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What's Next for LED Color Rendering?

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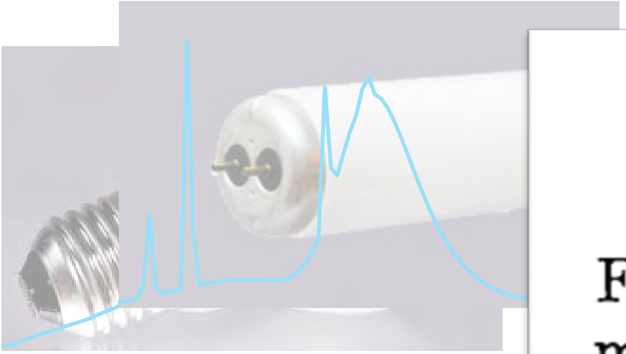
Pacific Northwest National Laboratory

Lightfair 2018

U.S. DEPARTMENT OF ENERGY

Color Rendition: An Incomplete History

Color Rendition: An Incomplete History



1950 1960

8SB

1948
CIE CR11

1955
CIE W1.3.2

1952
IES CR Subcommittee

STANDARDS NEEDED

There are a number of problems to be considered. For use in color work requirements for a light source may become quite specific, but there is also the more general problem of a lamp manufacturer who now can supply lamps in different colors and even in the same color but with different degrees of satisfaction as regards color rendering. In the home or factory there is room for a choice in which color, color rendering, and lumen efficiency of lamps may be weighed one against the other in making a choice. But what can be used as a reference standard against which to measure the color rendition of such a wide range of lamps?

Nickerson D. 1960. Light Sources and Color Rendering. Journal of the Optical Society of America 50(1):57-69.

Color Rendition: An Incomplete History

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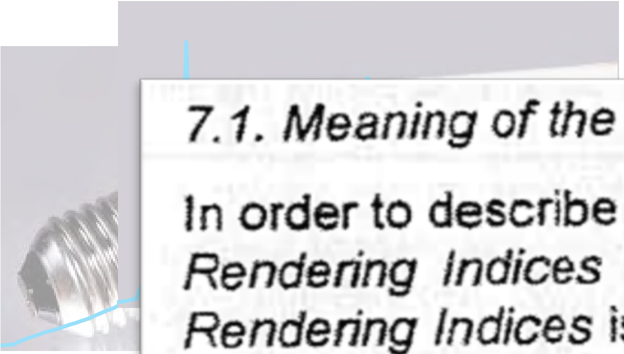

7.1. Meaning of the Colour Rendering Indices

In order to describe fully the colour rendering properties of a light source a series of *Special Colour Rendering Indices* is necessary. As stated in section 4, the derivation of the (special) *Colour Rendering Indices* is based on a general comparison of the lengths of colour difference vectors in the *1964 Uniform Space*, i.e. the amounts of the colour shifts. The importance of the directions of the colour shifts is recognised but not included in the *Colour Rendering Indices*.

1948
CIE CR11

1955
CIE W1.3.2

1965
CIE 13

1974
CIE 13.2

1952
IES CR Subcommittee

7.4. *Just perceptible differences in term of R*

Both practical experience and the knowledge about *DE* (the base of the index scale) as a measure or threshold [17] indicate that differences in R_i of about five units will correspond to visually perceptible colour differences under the best conditions, provided that the directions of the colour shifts are nearly the same. No such simple rule can be given for R_a. It is obtained as the average of eight R_i values, and even when two light sources have exactly the same R_a, differences about 5 units or more in one or more of the R_i's may still be possible, so that their colour rendering properties will be different for the object colours in question. Where the R_a values are close to 100, the R_i values are unlikely to show variation large enough to result in noticeable colour differences. But, as the value of R_a decreases from 100, the corresponding special indices R_i show increasing spread.

It should also be kept in mind that although the value R_i does determine the length of this colour difference vector, it gives no information about the direction of the vector (see section 7.1.). Therefore, if the R_i values for a given sample are 95 under two light sources of equal chromaticity, this does not imply that the sample has equal colour appearance under the two light sources. If the directions of the vectors are exactly opposite, there will be a colour difference corresponding to 10 units in the Colour Rendering Index Scale.

8SB

1948
CIE CR

1952
IES CR Subcommittee

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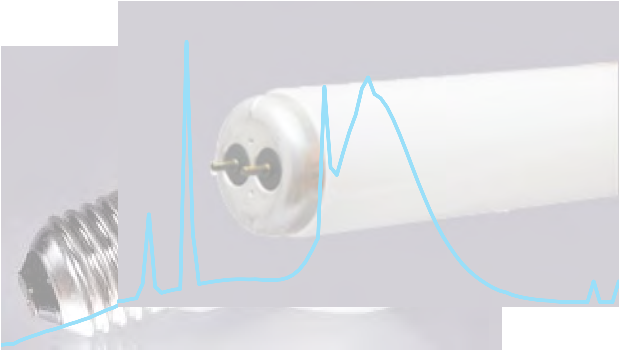

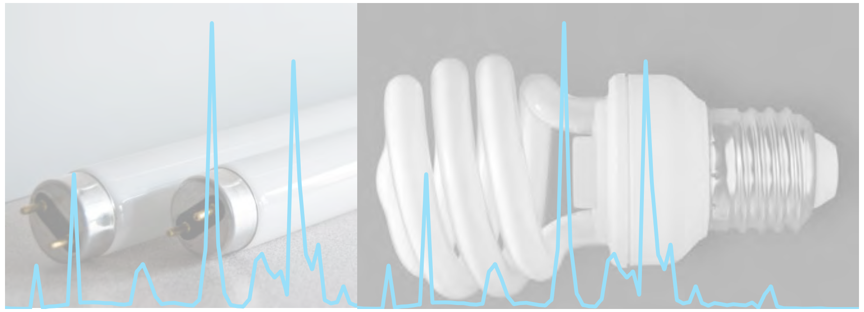

1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010

8SB

CRI

R_f

CDI
CPI
CRI

CRC

FCI

1948
CIE CR11

1955
CIE W1.3.2

1965
CIE 13

1974
CIE 13.2
(1967)

1991
CIE TC1-33

Defines "General Service Lamps".
For lamps > 35 W: CRI ≥ 69.
For lamps ≤ 35 W: CRI ≥ 45.
Lamps with CRI > 87 are "not general service".

1992
EPAct

1952
IES CR Subcommittee

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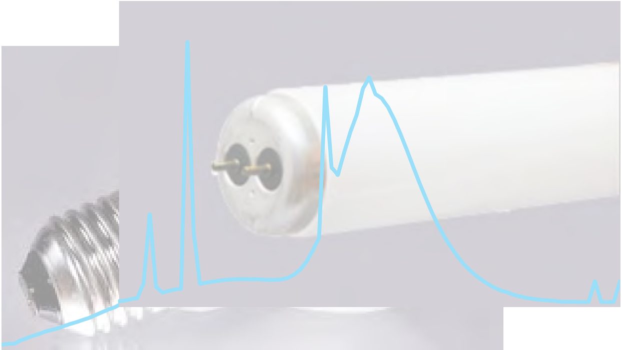

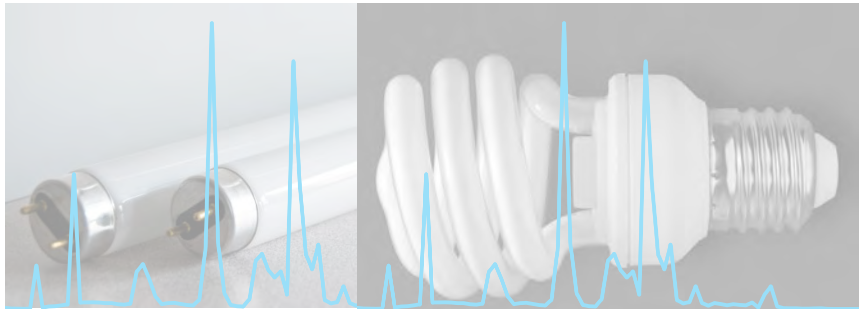

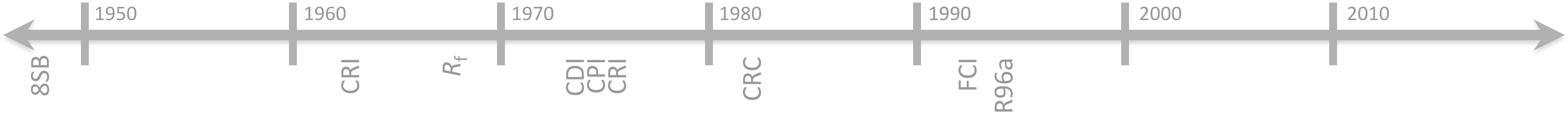

1948
CIE CR11

"This committee was not successful in its purposes mainly due to the disagreement between those who advocated including the advances of science and those who recommended that industry did not want change." [TC1-69 Report]

1995
CIE 13.3

1991-1999
CIE TC1-33

1992
EPAct ENERGY STAR

1952
IES CR Subcommittee

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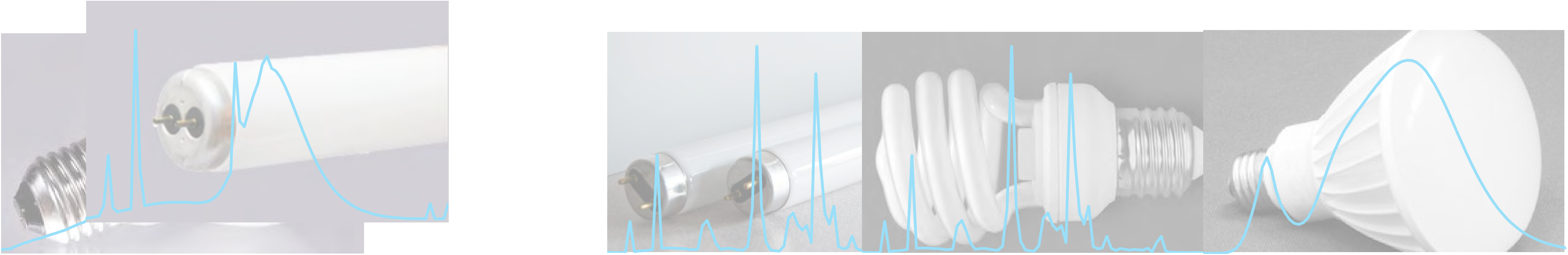

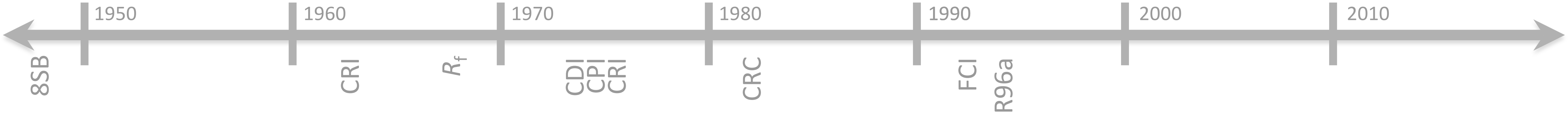

1948
CIE CR11

1955
CIE W1.3.2

1965
CIE 13

1974
CIE 13.2
(1967)

1995
CIE 13.3

1991-1999
CIE TC1-33

1999-2007
CIE TC1-62

ENERGY STAR CFLs version 2.0 (2001)
CRI ≥ 80.

19
EPA

ENERGY STAR

1952
IES CR Subcommittee

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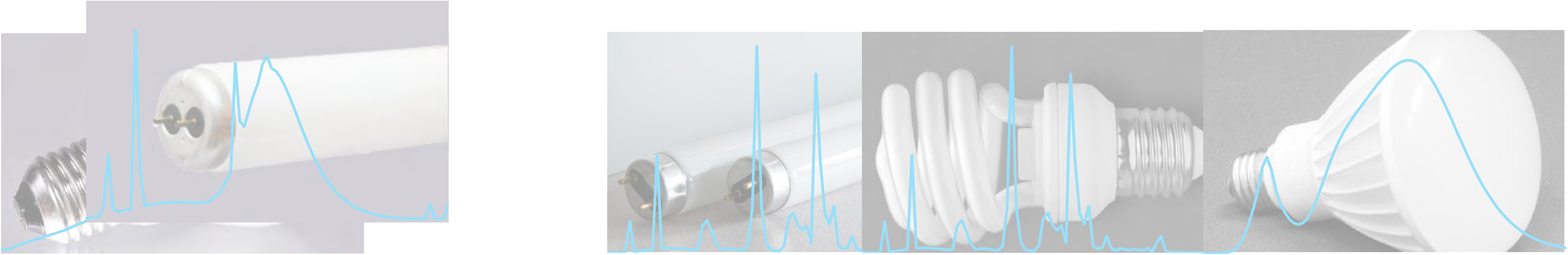

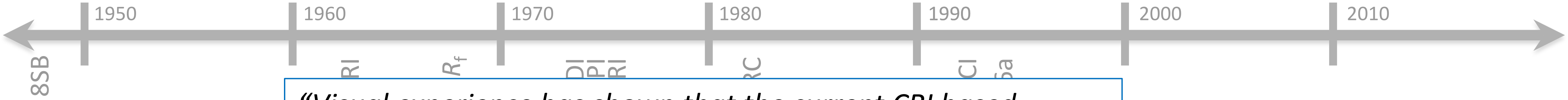

"Visual experience has shown that the current CRI based ranking of a set of light sources containing white LED light sources contradicts the visual ranking … the CIE CRI is generally not applicable to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in this set."

1948
CIE CR11

1955
CIE W1.3.2

2007
CIE 177

2006
E TC1-62

1992
EPAct

ENERGY STAR

2005
EPAct

1952
IES CR Subcommittee

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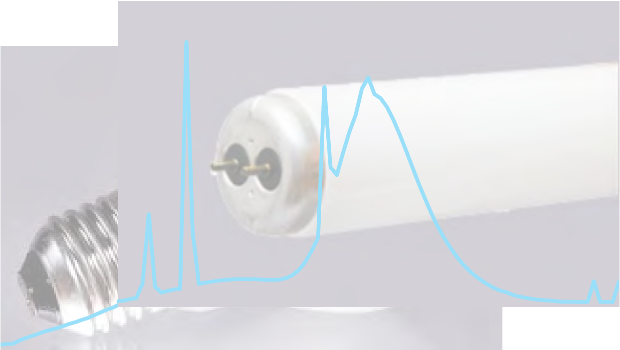

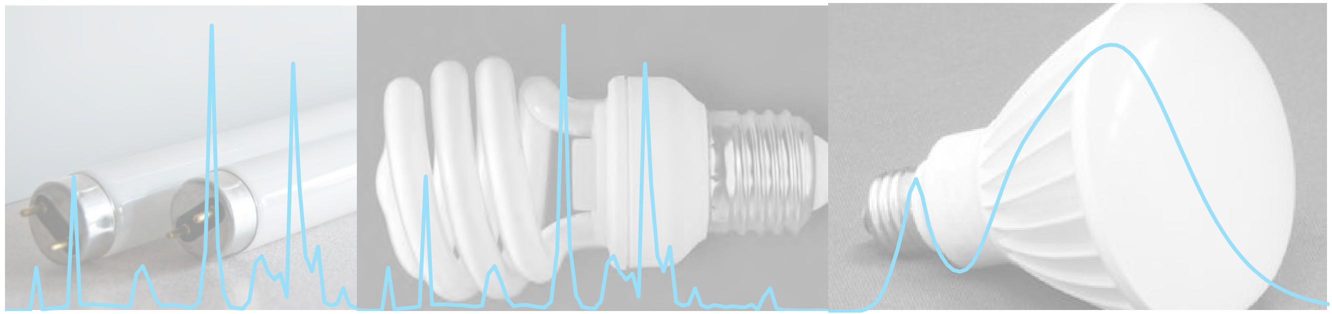

1950 1960 1970 1980 1990 2000 2010

8SB

CRI

R_f

CDI
CPI
CRI

CRC

FCI

R96a

1948
CIE CR11

1955
CIE W1.3.2

1965
CIE 13

1974
CIE 13.2
(1967)

1991-1999
CIE TC1-33

1995
CIE 13.3

1999-2006
CIE TC1-62

2007
CIE 177

General service incandescent lamps: CRI ≥ 80.
Modified spectrum general service lamps: CRI ≥ 75.

2007
EISA

1952
IES CR Subcommittee

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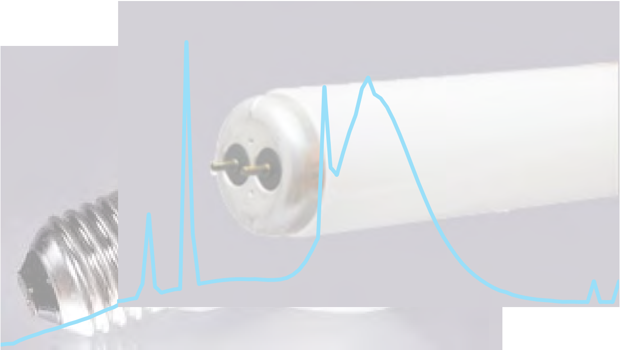

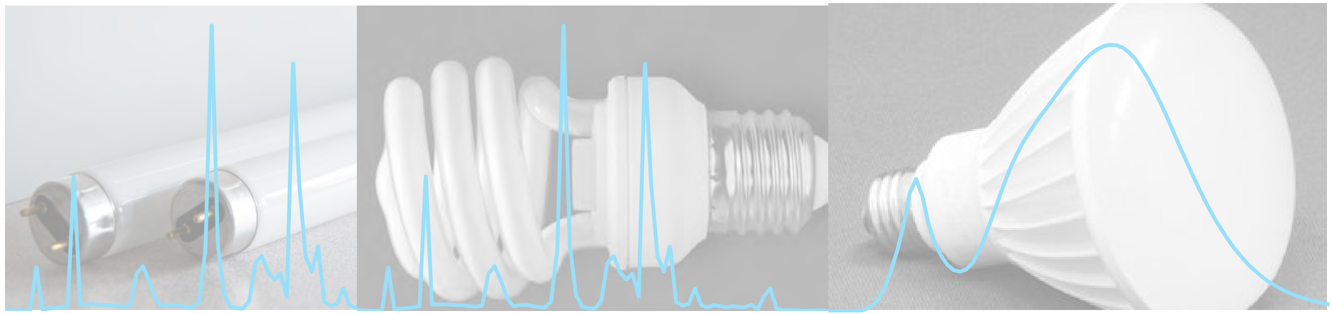

" … [CRI] values do not always correlate well with visual evaluation by general users. This mismatch arises, first, from inaccuracies of the CRI in its intended role as a colour fidelity index; and second, from perception-related colour quality effects beyond colour fidelity."

"… Therefore, it is considered that such unintended uses of CRI as an overall colour quality measure for end users is not better fulfilled by the more scientifically accurate general colour fidelity index, R_f. This is because the users' evaluation is influenced by factors beyond colour fidelity such as chroma effects, and the detailed nature of specific illumination tasks. The general colour fidelity index, R_f, is therefore not a replacement of the general colour rendering index, [CRI], neither for the purpose of rating and specification of products nor for regulatory or other minimum performance requirements."

8SB

1948
CIE CR1

2010

TM-30

G_a R_f GVI

2017
CIE 224

CIE TC1-90/91

1952
IES CR Subcommittee

2015
IES TM-30

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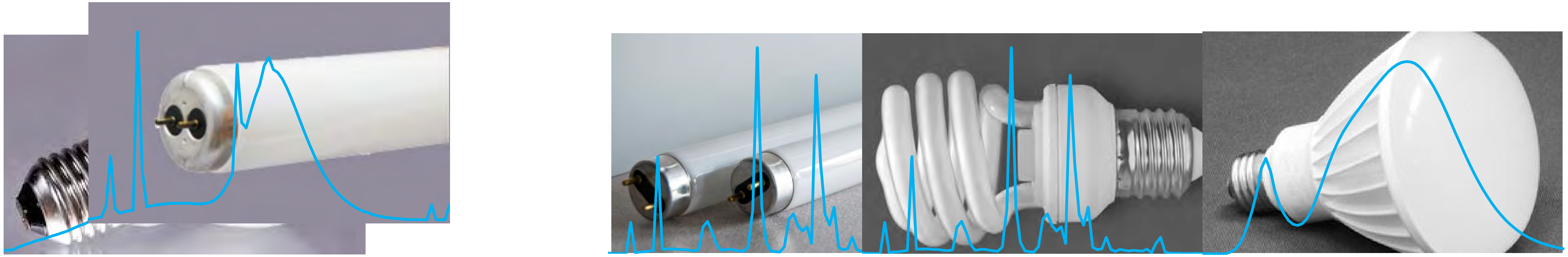
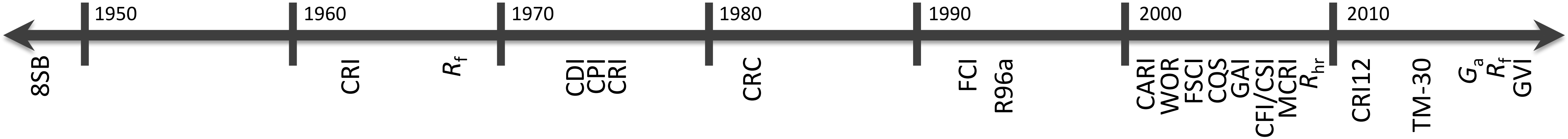


?



1948
CIE CR11

1955
CIE W1.3.2

1965
CIE 13

1974
CIE 13.2

1991-1999
CIE TC1-33

1995
CIE 13.3

1999-2006
CIE TC1-62

2006-2012
CIE TC1-69

2007
CIE 177

2012-
CIE TC1-90/91

2017
CIE 224

1992
EPAct

ENERGY STAR

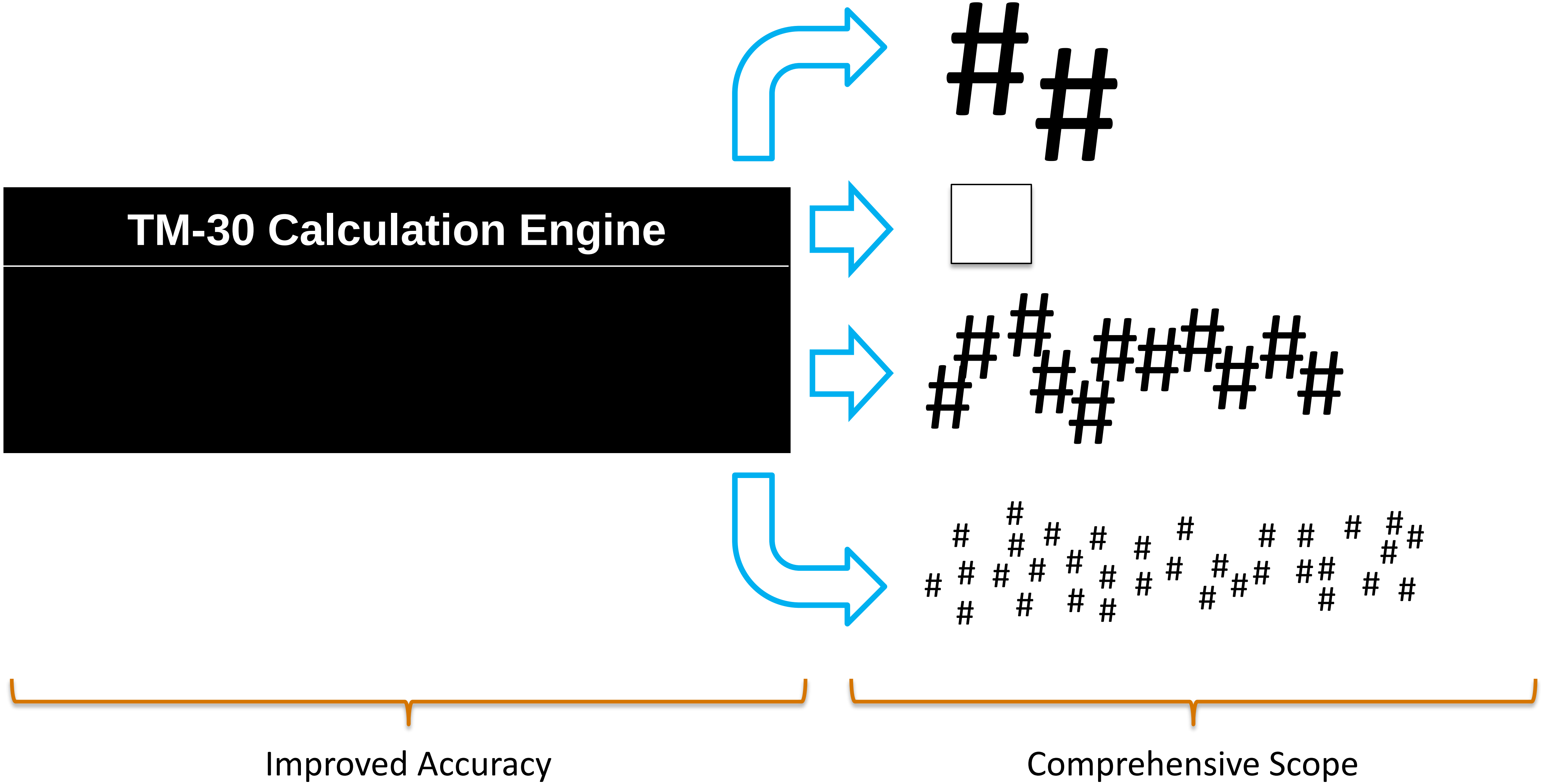
2005
EPAct

2007
EISA

1952
IES CR Subcommittee

2015
IES TM-30

2018?
IES TM-30


TM-30 Calculation Engine
Improved Accuracy
Comprehensive Scope

TM-30 Calculation Engine

1. Model of Human Color Vision (CAM02-UCS)
2. Model of Colors (99 CES)
3. Established Baseline (Reference)

Global Average Values
Fidelity Index (R_f)
Gamut Index (R_g)

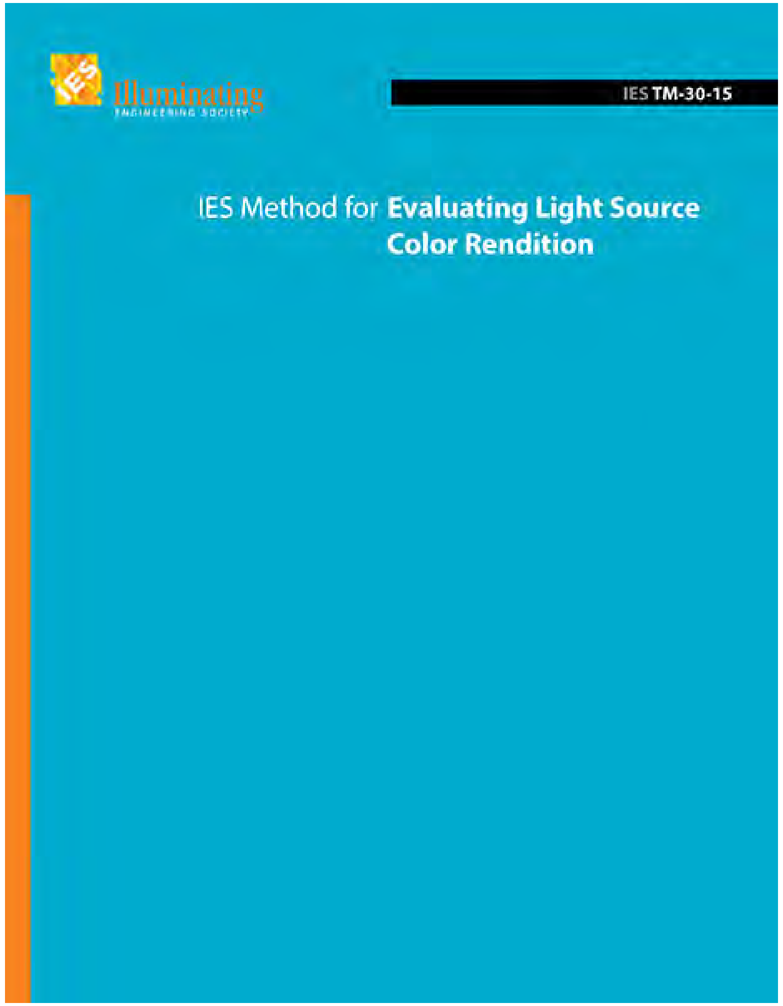
Graphical Representations
Color Vector Graphic

Local Average Values (Hue-Angle Groups)
16 Local Color Fidelity($R_{f,hj}$)
16 Local Chroma Shift ($R_{cs,hj}$)
16 Local Hue Shift ($R_{hs,hj}$)

Sample Specific Values
Color Sample Fidelity ($R_{f,CESi}$)

Improved Accuracy

Comprehensive Scope



IES TM-30-18 (PENDING)

Changes made to harmonize with CIE 224

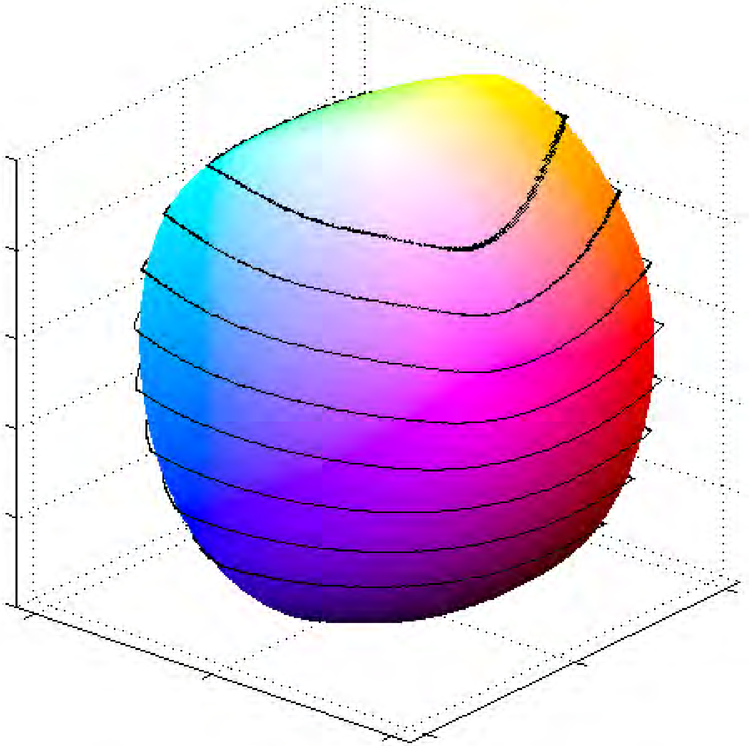
A. Flat extrapolation for color sample data <400 nm and >700 nm (changed from derivative based)
B. Mixed reference zone now 4000 K to 5000 K (changed from 4500 K to 5500 K)
C. Scaling factor now 6.73 (changed from 7.54)

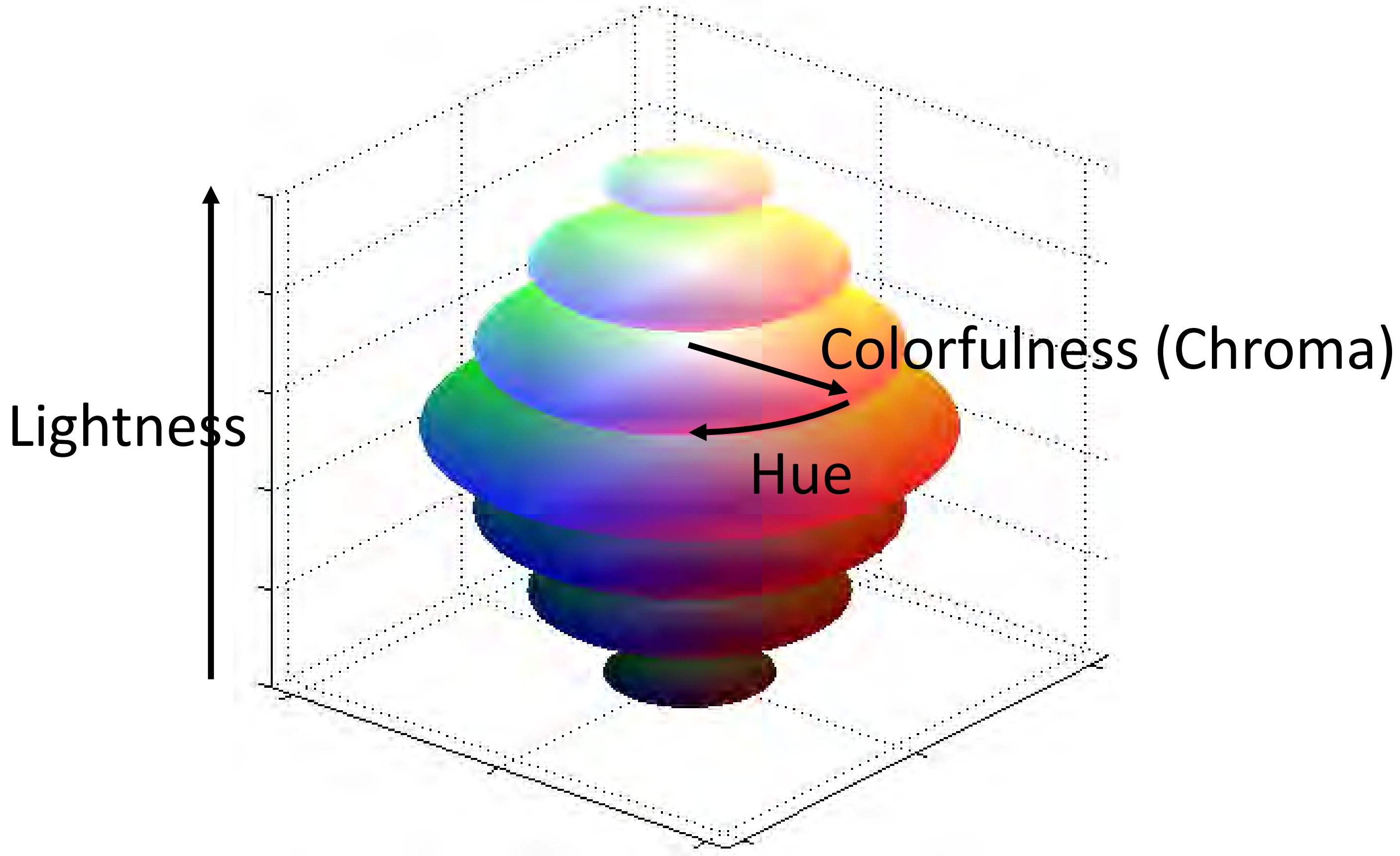
→ R_f 80 ~ 82

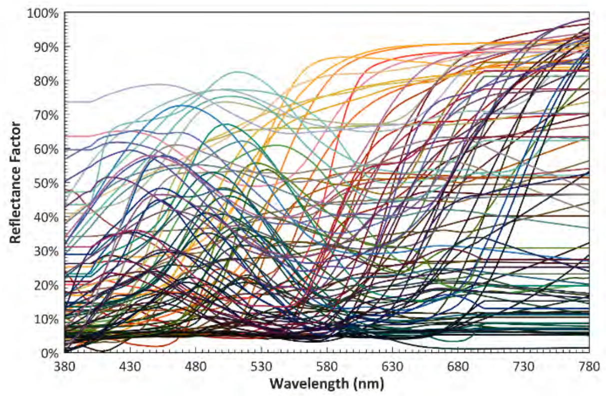
Additional updates

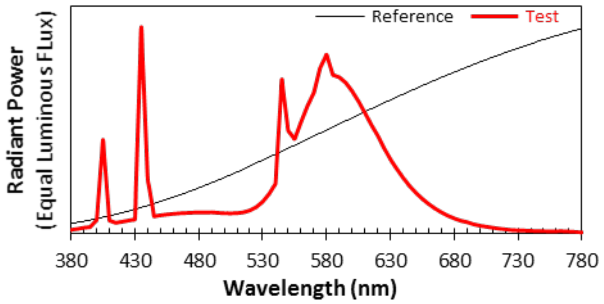
- Specification of Color Vector Graphic formatting
- Clarification on local value calculations and expected values
- Recommended specification sheets
- Updated calculator tools

Color Volume (CAM02-UCS)









(CIE F4)

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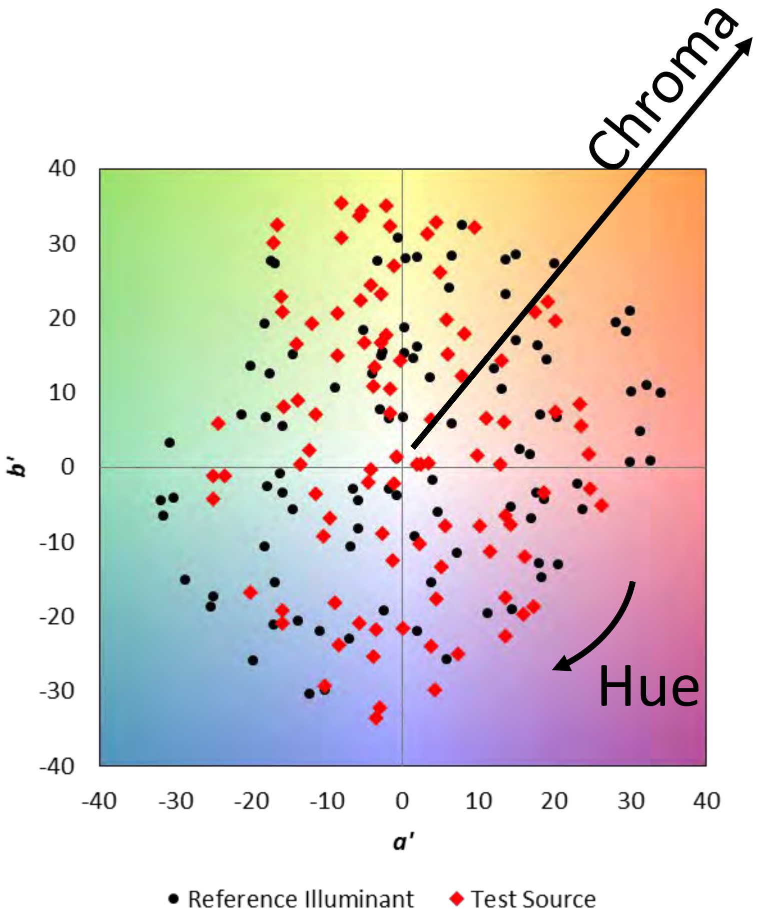
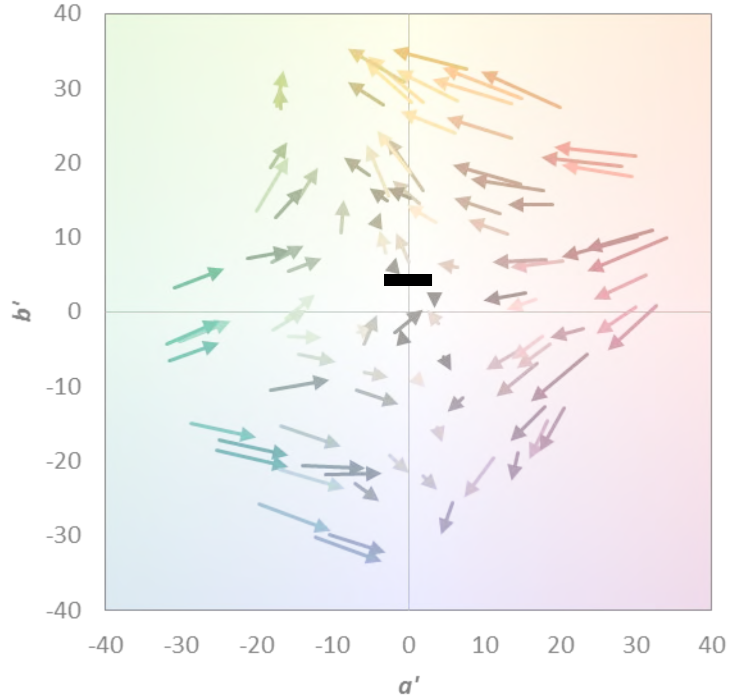




Average Color Fidelity

On average, how similar are colors rendered by the test source to the same colors rendered by the reference illuminant?

- Average length of arrows
- Does not capture direction of shift

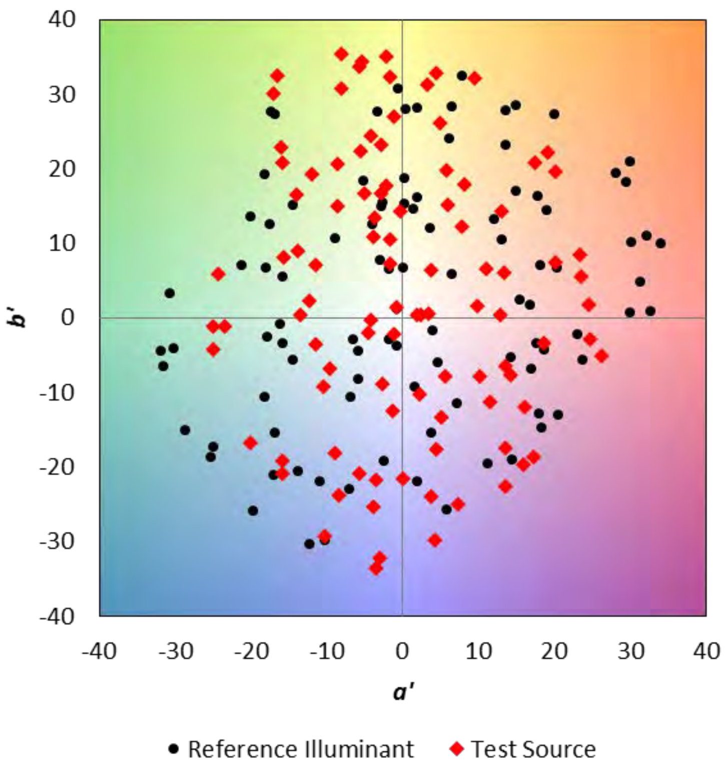
TM-30 Fidelity Index (R_f)

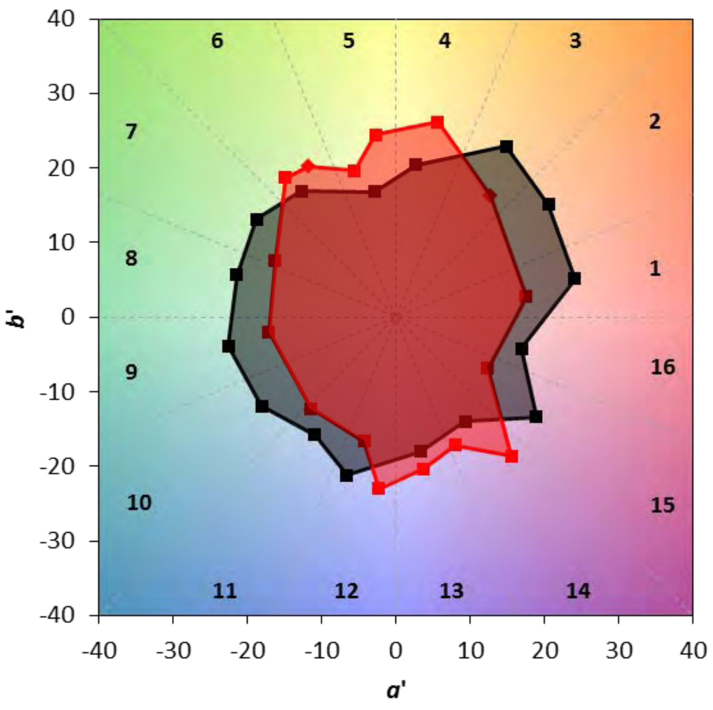
Range is 0 to 100, where 100 is an exact match.

TM-30-18 R_f = CIE 224 R_f

(pending final approval)

This is really a sphere, but it's compressed to 2D for ease of visualization!





Average Gamut Area

Approximation of average change in chroma.

- Average area enclosed by samples
- Does not capture how changes vary for different hues

TM-30 Gamut Index (R_g)

Range depends on R_f; about 80 to 120 at R_f = 80.

This is actually compressed to 2D for calculations!

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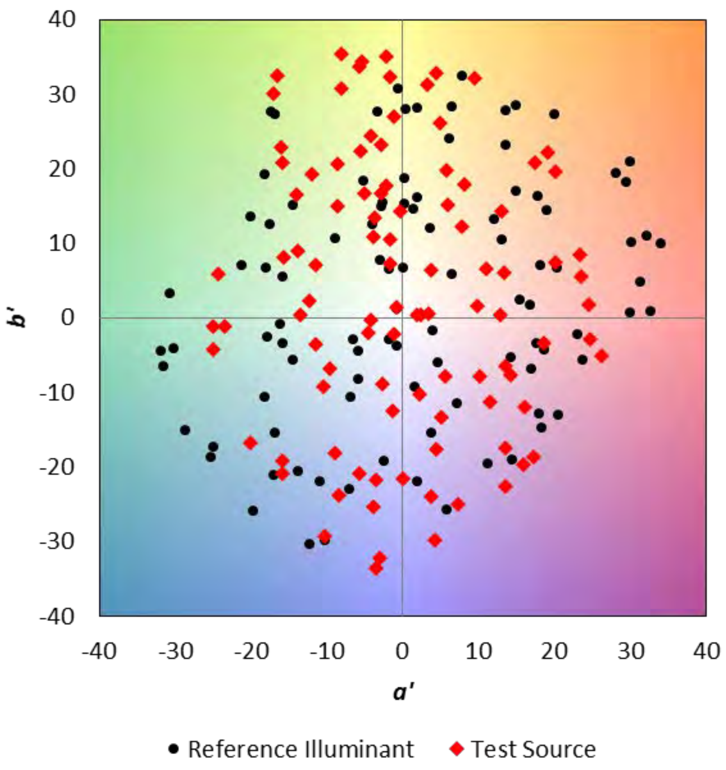
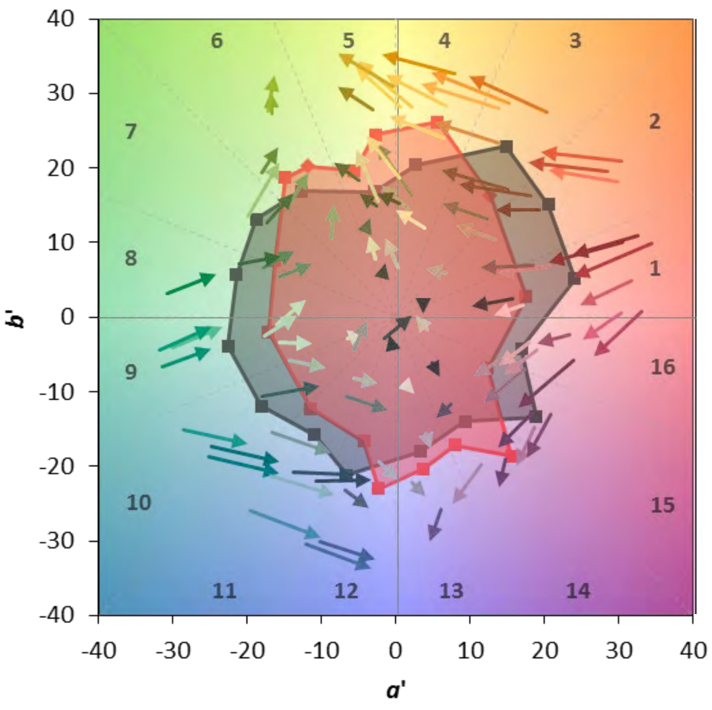
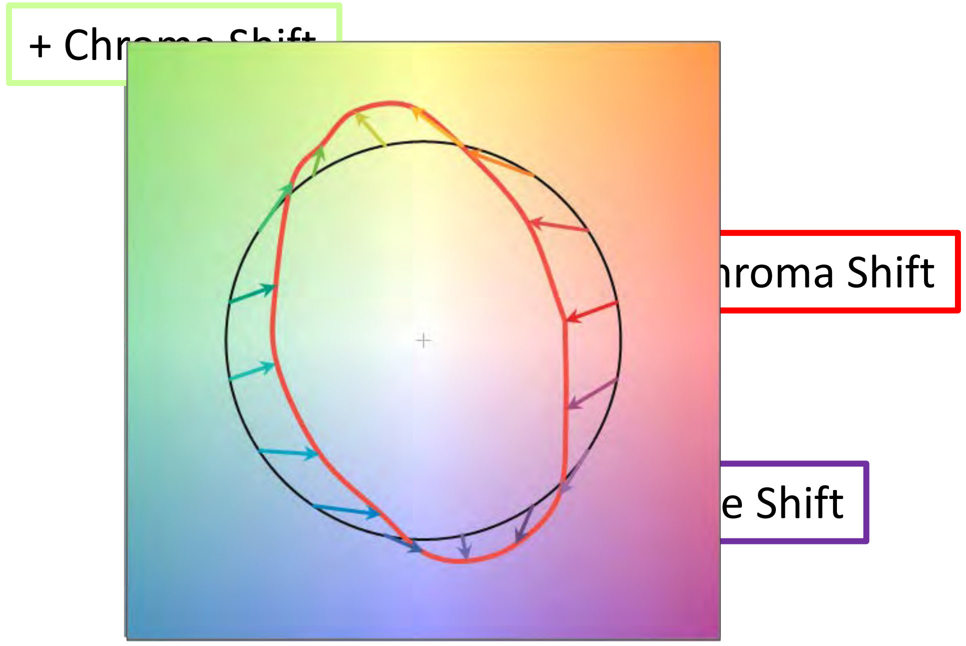
Color Vector Graphic

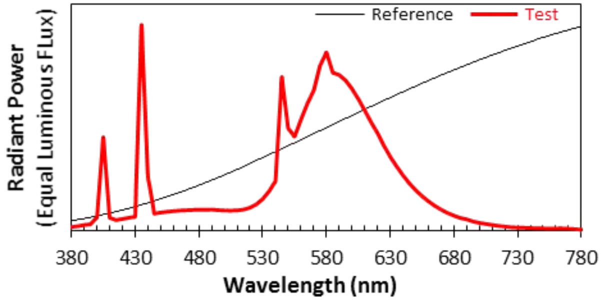


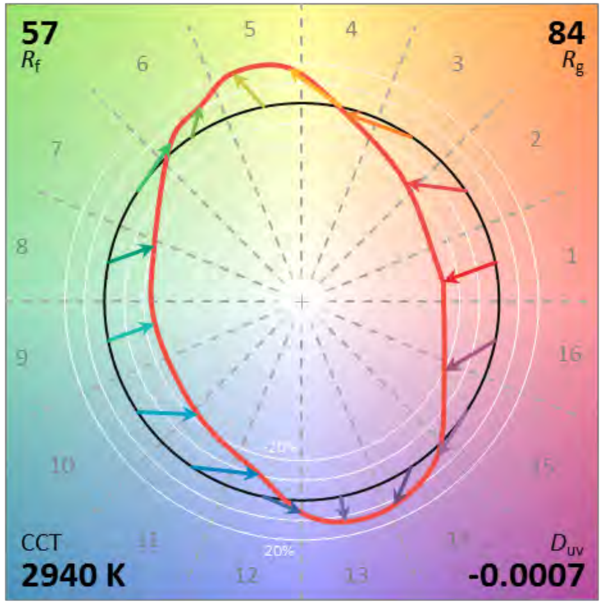




(Note: TM-30-18 Format is Pending)

Gamut Shape = The average pattern of color shifts across hues.





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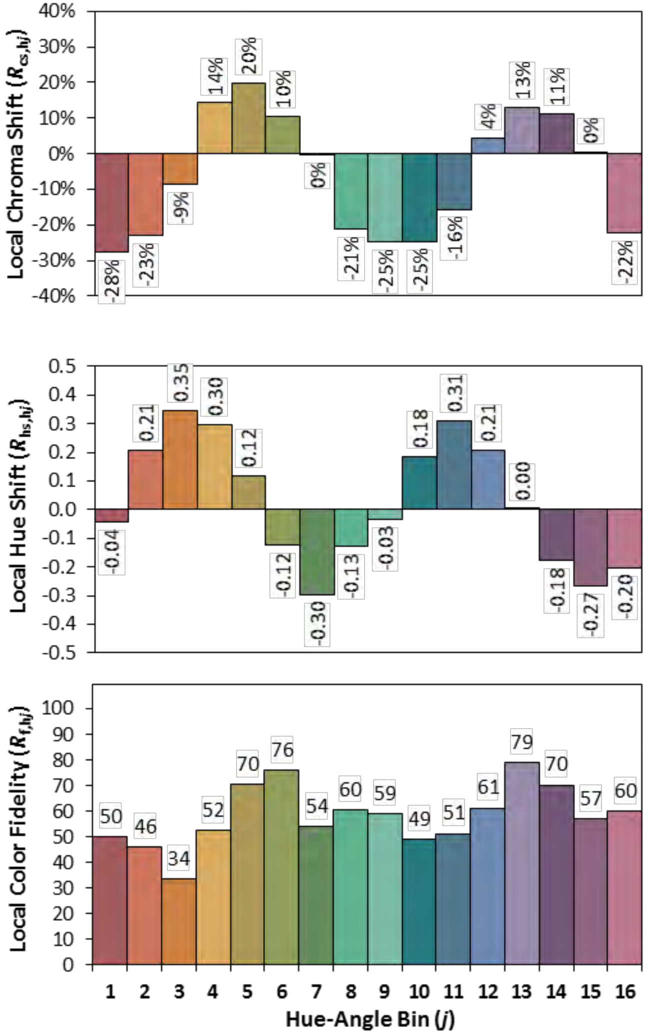

Local Chroma Shift

For a given range in hue angle, what is the average relative change in chroma. Values in percentages.

Local Hue Shift

For a given range in hue angle, what is the average relative change hue. Values in radians.

Local Color Fidelity

For a given range in hue angle, what is the average magnitude of change (3D). Values 0 – 100.

Local Chroma Shift: Expected Values

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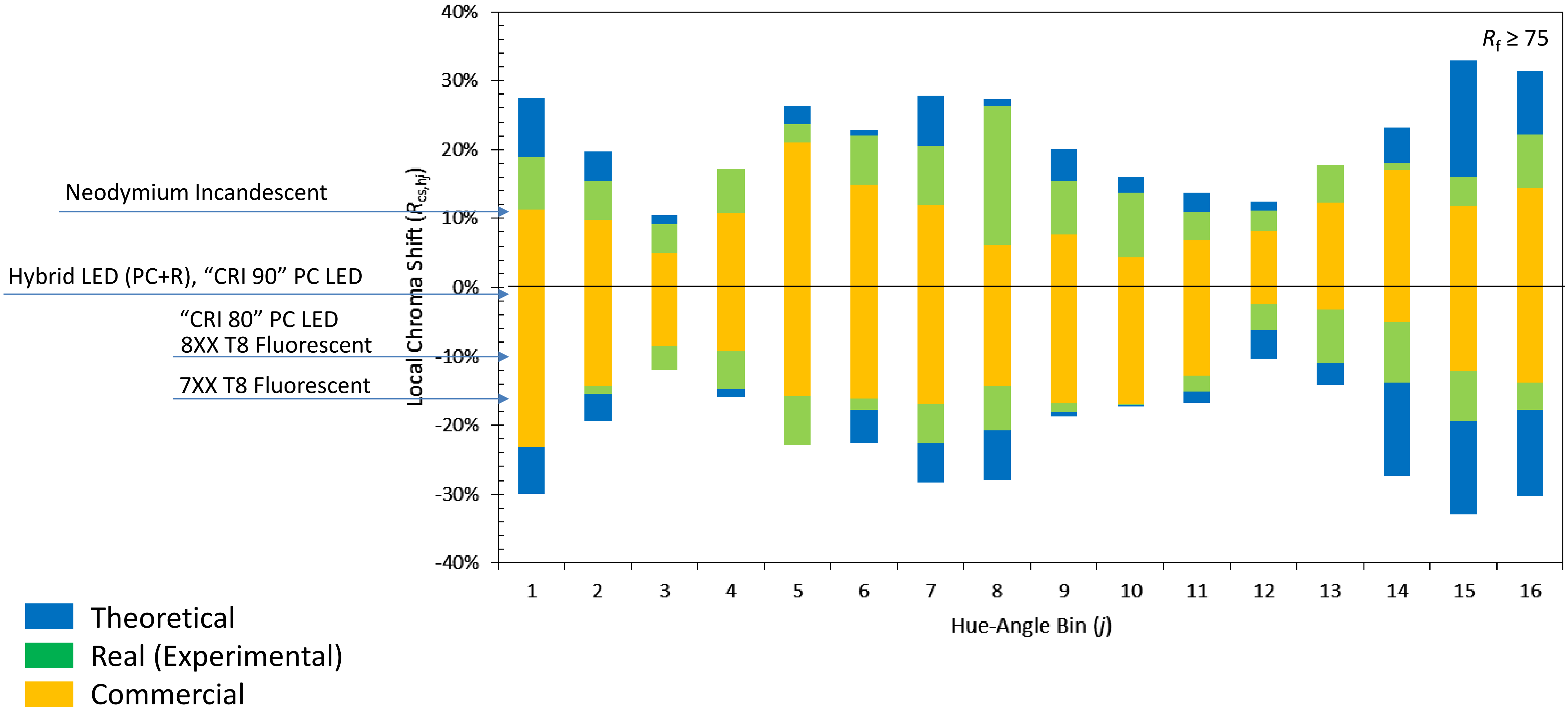
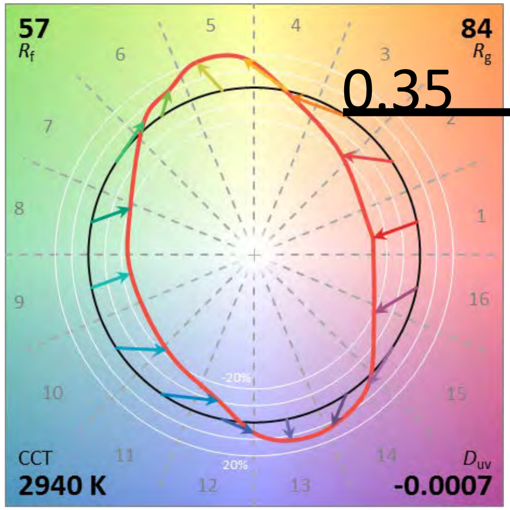
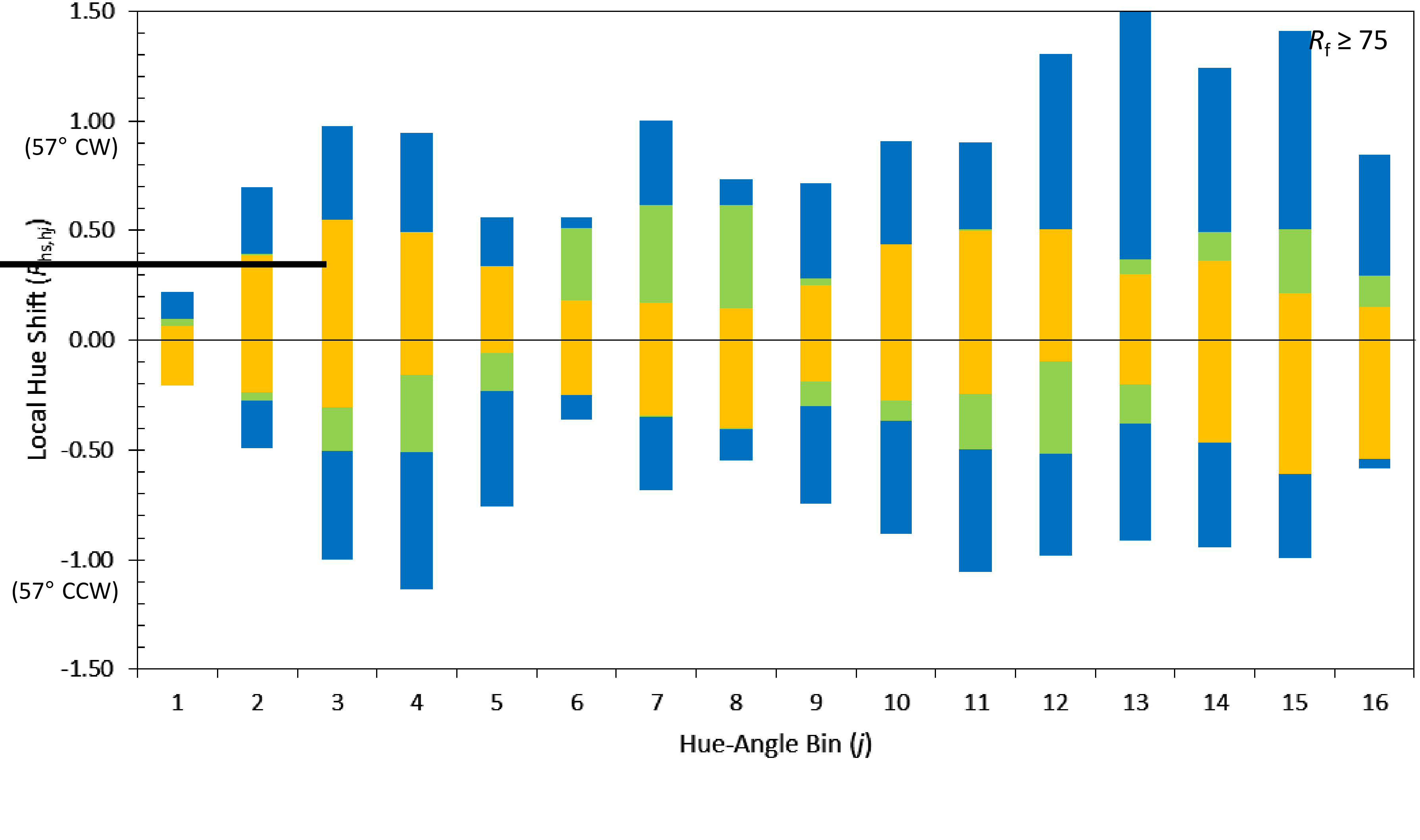
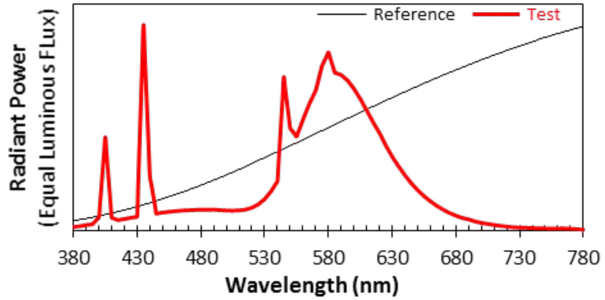
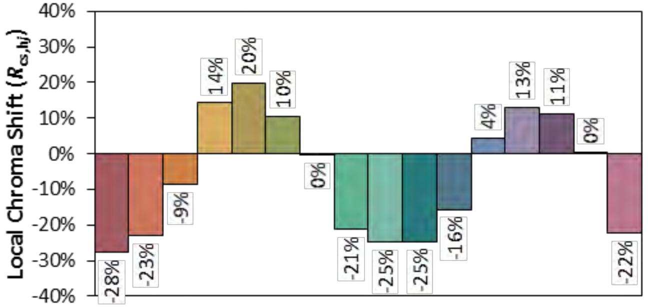


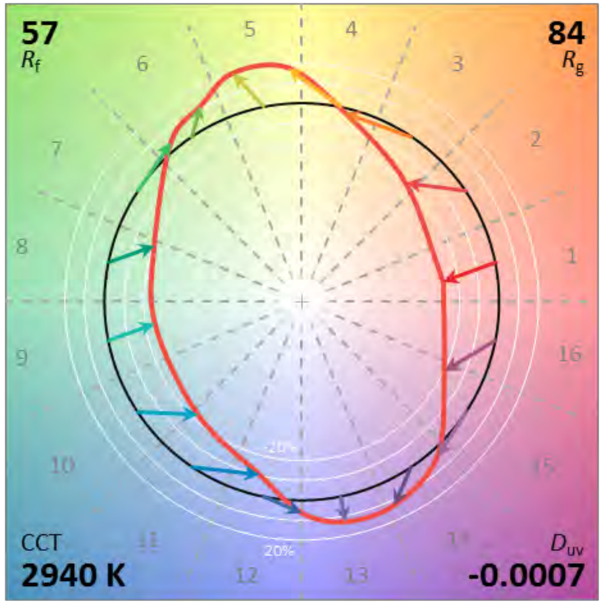
Local Hue Shift: Expected Values

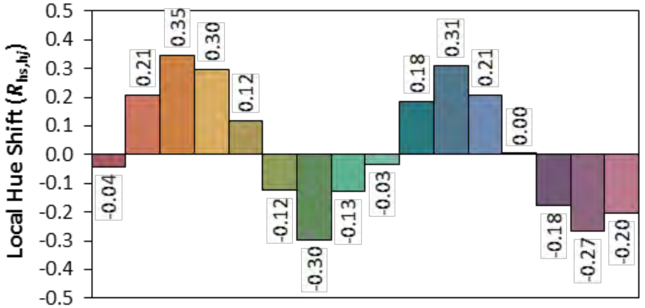


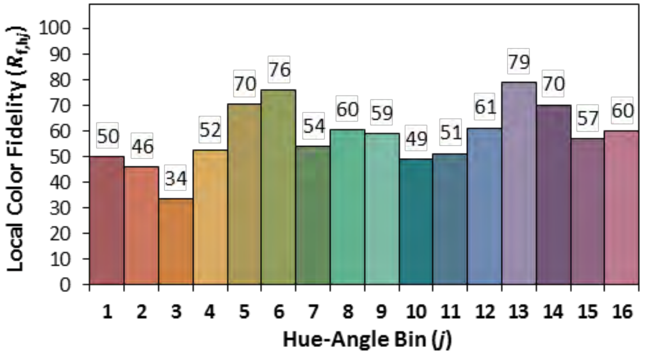












(Note: TM-30-18 Format is Pending)

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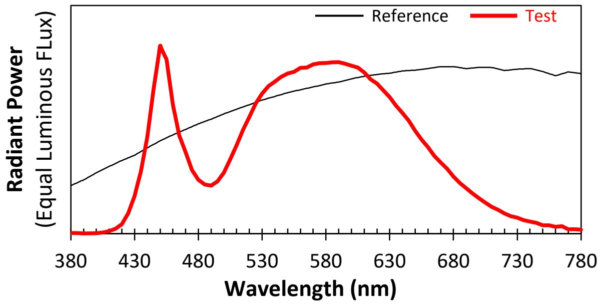
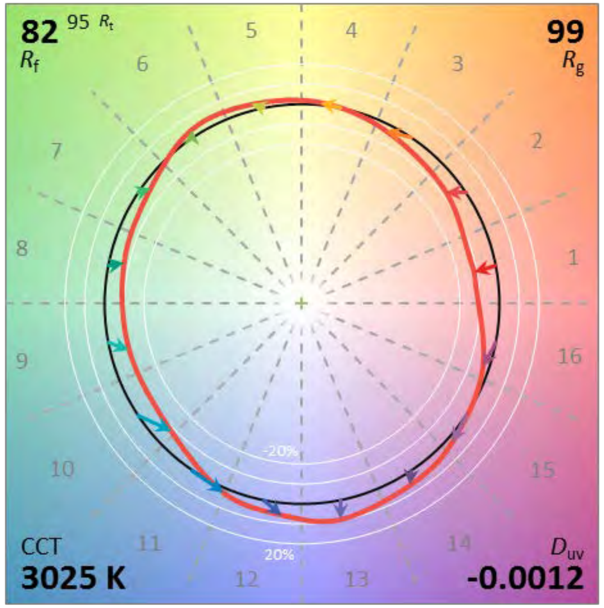
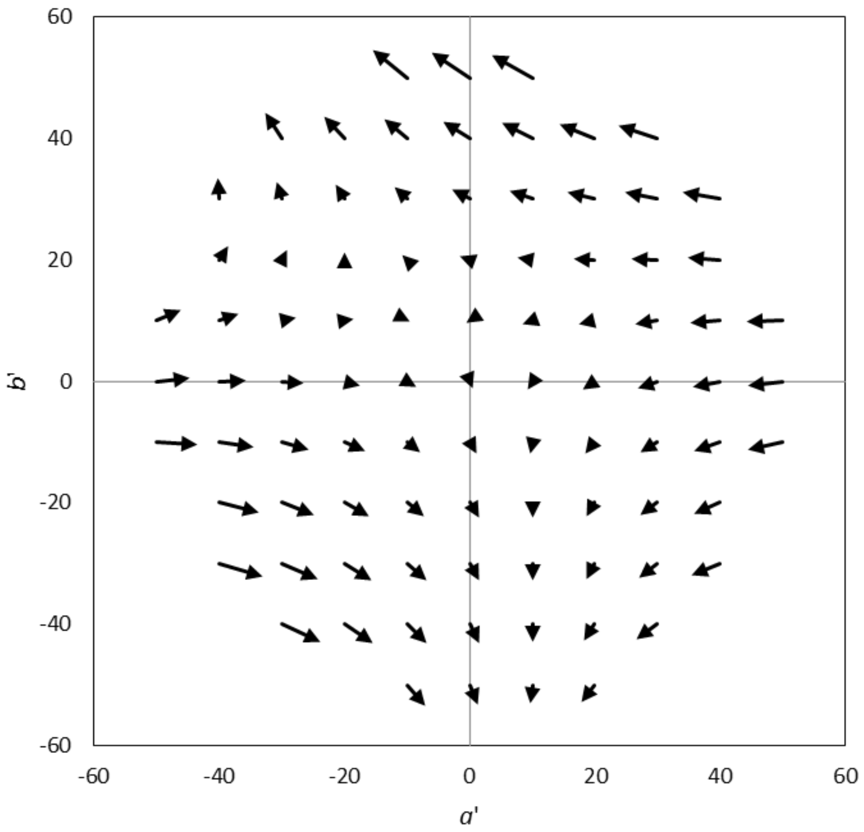
Vector Field Modelling







What's Next?

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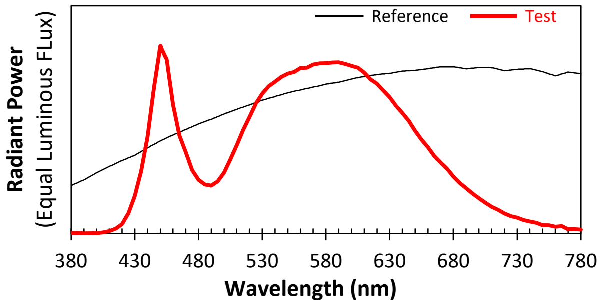
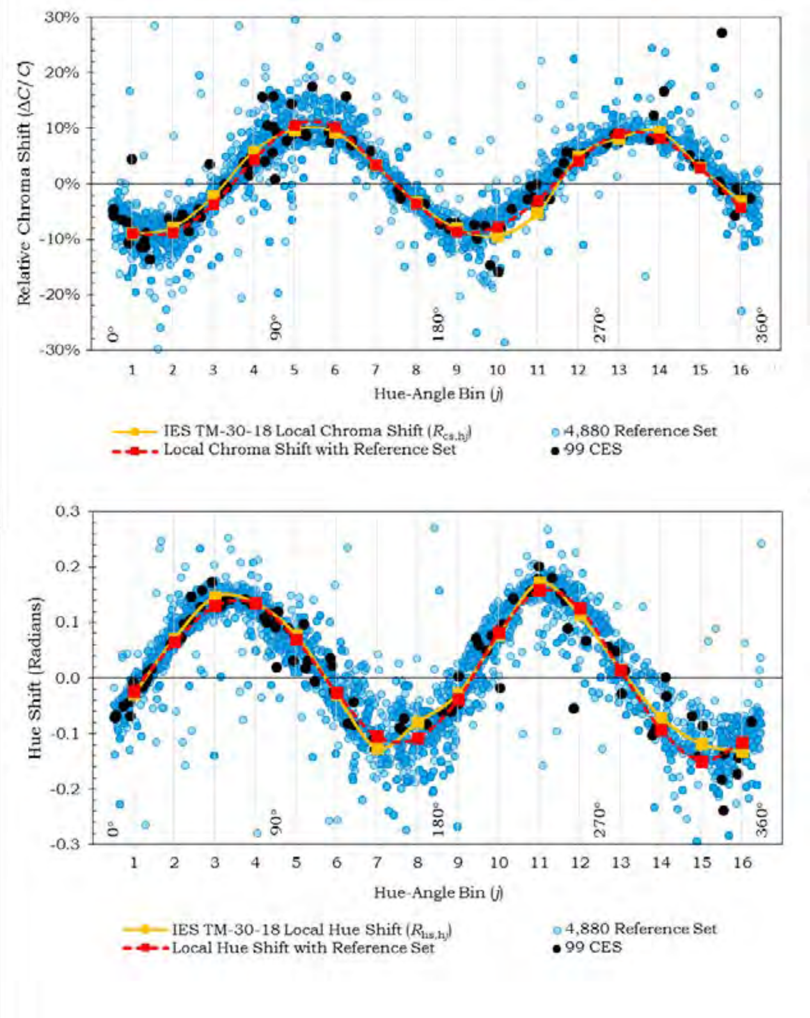
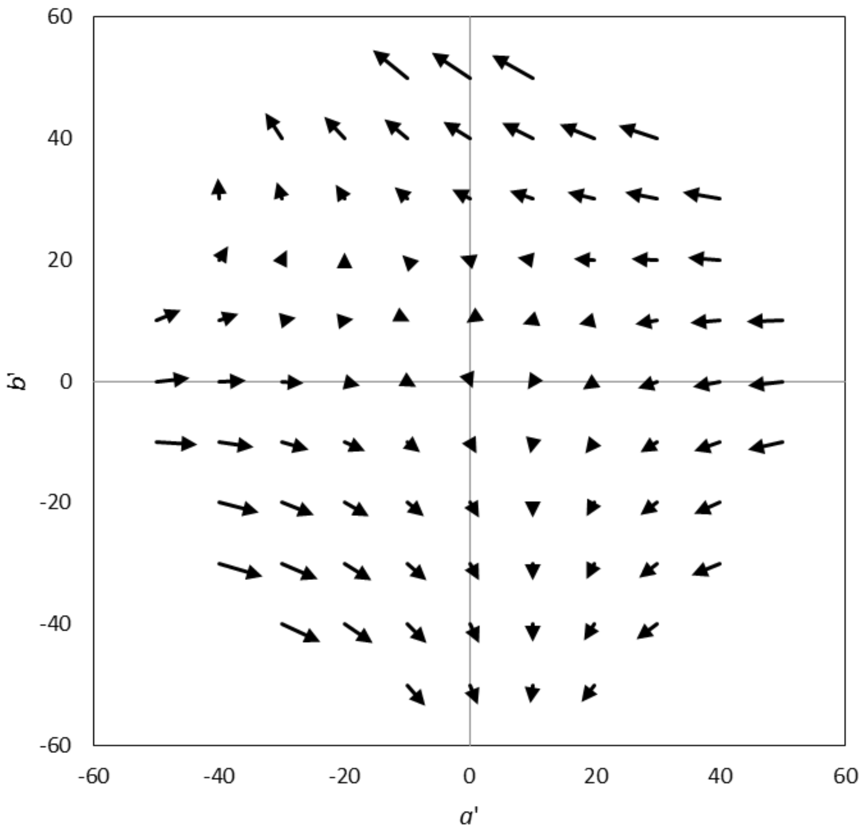
Vector Field Modelling







What's Next?

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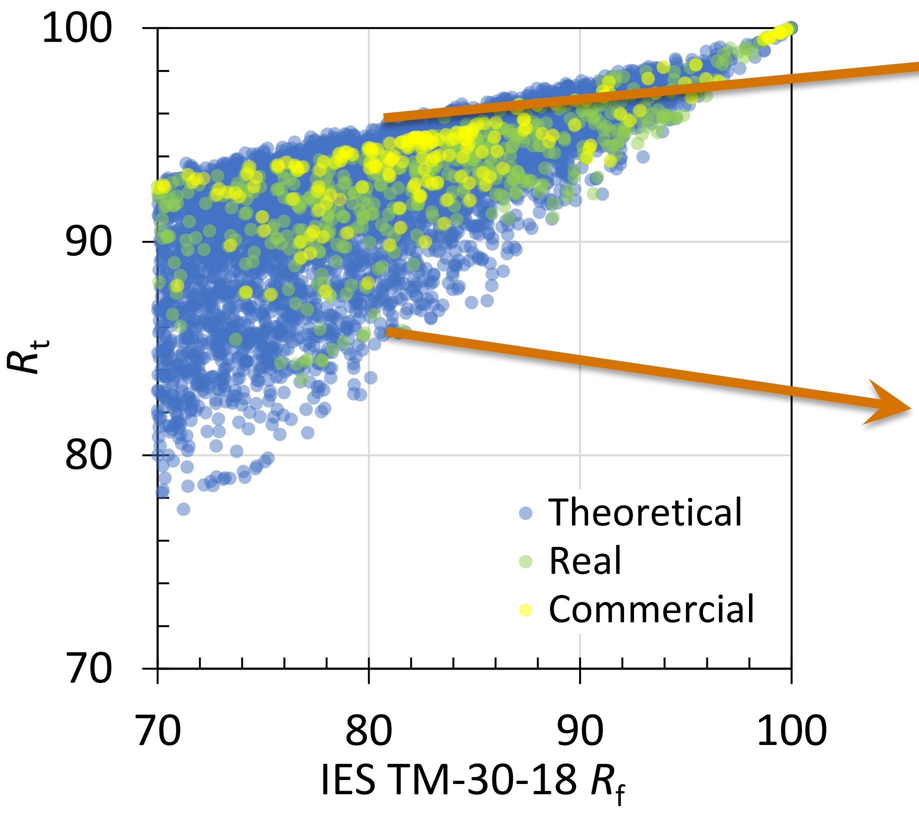
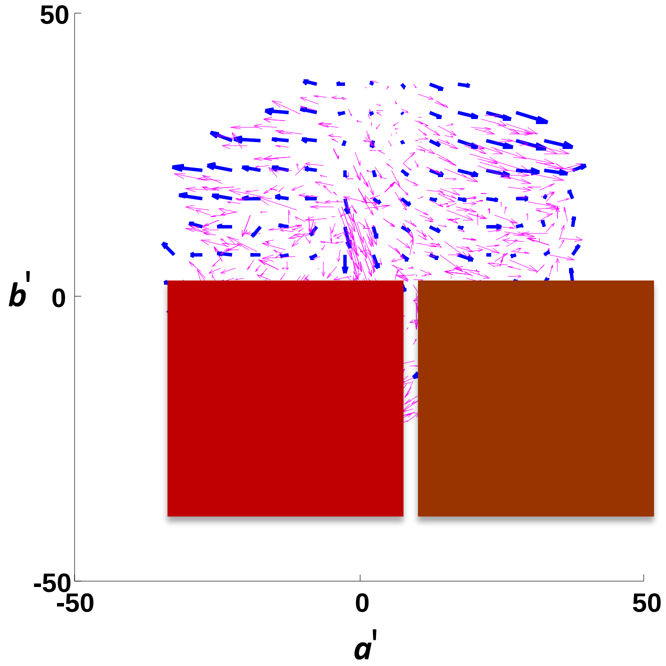
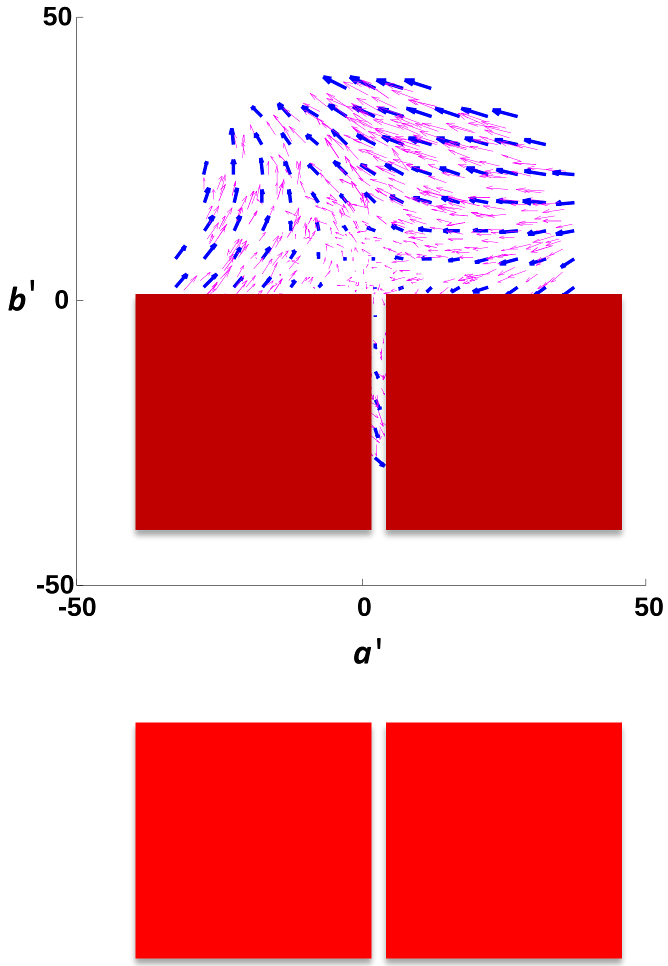
Metameric Uncertainty Index (R_t)

How much variation in color shifts for metameric colors?

0-100 Scale (Higher = less likelihood of metameric mismatch)







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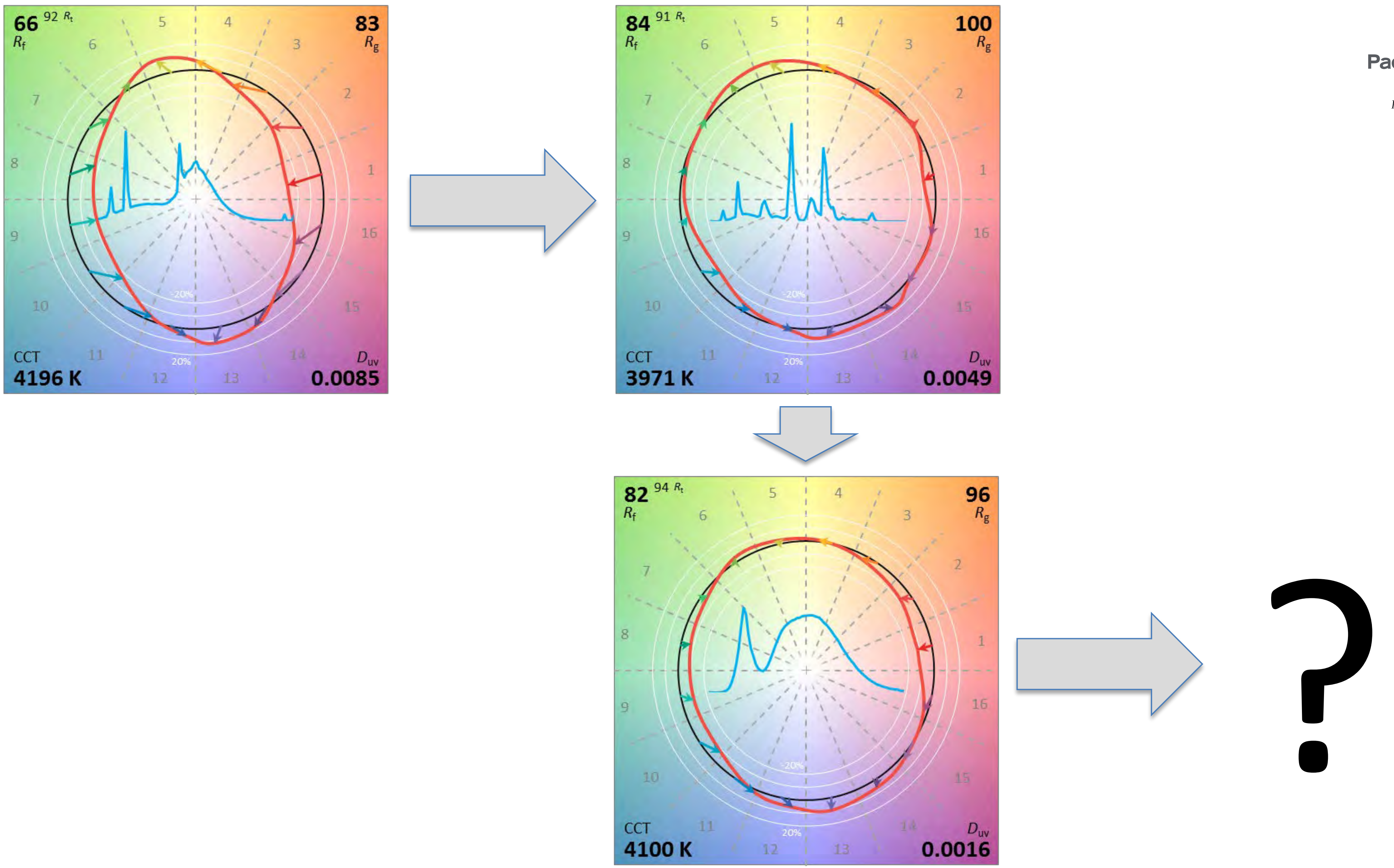
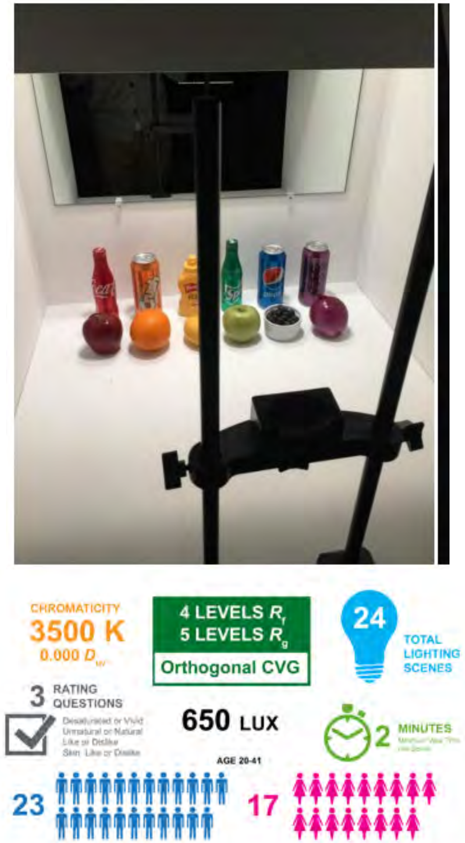


PNNL

R_f, R_g, $R_{cs,h16}$

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.

Penn State



R_f, R_g, $R_{cs,h16}$

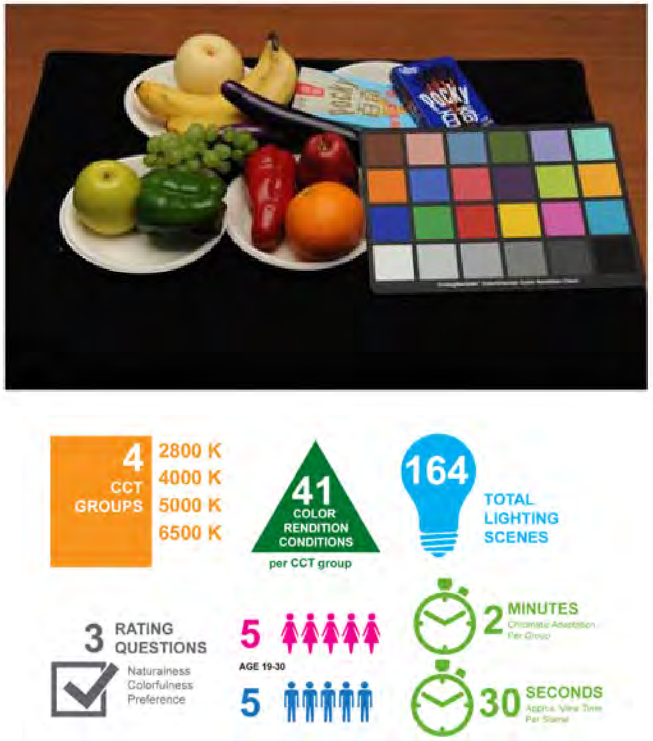
Esposito T, Houser K. 2018. Models of colour quality over a wide range of spectral power distributions. Lighting Research & Technology Online Before Print. DOI: 10.1177/1477153518765953.

PNNL

R_f, R_g, $R_{cs,h1}$

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.

Zhejiang



R_f, R_g, $R_{cs,h1}$

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

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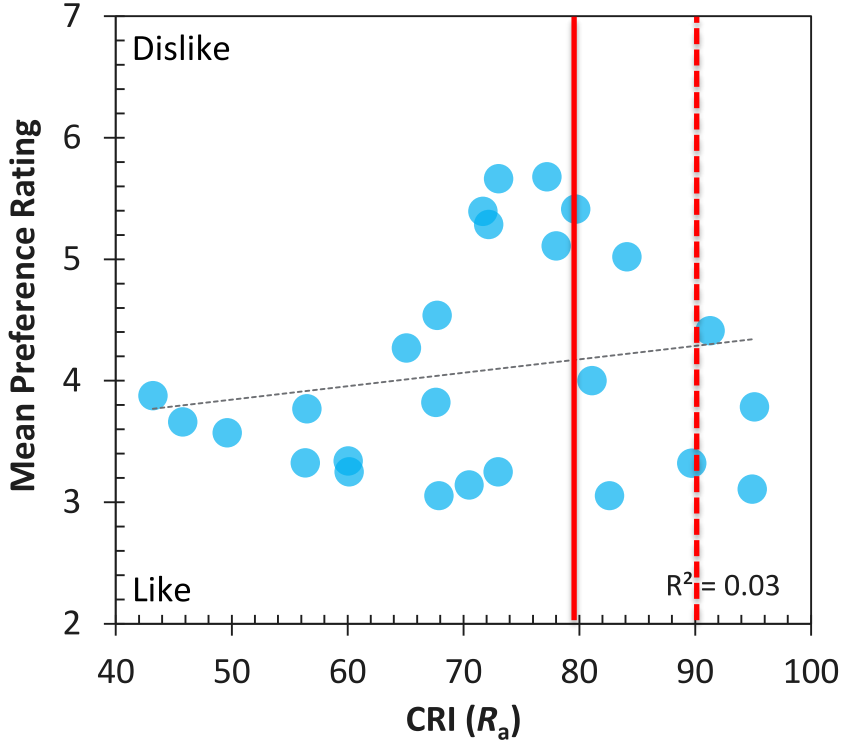
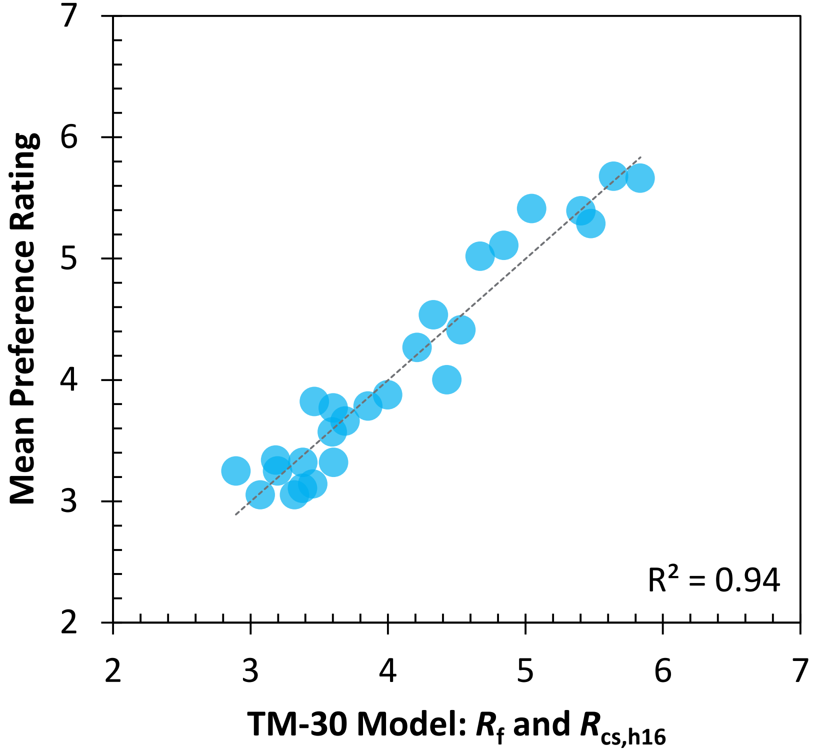
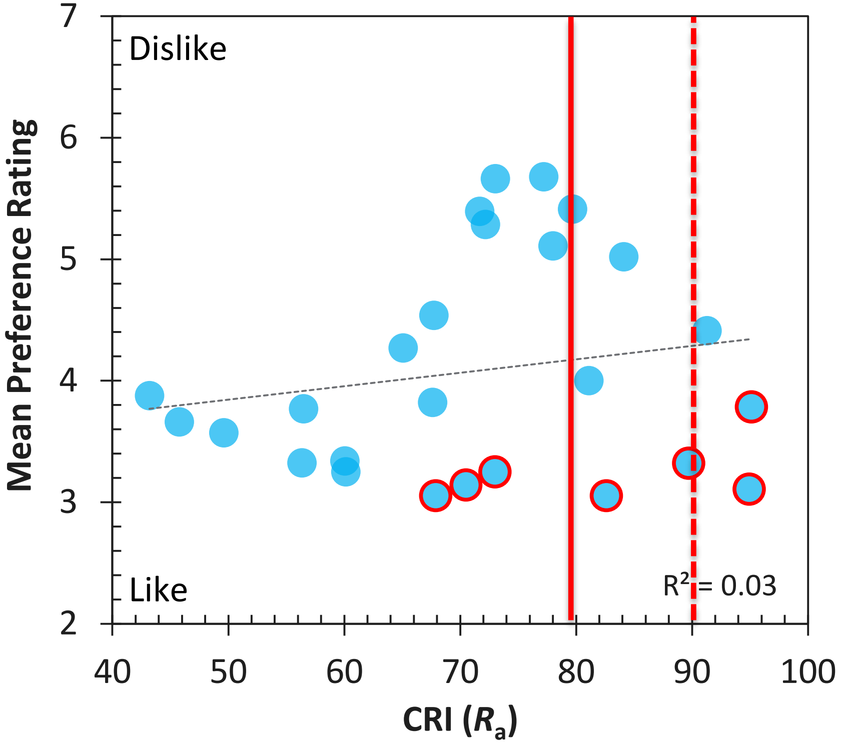
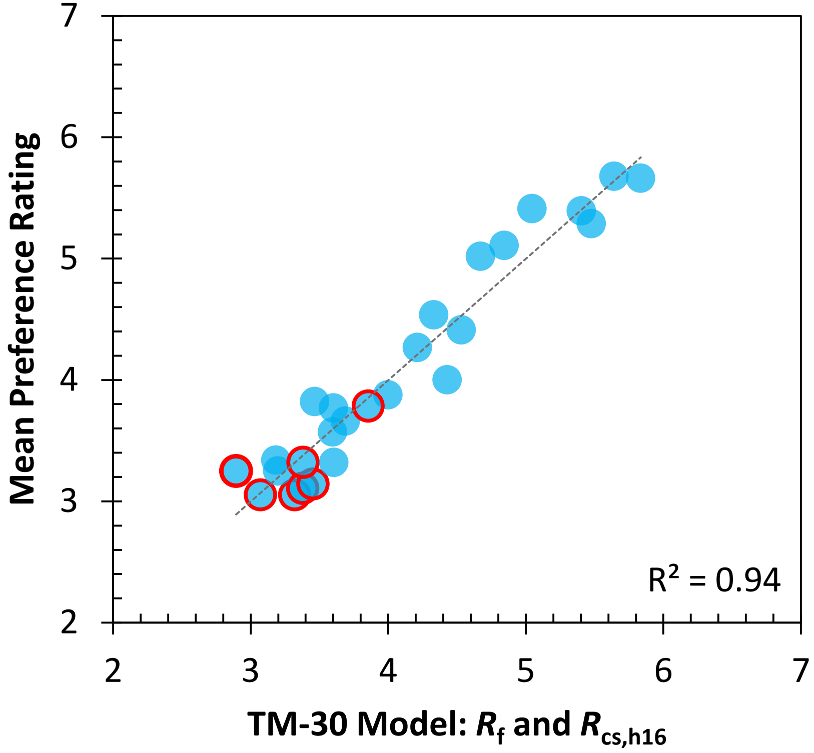
	OUT WITH THE OLD…	IN WITH THE NEW…
“Good”	CRI ≥ 80 ($R_9 \geq 0$)	$R_f \geq 70$ $-12\% \leq R_{cs,h1} \leq 18\%$ $R_g \geq 88$
“Better”	CRI ≥ 90 ($R_9 \geq 50$)	$R_f \geq 78$ $-7\% \leq R_{cs,h1} \leq 15\%$ $R_g \geq 98$
“Best”		$R_f \geq 78$ $-1\% \leq R_{cs,h1} \leq 9\%$ $R_g \geq 100$





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.





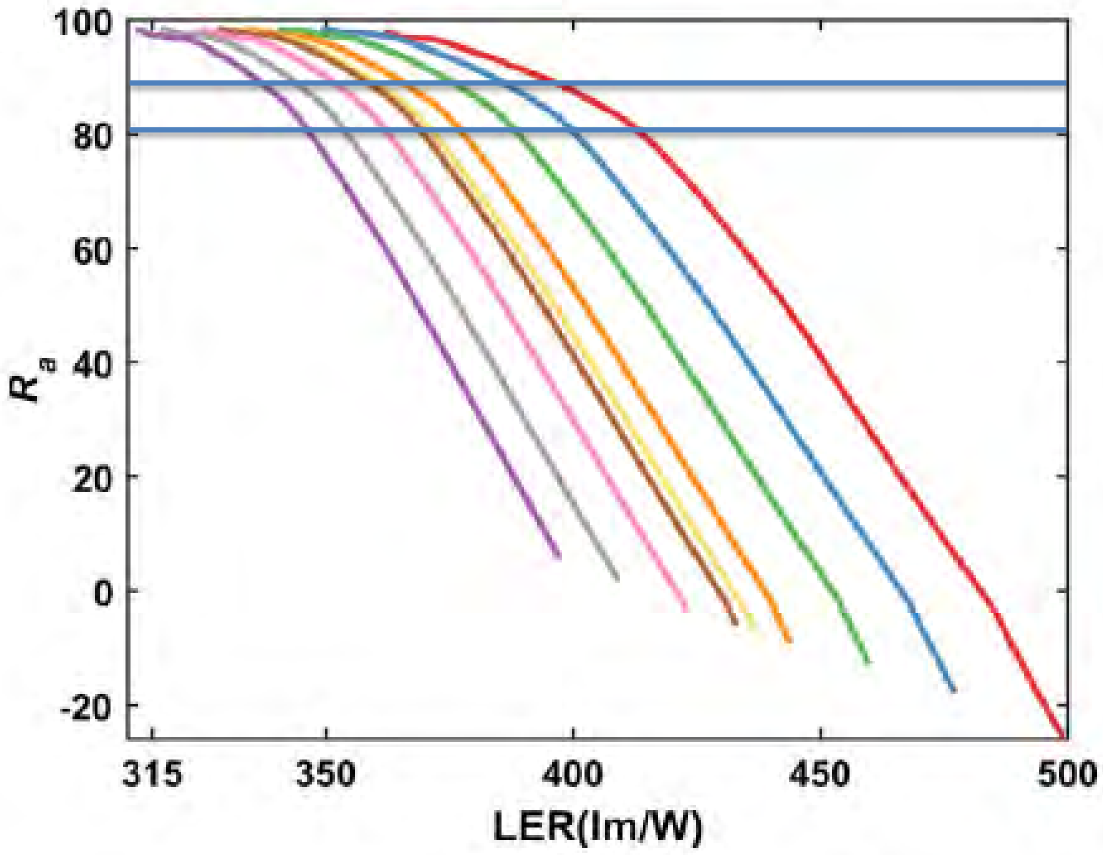
$R_f \geq 78$

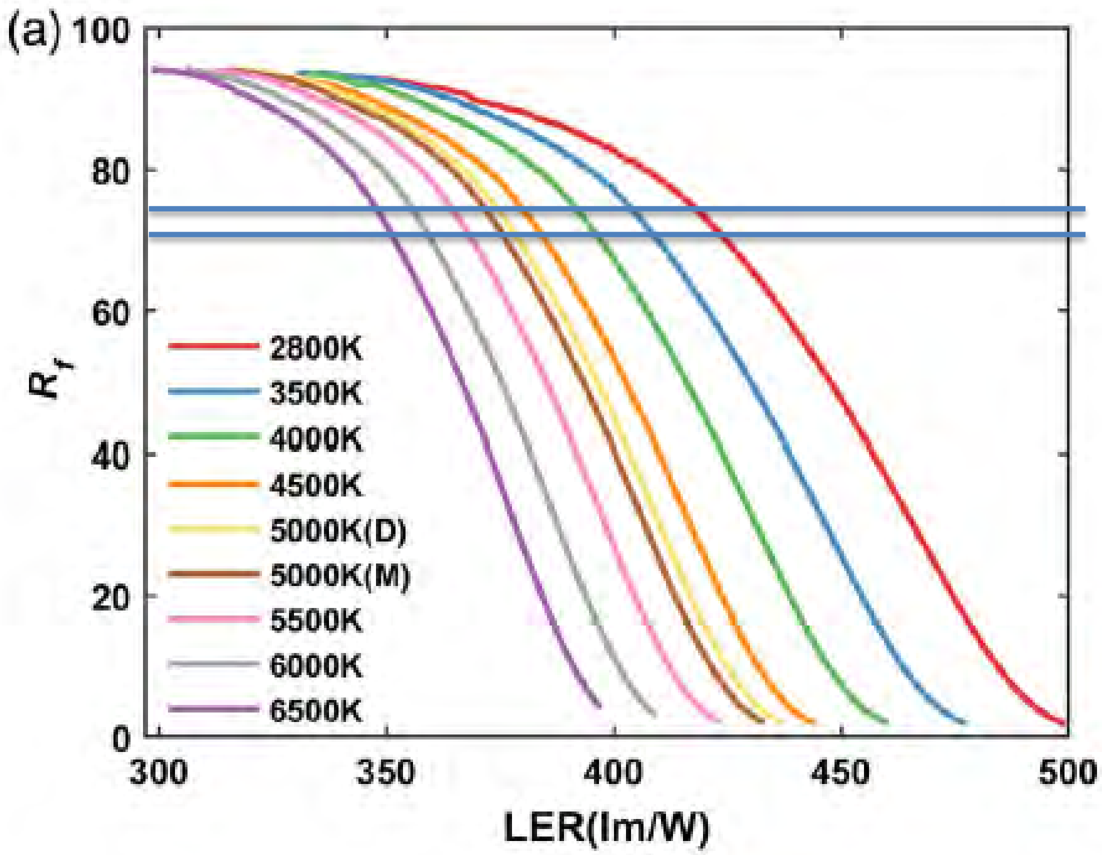
$-7\% \leq R_{cs,h1} \leq 15\%$

$R_g \geq 98$

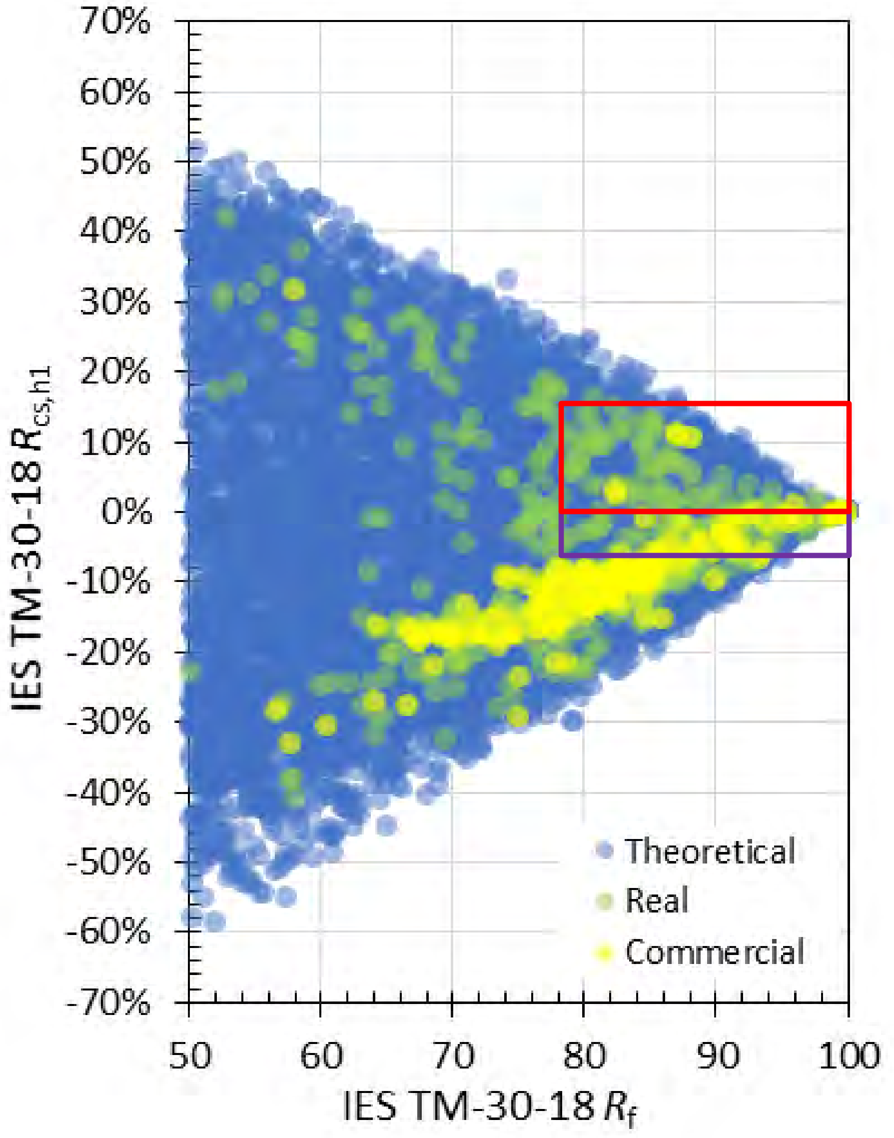
Royer M, Wilkerson A, Wei M. 2017b. Human Perceptions of Color Rendition at Different Chromaticities. Lighting Research & Technology. Online before print. DOI: 10.1177/1477153517725974.

Another reason not to restrict color fidelity:





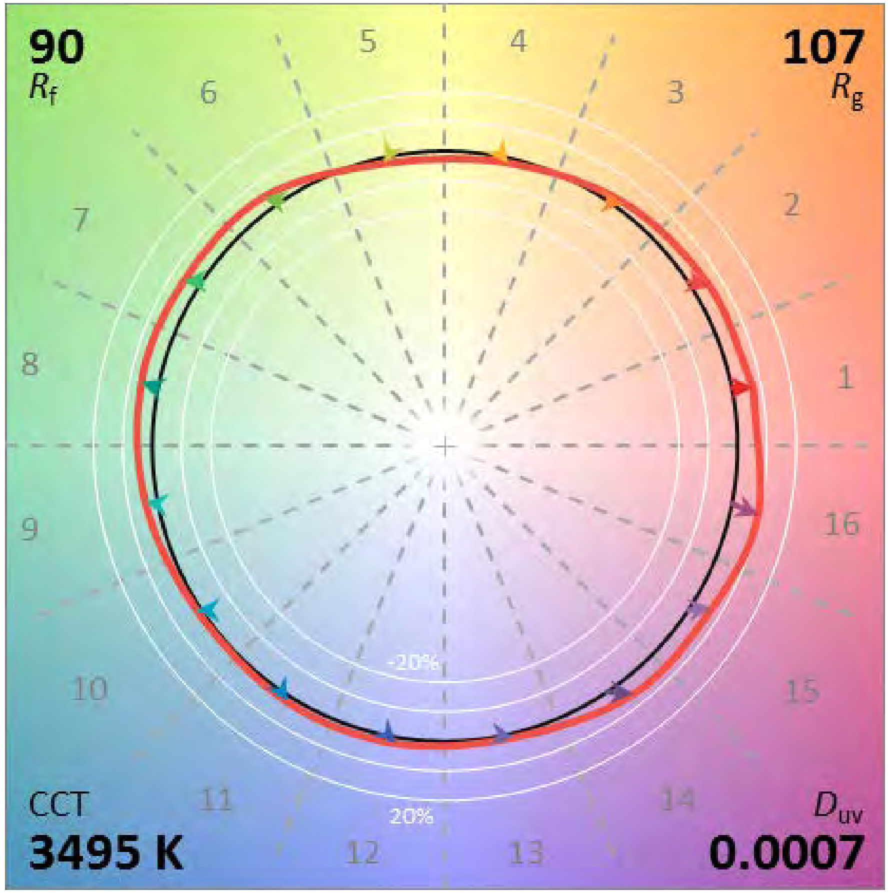
Zhang F, Xu H, Wang Z. 2017. Optimizing spectral compositions of multichannel LED light sources by IES color fidelity index and luminous efficacy of radiation. Applied Optics 56(7):1962-1971.



Products from TM-30-15 Library:

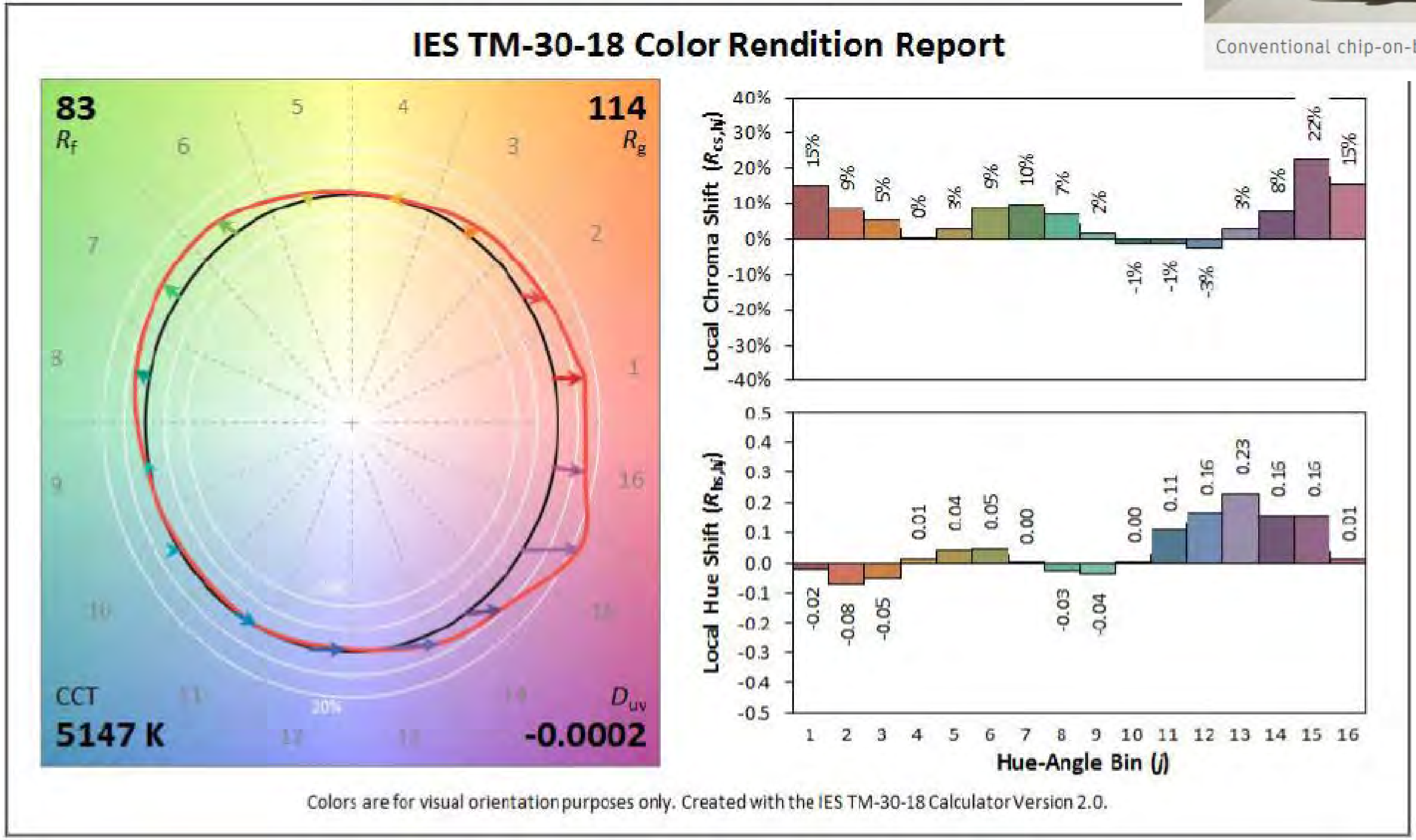
A. High Fidelity (R_f 90+) PC LED
   Some Hybrid (PC+R) LED
   Neodymium Incandescent
   Incandescent/halogen
   Some Specialty HID
B. Additional PC-LED (R_f 85+)
   Additional Hybrid LED (PC+R)

New products beginning to emerge…



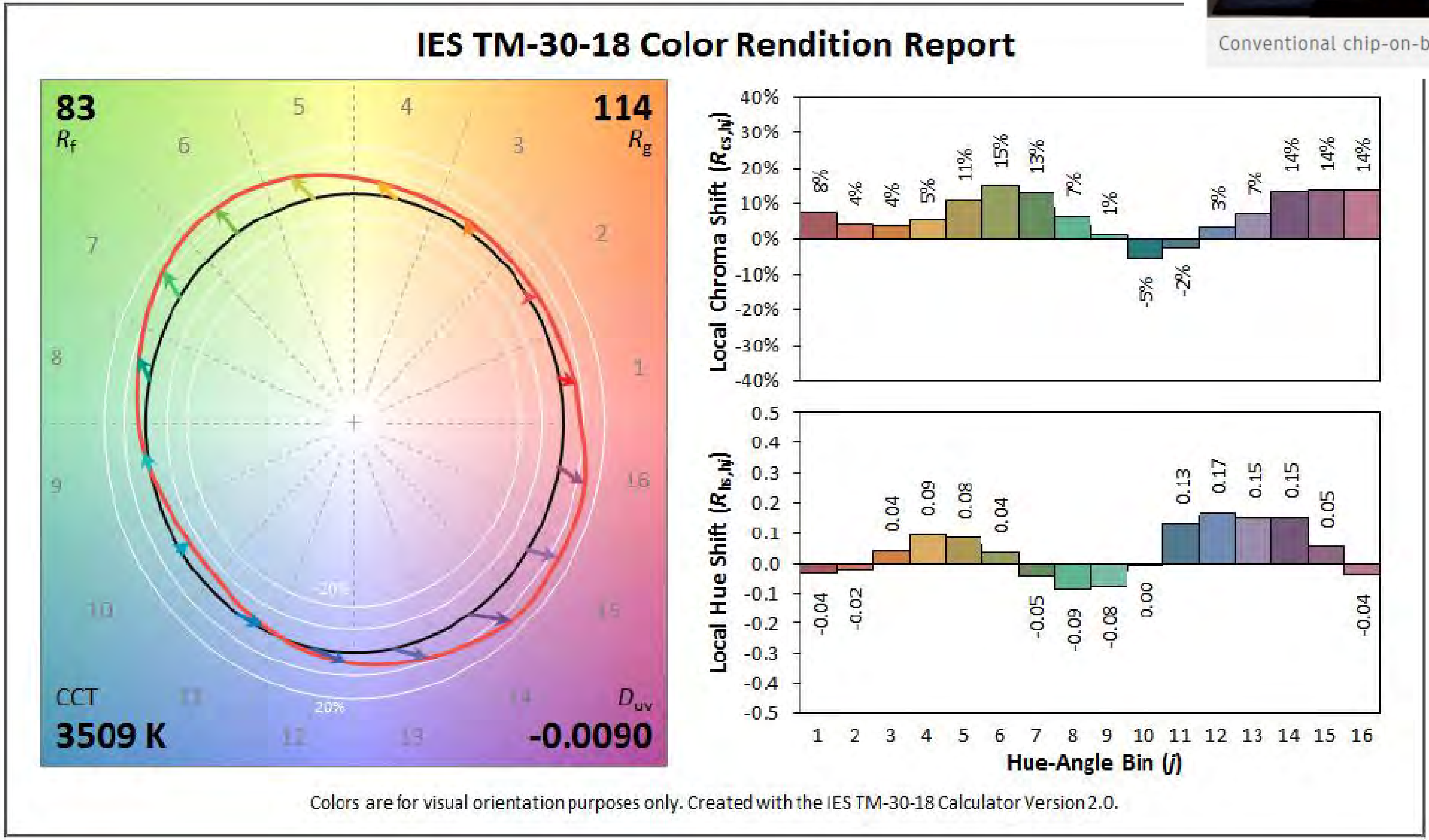
http://www.focalpointlights.com/PreferredLight

Conventional chip-on-board LED lighting (left) and “D-series Special Color”.

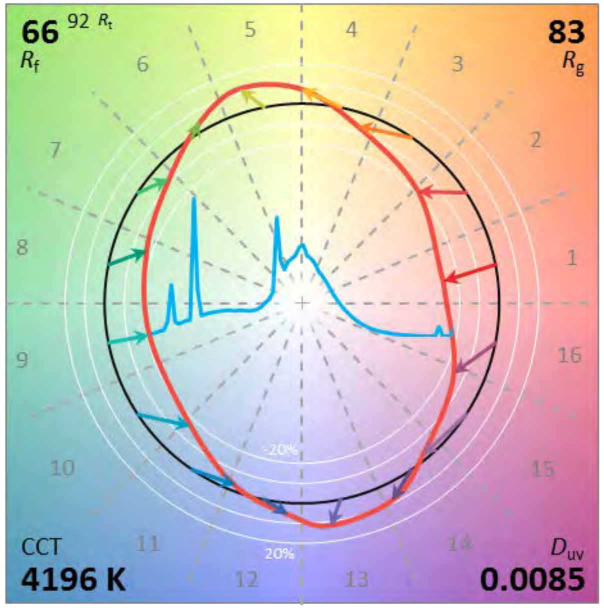


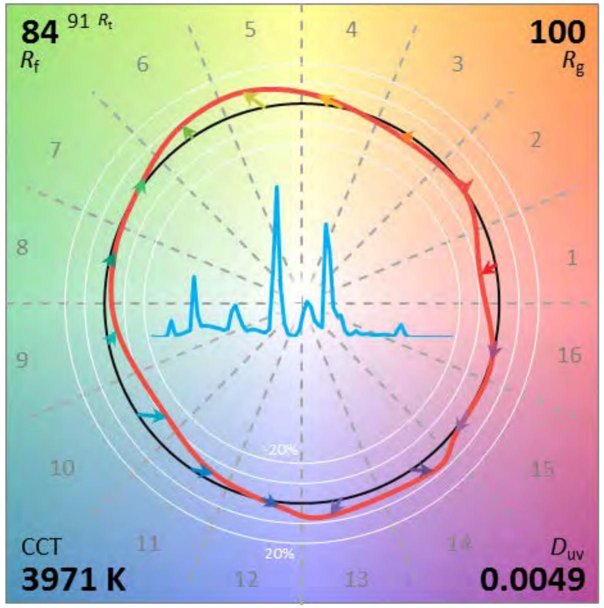
https://news.samsung.com/global/samsung-introduces-chip-on-board-led-packages-optimized-for-commercial-lighting

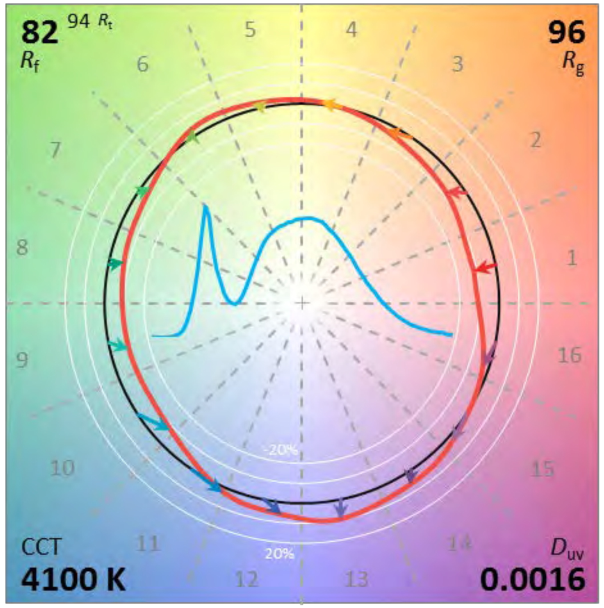
Conventional chip-on-board LED lighting (left) and “D-series Special Color”.



https://news.samsung.com/global/samsung-introduces-chip-on-board-led-packages-optimized-for-commercial-lighting


66
92 R_t
R_f
83
R_g
CCT
4196 K
D_{uv}
0.0085
-20%
20%


84
91 R_t
R_f
100
R_g
CCT
3971 K
D_{uv}
0.0049
-20%
20%


82
94 R_t
R_f
96
R_g
CCT
4100 K
D_{uv}
0.0016
-20%
20%

?

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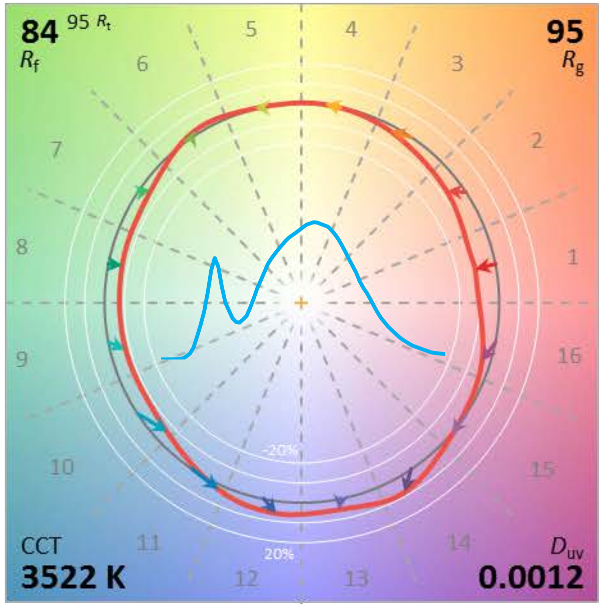
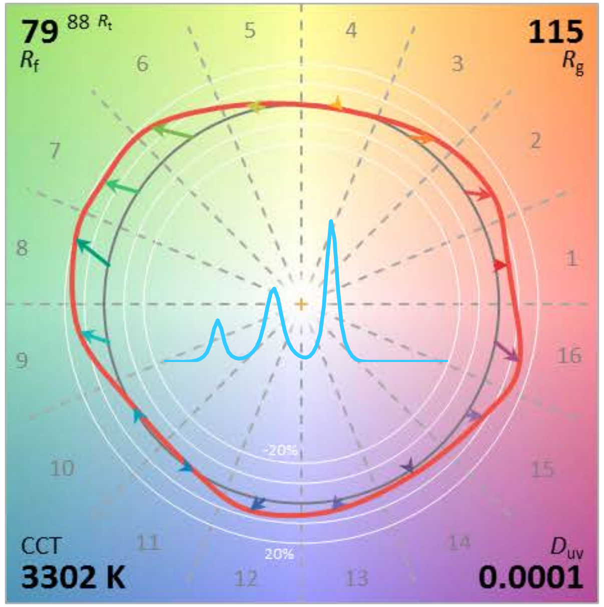
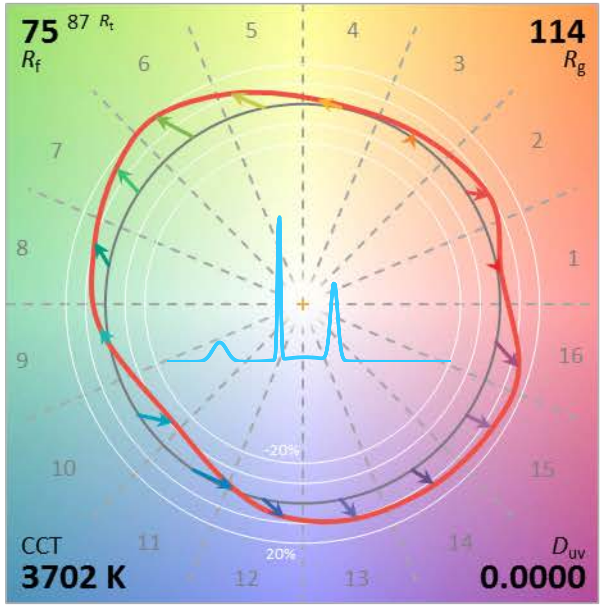
Current	Near Future?	Far Future?
		

Current	Near Future?	Far Future?
Preference = Low	*Preference = High*	*Preference = High*
R_a = 83, R_9 = 23	R_a = 68, R_9 = 78	R_a = 73, R_9 = 80.5
LER = 316	LER = 363	LER = 385

+15% Spectral Efficiency

+22% Spectral Efficiency

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