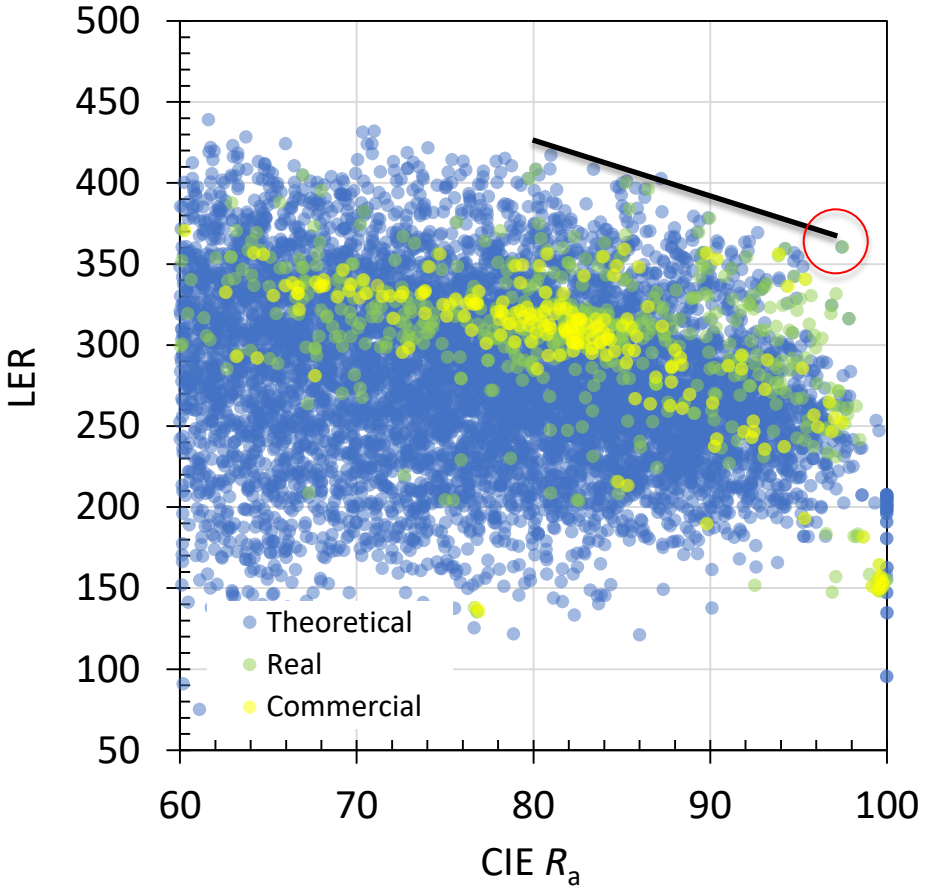
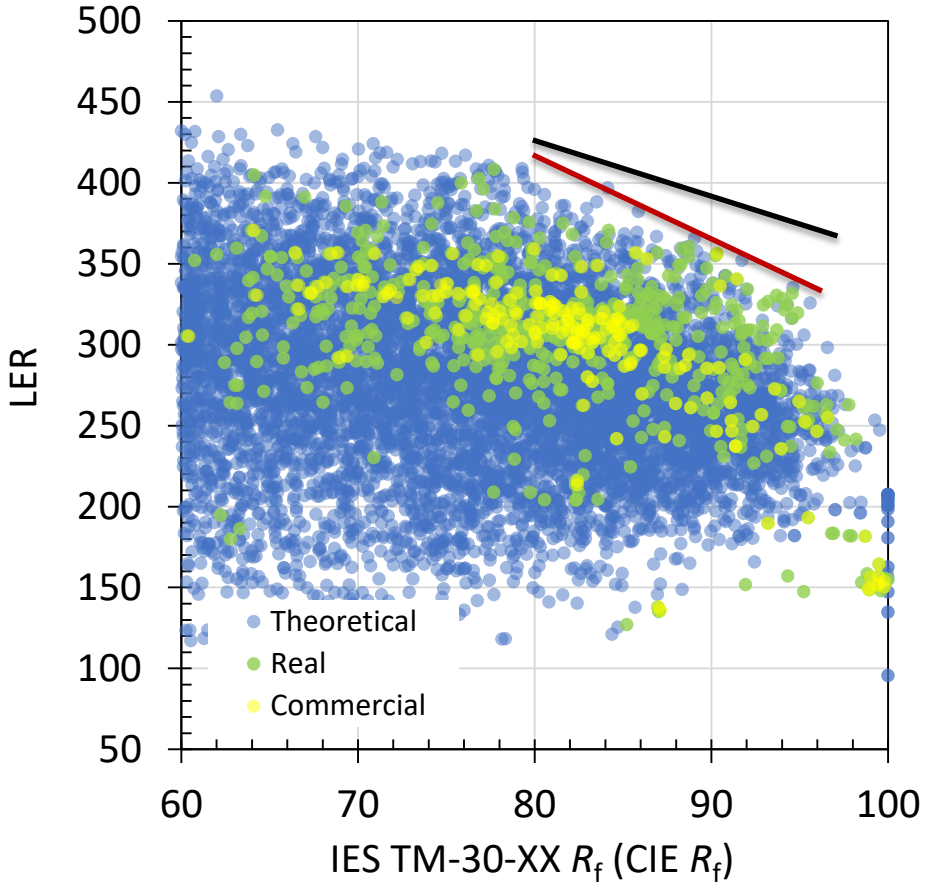
Influence of Measures on Energy Efficiency





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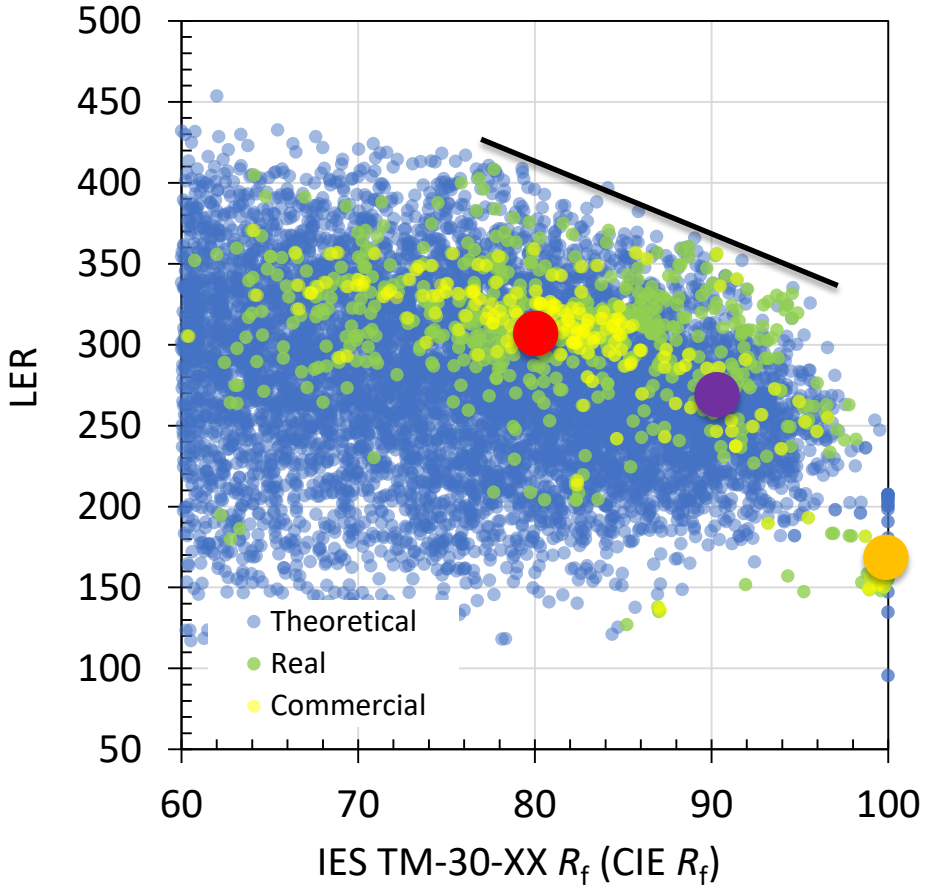
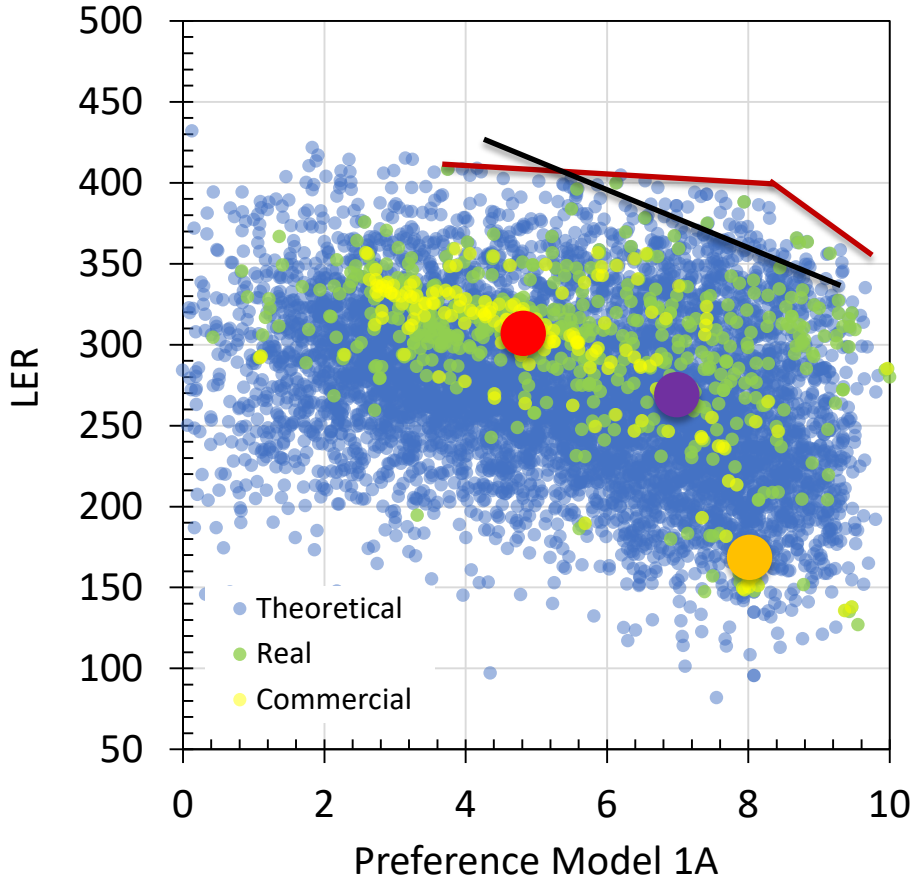
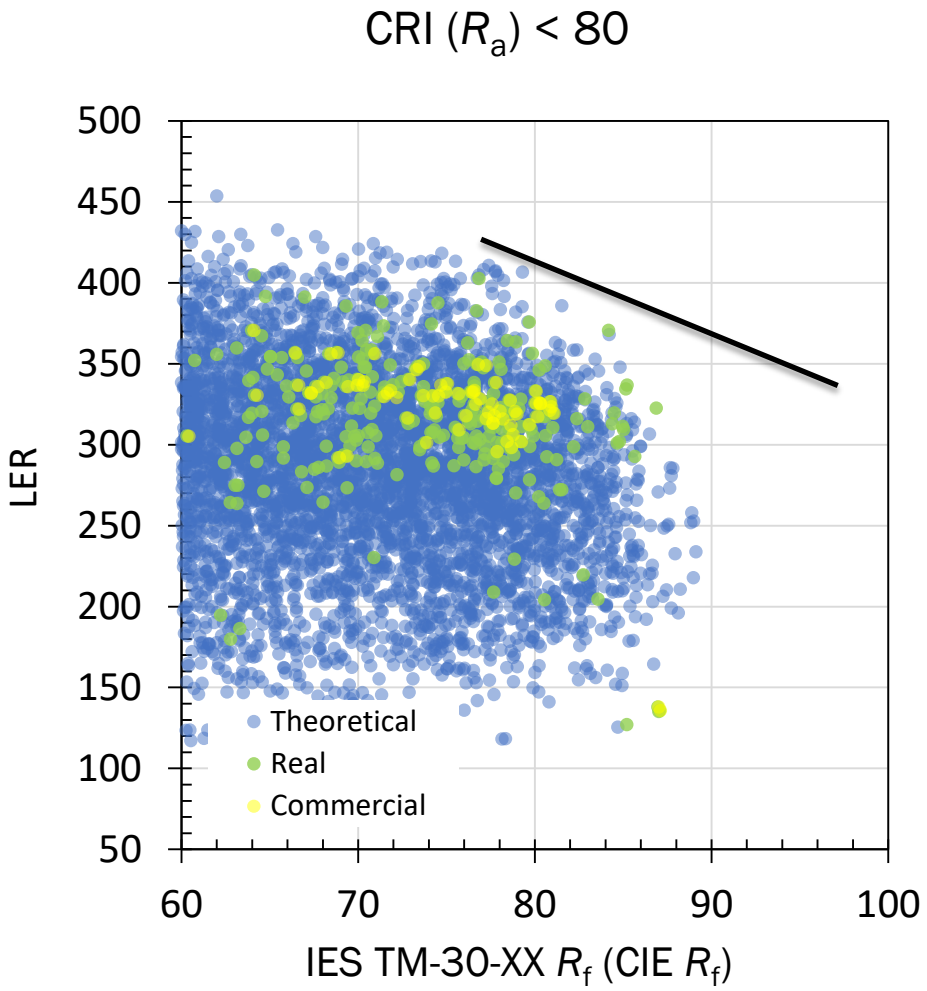
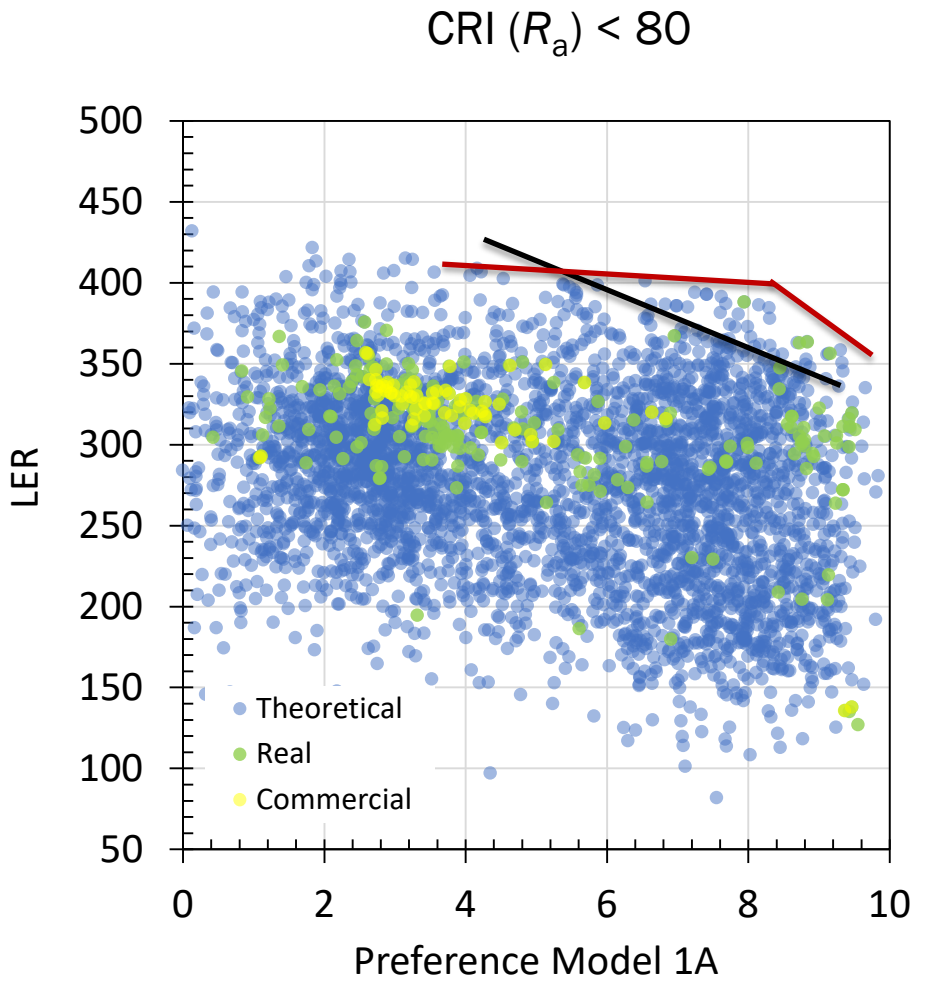




PC-LED ($80 \leq R_a \leq 83$) PC-LED ($90 \leq R_a$) Planckian/D Series

Influence of Measures on Energy Efficiency





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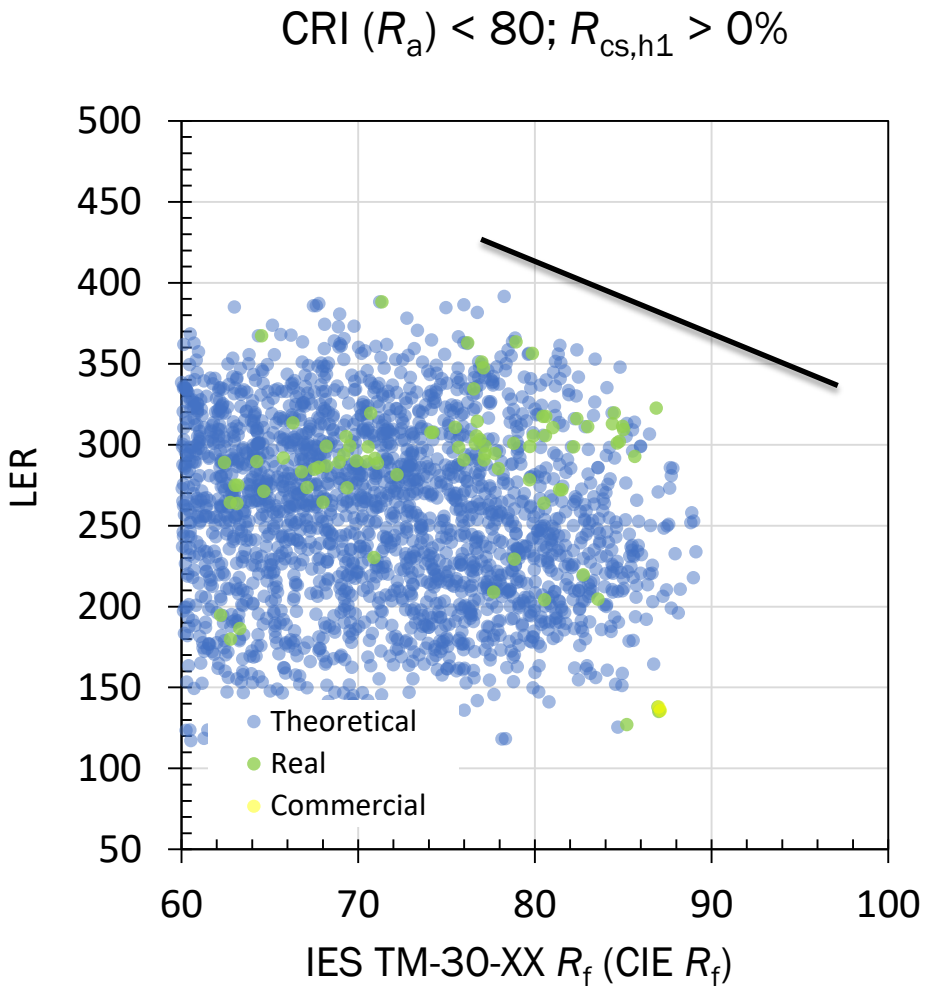

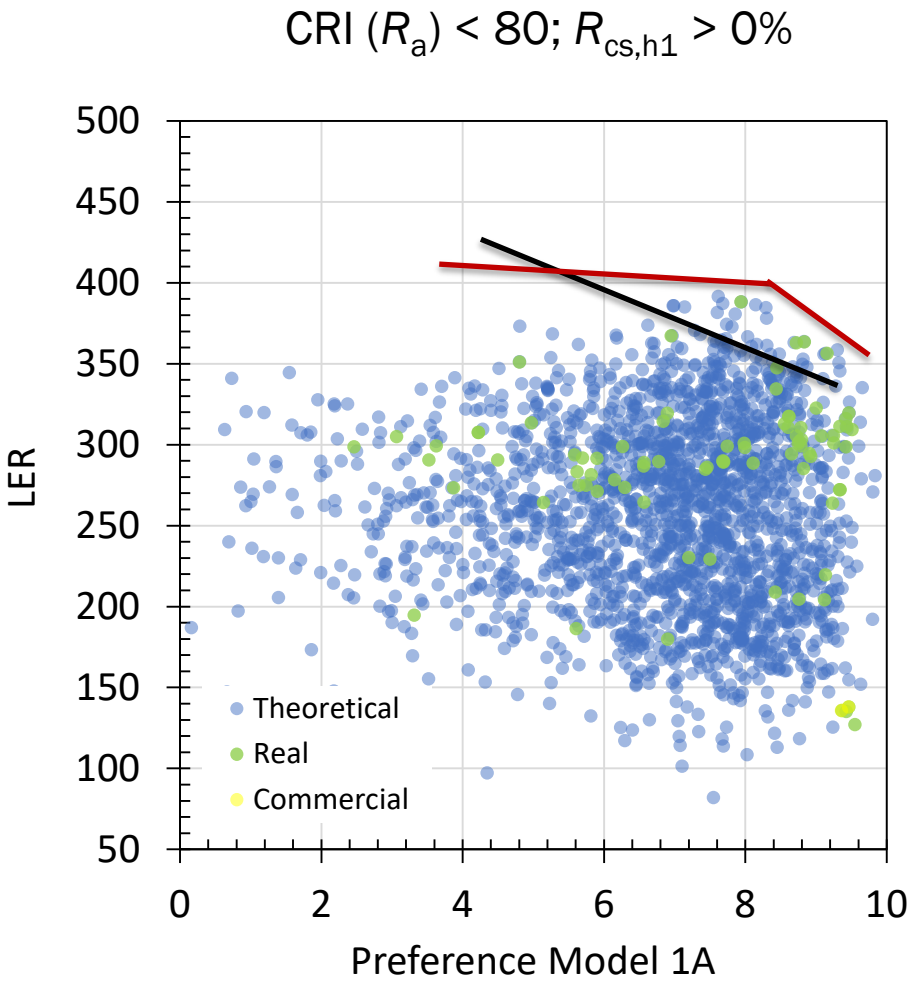

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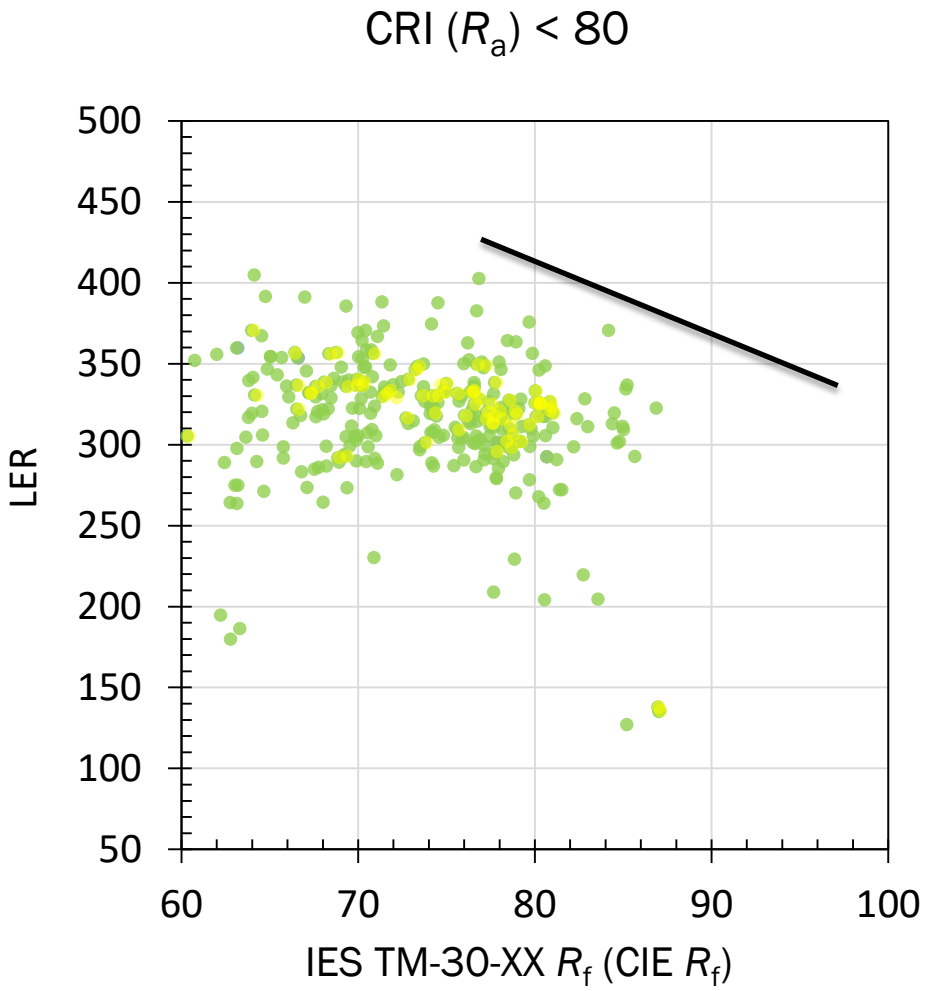

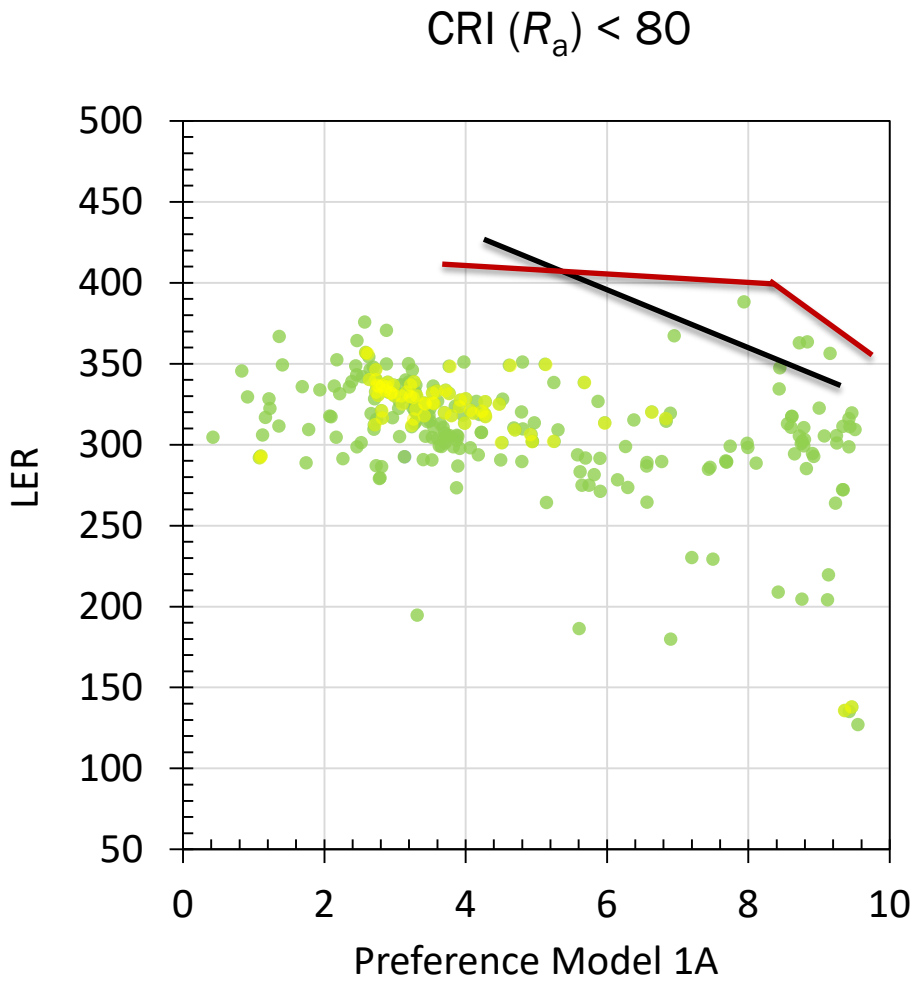

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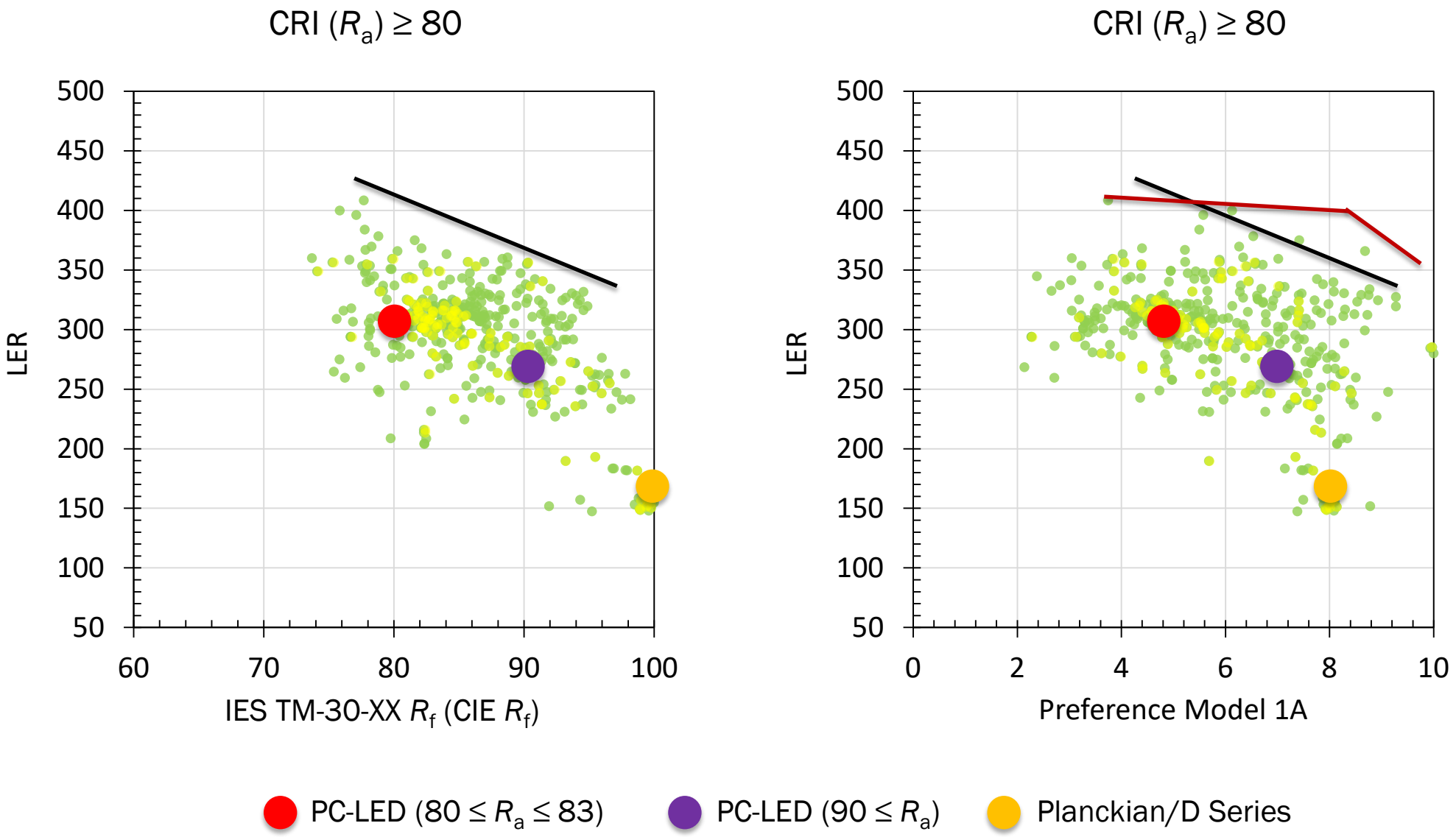
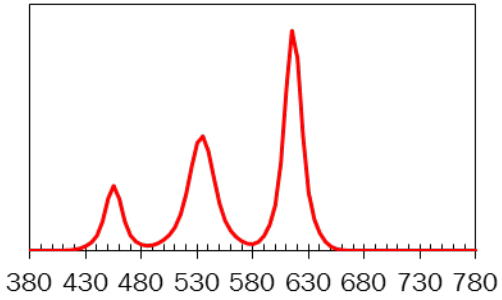
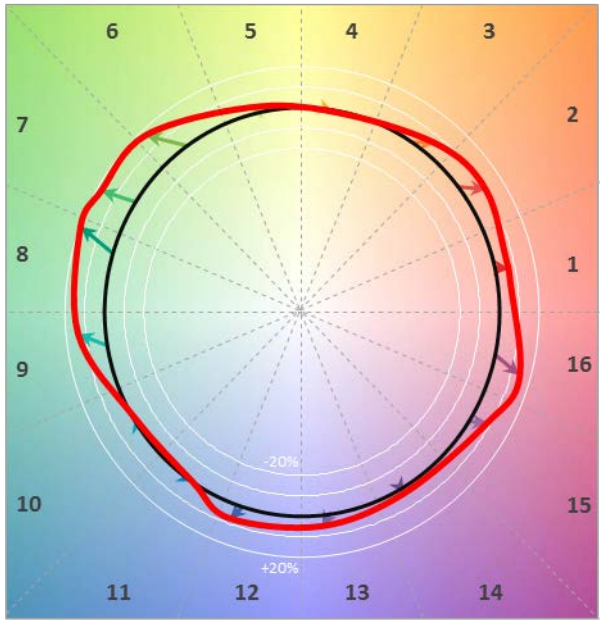


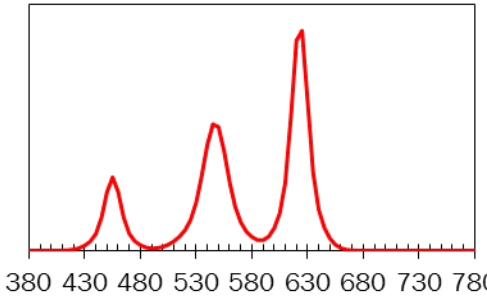
High Quality, High LER

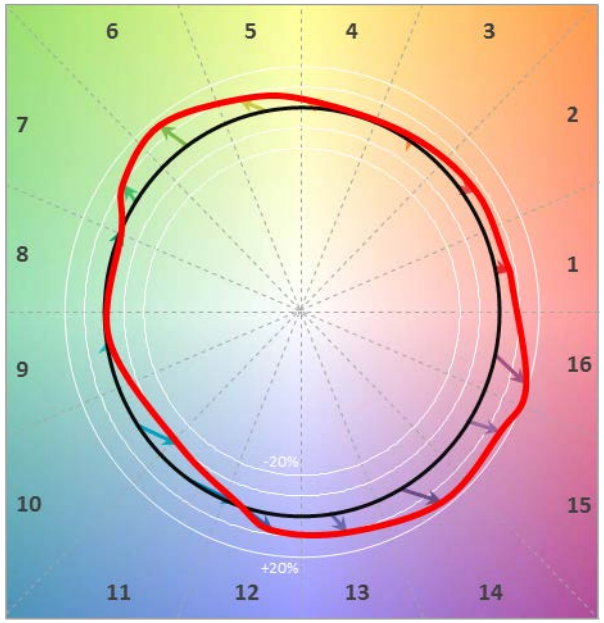
Real light sources with 7+ Preference, 359+ LER:



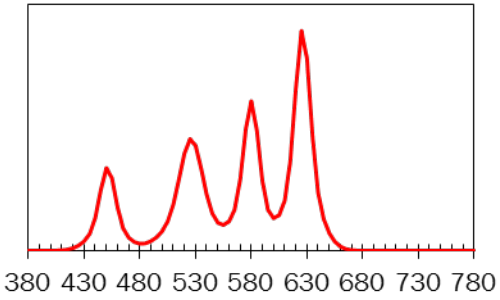


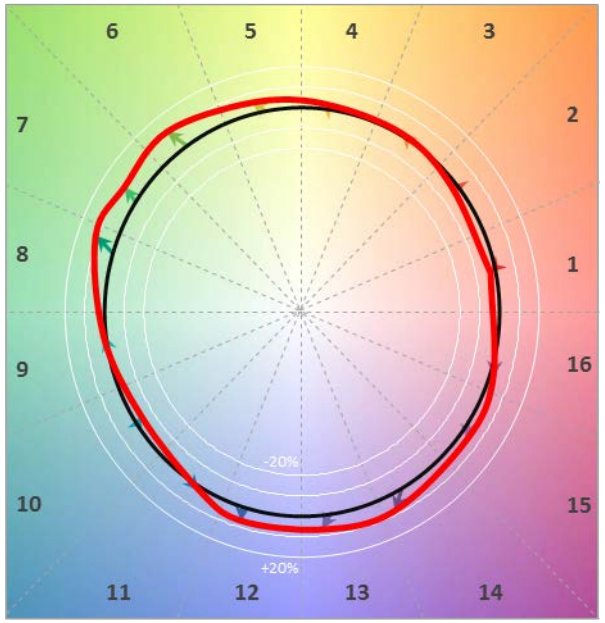
R_f = 79, R_g = 115, $R_{cs,h1}$ = 7%
R_a = 68, LER = 363, R_9 = 78





R_f = 76, R_g = 113, $R_{cs,h1}$ = 7%
R_a = 73, LER = 363, R_9 = 37

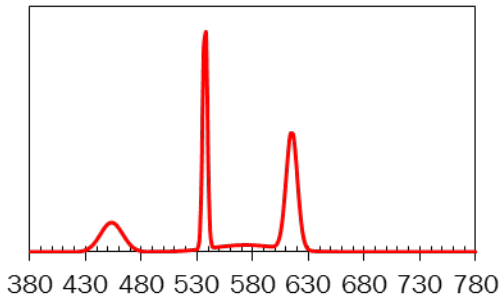


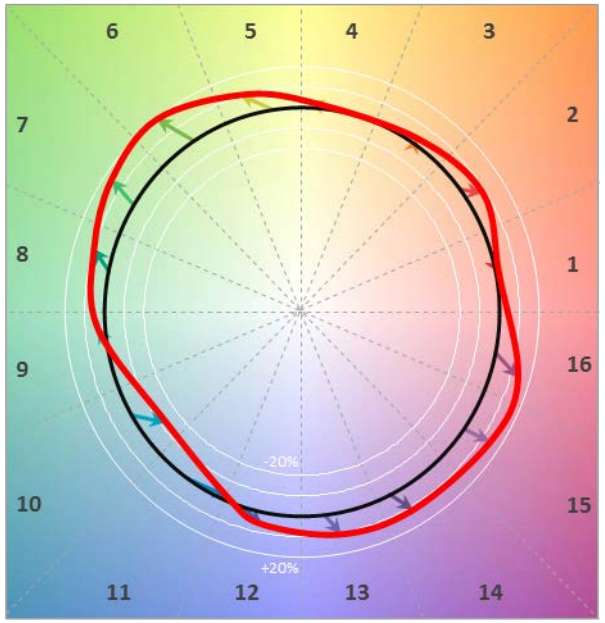


R_f = 88, R_g = 107, $R_{cs,h1}$ = -3%
R_a = 94, LER = 359, R_9 = 88

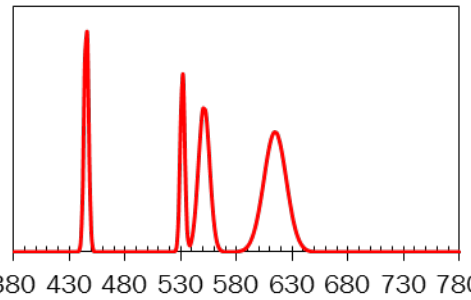
High Quality, High LER

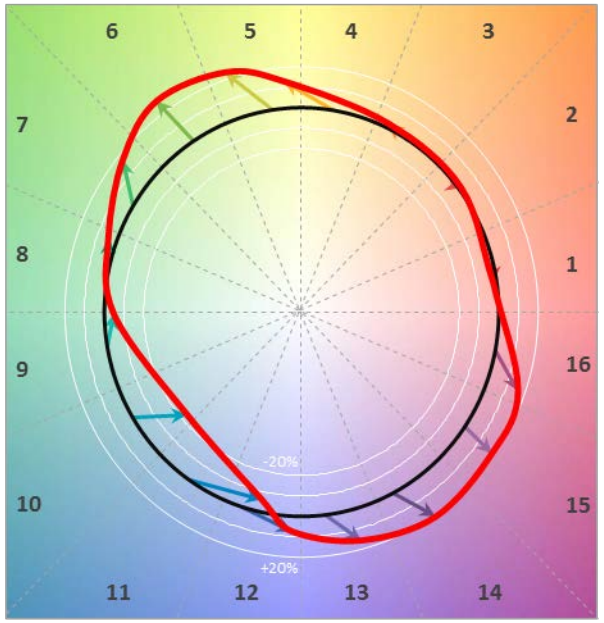
Theoretical light sources with 7+ Preference, 385+ LER:



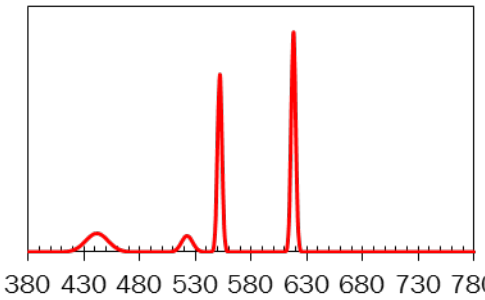


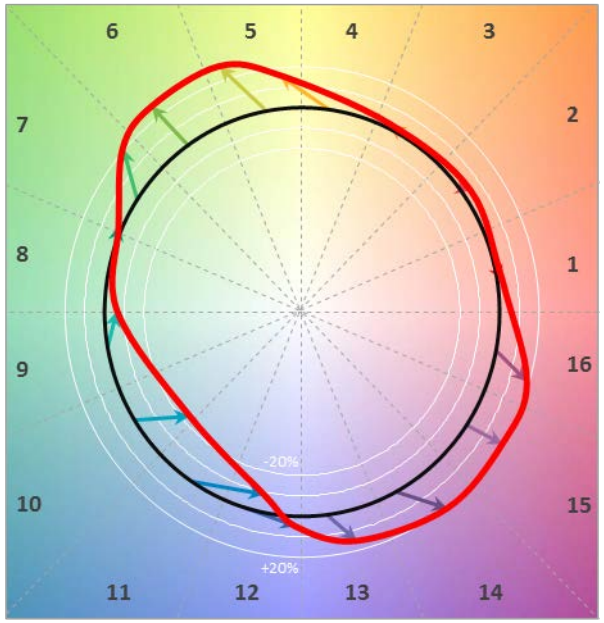
R_f = 75, R_g = 114, $R_{cs,h1}$ = 2%
R_a = 73, LER = 385, R_9 = 80





R_f = 65, R_g = 113, $R_{cs,h1}$ = -2%
R_a = 72, LER = 394, R_9 = 62





R_f = 63, R_g = 113, $R_{cs,h1}$ = 3%
R_a = 68, LER = 385, R_9 = 75

Conclusions

- **Average fidelity alone is unrelated to any perceptual attribute.**
  - CRI more strongly penalizes shifts that increase perceptions of normalness/preference
  - More research is available today to support specifications based on IES TM-30-15 than there ever was to support CRI ≥ 80 (or 90)
- **IES TM-30-15 can be boiled down to 2 (or 3) numbers for an effective specification based on acceptability, normalness (naturalness), and/or preference**
  - Key values, for a general application, are $R_{cs,h1}$ (red chroma), R_f, (and R_g)
- **Development of narrow emitters is important for developing high quality, high efficiency products.**

What's Else Can We Research

- Perceptions at different illuminance levels
- Application specific performance criteria
- Hue shift versus chroma shift
- Long-term perceptions

More Information

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