IES TM-30-15:
A Robust Characterization of Color Rendering

IES San Francisco & the Pacific Energy Center | March 3, 2016

Aurelien David
Soraa, Inc.

Michael Royer
PNNL

Color Rendering…

“Effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant.” (CIE)

The effect of **Light** on **Objects’** appearance**,** as judged by a **Human** observer based on their expectations.

Color Rendering Metrics Help Us To…

Understand.

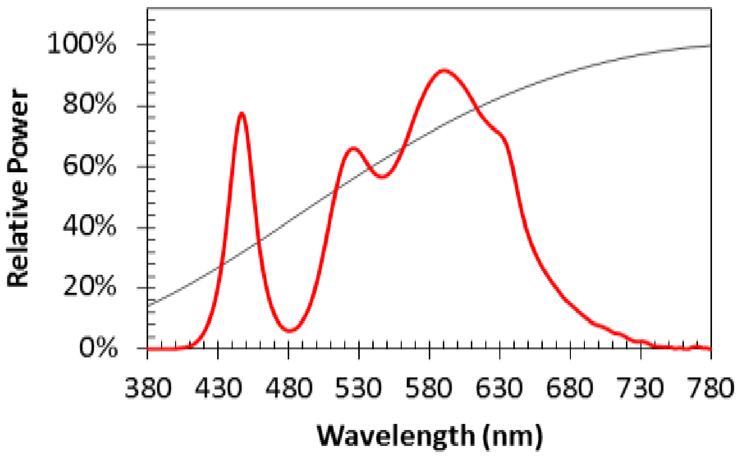
Communicate.

Engineer.

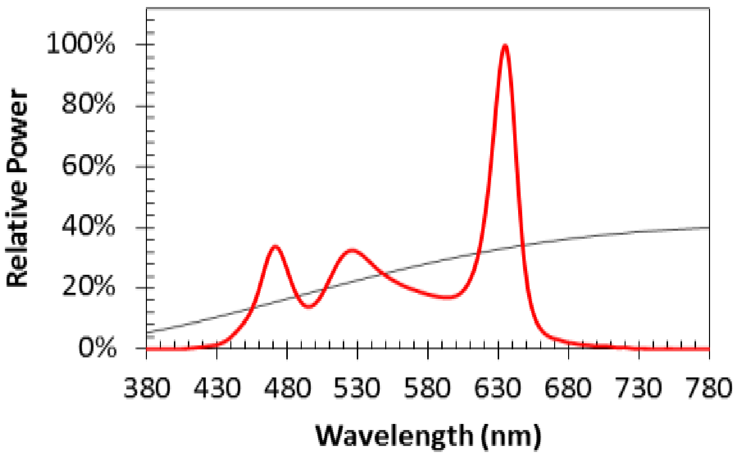
Compare.

Predict.

Which do you prefer?

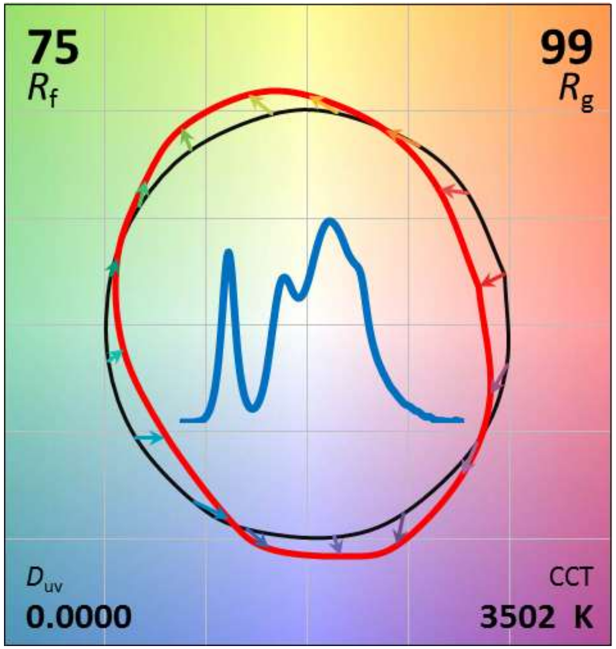


R_a (CRI) = 78
R_9 = -11

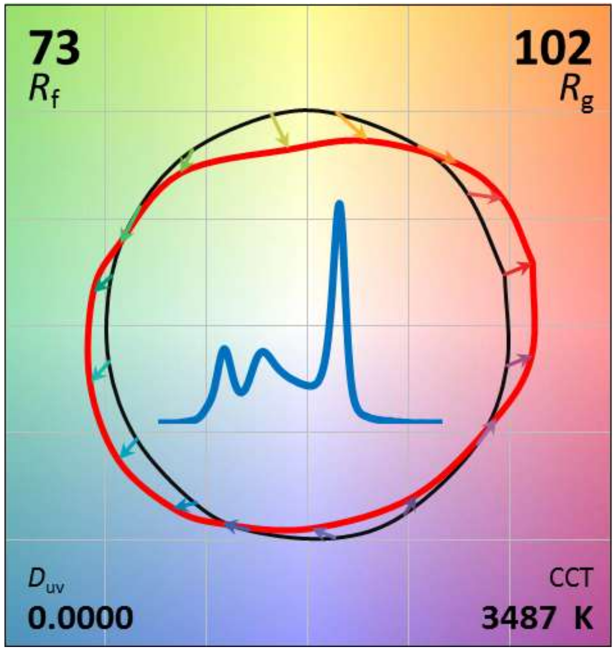


R_a (CRI) = 68
R_9 = -37

Which do you prefer?



R_a (CRI) = 78
R_9 = -11



R_a (CRI) = 68
R_9 = -37

Outline

1. Color Science Fundamentals
2. Quantifying Color Distortions, the CRI
3. TM-30
    - TM-30 Outputs
    - [Questions]
    - TM-30 Technical Details
4. Demonstration and Research Results
5. Case Studies

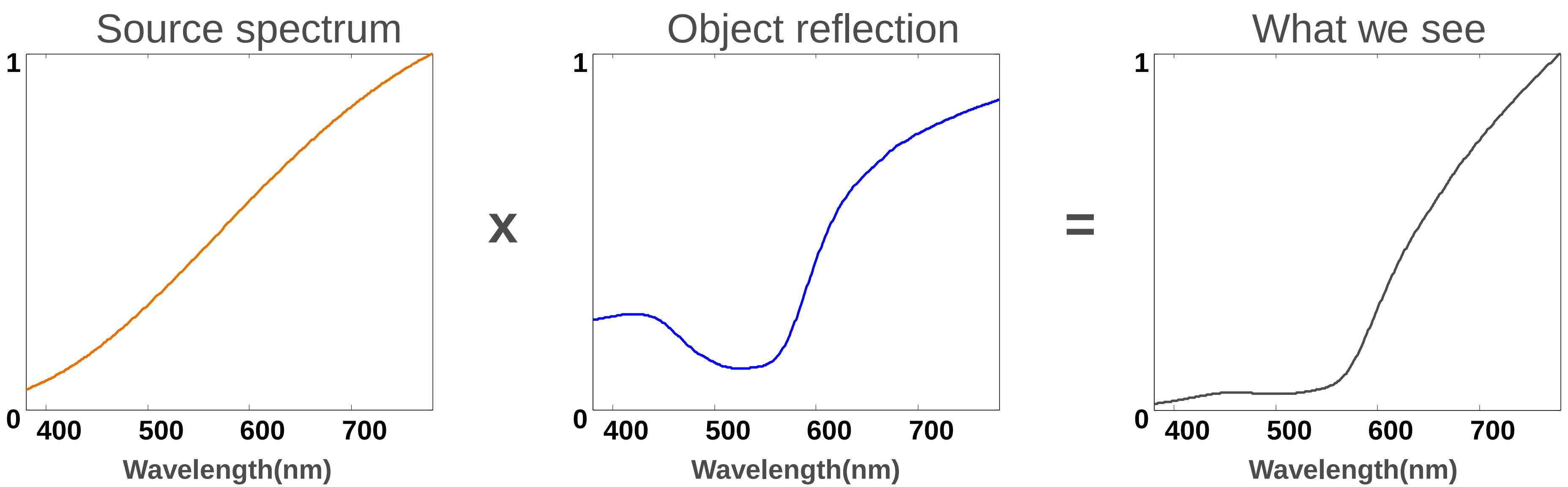
    [Questions]

Part 1:

Color Science Fundamentals

Object colors

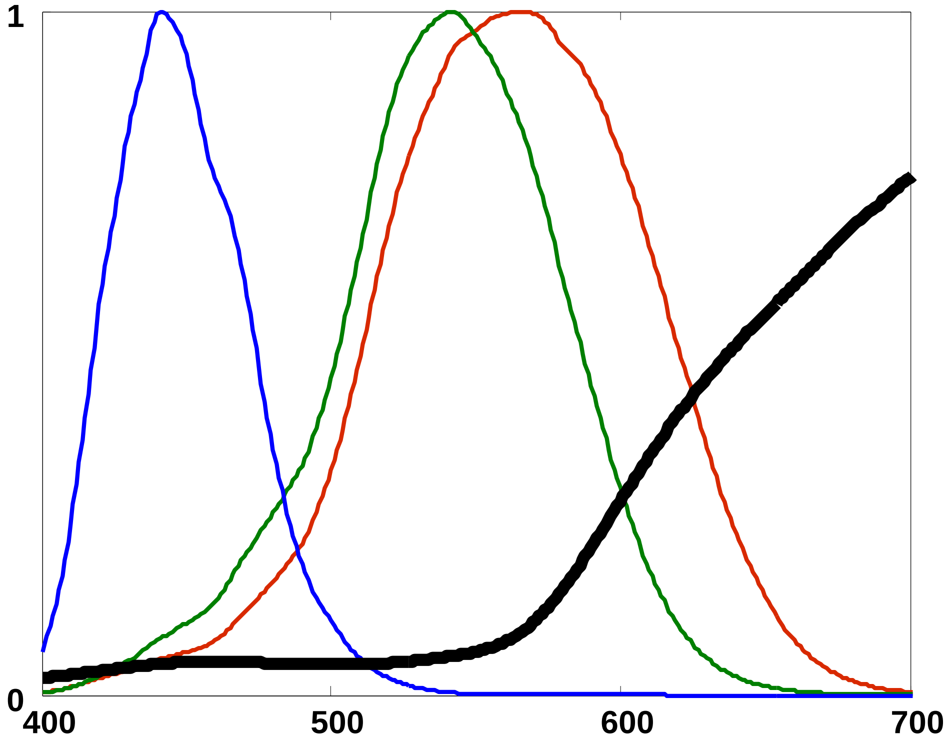
The colors we see come from light reflected by objects



Object colors

These spectra are reduced to “three numbers” by the three cone sensors in our eyes (similar to an RGB digital camera)

→ Each object is assigned three values which make up its color

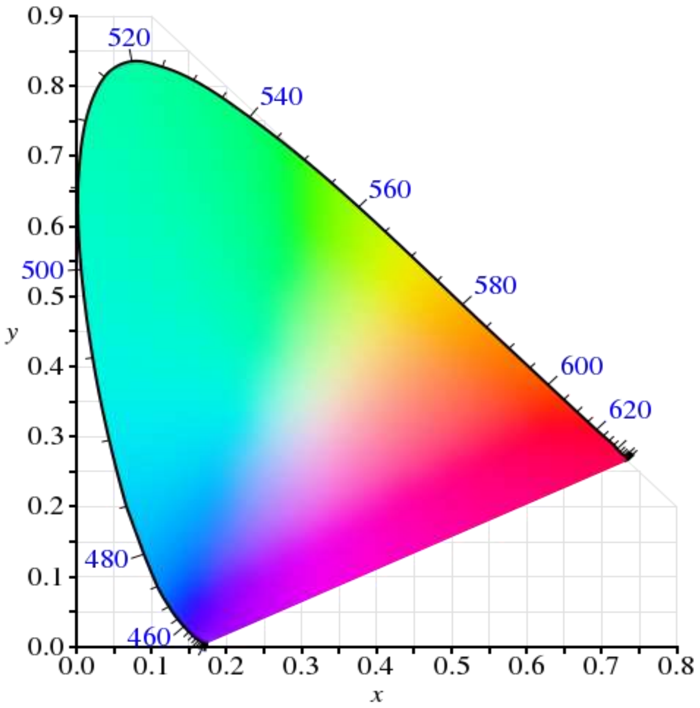


Color space

A color space is a 3-dimensional space which corresponds to visual stimuli

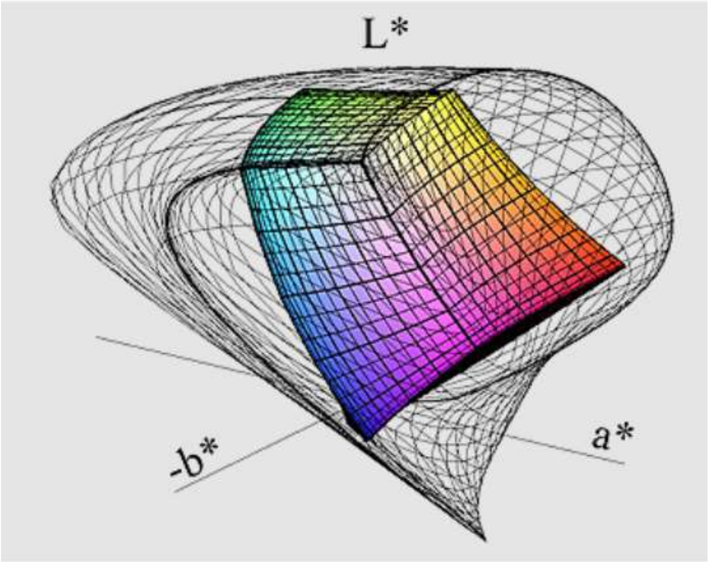
→ Mathematical model attempting to describe our visual system…

"Source color space" – characterizes the color of a light source



CIEXYZ

"Object color space" – characterizes the color of objects under a light source

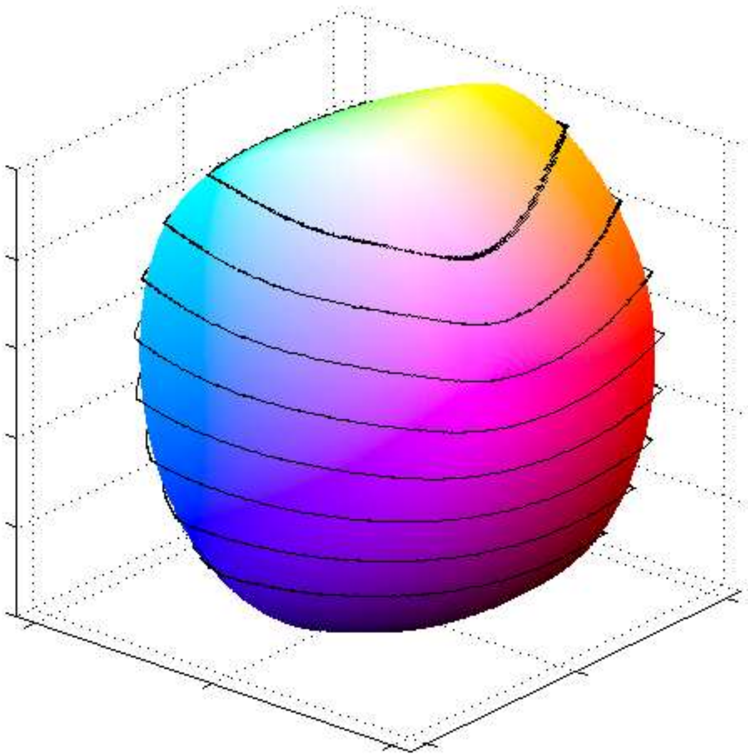


CIELAB

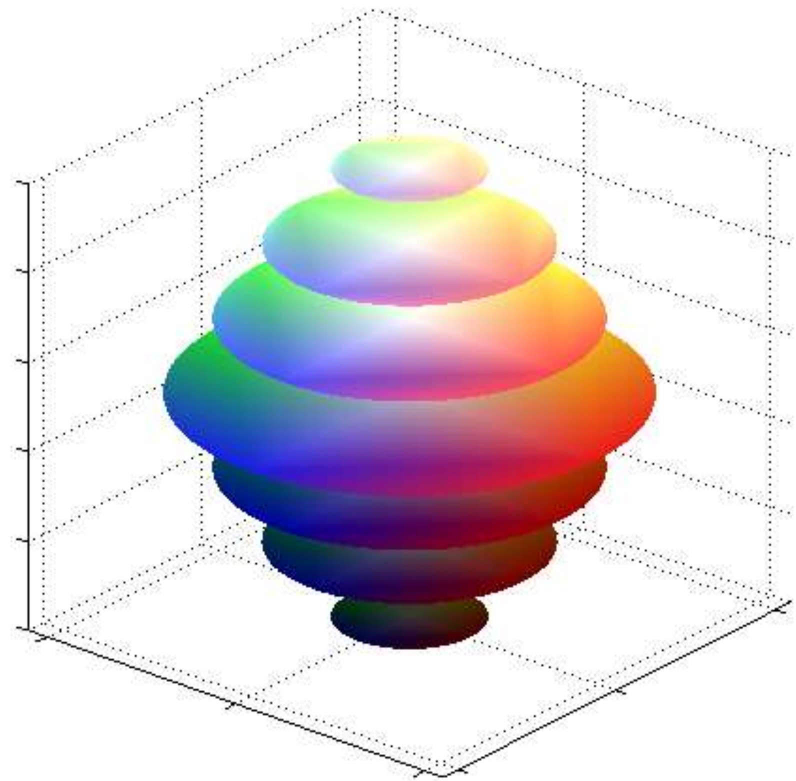
Object Color space

An “object color space” is a 3-dimensional space where the colors of objects can be placed

Color volume

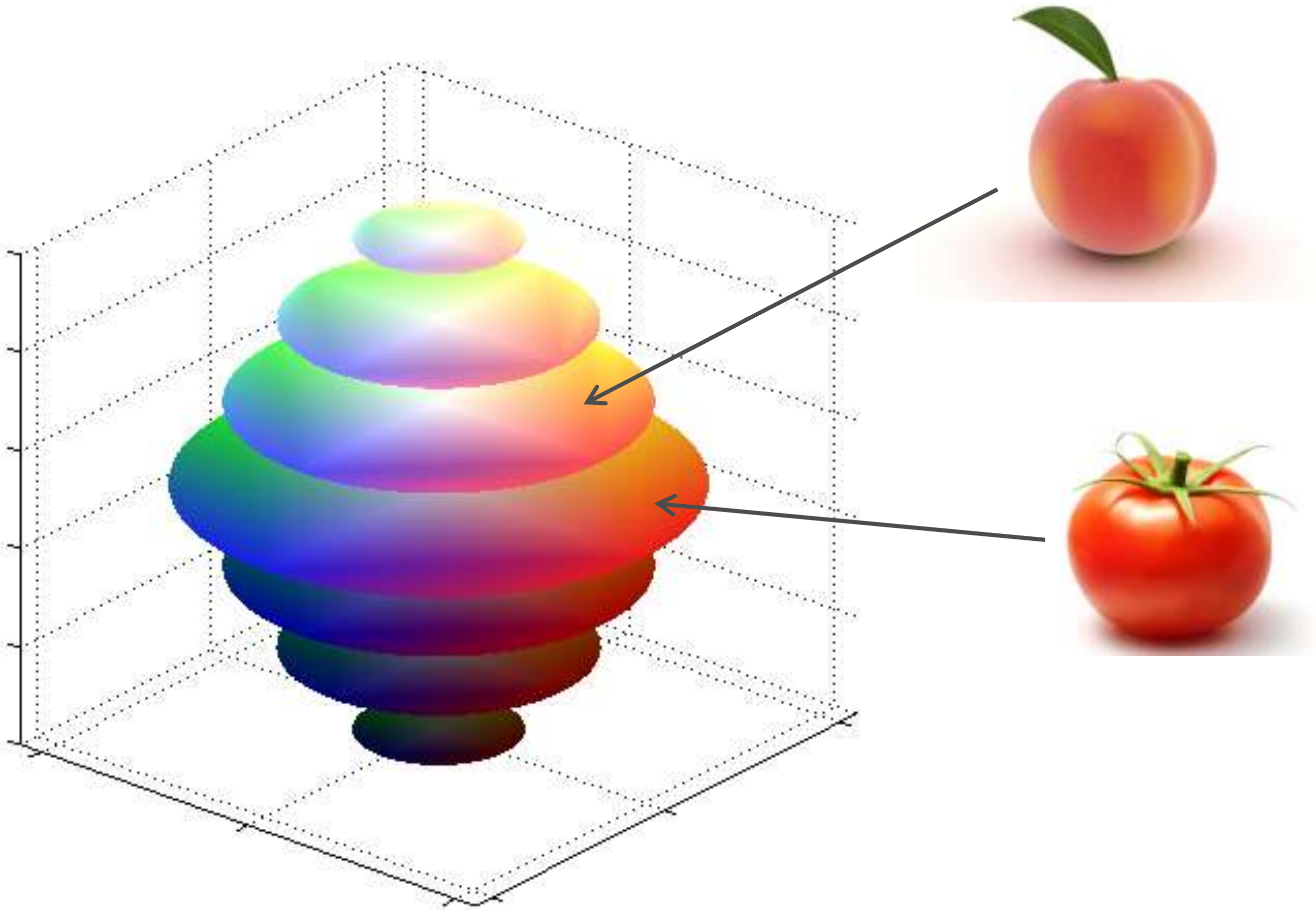


“slices” in the color volume



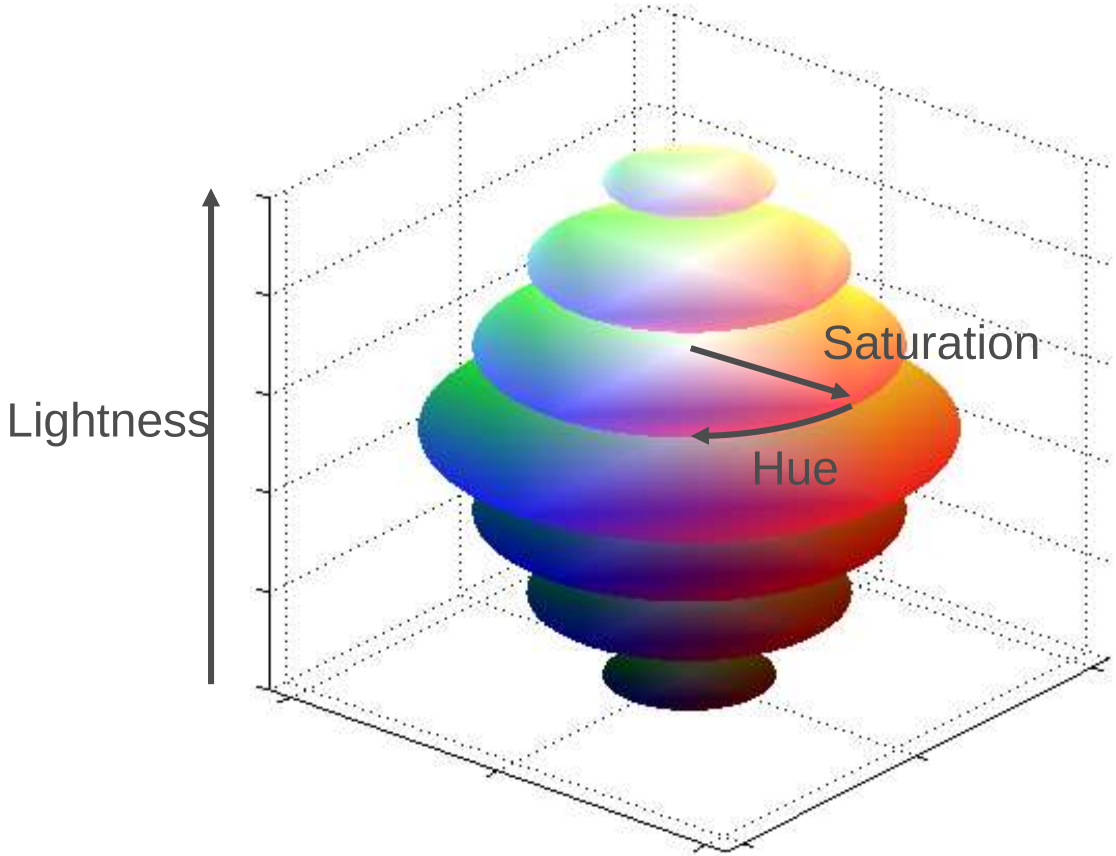
Object Color space

An “object color space” is a 3-dimensional space where the colors of objects can be placed



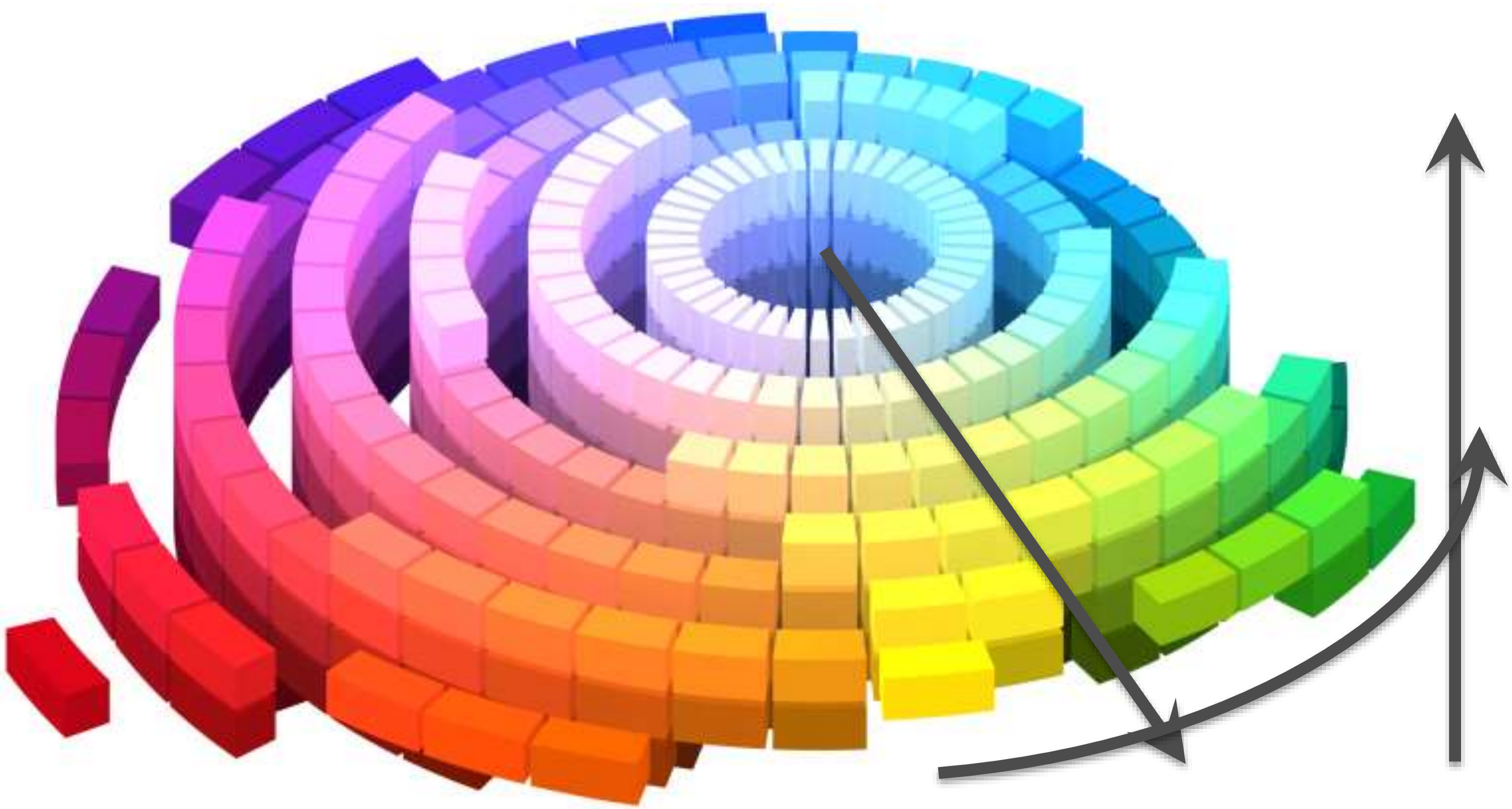
Object Color space

An “object color space” is a 3-dimensional space where the colors of objects can be placed



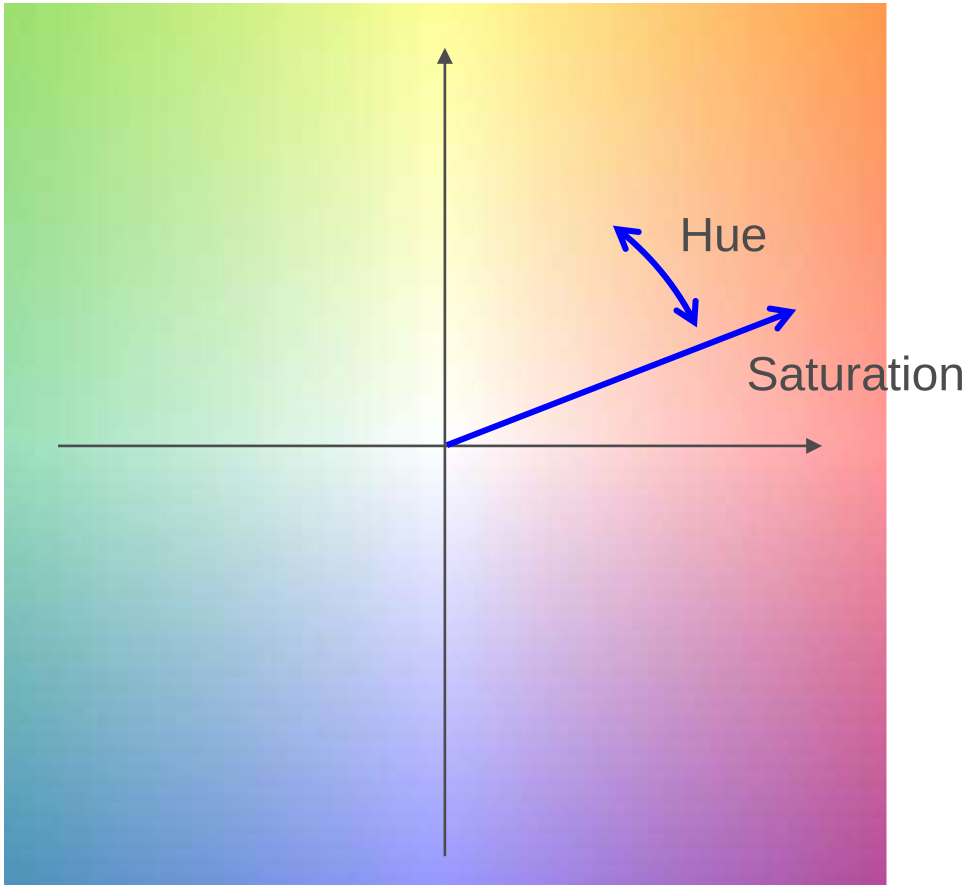
Object Color space

[illegible]

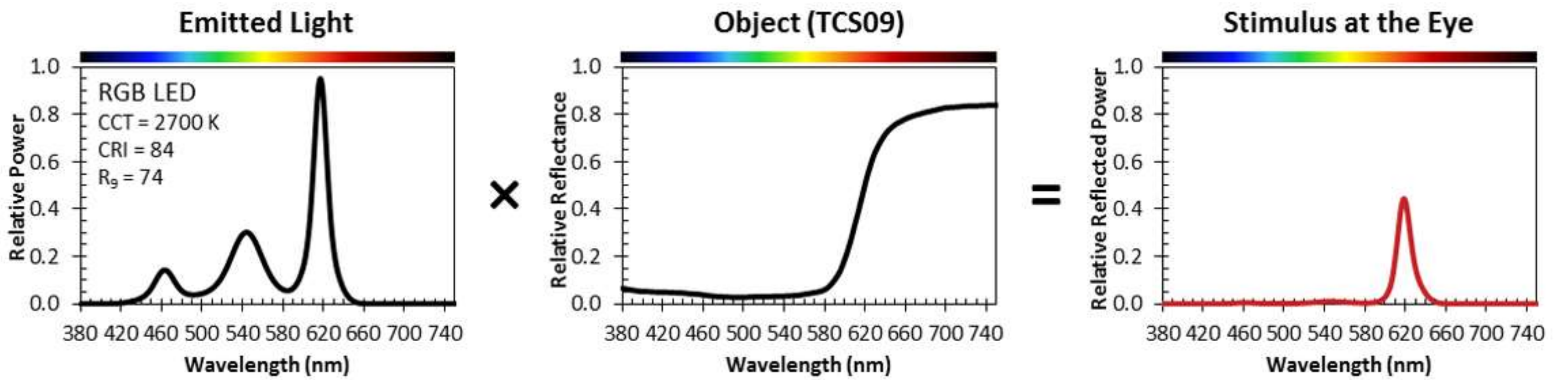


Object Color space

2-dimensional plot (“seen from above”)



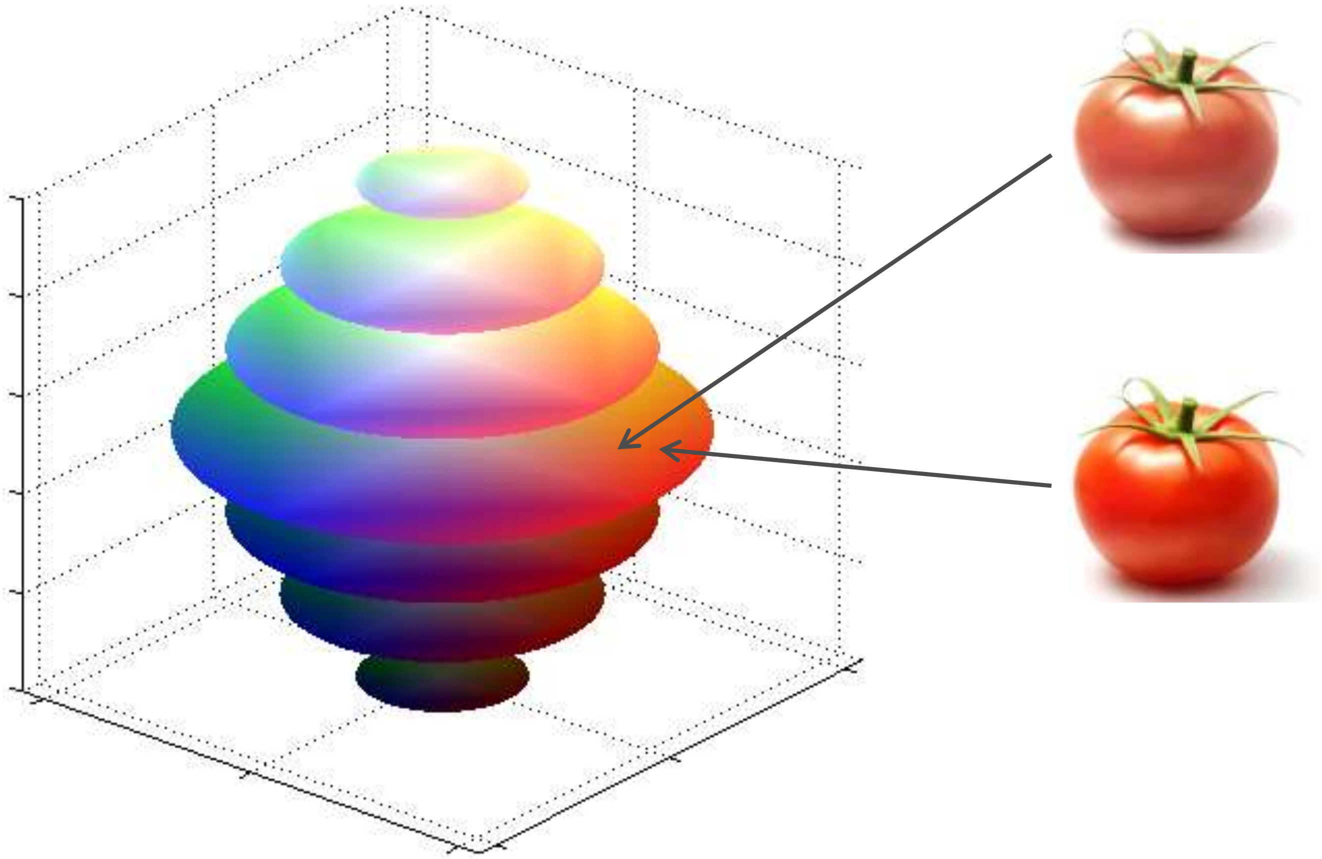
Colors and light sources



For the same object: different light sources create different stimuli

Colors and light sources

Different light sources can change the way we see colors…



Color rendition = quantify this effect

Basics on color rendition - Summary

- The perceived colors of objects are “coded” by three values in our visual system

- There are a variety of color spaces which attempt to approximate our visual system

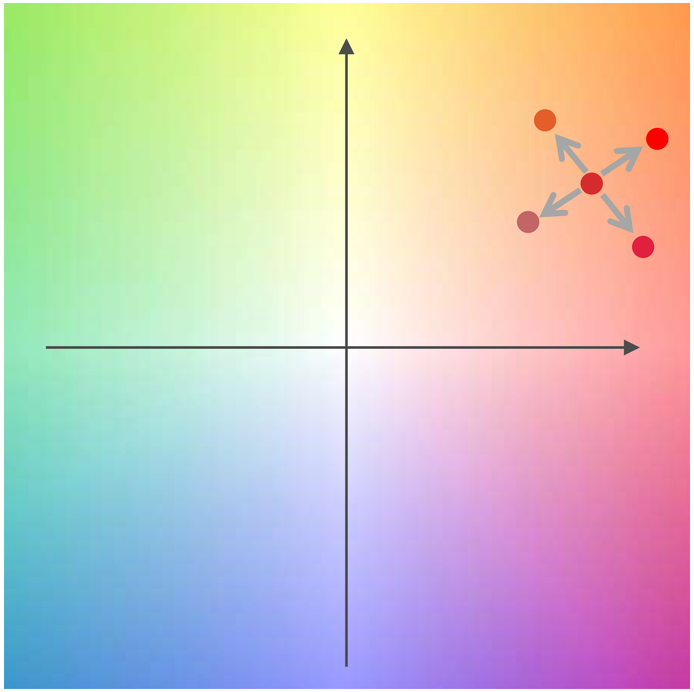
- Colors can be characterized by hue + chroma + lightness

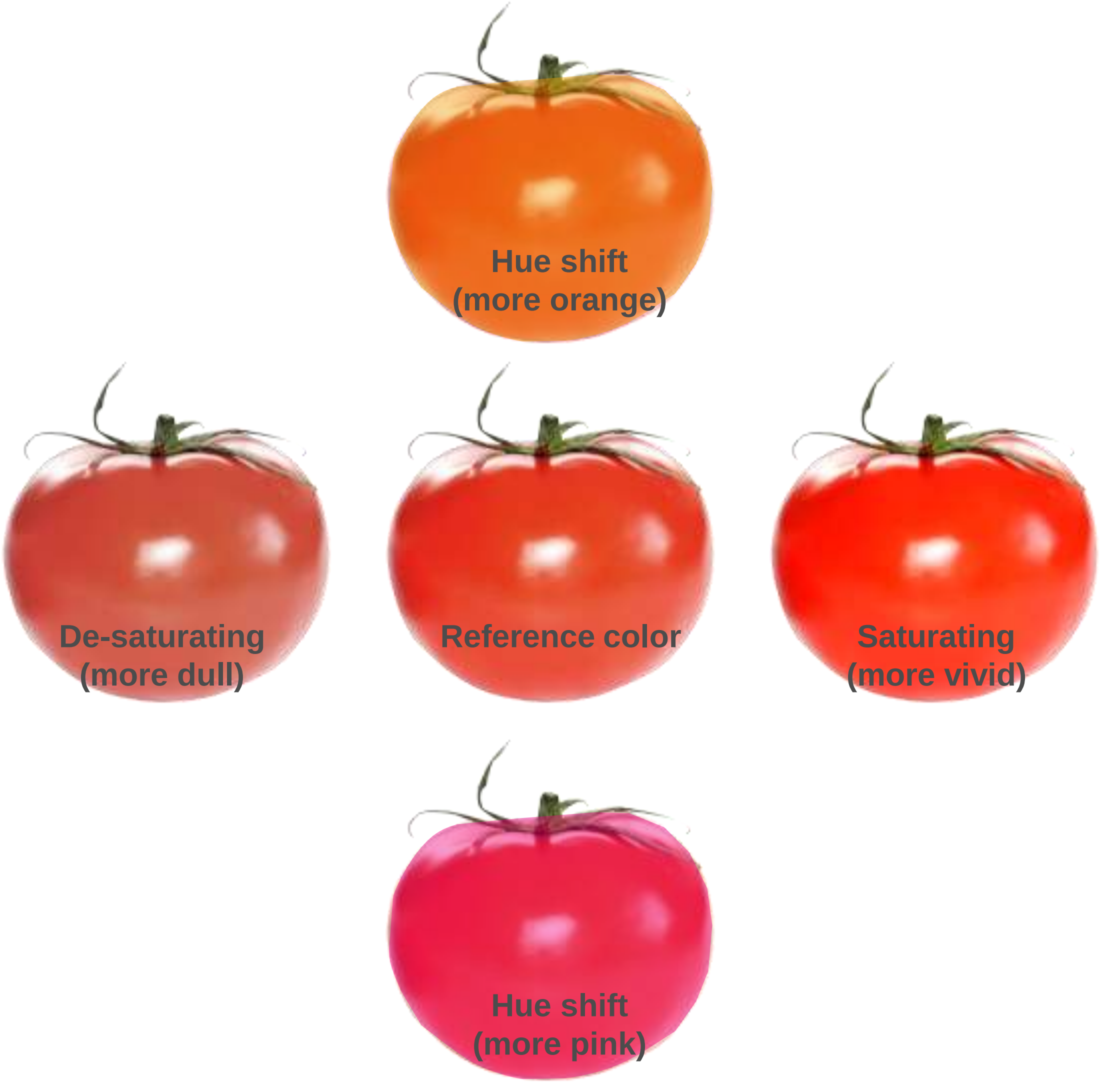
- Different light sources can render the color of an object differently

Part 2:

Quantifying color distortions - the CRI

Colors shifts (e.g. color distortions)





Color shifts

What does “reference color” mean?

It is the color of an object illuminated by a reference light source.

Ok then… what does a “reference light source” mean?

By convention, here is what we call reference light sources:

- sunlight (for CCT > 5000K)

- incandescent/halogen lamps (for CCT < 5000K)

In all color rendering calculations, we pick a reference light source and compare it to the source we want to test.

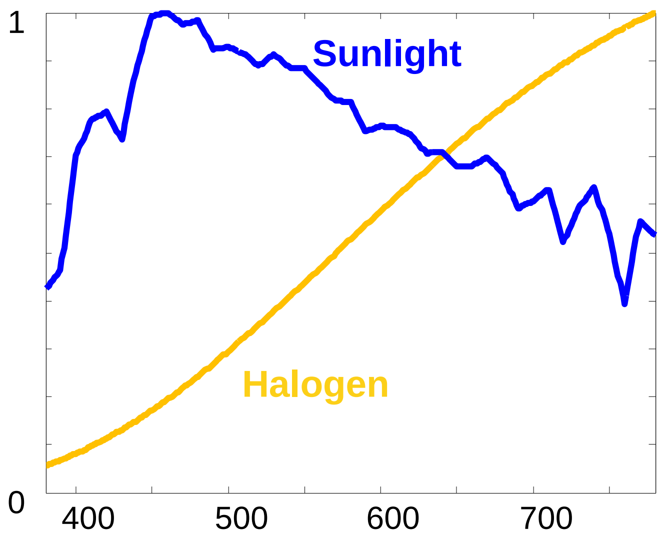
In the case of warm white, the reference is incandescent / halogen.

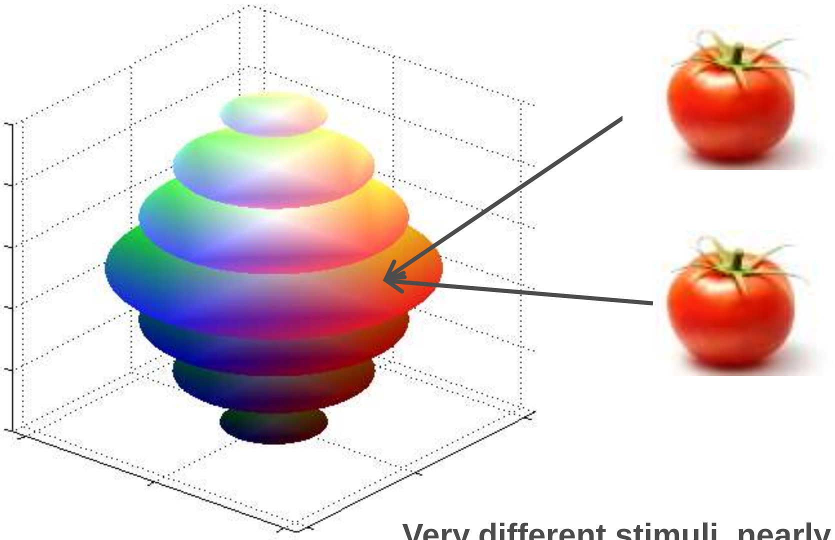
“Reference colors”?

Incandescent bulbs and sunlight have very different spectra!

But – an object seen under either source usually has nearly the same color

Our brains compensate for the change in source spectrum: “chromatic adaptation”





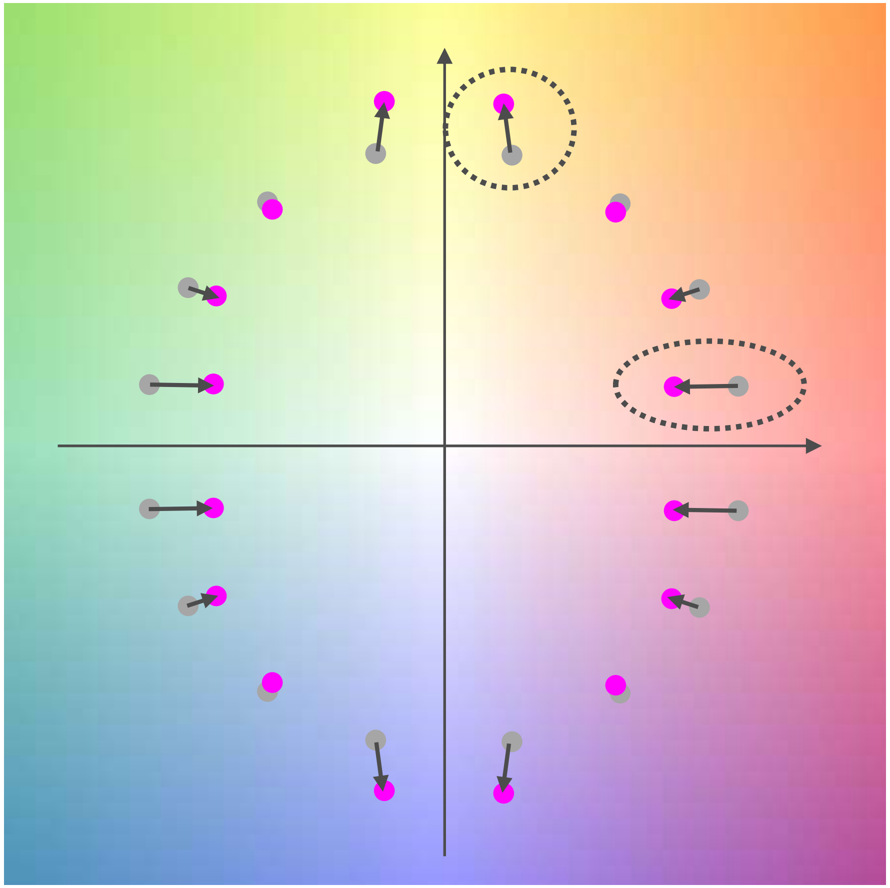
Very different stimuli, nearly the same coordinates in object color space

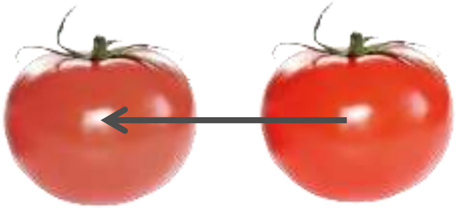
Without chromatic adaptation, color vision would not be very useful!

“Reference color” is a reasonable concept

Colors shifts

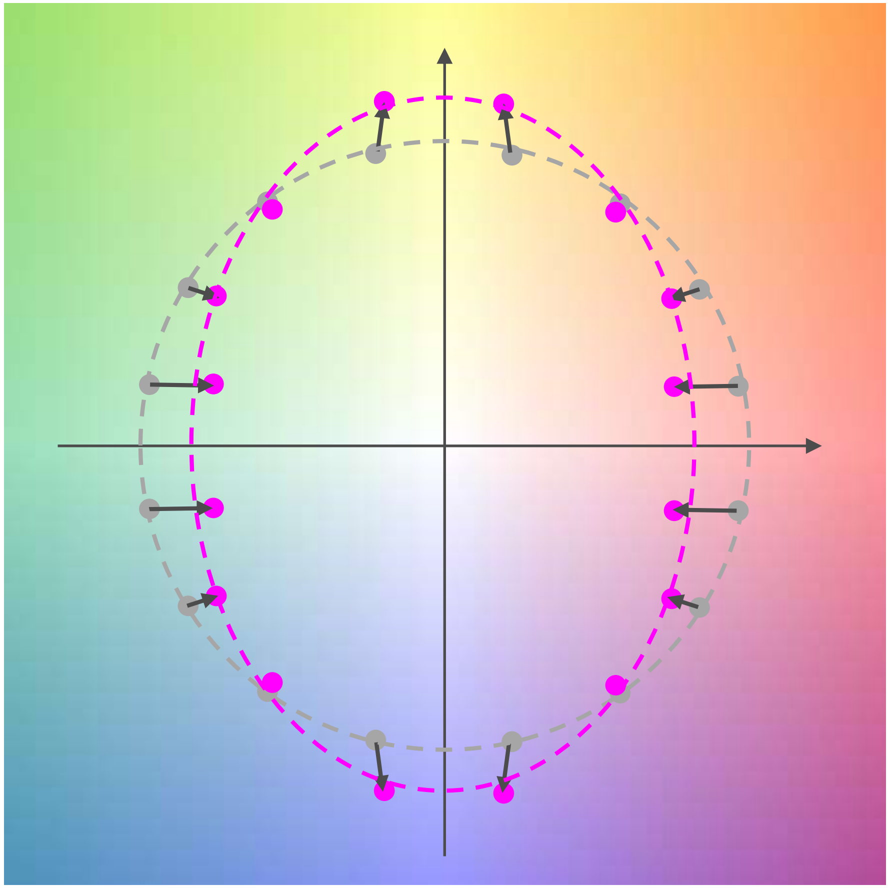
Gray points: reference colors for a series of objects
Pink points: colors under a low-CRI LED source





Colors shifts

Gray points: reference colors for a series of objects
Pink points: colors under a low-CRI LED source



Let’s put a number on these shifts!

CRI

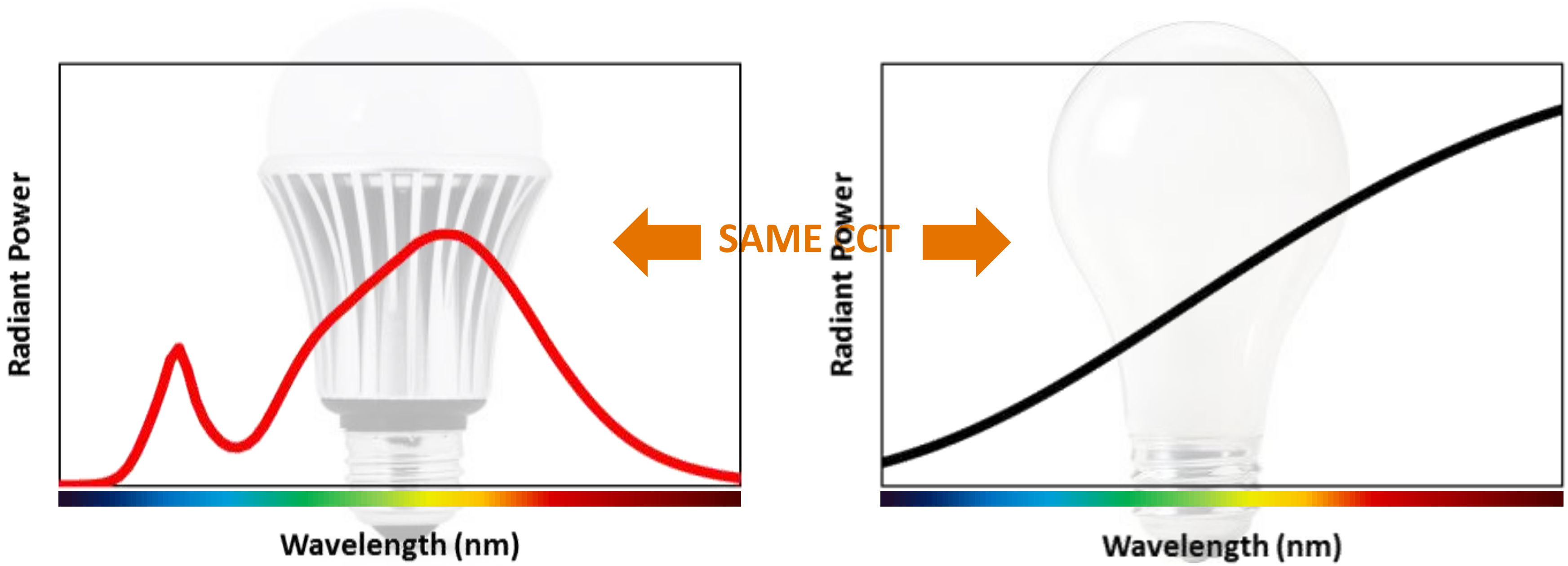
Steps of the CRI calculation:

1. Determine the CCT of the test source.
2. Calculate a reference source at the same CCT
3. Calculate the color of test samples under the test and reference sources
4. Determine the average difference in color for the two sets.

CRI

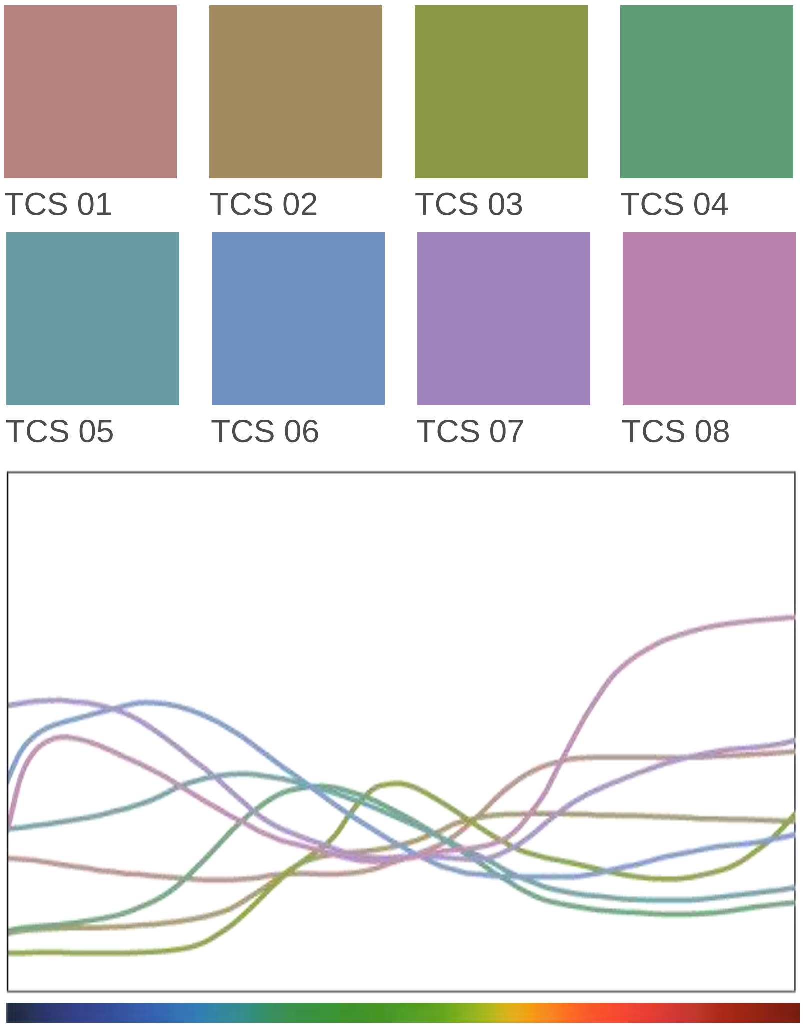
Test Source

Reference Illuminant

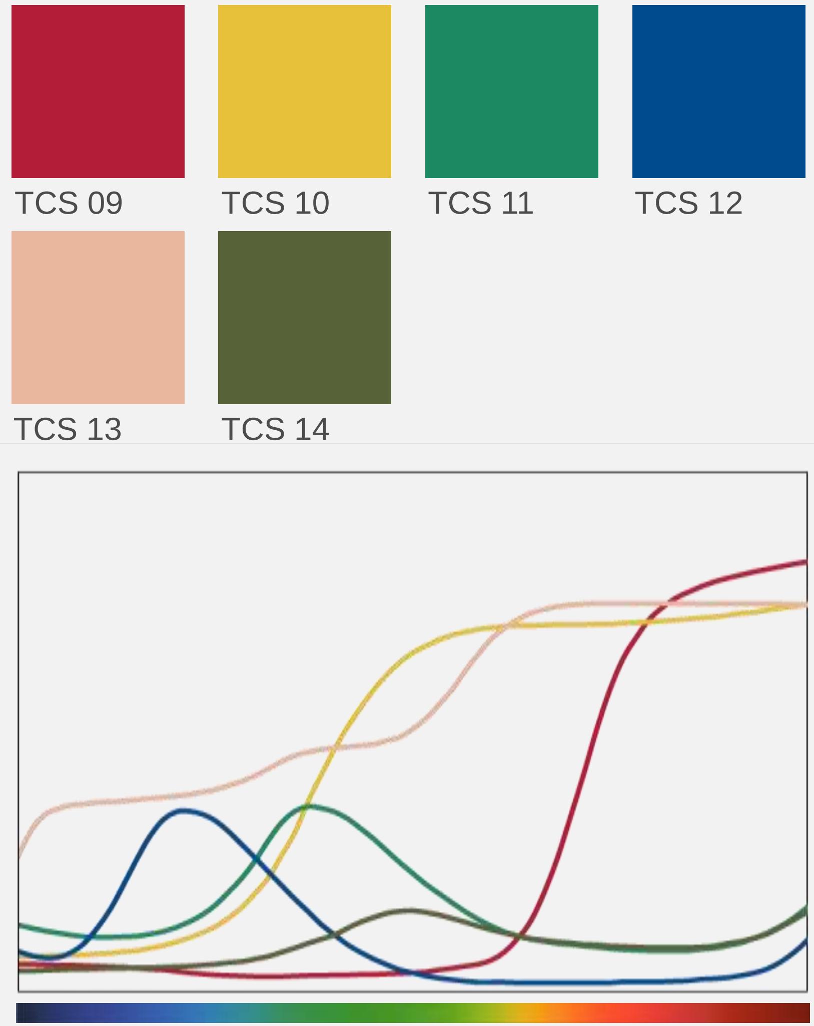


CRI

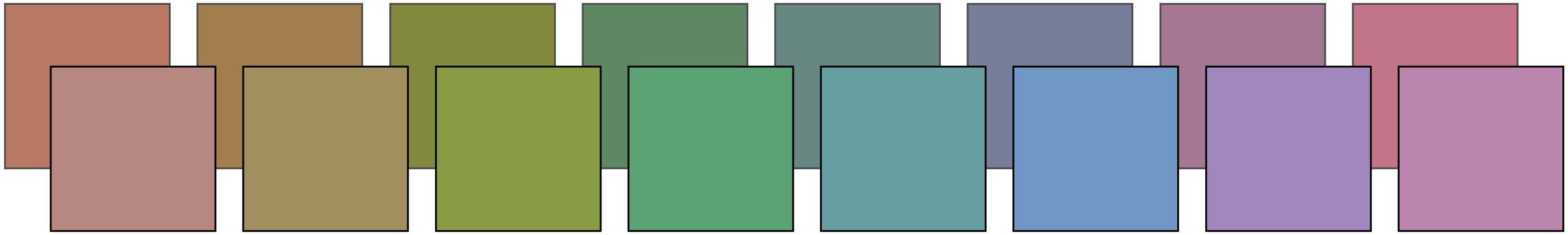
Color Samples for R_a

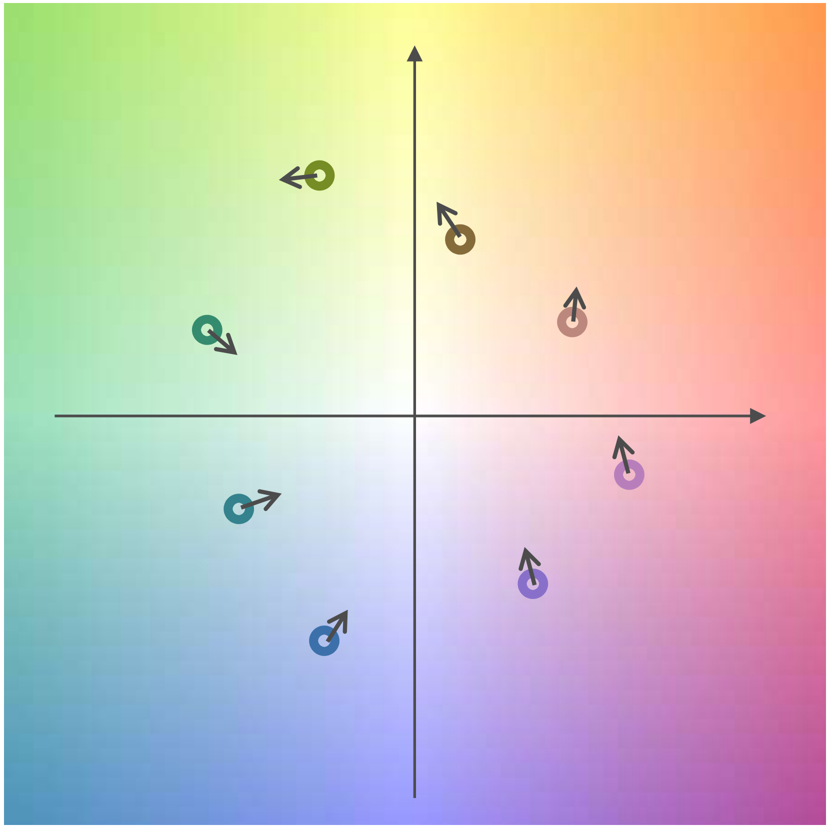


Color Samples for R_9–R_{14}



CRI





Each "color error" lowers the CRI score. The longer the arrow, the lower the CRI score.

The CRI tells us whether a light source renders colors "naturally" [eg like the reference], on average.

$$R_i = 100 - 4.6\mathrm{D}E_i$$

$$R_\mathrm{a} = \frac{1}{8}\sum_{i=1}^{8} R_i$$

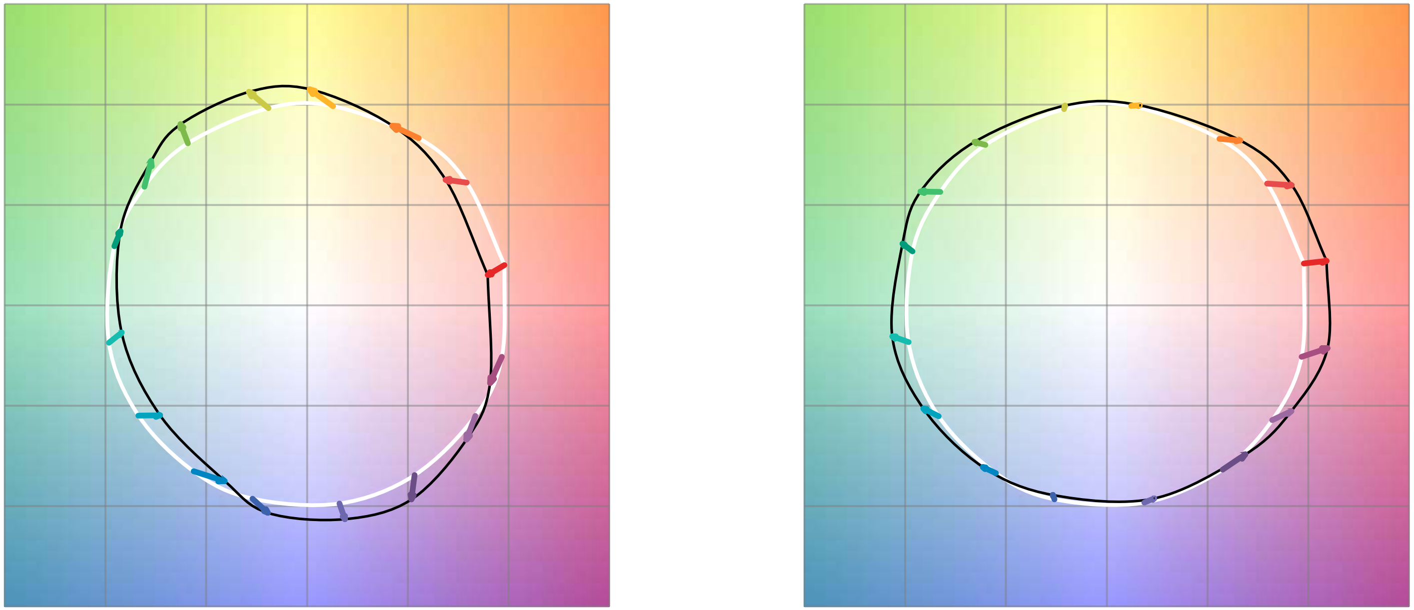
Longer arrows → lower score

What does the CRI tell us?

CRI only measures the average color error (**the average length of the arrows**)
Any error is counted the same, whether it is saturating, de-saturating or hue shift…

CRI is a fidelity metric:

A CRI close to 100 tells us that colors look like the reference colors (high fidelity)
A CRI lower than 100 tells us that colors are distorted, but now *how* they are distorted



Same CRI, very different color distortions! The CRI gives us **limited information.**

What does CRI tell us?

CRI = **average** color error

A given score can correspond to dull-looking or saturated-looking colors!

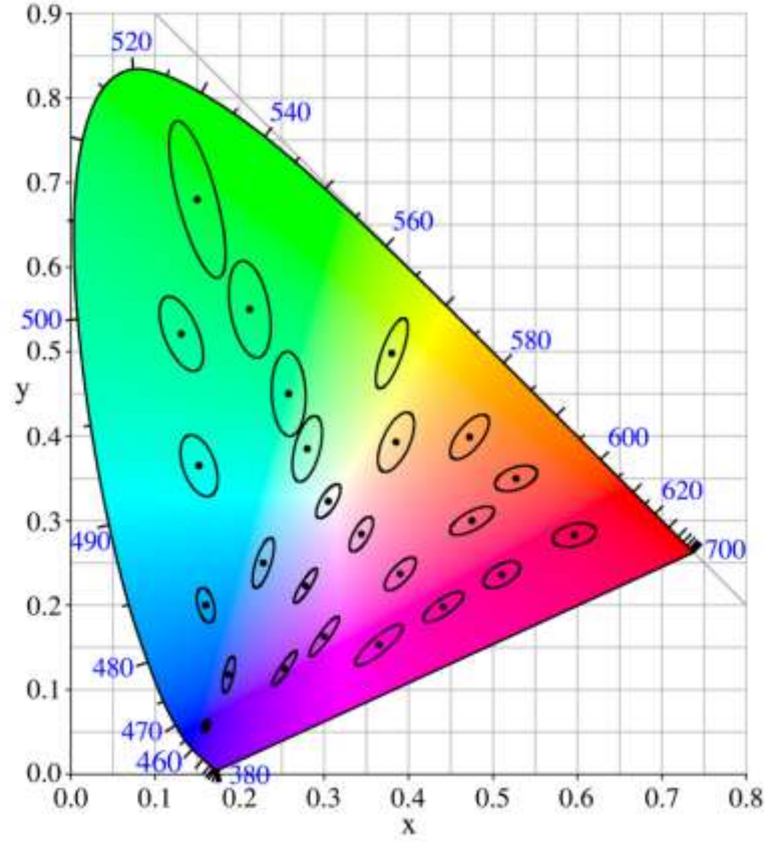
These scenarios are not equally acceptable. People dislike de-saturated colors, but often are ok with over-saturated colors.

Problems with the CRI

Some of the color science used in the CRI is outdated / inaccurate:

- Non-uniform color space

Color distortions are not all weighted equally



Problems with the CRI

Some of the color science used in the CRI is outdated / inaccurate:

- Non-uniform color space

Color distortions are not all weighted equally

- Bad chromatic adaptation

Problems with the CRI

Some of the color science used in the CRI is outdated / inaccurate:

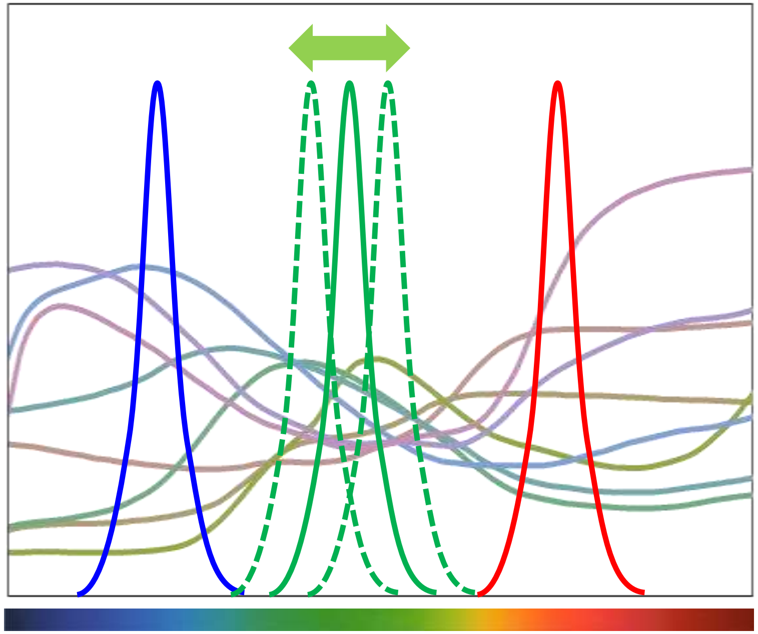
- Non-uniform color space

Color distortions are not all weighted equally

- Bad chromatic adaptation

- Only 8 test samples – can be tricked!

Fine-tuning of spectral peaks can lead to several points difference in CRI score – this is artificial…



Problems with the CRI

Some of the color science used in the CRI is outdated / inaccurate:

- Non-uniform color space

Color distortions are not all weighted equally

- Bad chromatic adaptation

- Only 8 test samples – can be tricked!

Fine-tuning of spectral peaks can lead to several points difference in CRI score – this is artificial…

- Samples lack color variety – no deep red…

CRI - Summary

- Light sources can induce various color shifts:
  - Hue (either direction)
  - Saturation
  - Desaturation

- Color shifts are usually evaluated with respect to “reference colors” (colors under a *reference illuminant*)

- **Color fidelity** = how much total color distortion is there, on average?

- CRI is a color fidelity measure: it gives limited information.

- CRI suffers from technical deficiencies
  - Outdated color science
  - Few pastel test samples which can be “tricked”

Part 3:

TM-30

Timeline of Color Rendering Metric Committees

1965 CIE E1.3.2 recommends the CIE General Color Rendering Index (R_a). Research dates to 1937.

1974 Major revision of CRI (CIE 13.2-1974). Some limitations addressed.

1995 Last revision of CRI (CIE 13.3-1995). No major changes.

1991 CIE TC1-33: *Color Rendering*
[No Agreement Reached; Closed 1999]

"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."[1]

2002 CIE TC1-62: *Color Rendering of White LED Light Sources*
[Published CIE 177:2007, recommends a new metric be developed]

"The Committee recommends the development of a new colour rendering index…This index…shall not replace the current CIE colour rendering index immediately. The usage of the new index or indices should provide information supplementary to the current CIE CRI, and replacement of CRI will be considered after successful integration of the new index."[2]

1. http://cie2.nist.gov/TC1-69/dql_or7.pdf 2. CIE 177:2007.

Timeline of Color Rendering Metric Committees

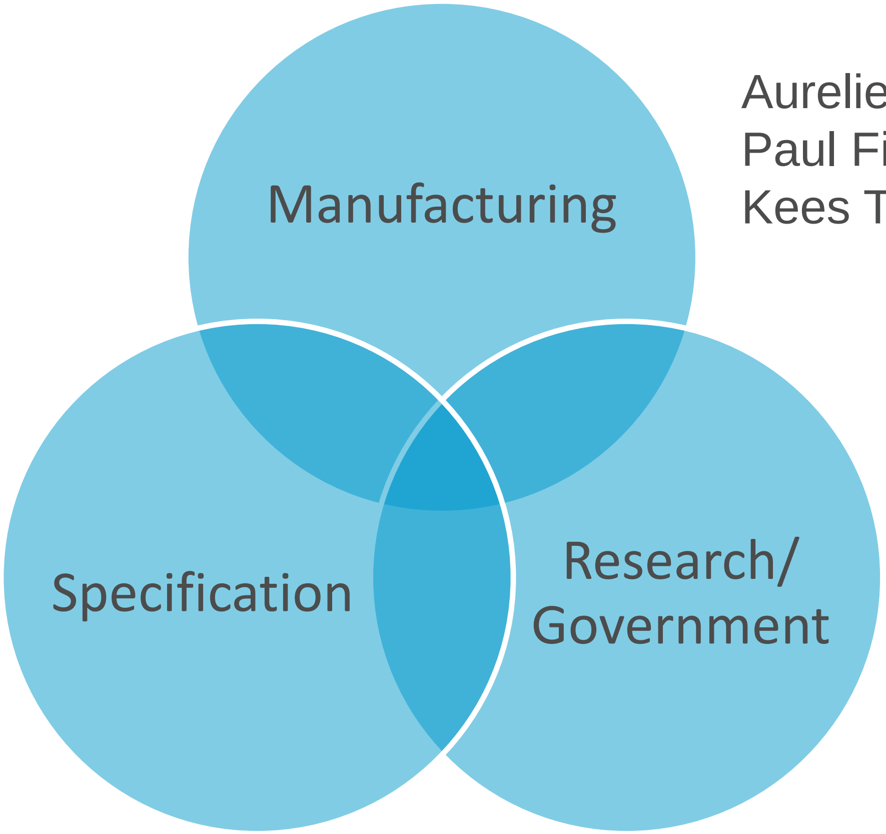
2006 CIE TC1-69: *Color Rendition by White Light Sources*
Goal of developing single number replacement for CRI, with a focus on psychophysical research.
[No Agreement Reached]

2012 CIE TC1-90: *Color Fidelity Index*
[Ongoing]

2012 CIE TC1-91: *New Methods for Evaluating the Colour Quality of White-Light Sources*
[Ongoing]

2013 IES Color Metrics Task Group
[Developed TM-30-15]

IES Color Metrics Task Group (Formed June 2013)

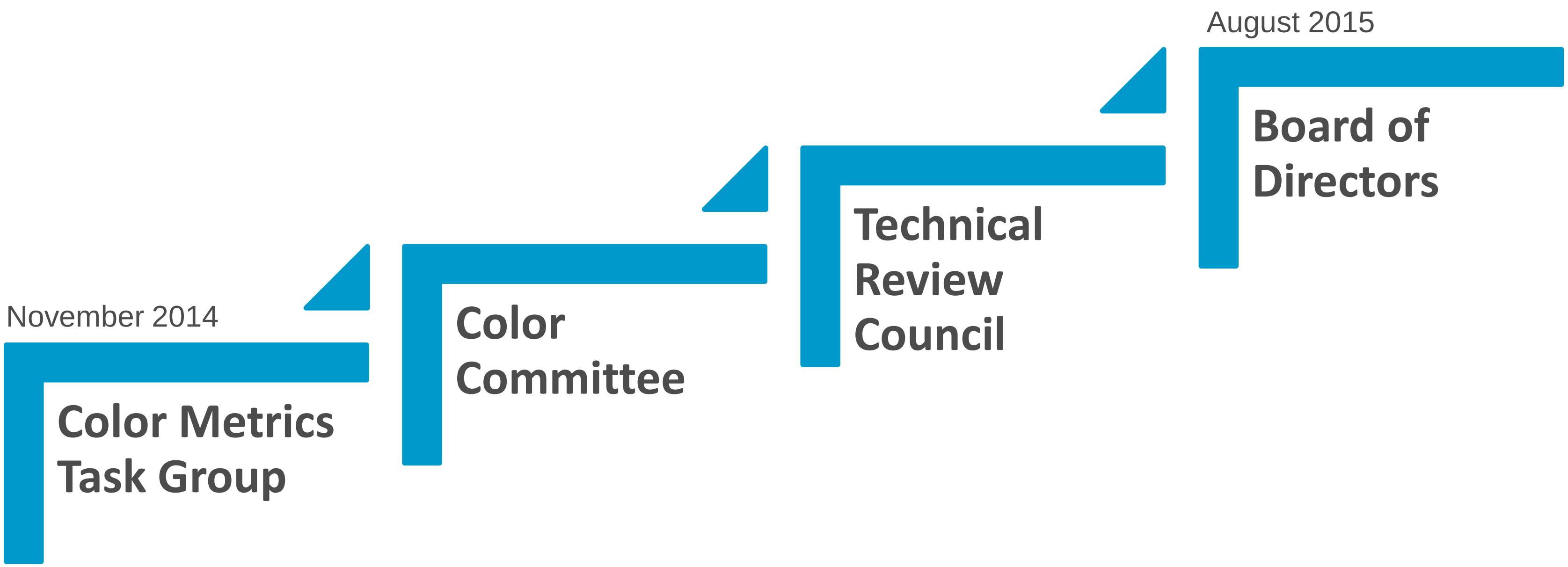


Aurelien David
Paul Fini
Kees Teunissen

Kevin Houser
Yoshi Ohno
Michael Royer
(Tommy Wei)

Randy Burkett

IES Balloting Process



- At least 2/3 majority approval required at each step.
- Any non-editorial revision require recirculation ballot.
- Must attempt to resolve any disapproval vote.

TM-30 Method for Color Rendition

Color Fidelity

The accurate rendition of color so that they appear as they would under familiar (reference) illuminants

Fidelity Index (*R_f*)

(0-100)

Color Gamut

The average level of saturation relative to familiar (reference) illuminants.

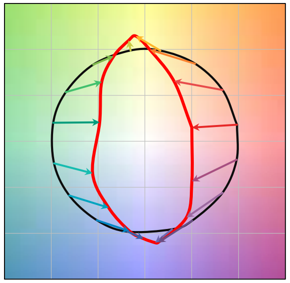
Gamut Index (*R_g*)

~60-140 when $R_f > 60$

Gamut Shape

Changes over different hues

Color Vector Graphic
Hue Bin Chroma Shift



CIE CRI (1965/1974)	IES TM-30-15 (2015)
Fidelity Metric Only	Fidelity, Gamut, Graphical, Detailed/Hues
CIE 1964 U*V*W*	CAM02-UCS (CIE CAM02)
8 color samples Medium chroma/lightness Spectral sensitivity varies Munsell samples only	99 color samples Uniform color space coverage Spectral sensitivity neutral Variety of real objects
Ref Illuminant Step Function	Ref Illuminant Continuous (Uses same reference sources, but blended between 4500 K and 5500 K)
No lower limit for scores and inconsistent scales	0 to 100 scale (fidelity)

Metrics/Measures

R_f (IES TM-30-15)
R_g (IES TM-30-15)
CRI R_a (CIE13.3-1995)
CRI R_9 (CIE13.3-1995)
CCT
$\Delta u'v'$
D_{uv}

Criteria

≥ 80
≥ 0
2700 K – 5000 K
≤ 0.007

Standards

ANSI C78.377
ANSI/IES RP-1-12
ISO 8995-1 (CIE S 008)

Design Guidance

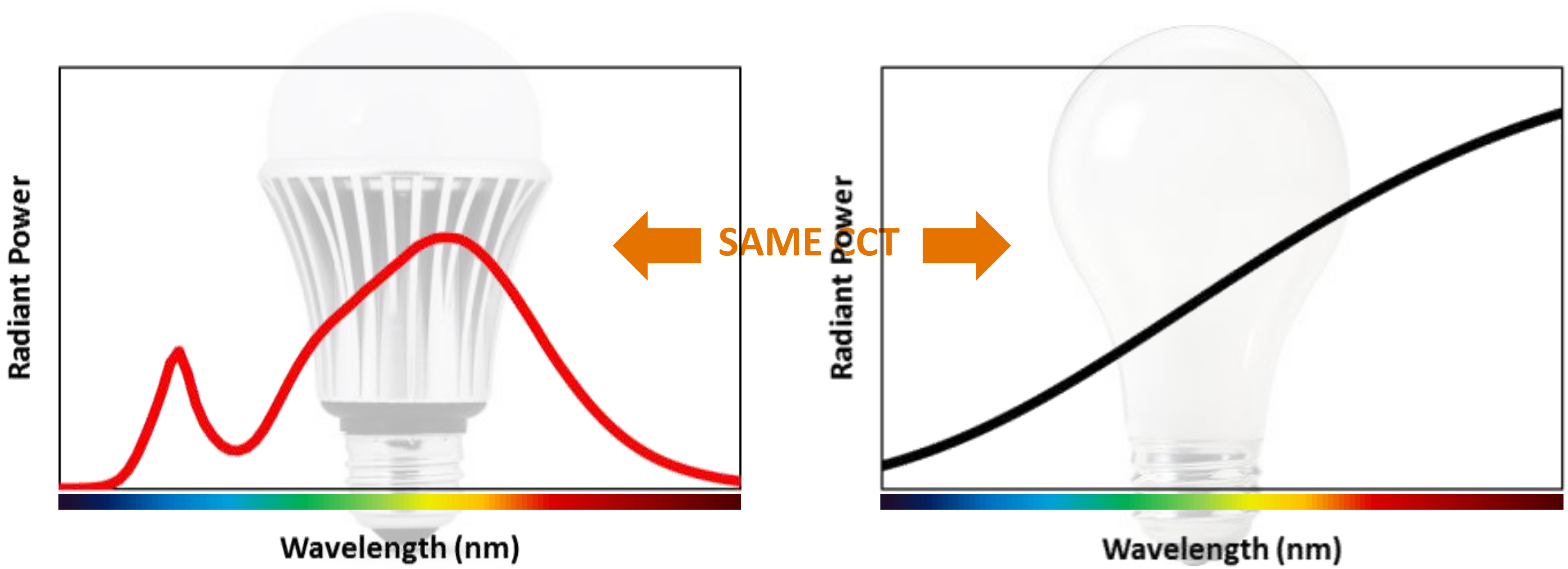
IES DG-1

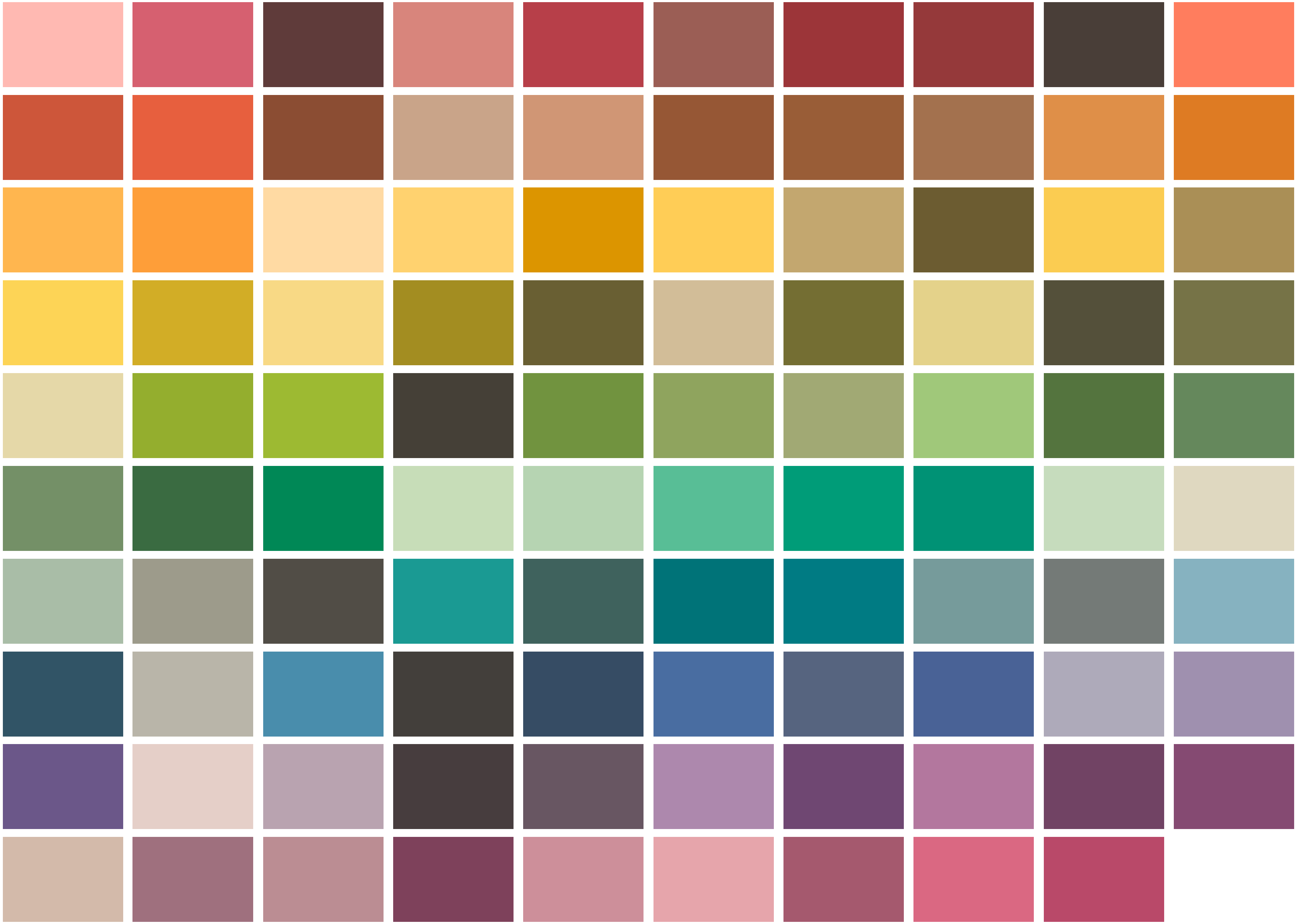
TM-30 is a method that includes several related measures.
TM-30 is not a required standard, and does not provide design guidance or criteria.

Reference Illuminants

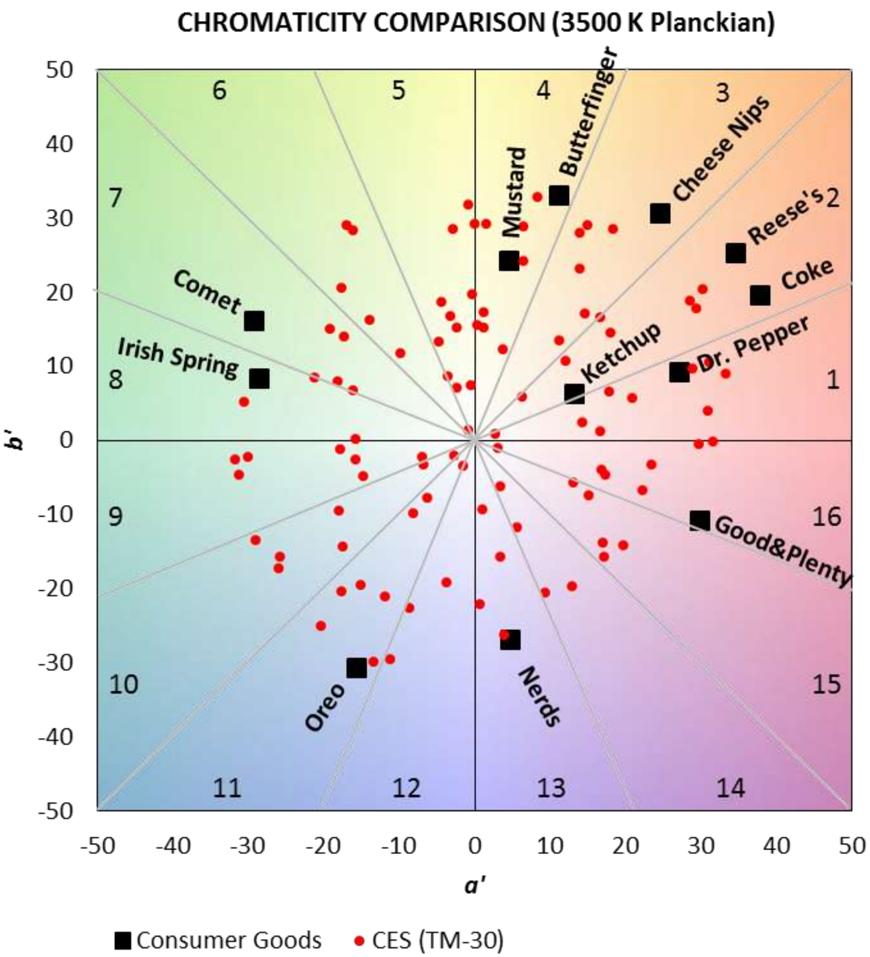
Test Source

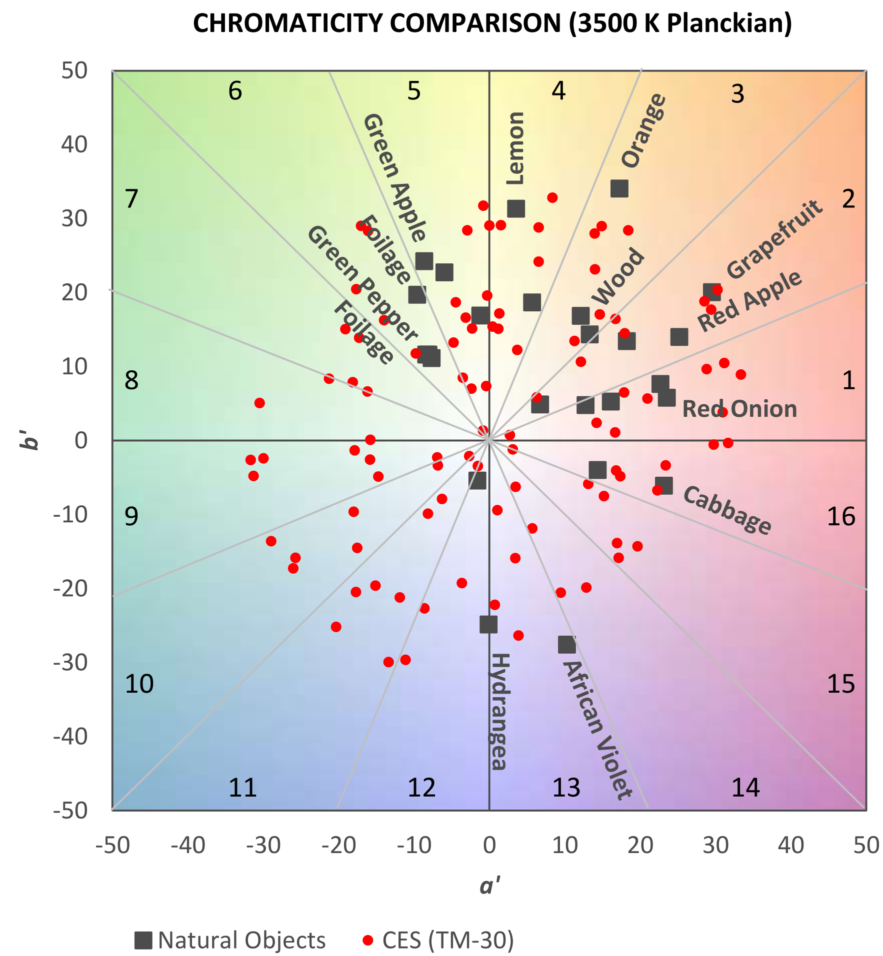
Reference Illuminant
(approximately)



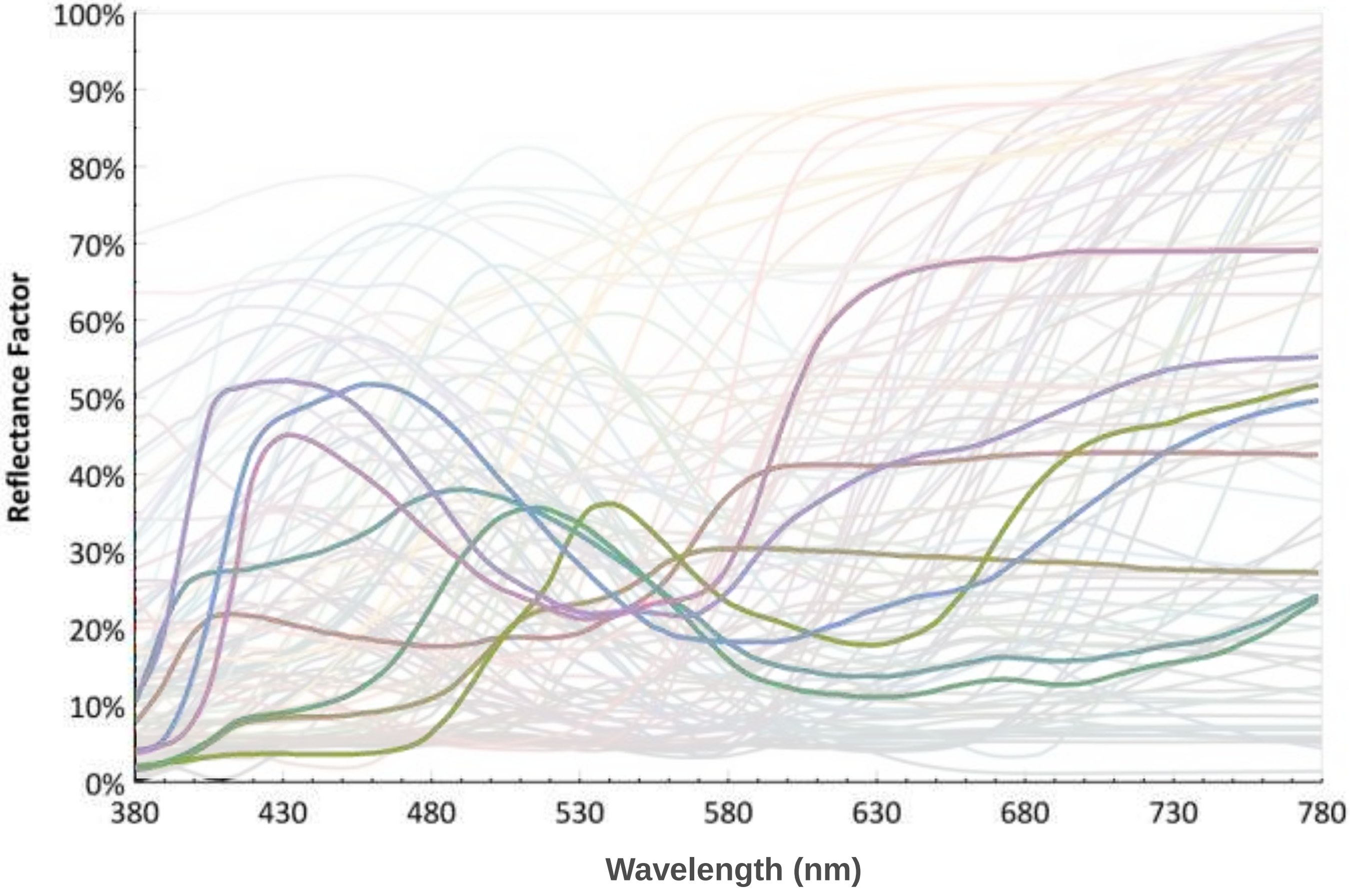


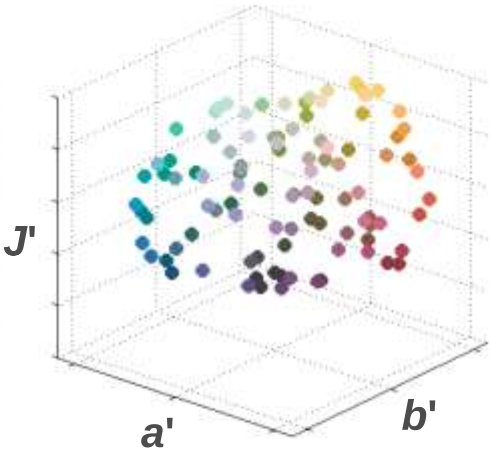
TM-30 Color Evaluation Samples (CES)



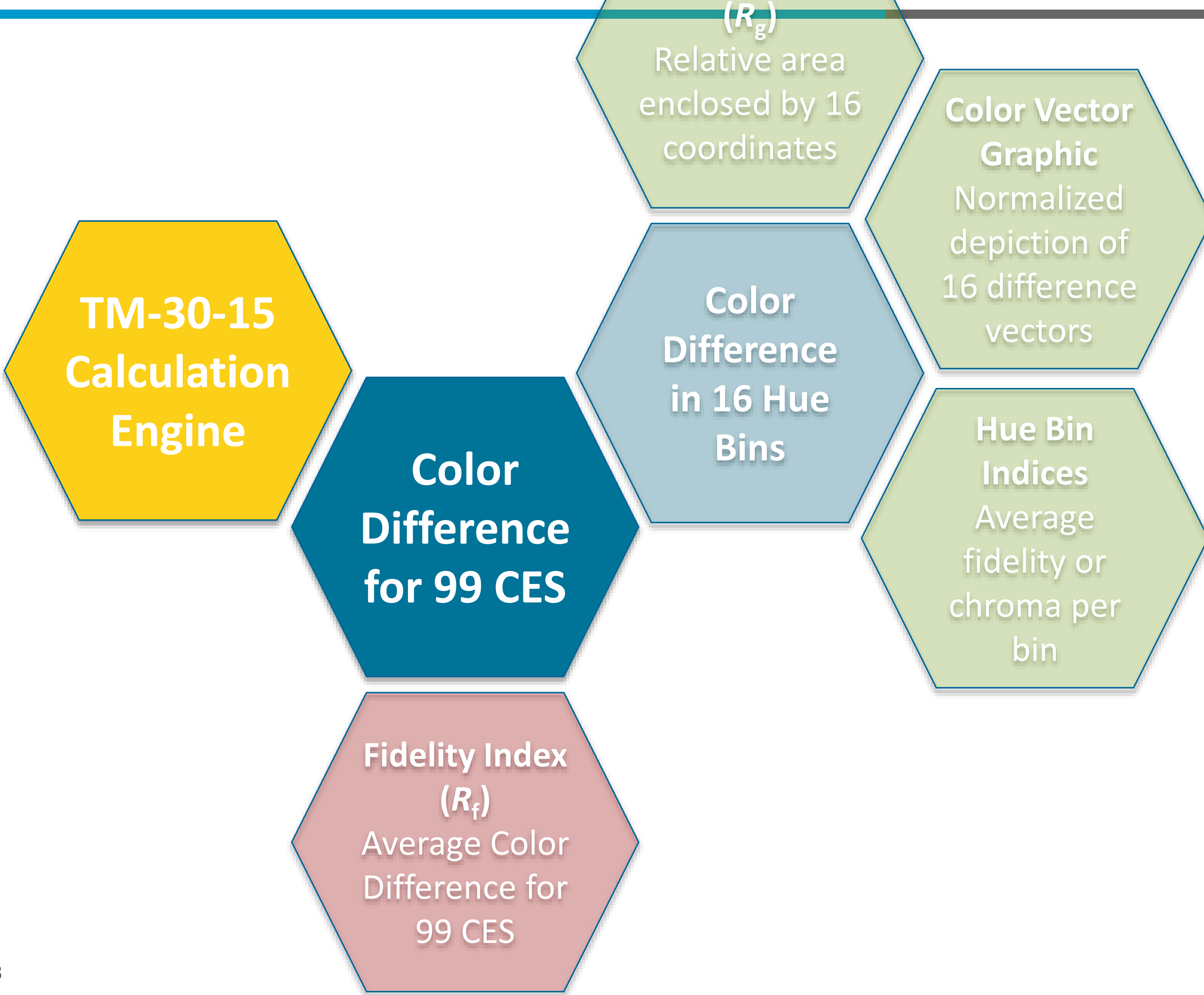


TM-30 Color Evaluation Samples (CES)

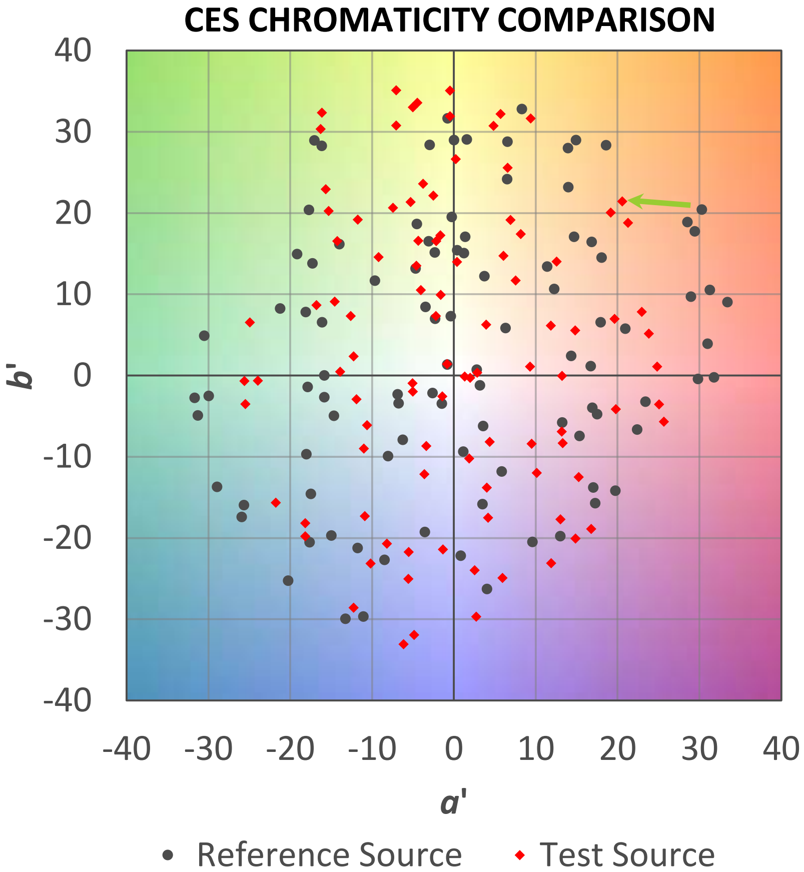




Hierarchy of Information



Color Difference



[Flattened to 2D]

1. Calculate chromaticity of 99 CES with test source and reference illuminant using CAM02-UCS

2. Calculate color difference for each pair of color coordinates

$$\Delta E_{Jab,i} = \sqrt{\left(J'_{t,i} - J'_{r,i}\right)^2 + (a'_{t,i} - a'_{r,i})^2 + (b'_{t,i} - b'_{r,i})^2}$$

Hierarchy of Information

TM-30-15 Calculation Engine

Color Difference for 99 CES

Fidelity Index (R_f)
Average Color Difference for 99 CES

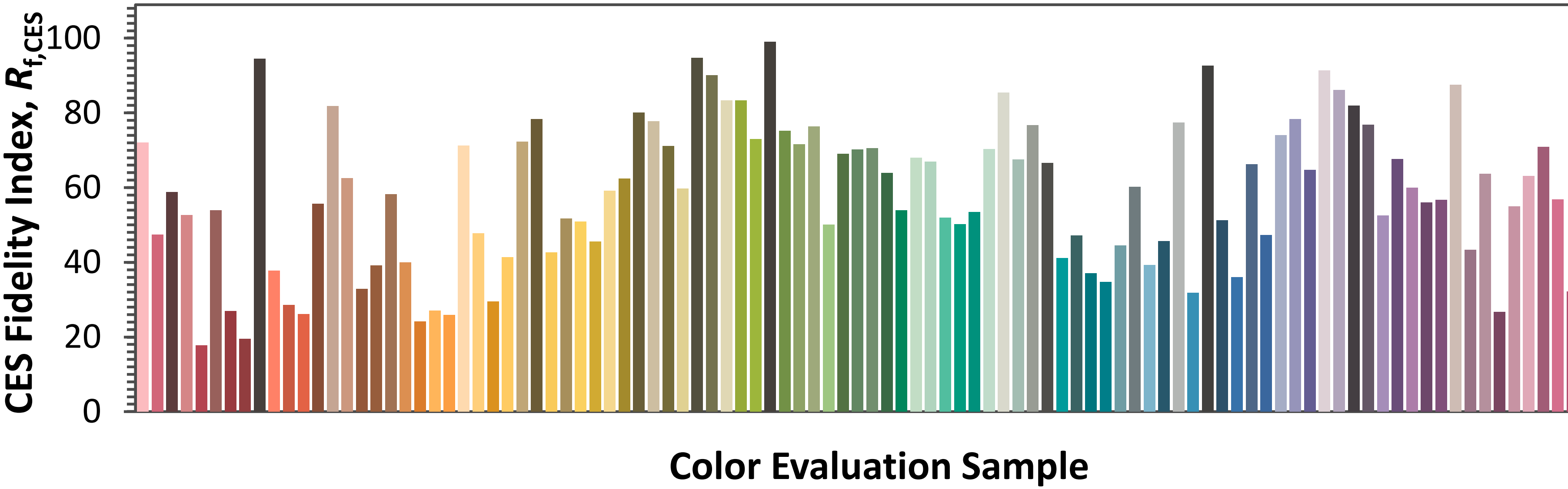
Color Difference in 16 Hue Bins

Gamut Index (R_g)
Relative area enclosed by 16 coordinates

Color Vector Graphic
Normalized depiction of 16 difference vectors

Hue Bin Indices
Average fidelity or chroma per bin

TM-30 Fidelity (Each CES)

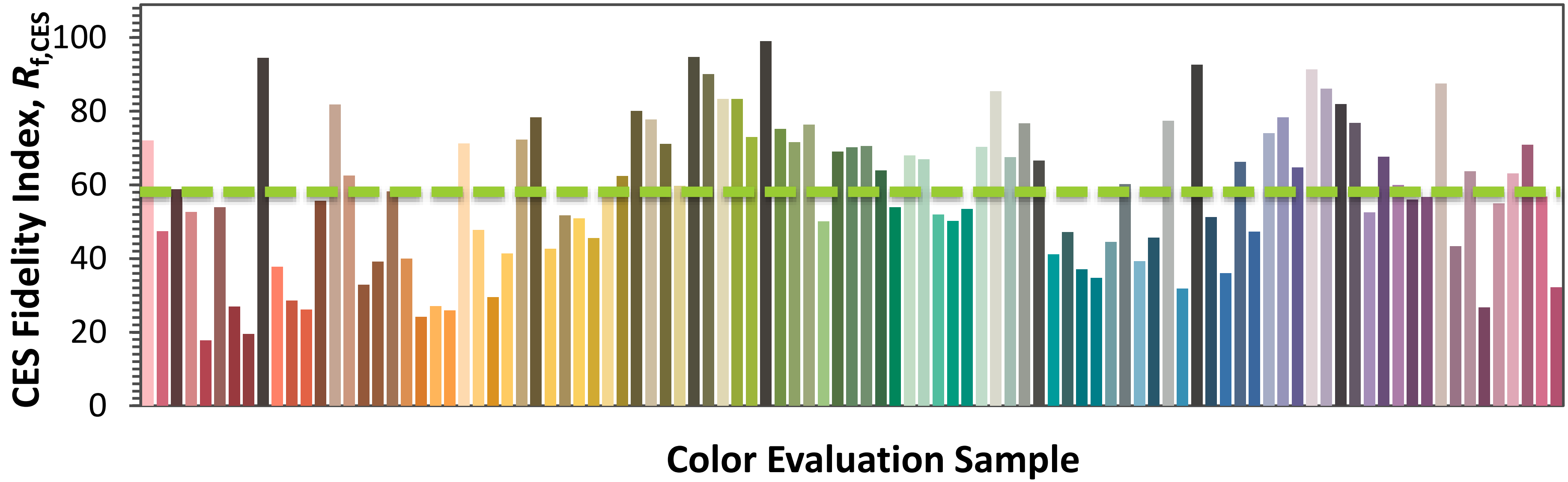


$$R'_{\mathrm{fces},i} = 100 - 7.54 \times \Delta E_{Jab,i}$$

Scaling Factor

Maximum value of 100

TM-30 Fidelity (Average)



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

Arithmetic Mean

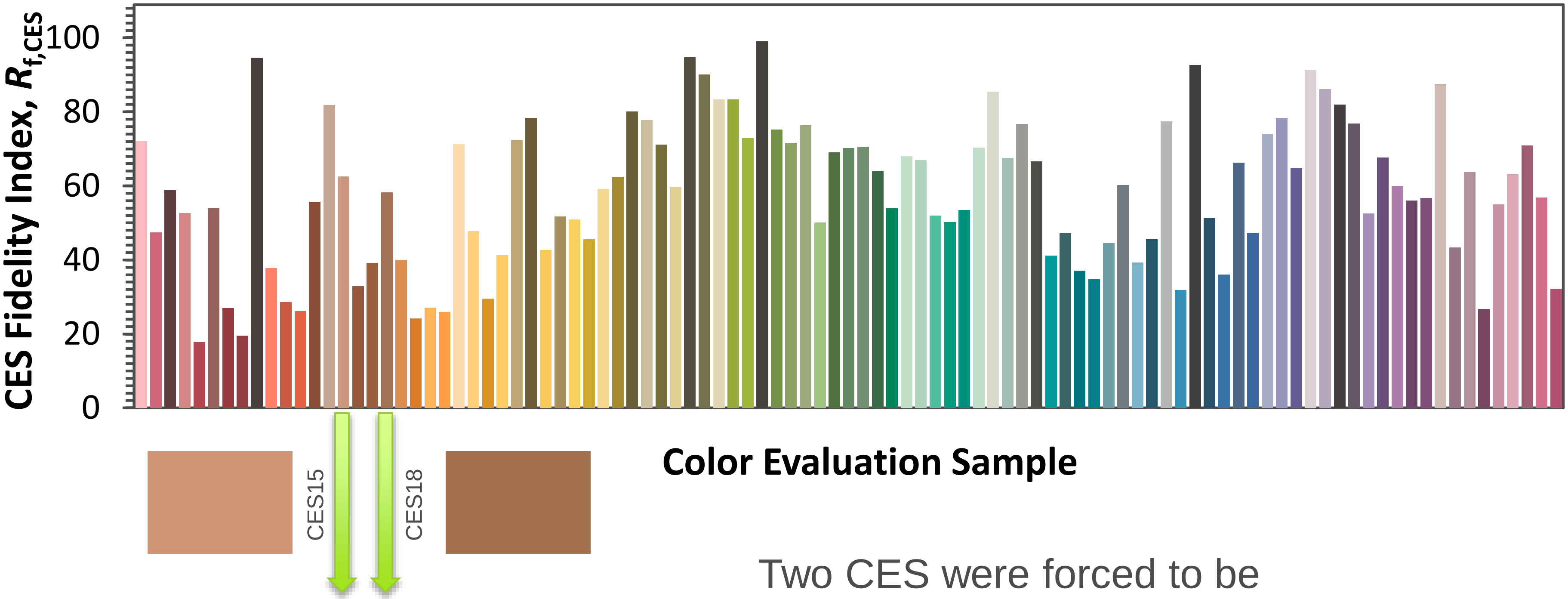
Scaling Factor

Maximum value of 100

$$R_{f} = 10\ln\left(e^{R'_{f}/10} + 1\right)$$

Lower limit = 0

TM-30 Fidelity (Skin)

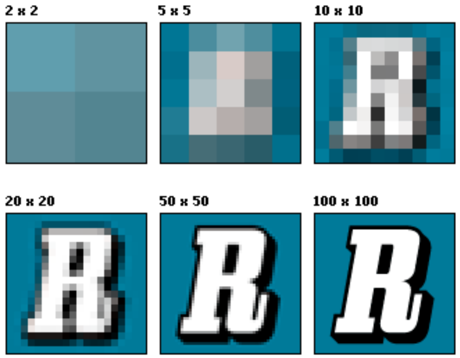


$$R_{f,skin} = \frac{R_{f,CES15} + R_{f,CES18}}{2}$$

Two CES were forced to be measurements of human skin. The two samples lead to the highest correlation in R_f compared the full set of thousand of measured skin samples.

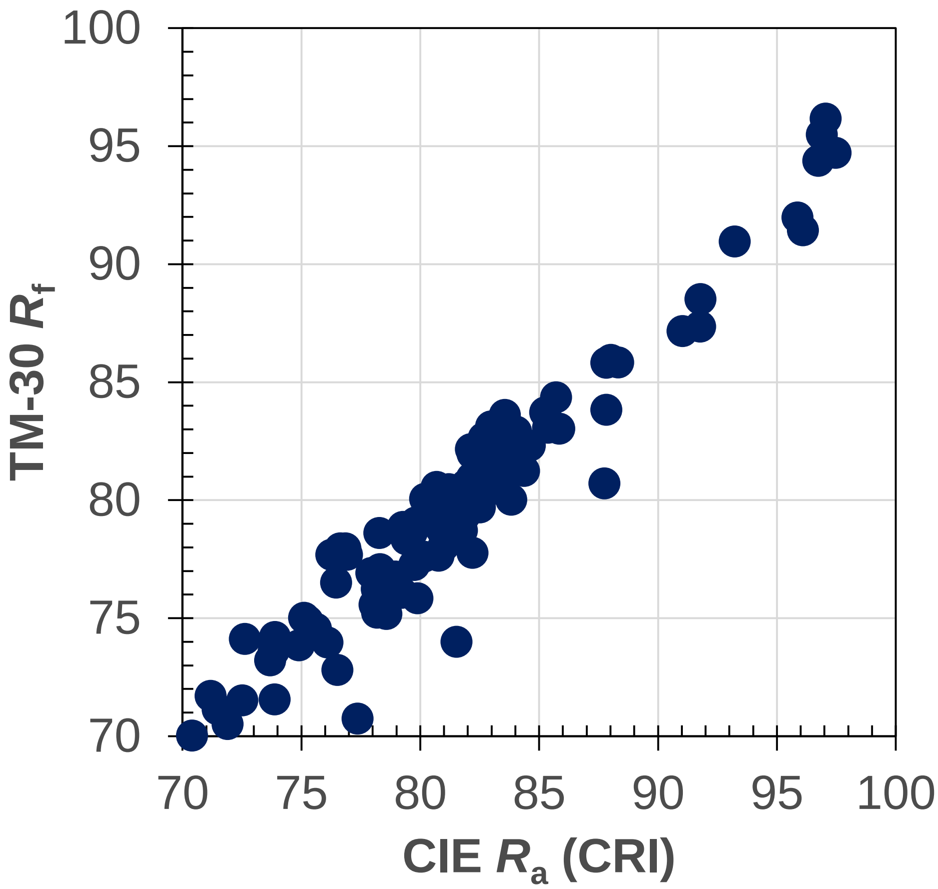
Is TM-30 R_f Different from CRI (R_a)?

- Uniform color space: 1-3 Points Typical, Up to ~6 Points
- Spectrally neutral samples: 1-3 Points Typical, Up to ~6 Points
- Increased number of samples: 1 unit vs. 6 unit precision
- Full coverage of color space: 5+ Points

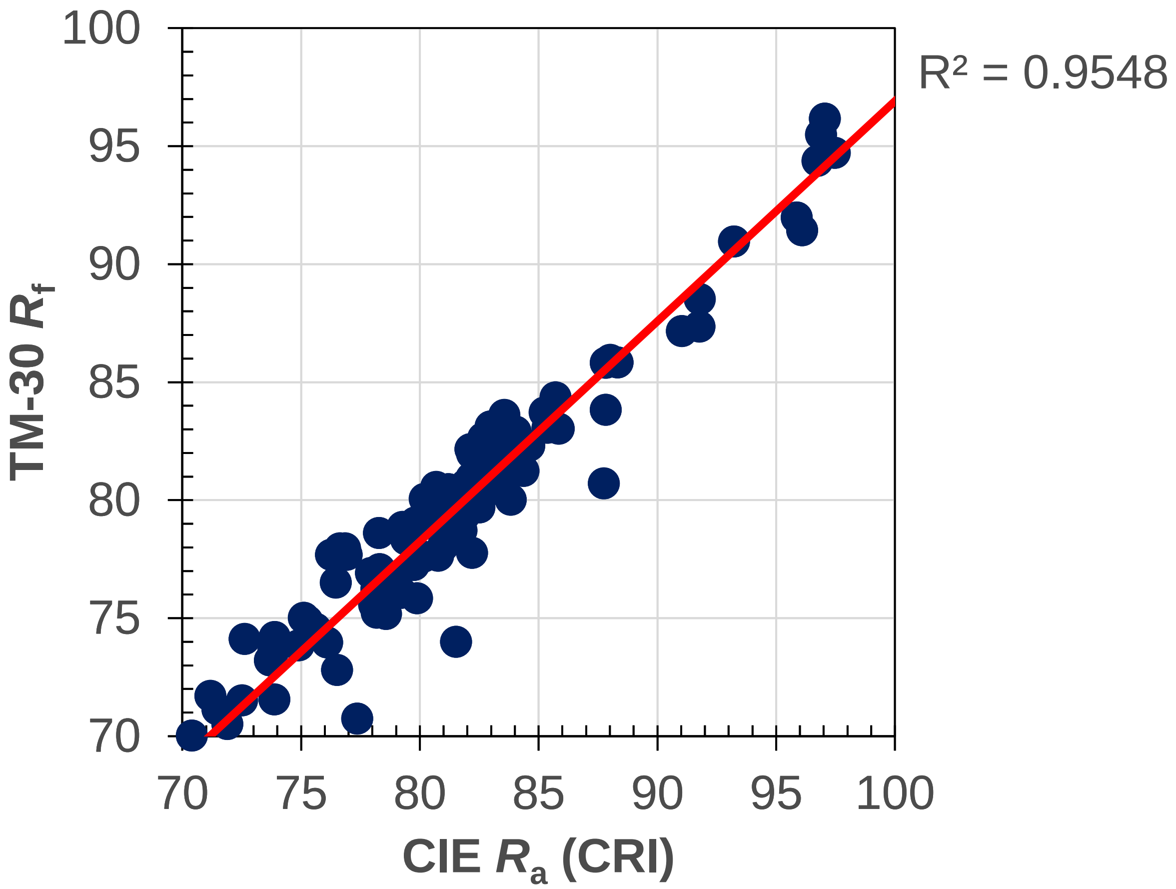


Smet et al. 2015. Why Color Space and Spectral Uniformity Are Essential for Color Rendering Measures. Leukos 12(1).

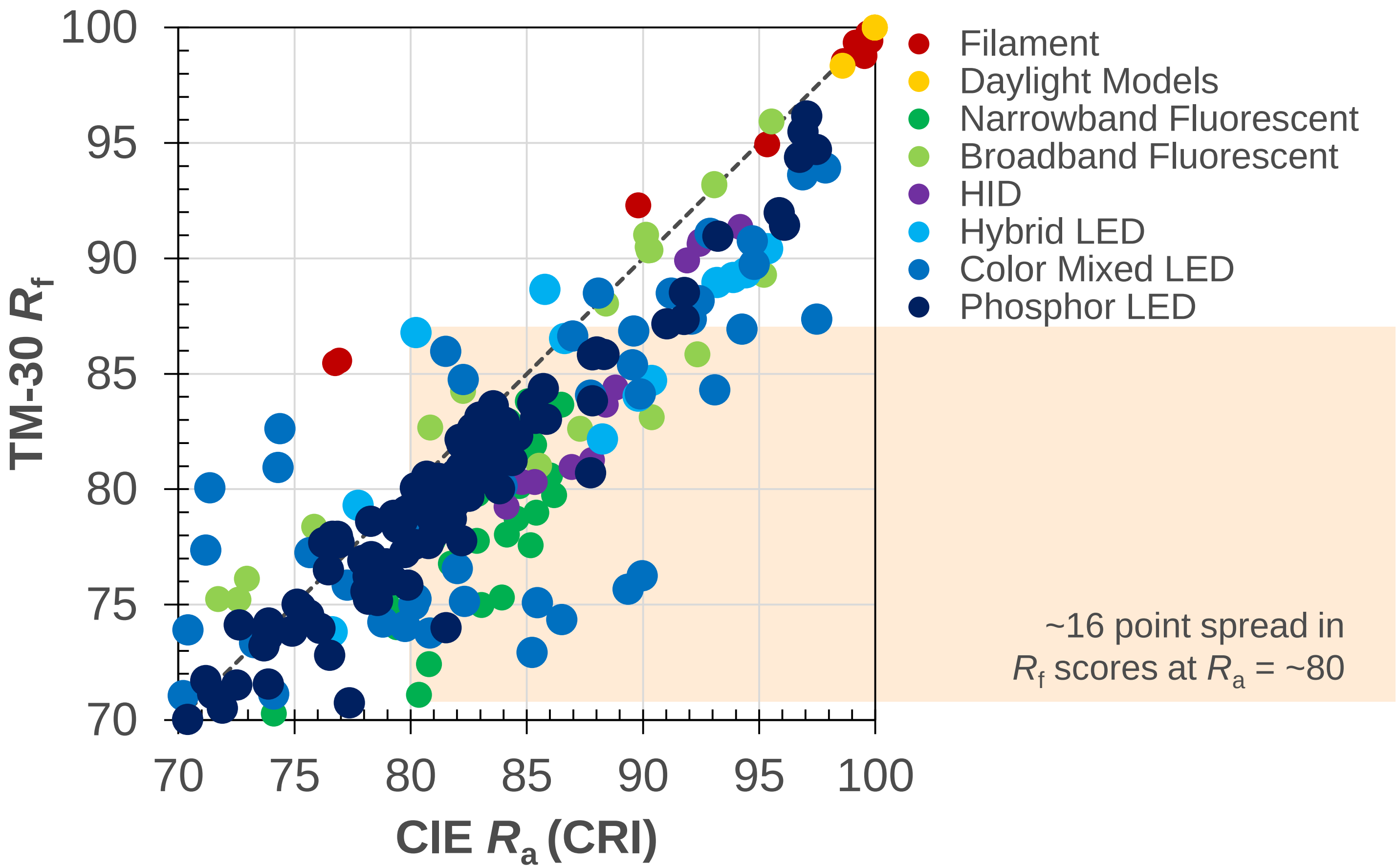
Is TM-30 R_f Different from CRI?



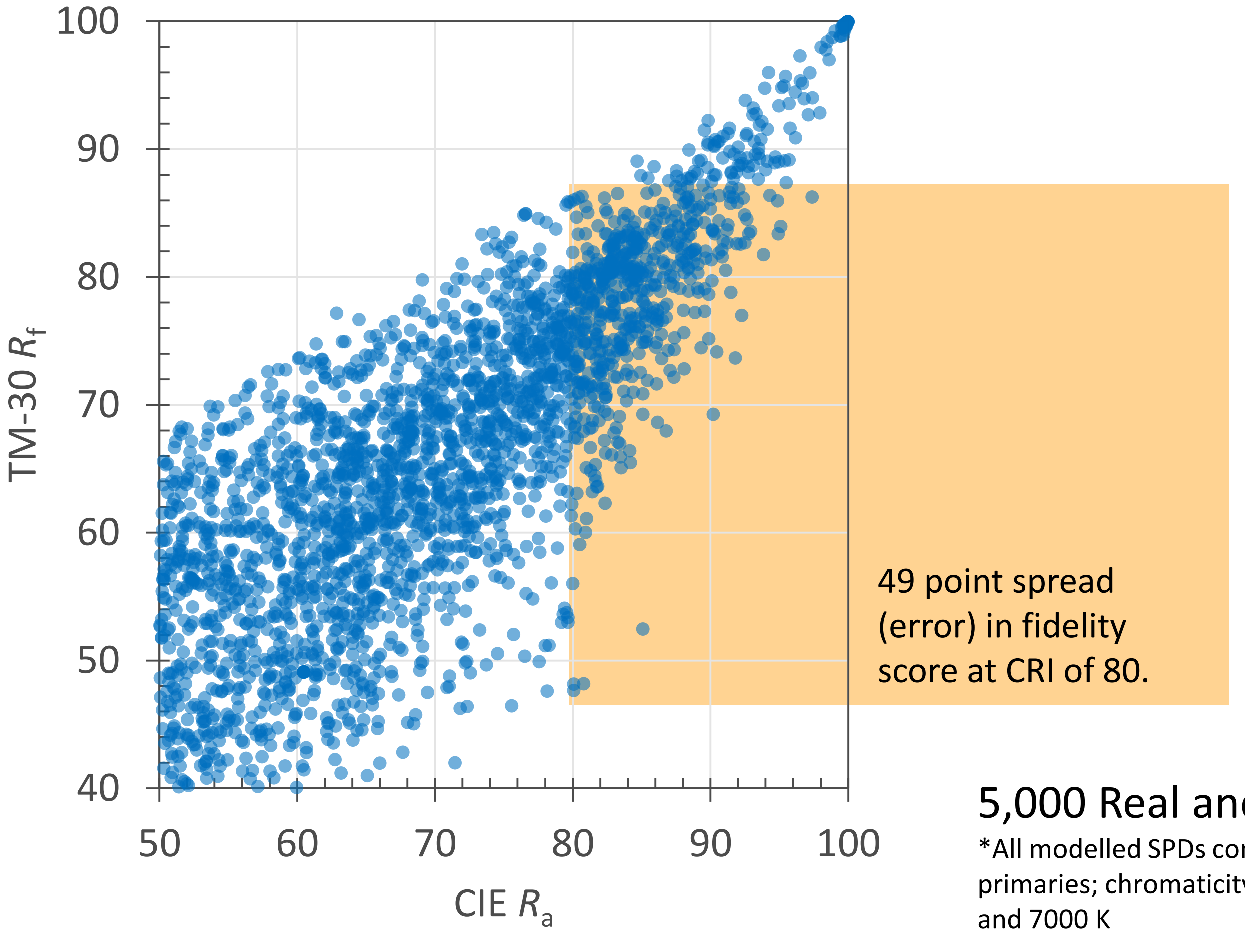
Is TM-30 R_f Different from CRI?



Is TM-30 R_f Different from CRI?



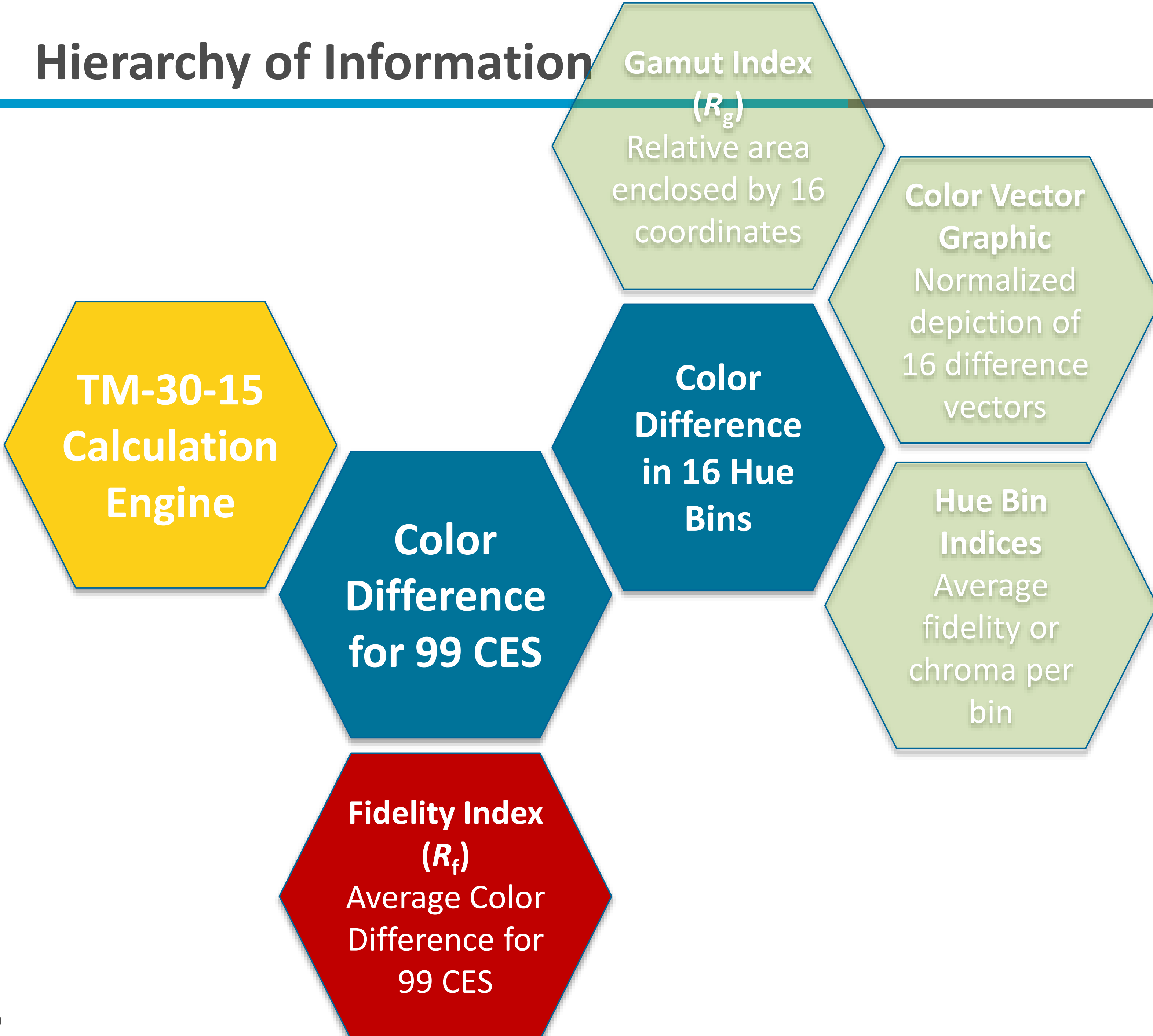
Is TM-30 R_f Different from CRI?



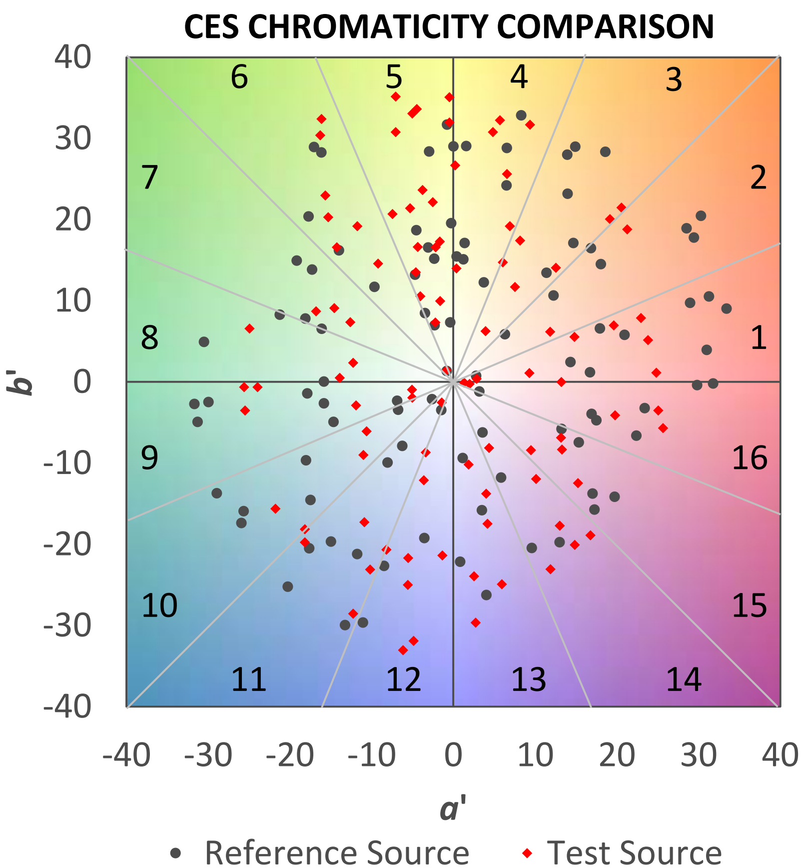
5,000 Real and Modelled* SPDs

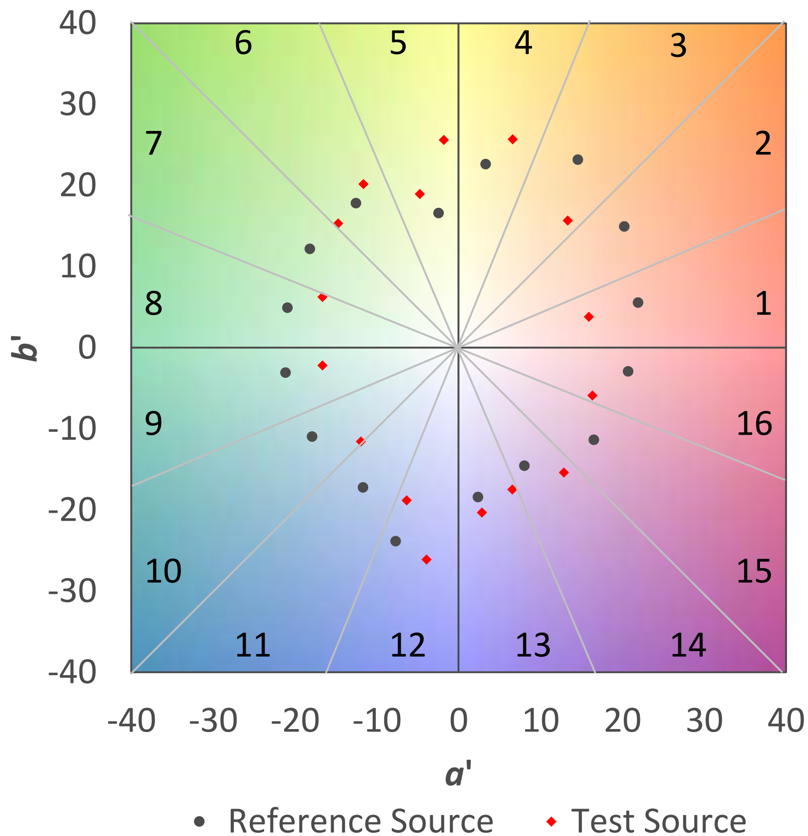
*All modelled SPDs composed of combinations of Gaussian primaries; chromaticity on Planckian locus between 2700 K and 7000 K

Hierarchy of Information



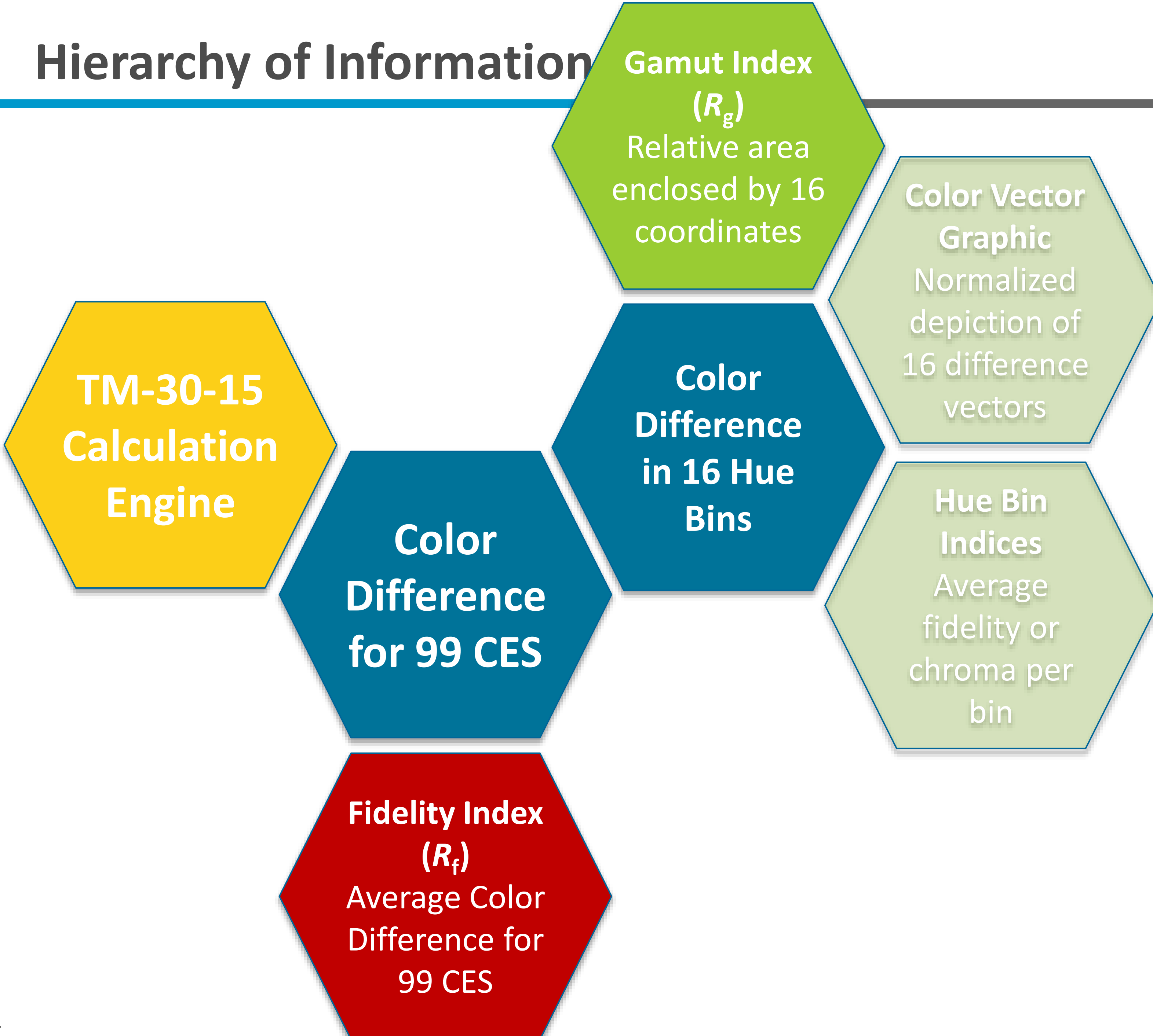
TM-30 Hue Bins





Average (*a*', *b*') chromaticity coordinates in each bin (binned by <u>reference</u> condition).

Hierarchy of Information

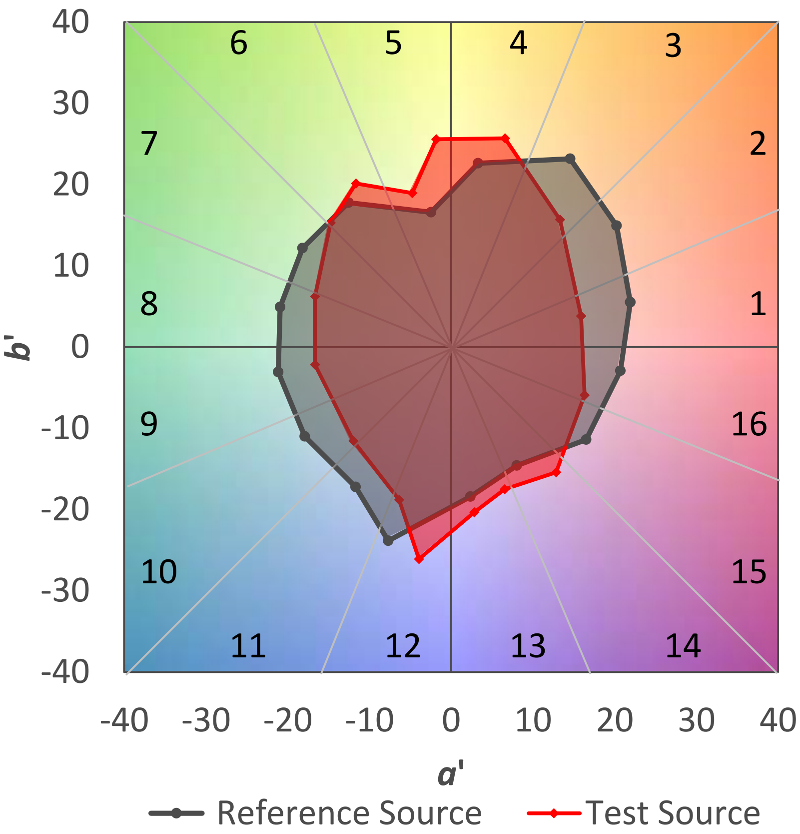


TM-30-15 Relative (Average) Gamut

$$R_g = 100 \times \frac{A_t}{A_r}$$

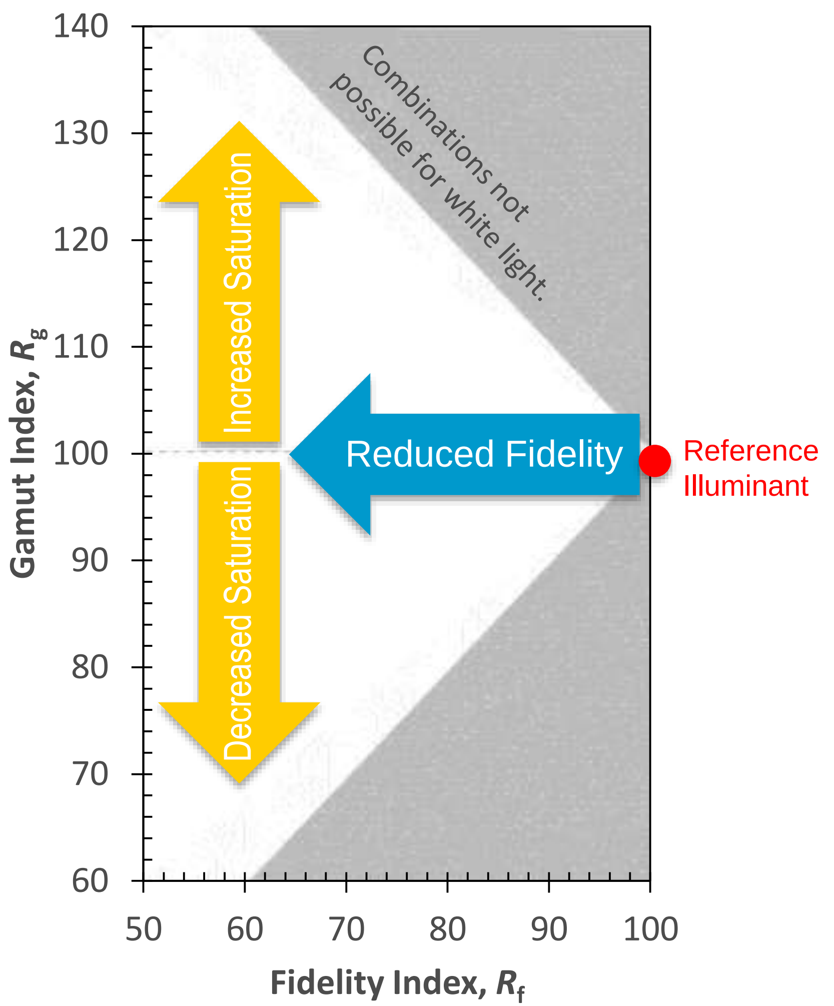
$R_g > 100$: Average increase in saturation

$R_g < 100$: Average decrease in saturation



A Cohesive Two-Axis System

- Evaluate tradeoffs between fidelity and saturation.
- When disparate fidelity and gamut measures are used together, the tradeoffs are less apparent.
- **But average values don't tell the whole story…**

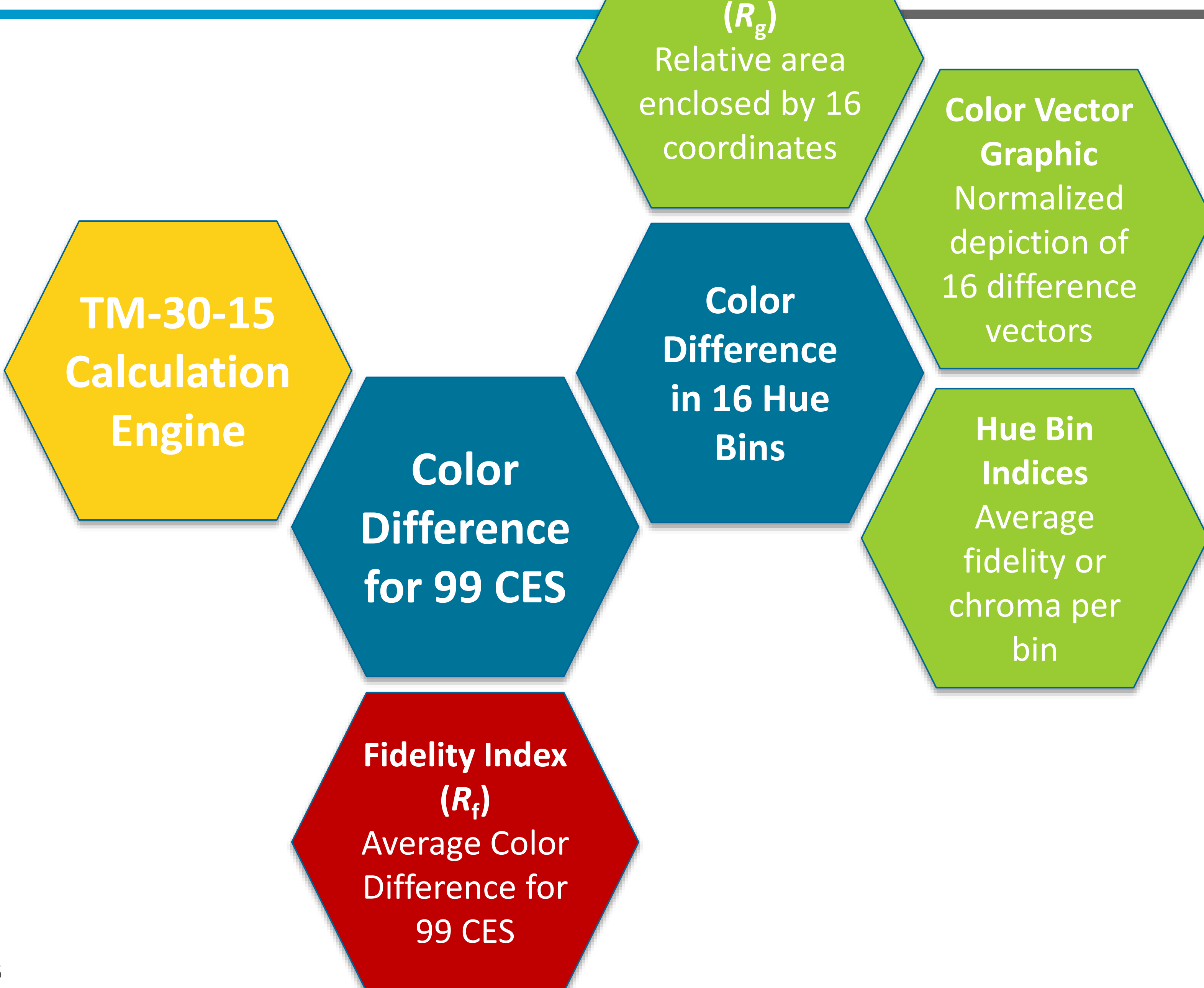


(Theoretical)

Original	**Desaturated**	**Red-Enhanced**
CRI = 95	CRI = 80	CRI = 80
R_f = 93	R_f = 78	R_f = 78
R_g = 100	R_g = 90	R_g = 110

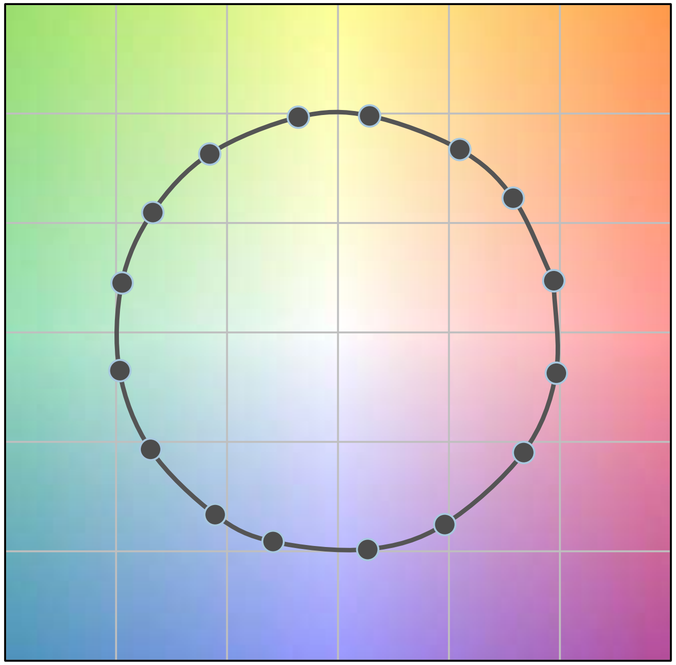
Images courtesy of Randy Burkett Lighting Design

Hierarchy of Information

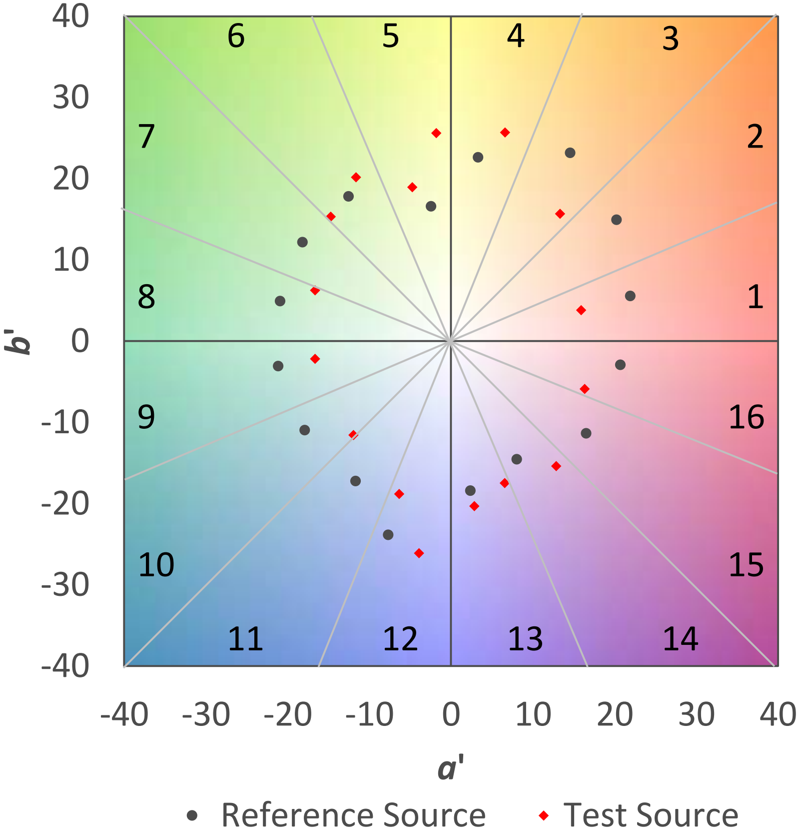


TM-30 Vector Graphics

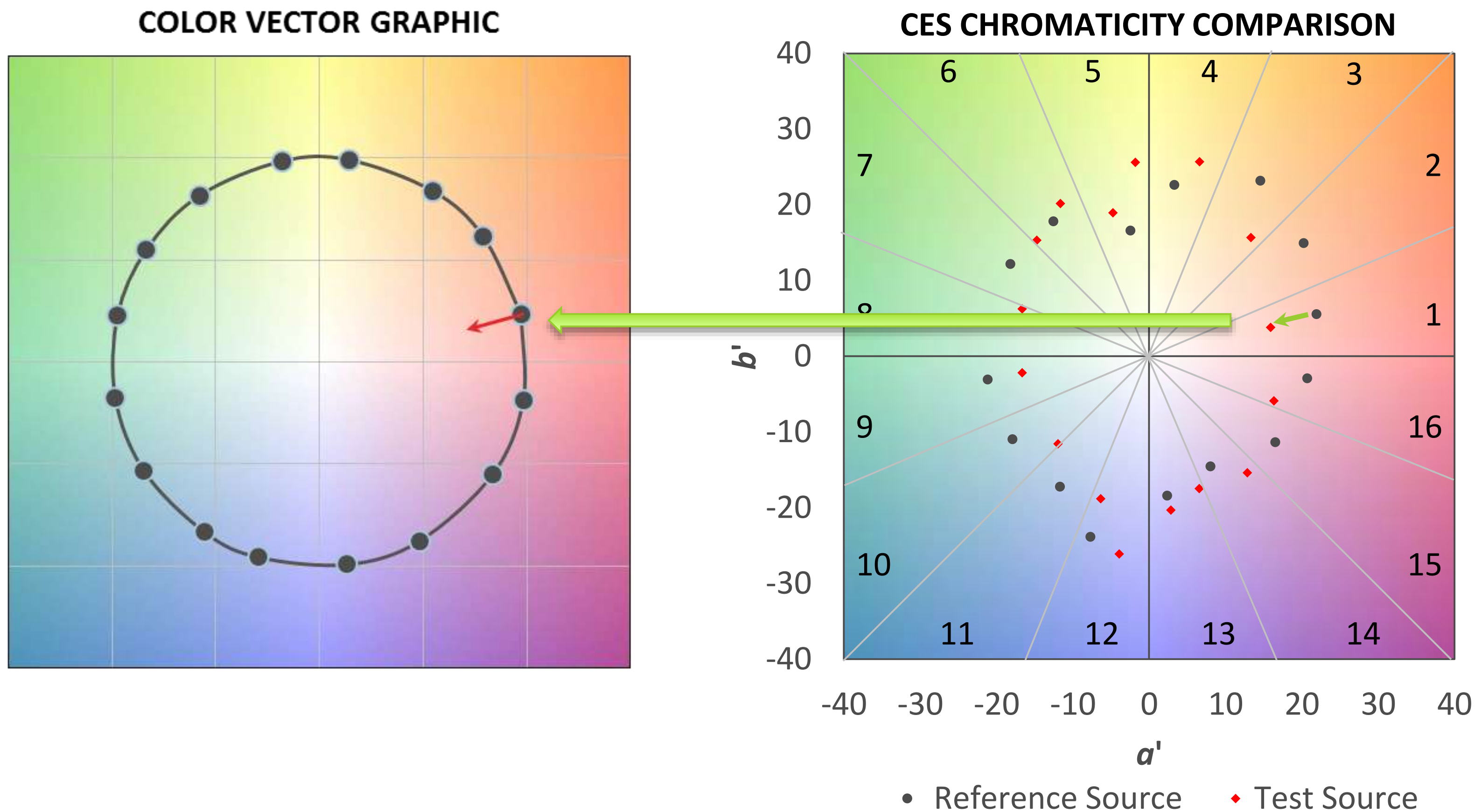
COLOR VECTOR GRAPHIC



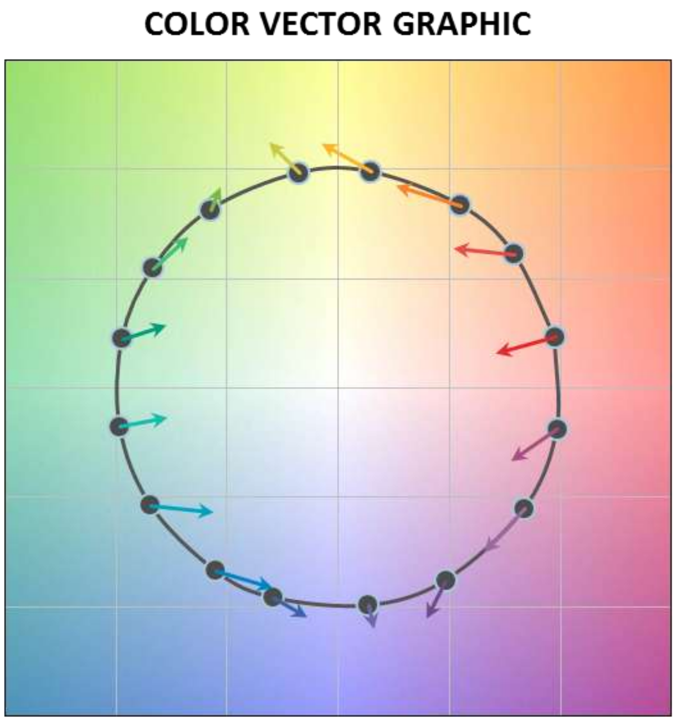
CES CHROMATICITY COMPARISON

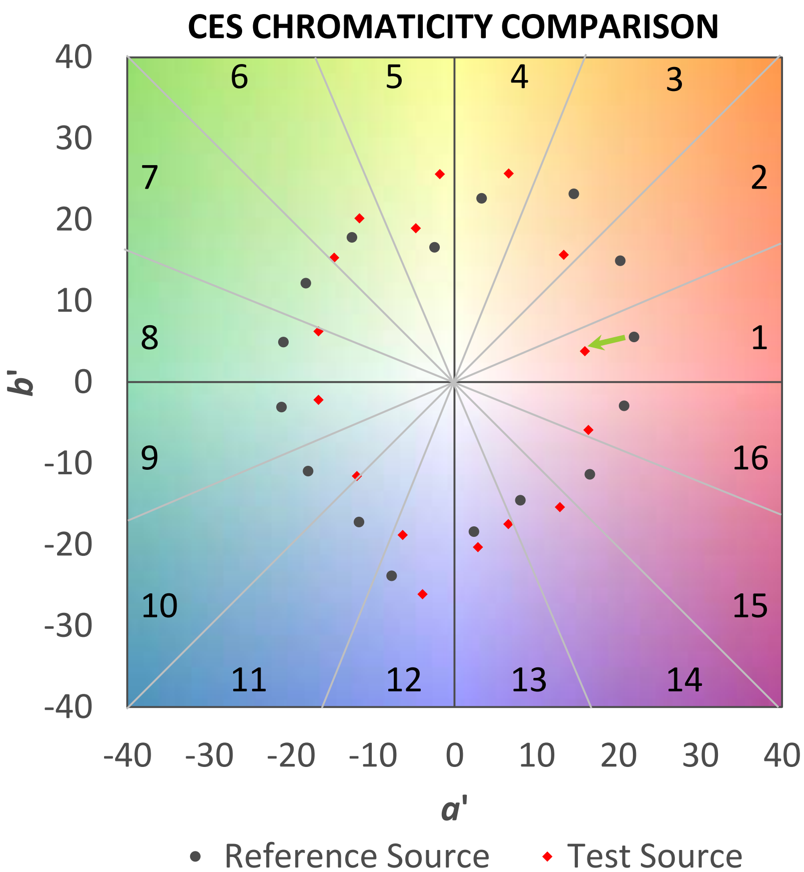


TM-30 Vector Graphics

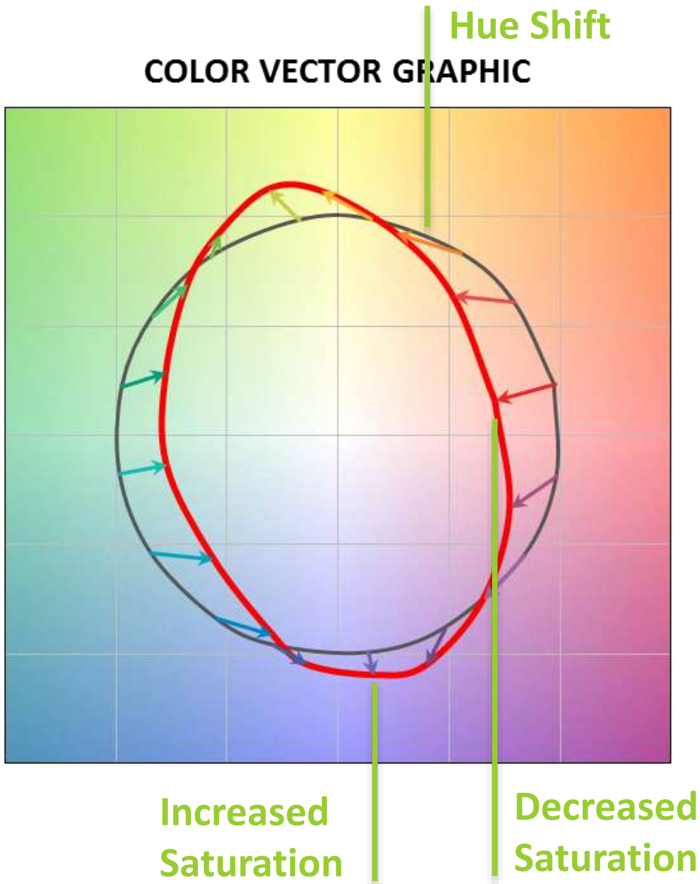


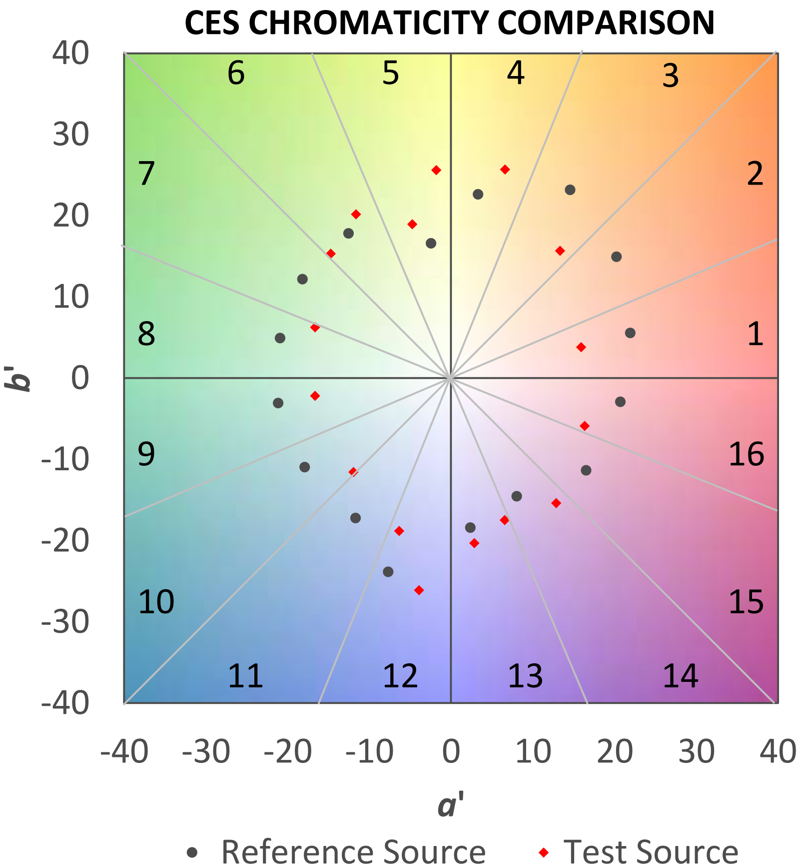
TM-30 Vector Graphics



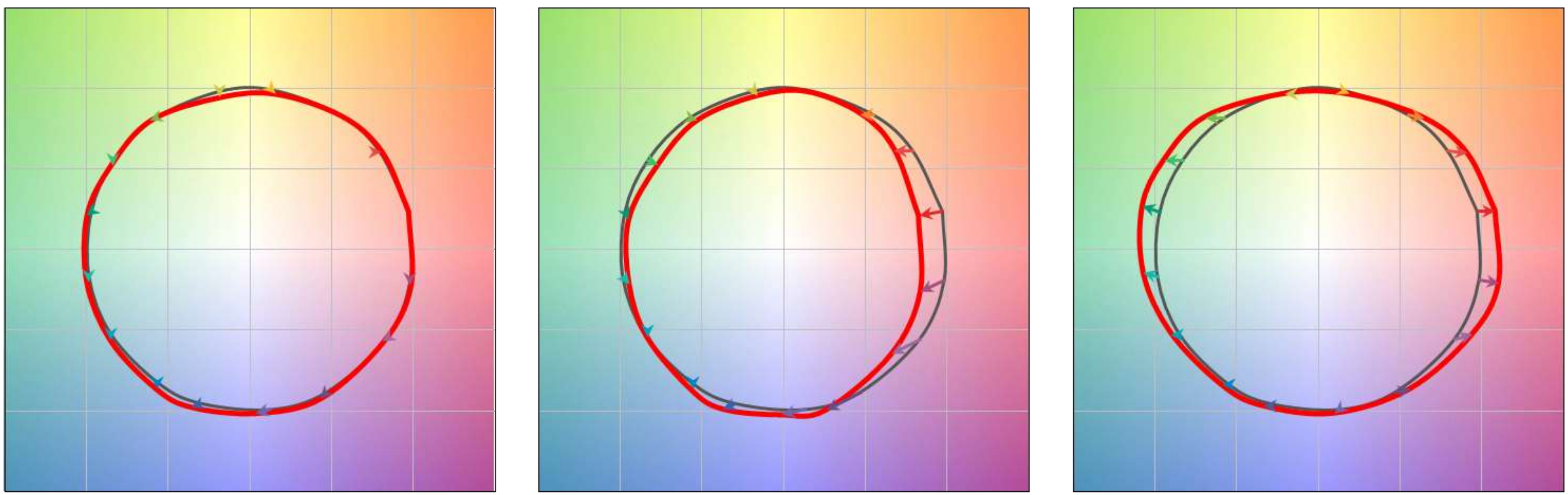


TM-30-15 Vector Graphics

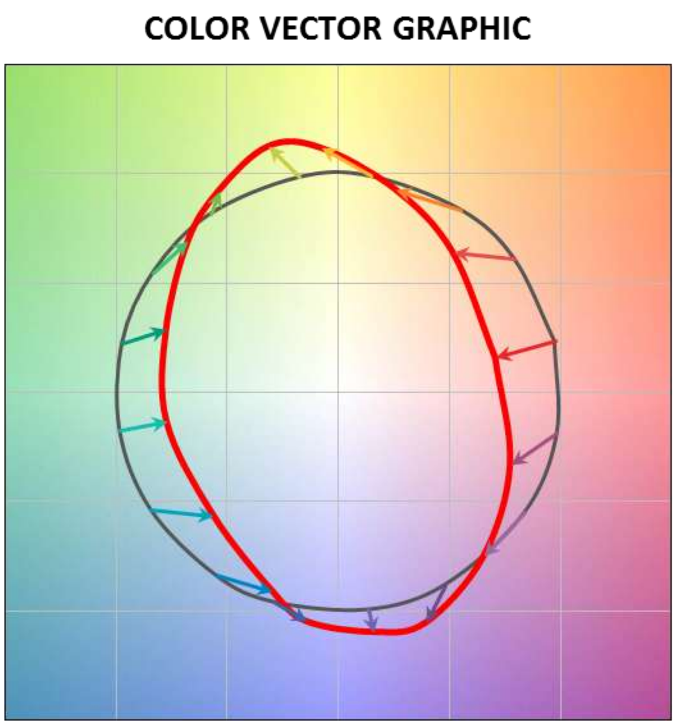




Original **Desaturated** **Red-Enhanced**



TM-30-15 Vector Graphics vs. Fidelity

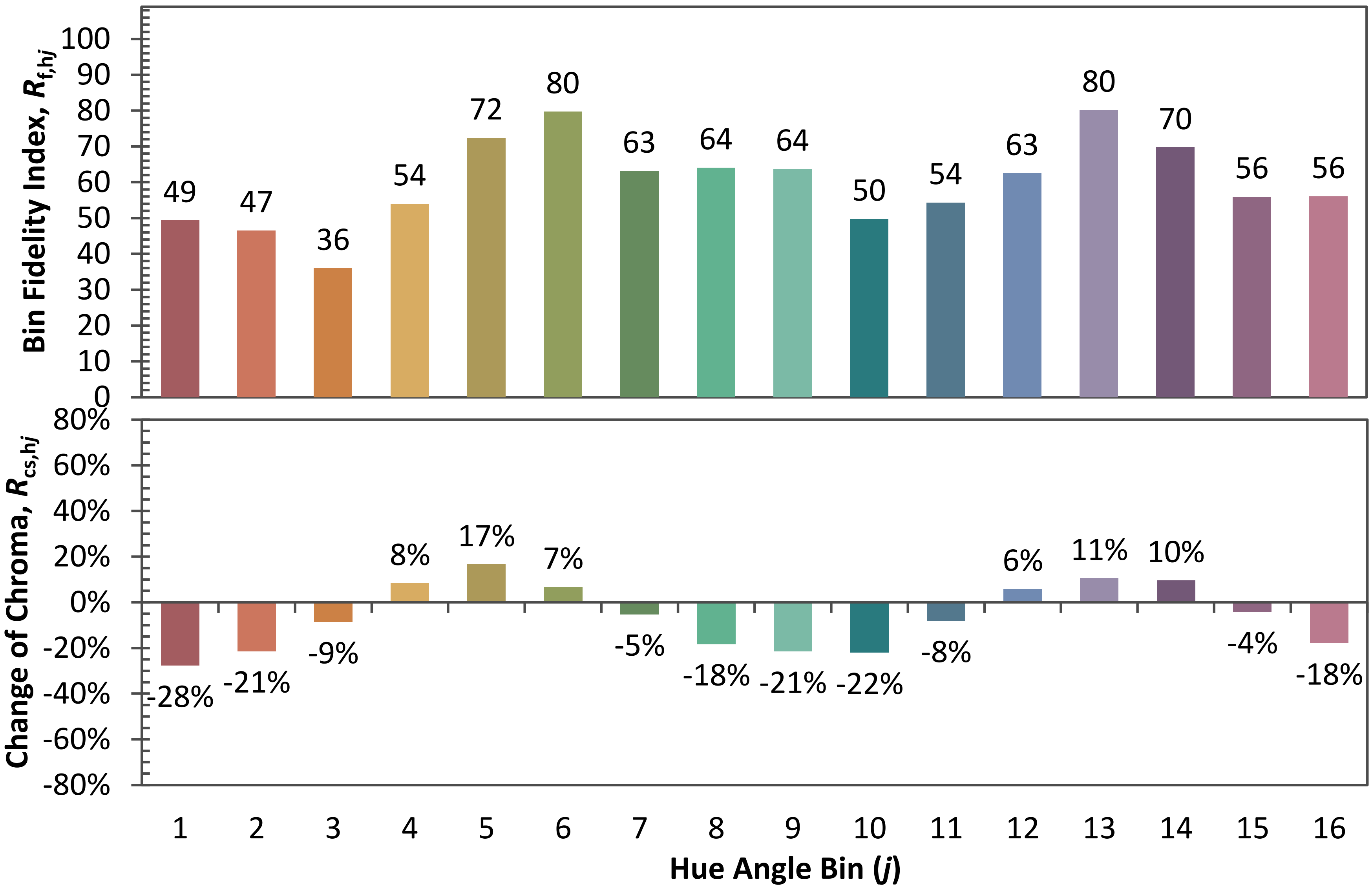


Fidelity is approximately the average length of the arrows.

Gamut is the ratio of the area of the black circle and red shape.

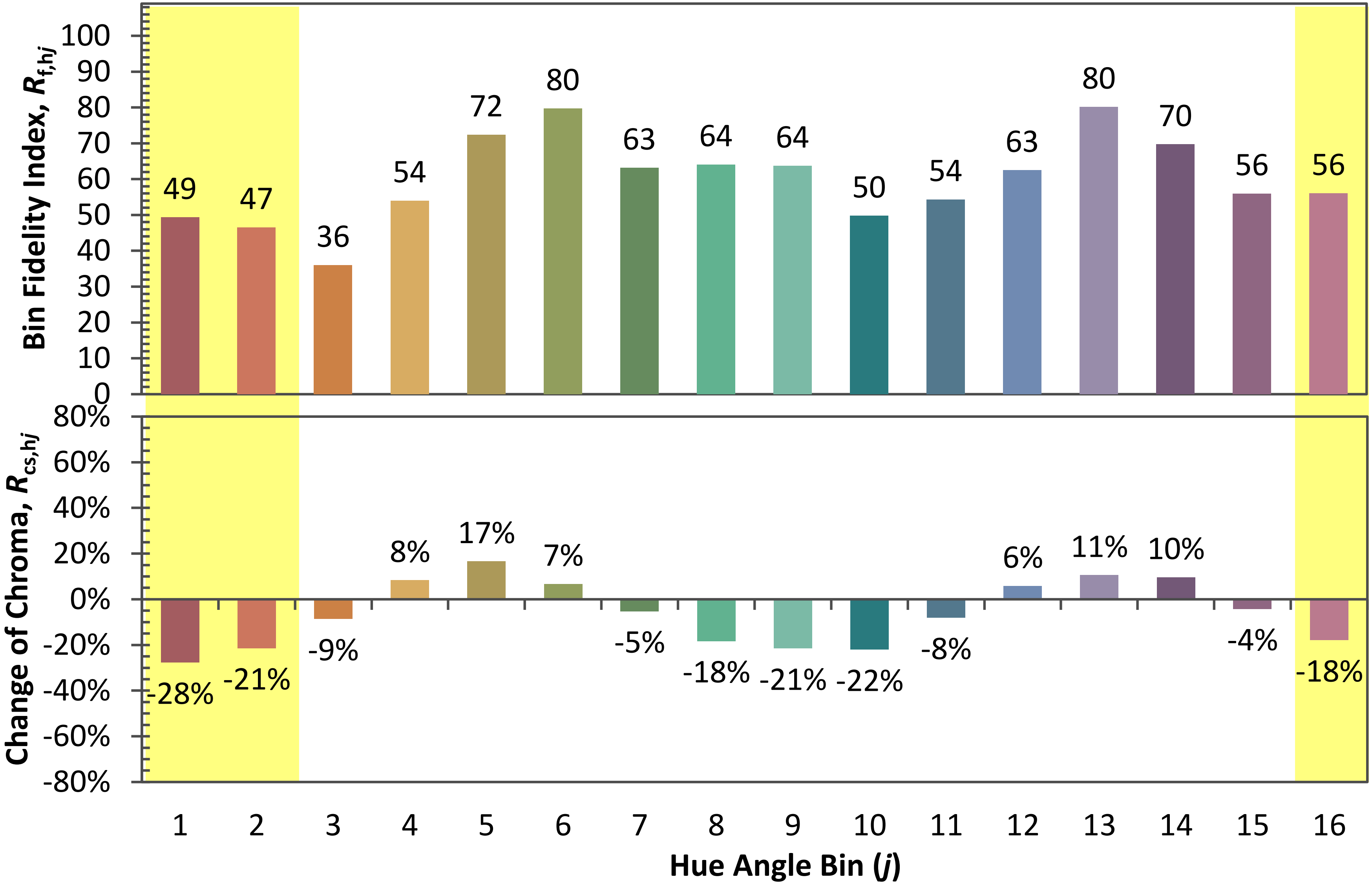
Each arrow corresponds to a hue bin change. We can look at the length of the arrow (fidelity), or the isolate the amount of chroma change by calculating how much the arrow is pointing inward/outward.

TM-30 Hue Bin Indices



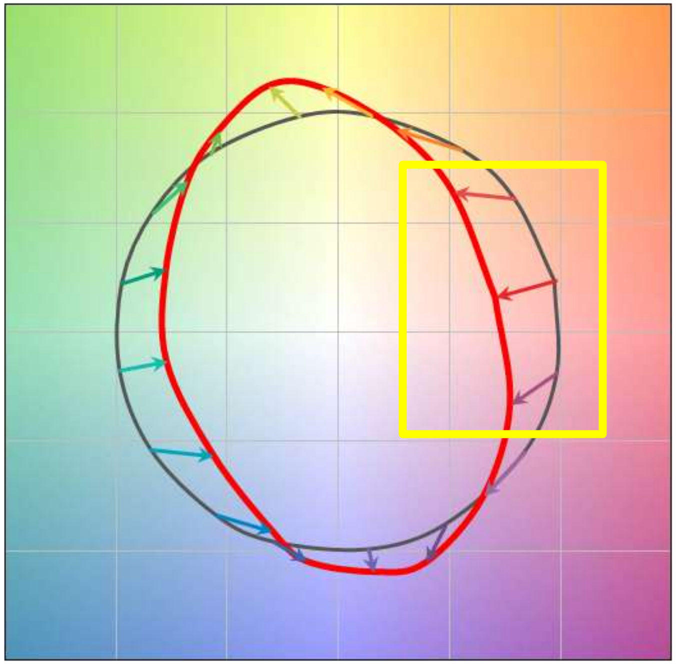
What about Red?

TM-30 Hue Bin Indices



TM-30-15 Vector Graphics vs. Fidelity

COLOR VECTOR GRAPHIC



Fidelity is approximately the average length of the arrows.

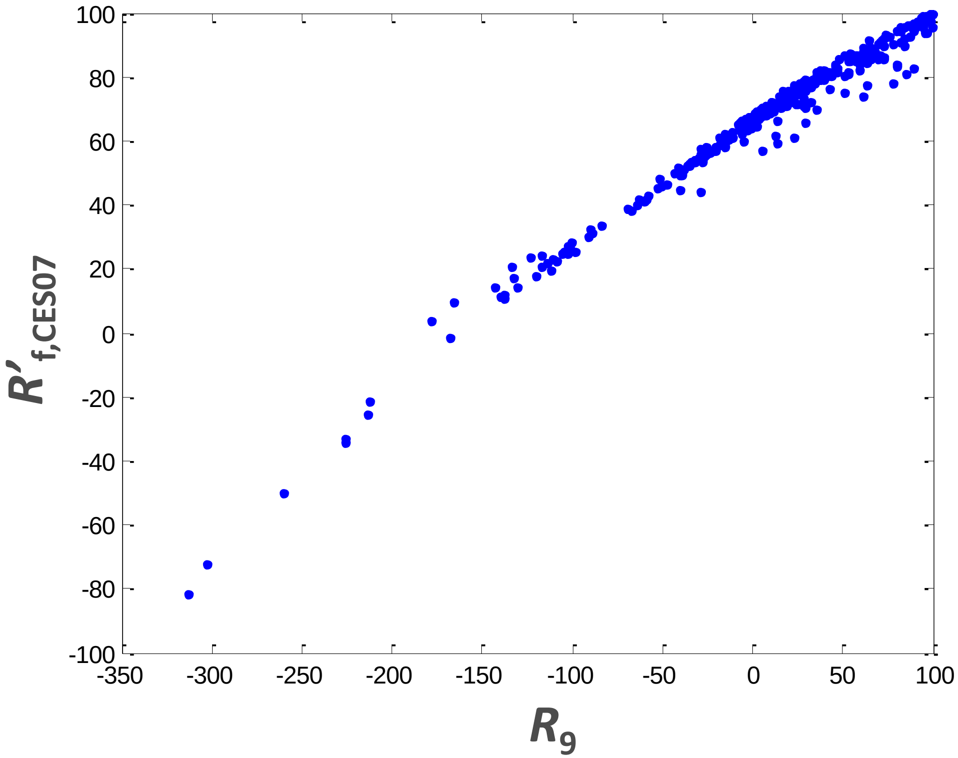
Gamut is the ratio of the area of the black circle and red shape.

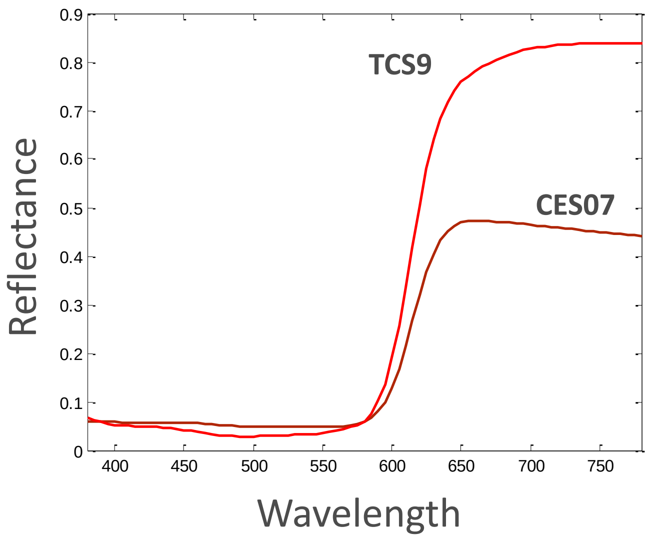
Each arrow corresponds to a hue bin change. We can look at the length of the arrow (fidelity), or the isolate the amount of chroma change by calculating how much the arrow is pointing inward/outward.

What do we want to know?

- What is more representative of a red we will encounter in an unknown space? One sample or several samples?
- Fidelity measures tell us how similar the reds look to the reference. Differences could be due to hue shift, oversaturation, or under saturation.
- Are saturation changes or hue shifts more important?
- Are the reference sources ideal in all contexts (i.e., do we want perfect red fidelity?)

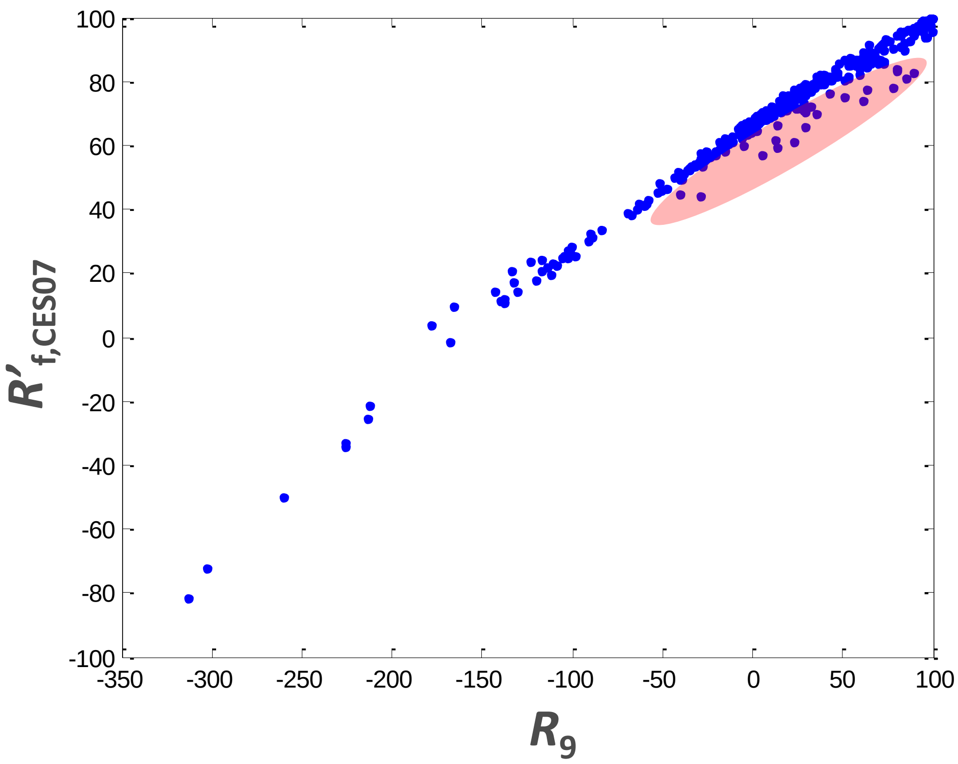
CRI R_9 versus TM-30

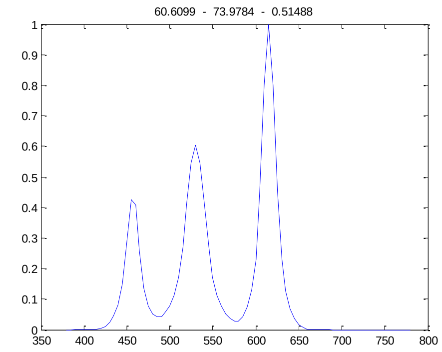


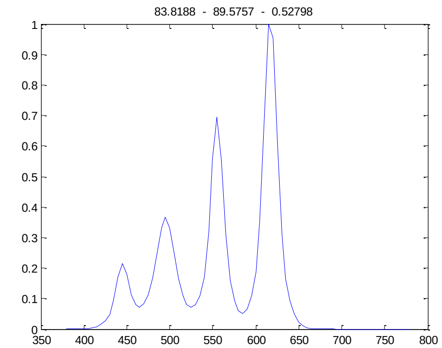


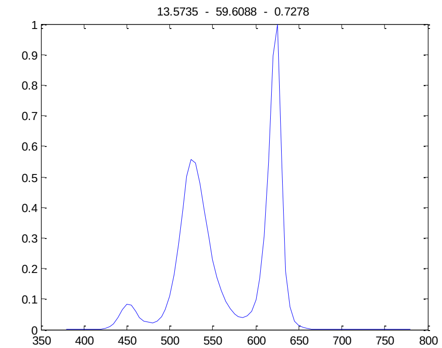
One sample of TM-30 is very well correlated to R9…

What about R_9?





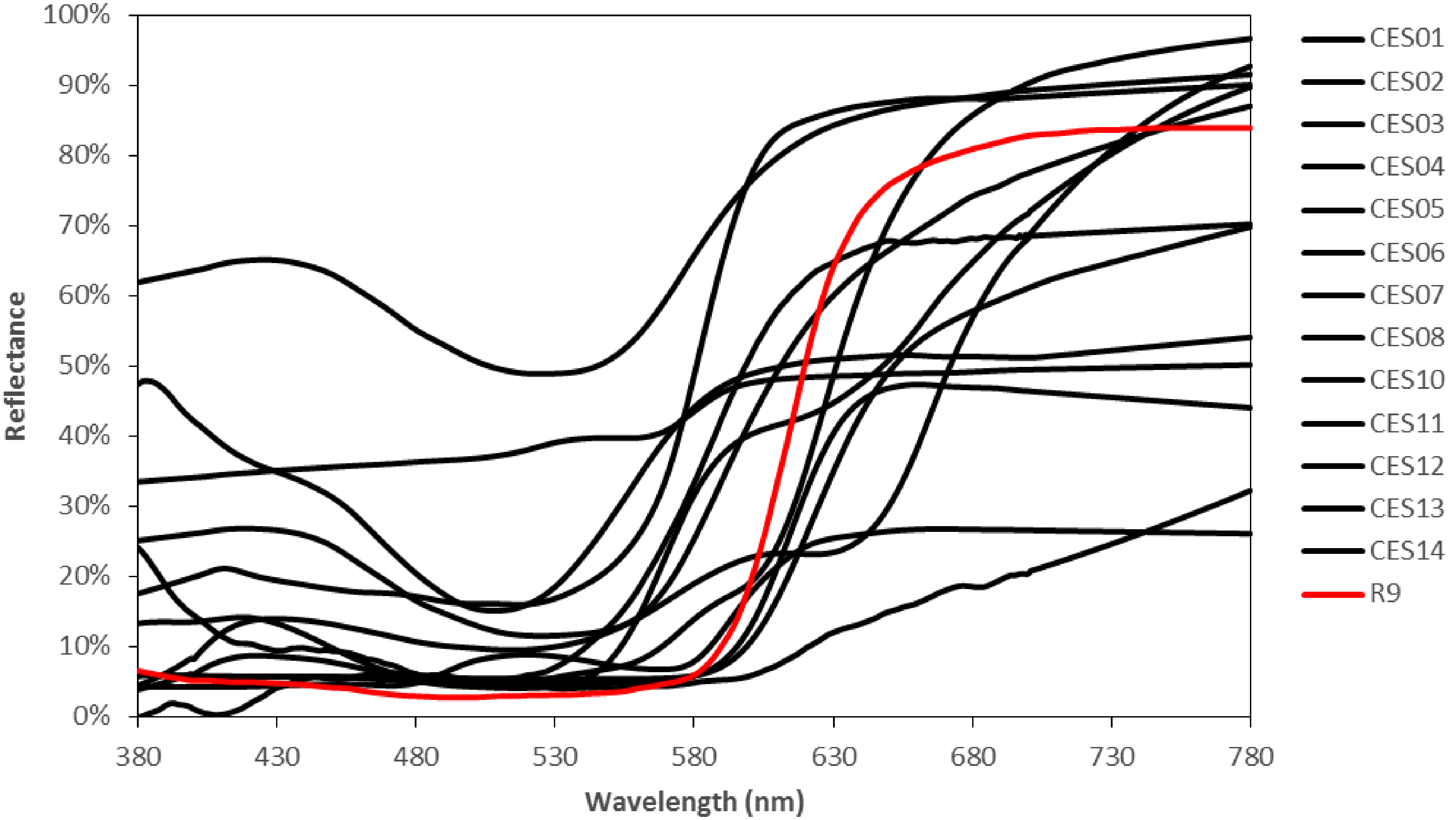




One sample of TM-30 is very well correlated to R9…

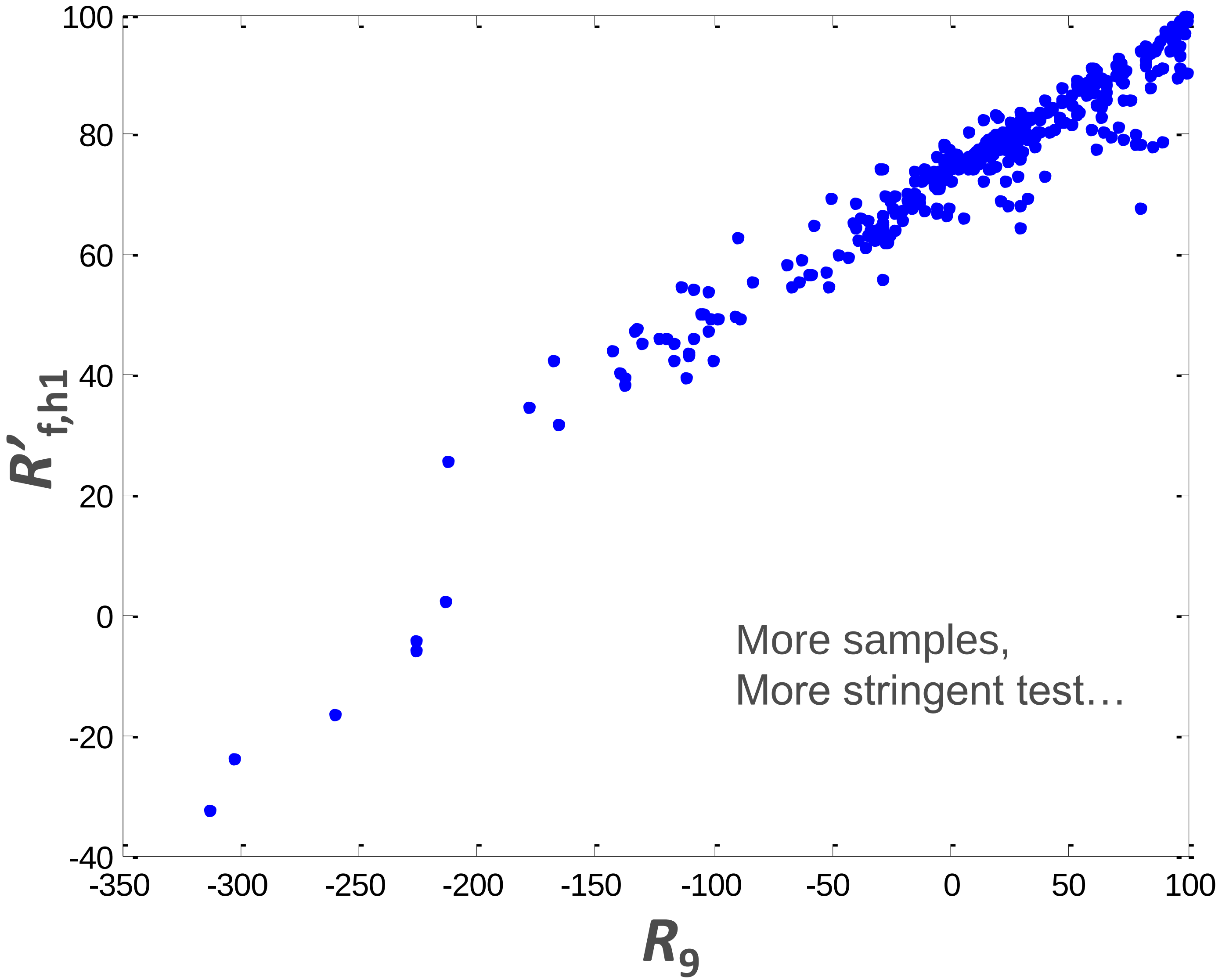
…except for a few narrowband sources

Is R_9 Special?

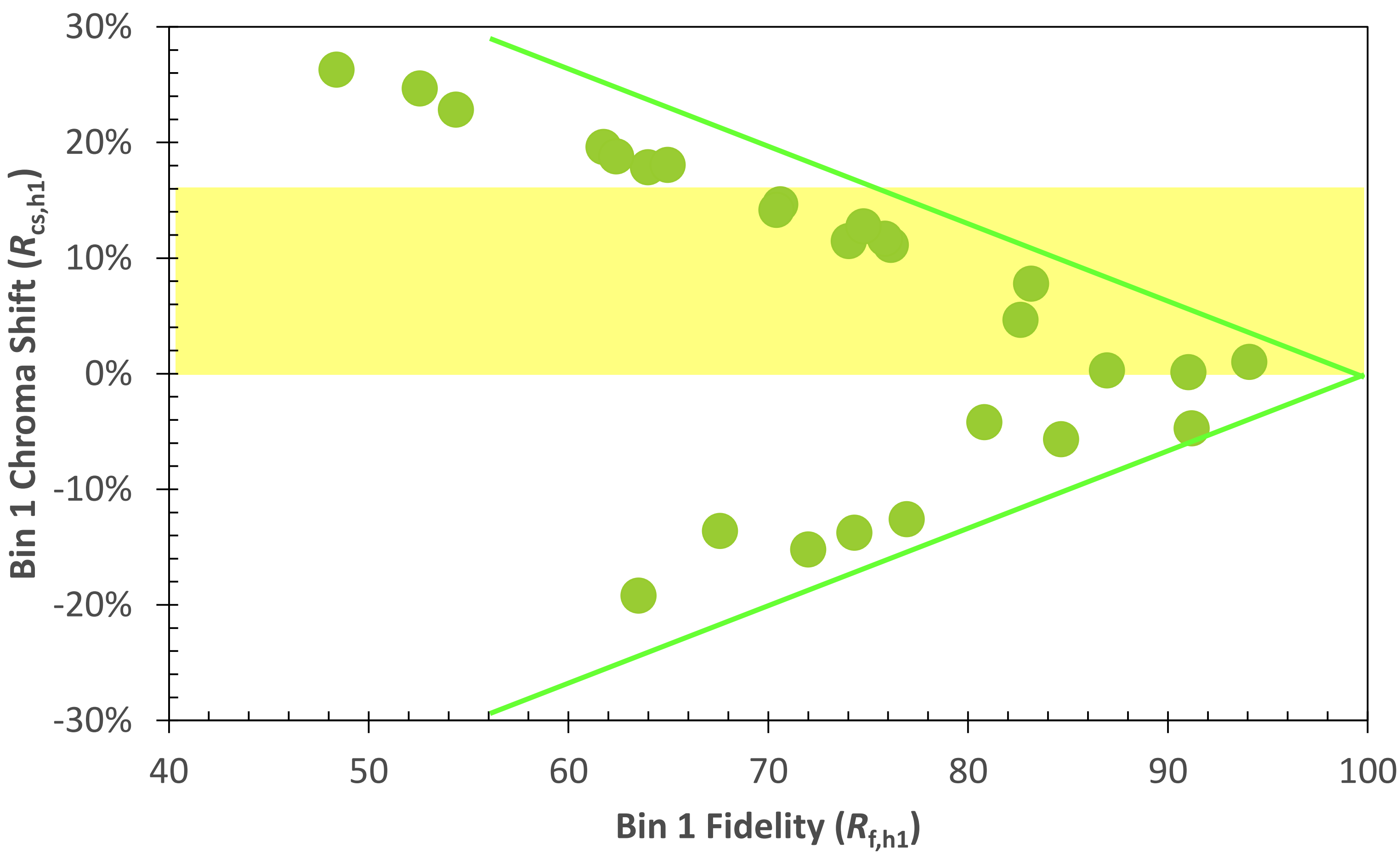


TM30 offers a lot more samples for characterizing red / warm tones.

R_9 versus $R_{f,h1}$?

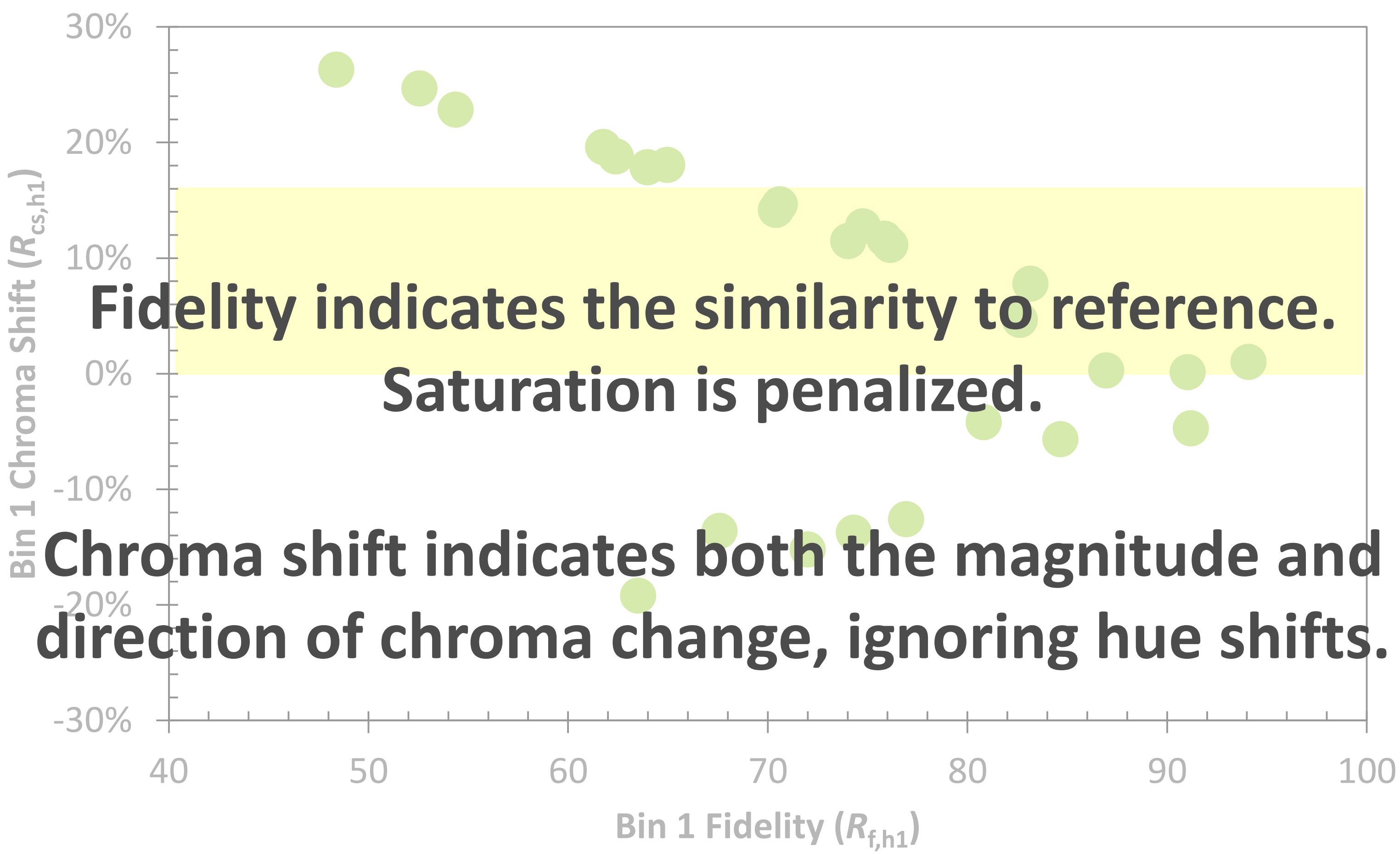


Fidelity versus Chroma Shift



(Set of 26 Experimental SPDs)

Fidelity versus Chroma Shift

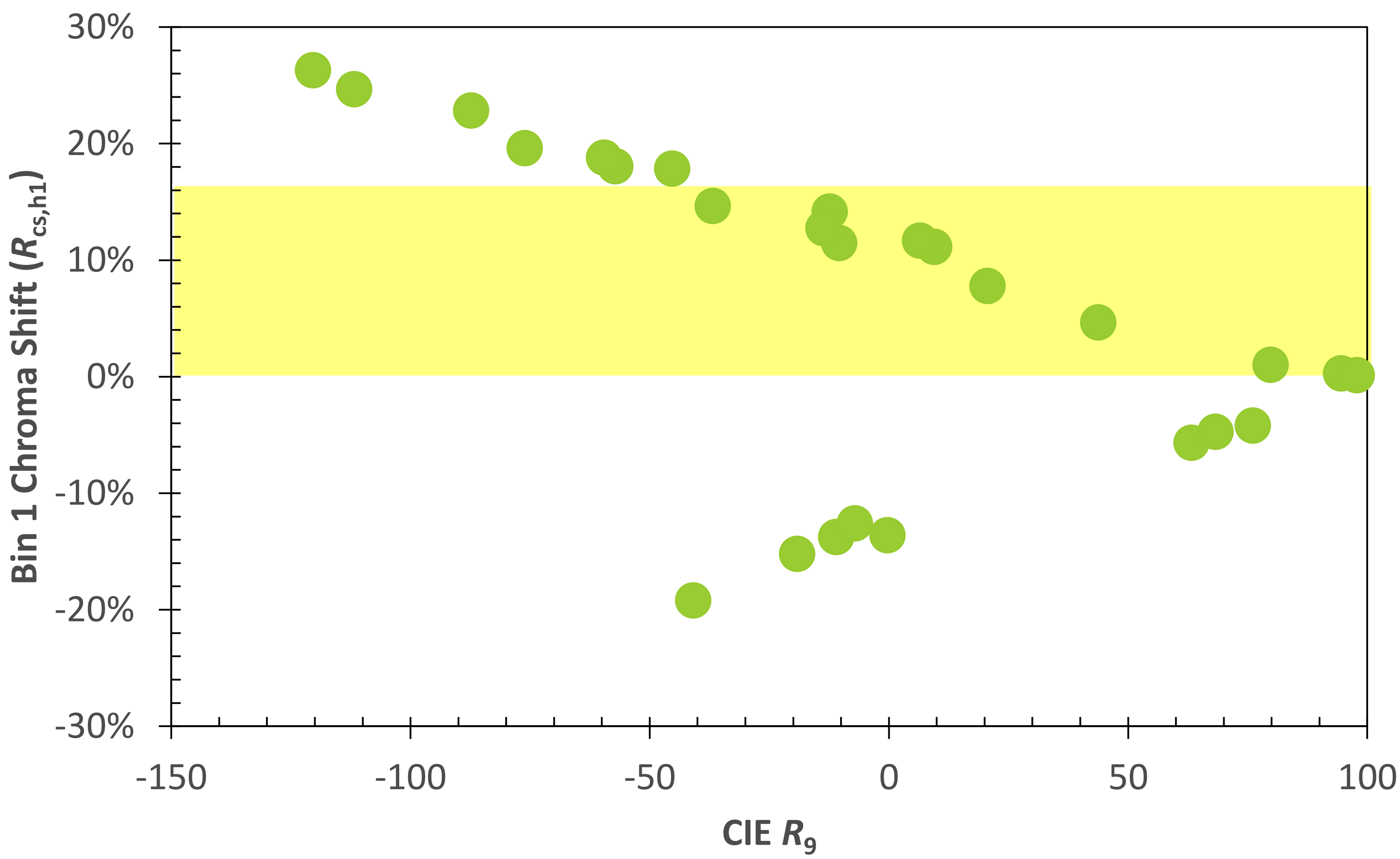


Fidelity indicates the similarity to reference. Saturation is penalized.

Chroma shift indicates both the magnitude and direction of chroma change, ignoring hue shifts.

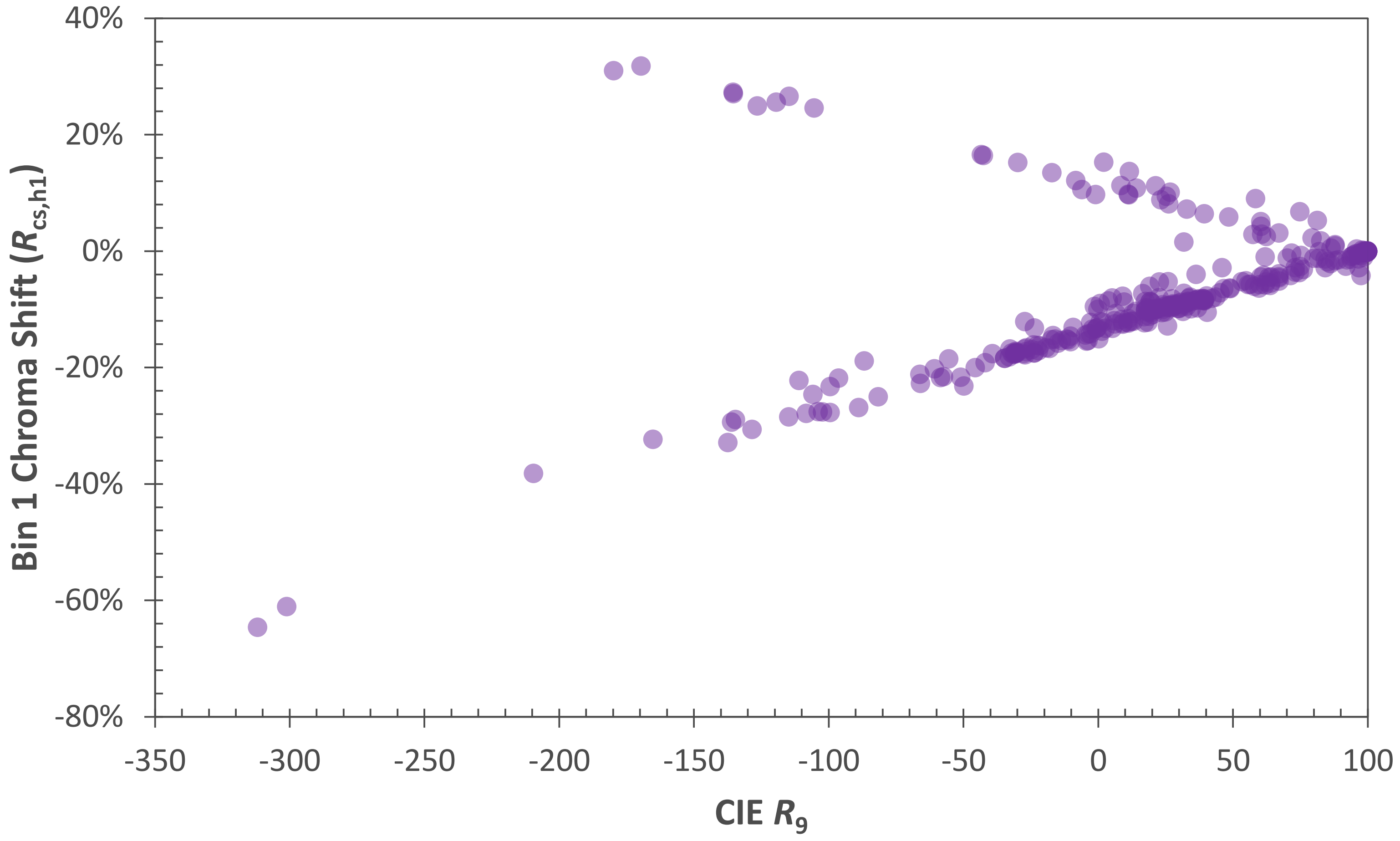
(Set of 26 Experimental SPDs)

Fidelity versus Chroma Shift



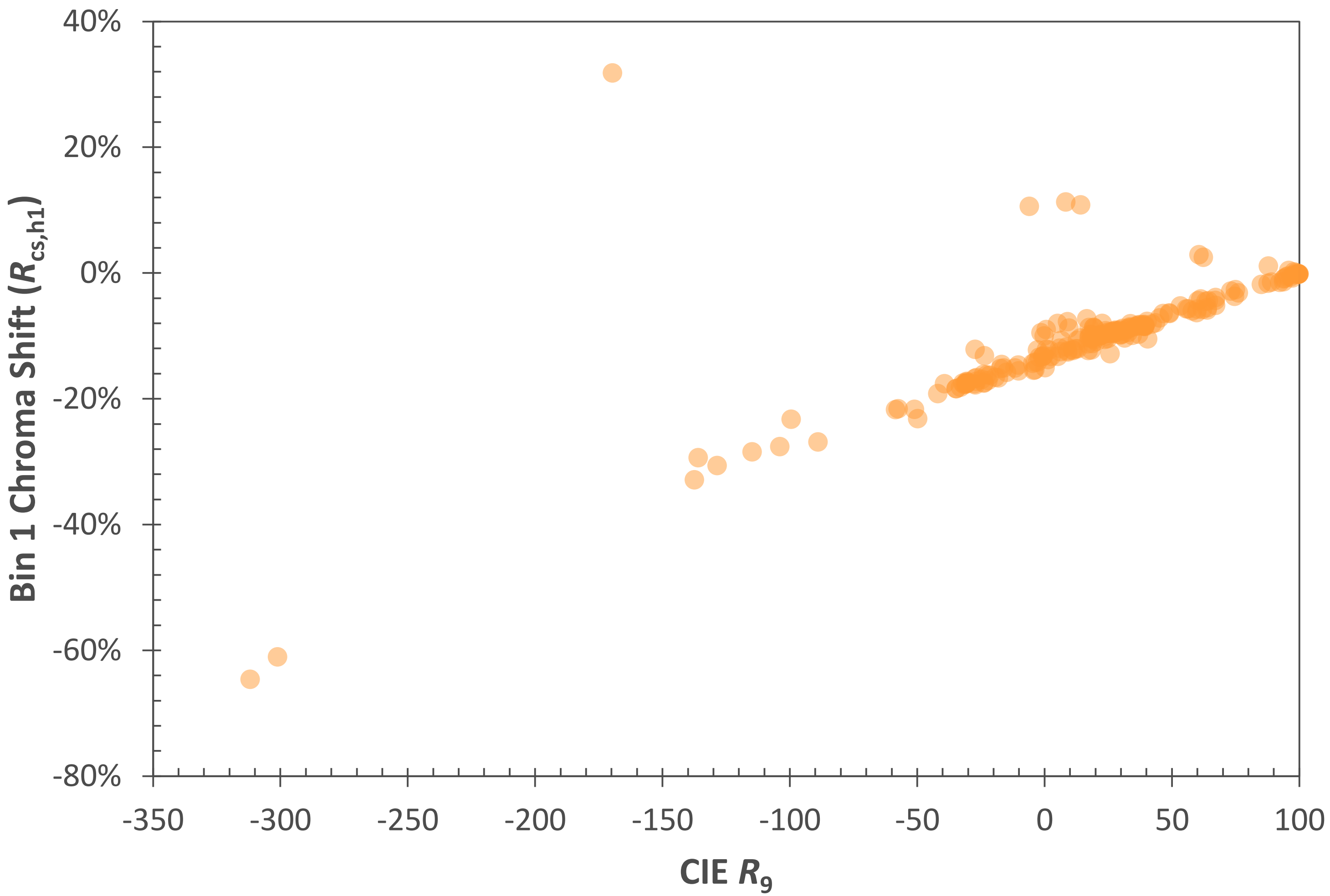
(Set of 26 Experimental SPDs)

Fidelity versus Chroma Shift



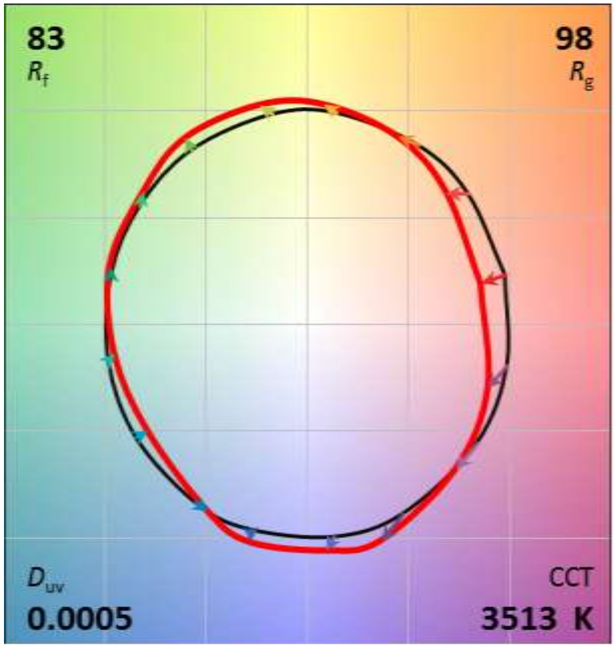
(All TM-30 Library)

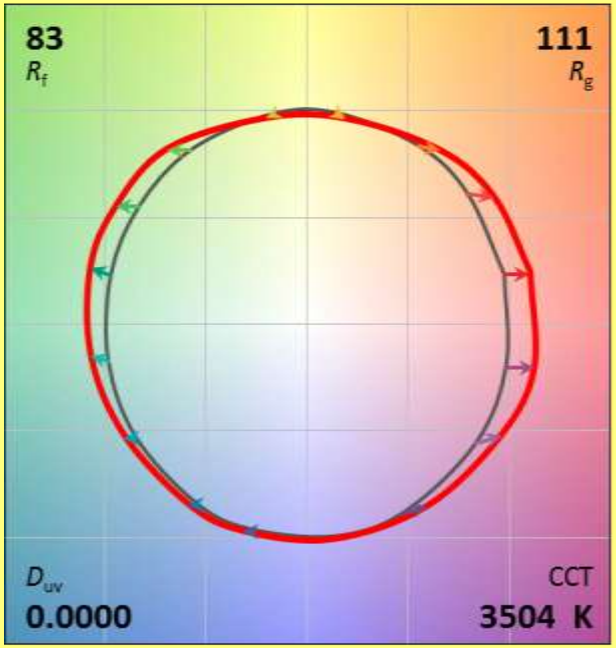
Fidelity versus Chroma Shift

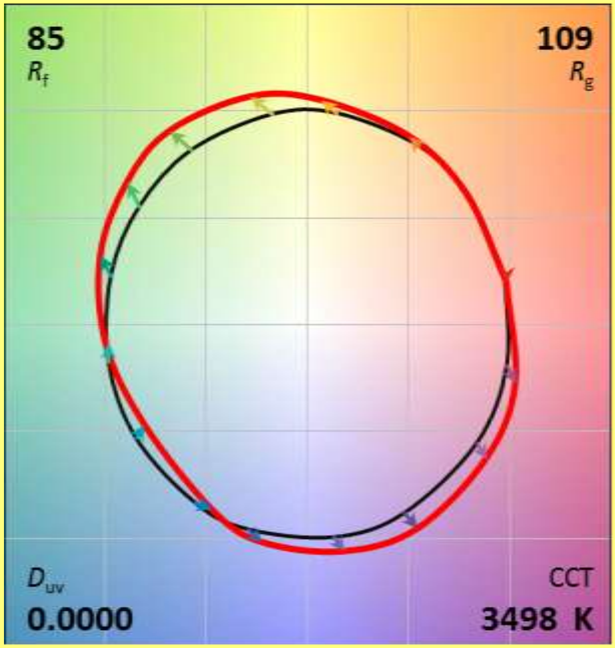


(Commercial Sources)

Changes in Red Rendering







$R_{f,h1} = 77$
$R_{cs,h1} = -13\%$

$R_9 = -7$

$R_{f,h1} = 75$
$R_{cs,h1} = 13\%$

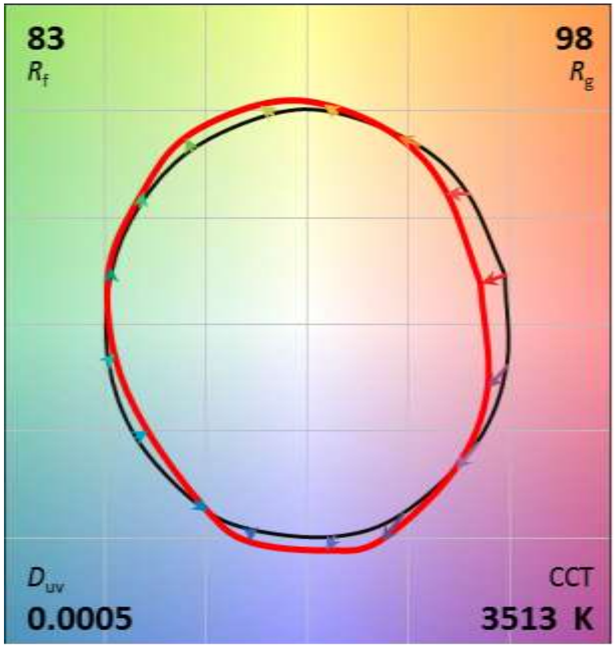
$R_9 = -21$

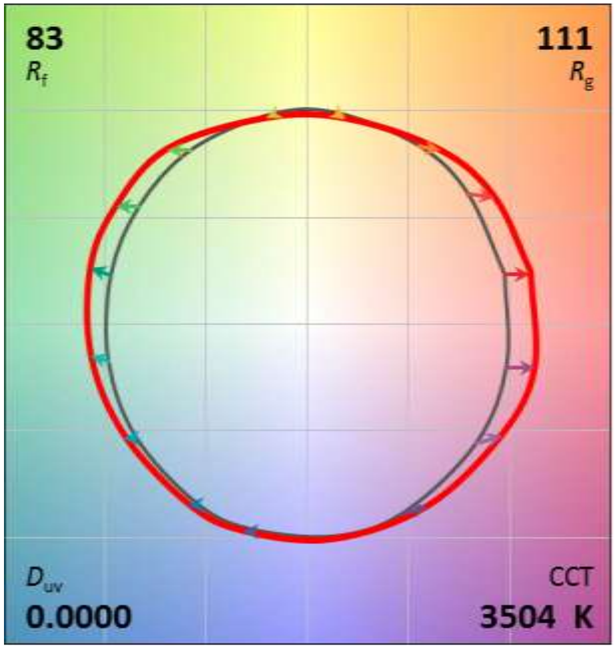
$R_{f,h1} = 91$
$R_{cs,h1} = 0\%$

$R_9 = 98$

21, 23, 24

Changes in Red Rendering





$R_{f,h1}$ = 77

$R_{cs,h1}$ = -13%

R_9 = -7

$R_{f,h1}$ = 75

$R_{cs,h1}$ = 13%

R_9 = -21

Same red fidelity

Shift in different directions.

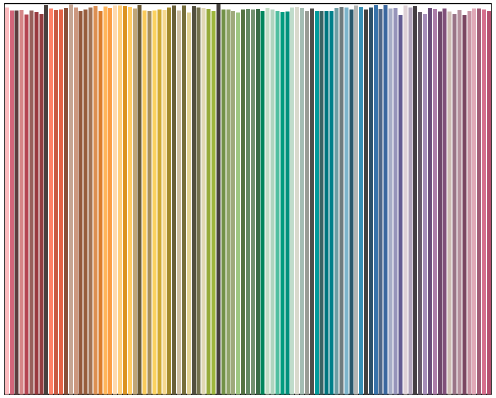
TM-30 Interpretation Summary

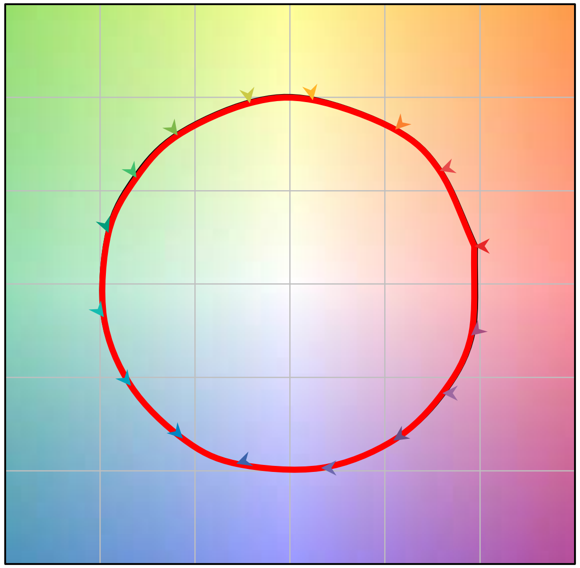
- **Fidelity Index (*R_f*):** How similar is a source to the reference, on average.
- **Gamut Index (*R_g*):** Is saturation/chroma being increased or decreased, on average.
- **Color Vector Graphic:** Visual of magnitude and direction of shift for all hues.
- **Hue Bin Fidelity:** Average fidelity for reds, yellows, greens, blues, etc.
- **Hue Bin Chroma Shift:** Average chroma change for reds, yellows, greens, blues, etc.

Which Source is Best?

Questions?

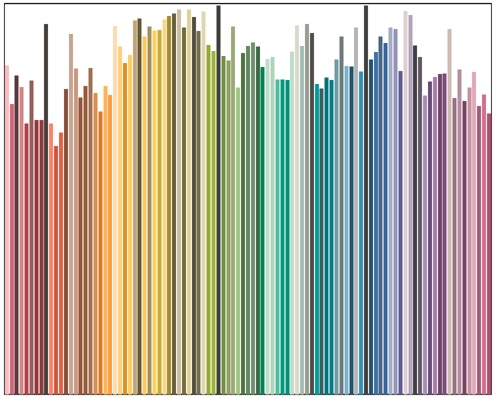
Halogen MR16, 3000 K (Source No. 80)

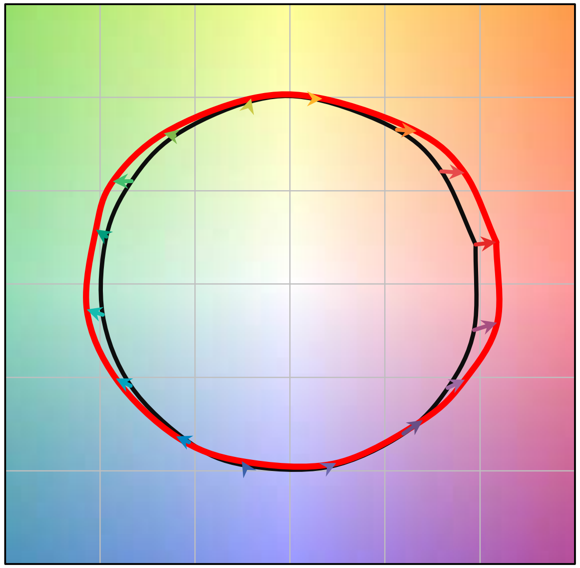




R_f	=	99
R_g	=	99
$R_{f,skin}$	=	99
CCT	=	2988 K
D_{uv}	=	0.0010
R_a	=	99
R_9	=	93

Neodymium Incandescent (Source No. 88)

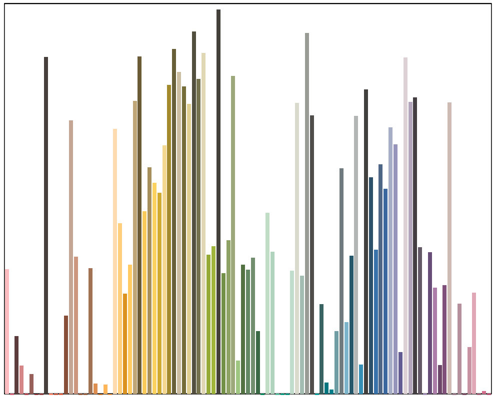


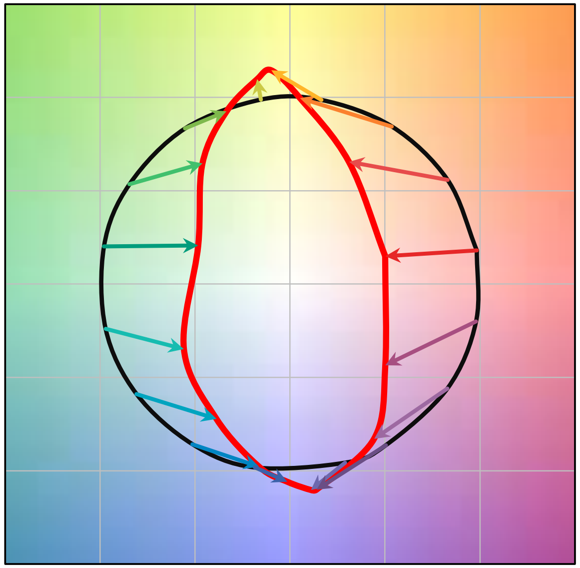


R_f = 86
R_g = 109
$R_{f,skin}$ = 83

CCT = 2757 K
D_{uv} = -0.0048
R_a = 77
R_9 = 15

High Pressure Sodium (Source No. 56)

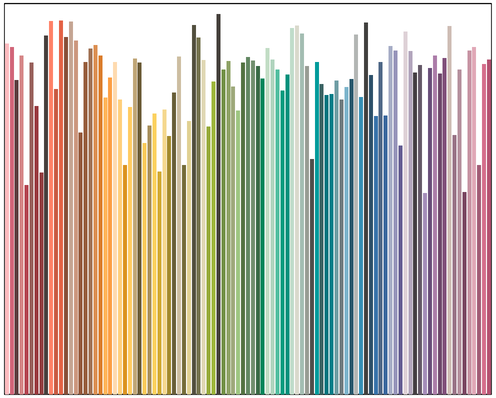


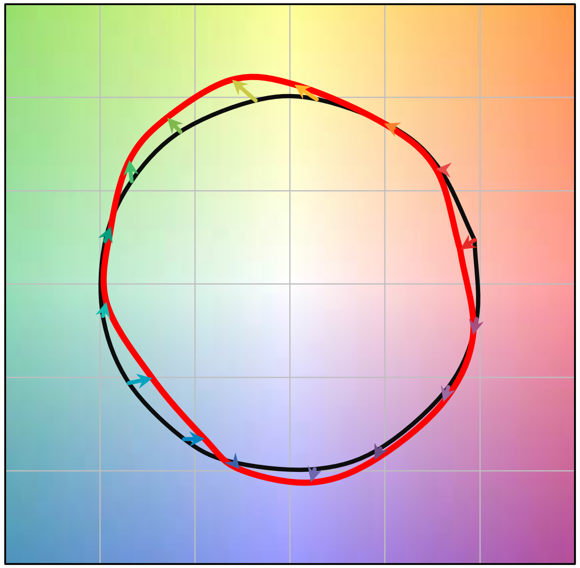


R_f = 32
R_g = 61
$R_{f,skin}$ = 34

CCT = 1967 K
D_{uv} = -0.0002
R_a = 16
R_9 = -226

F32T8 835 (Source No. 37)





R_f = 80

R_g = 102

$R_{f,skin}$ = 89

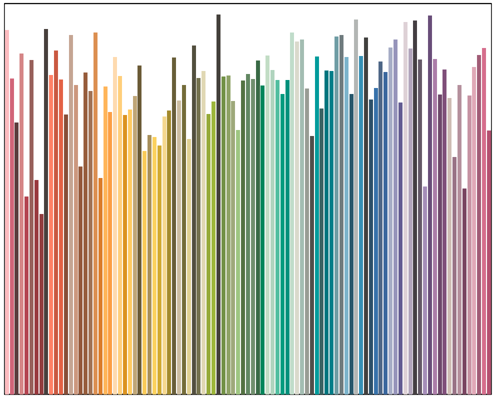
CCT = 3480 K

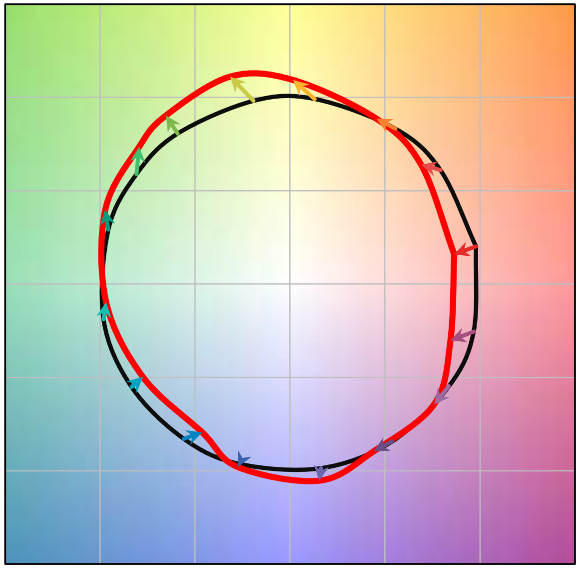
D_{uv} = 0.0007

R_a = 86

R_9 = 15

Ceramic Metal Halide, 3000 K (Source No. 62)



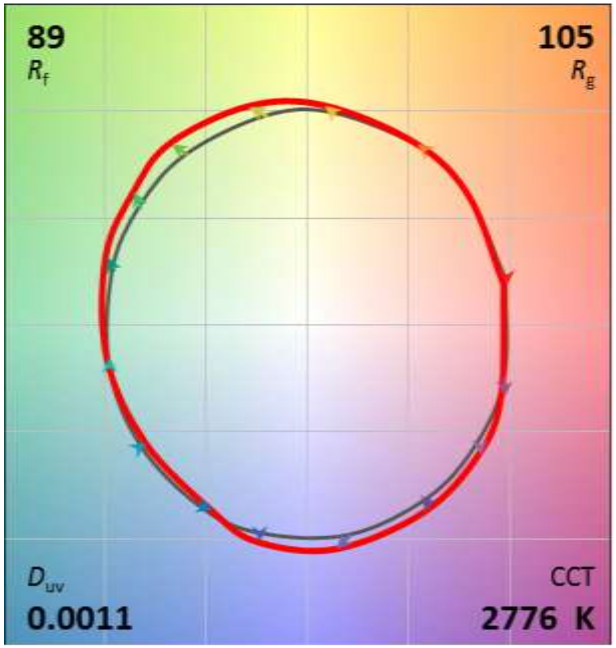


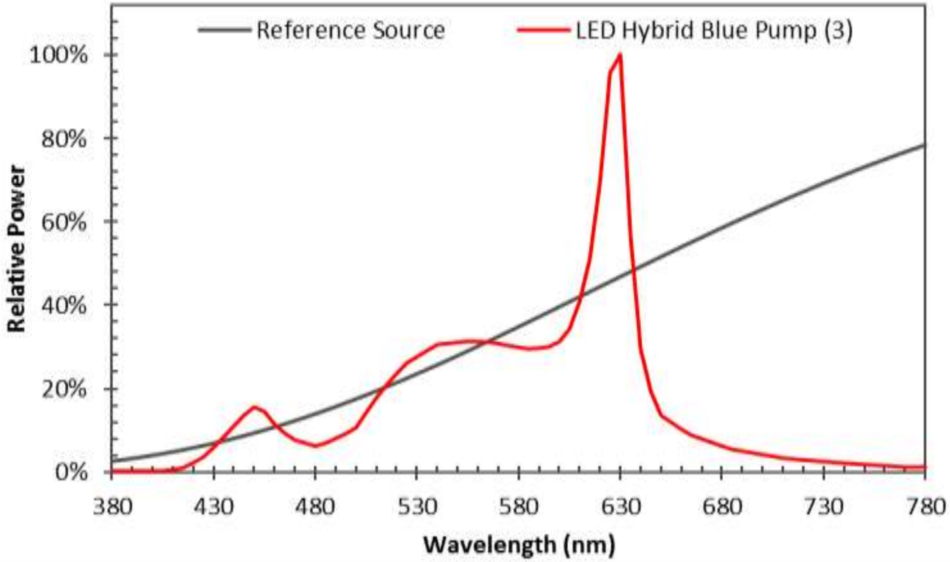
R_f = 79
R_g = 100
$R_{f,skin}$ = 78

CCT = 3080 K
D_{uv} = -0.0024
R_a = 84
R_9 = -30

Hybrid LED

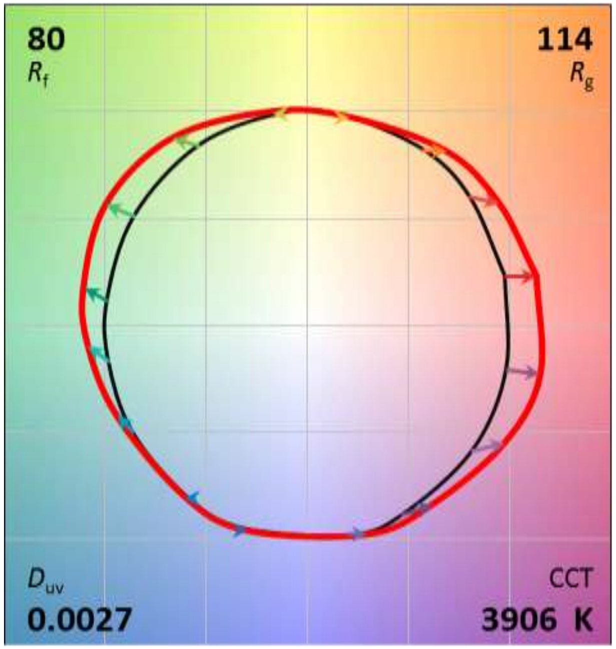
(Source No. 92)

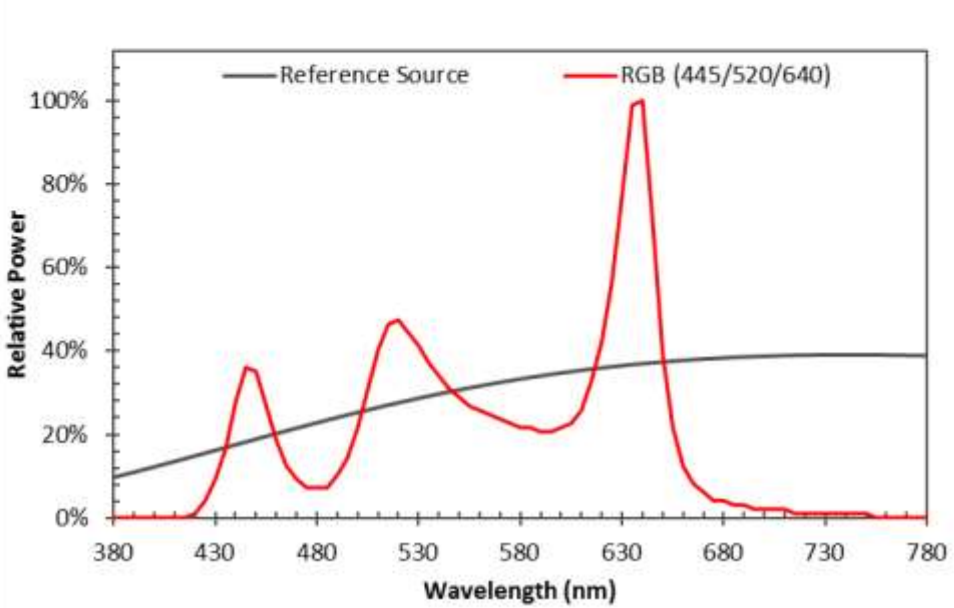




RGB LED

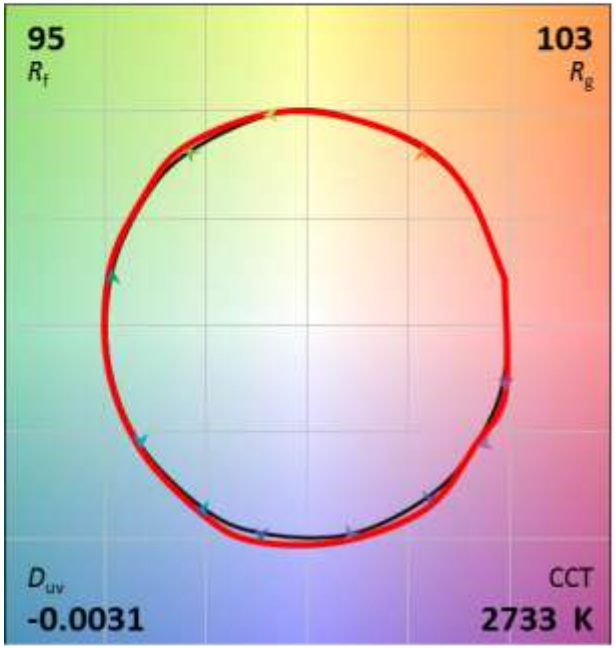
(Source No. 108)

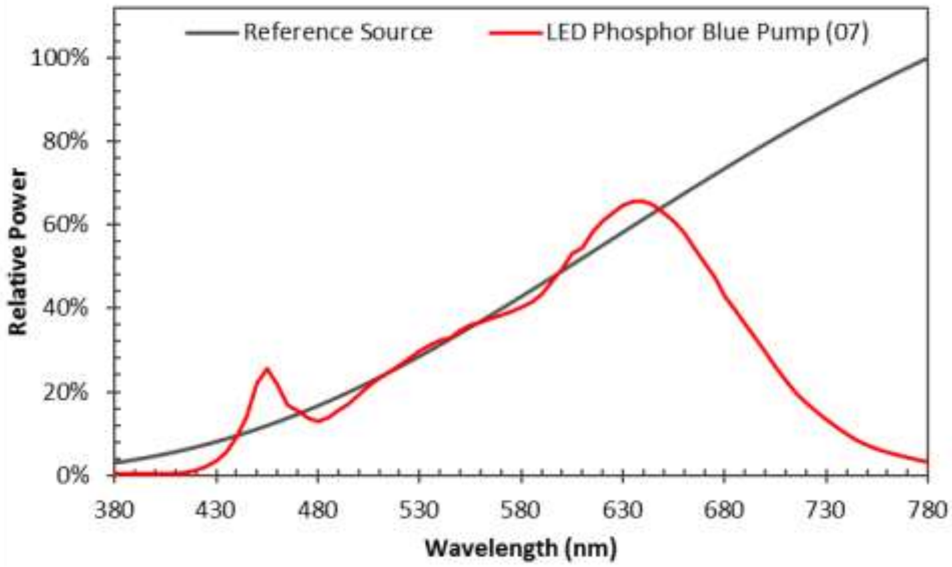




PC-LED

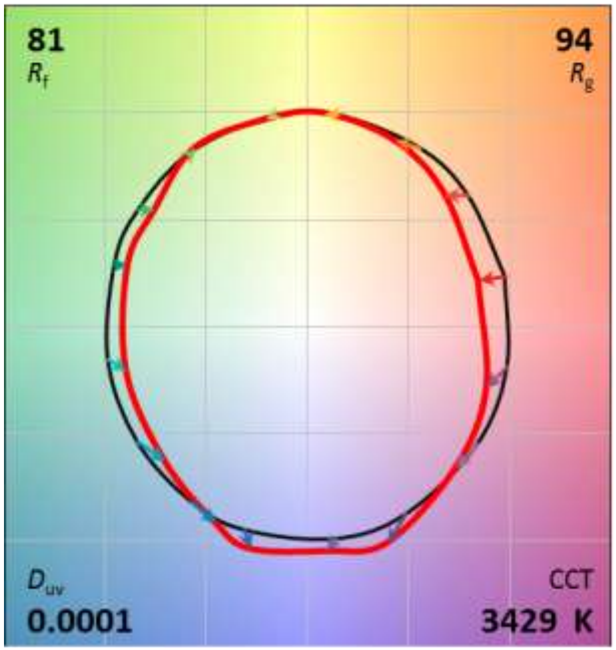
(Source No. 175)

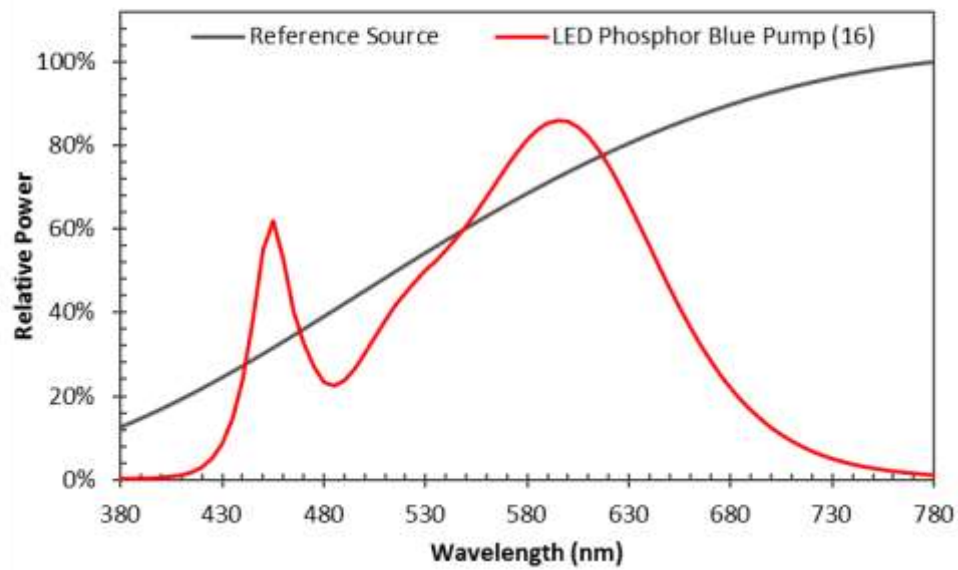




PC-LED

(Source No. 184)





TM-30 “under the hood“

A lot of technical improvements are included in TM-30

Some of these are crucial to make the calculations *accurate*!

- Slight change in reference illuminant

- Better color science
  - Uniform color space
  - Good chromatic adaptation

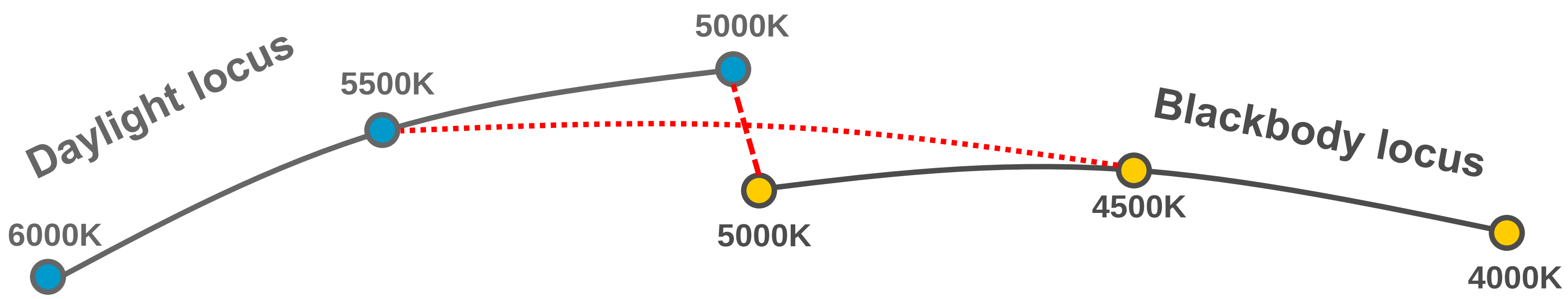
- Optimized set of test samples

Reference Illuminants

CRI: **CCT ≥ 5000 K** | **CCT < 5000 K**

CIE D Series
(Model of Daylight)

Planckian Radiation
(Think Incandescent)



TM-30: **CCT ≥ 5500 K** | **5500 K > CCT > 4500 K** | **CCT ≤ 4500 K**

CIE D Series
(Model of Daylight)

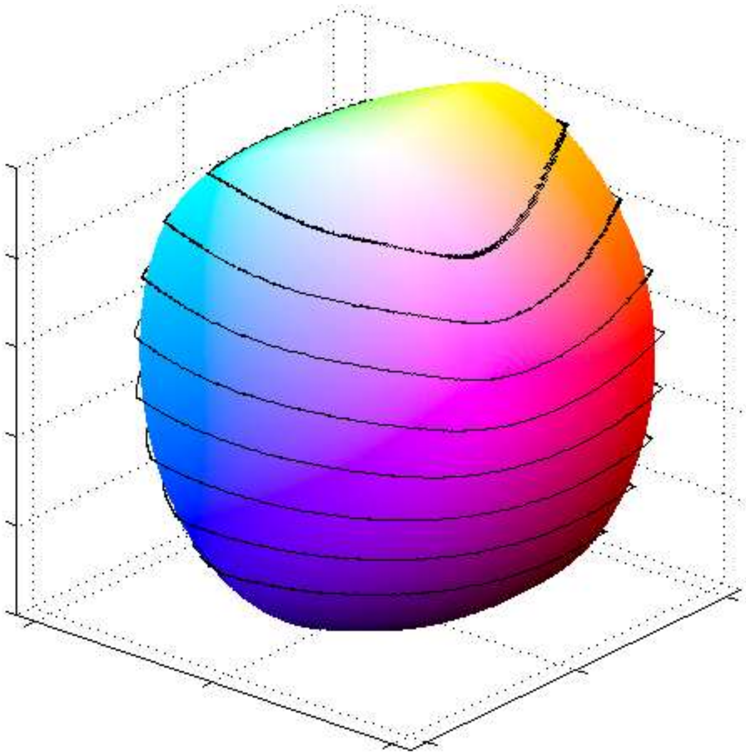
Proportional blend of
D Series and Planckian

Planckian Radiation
(Think Incandescent)

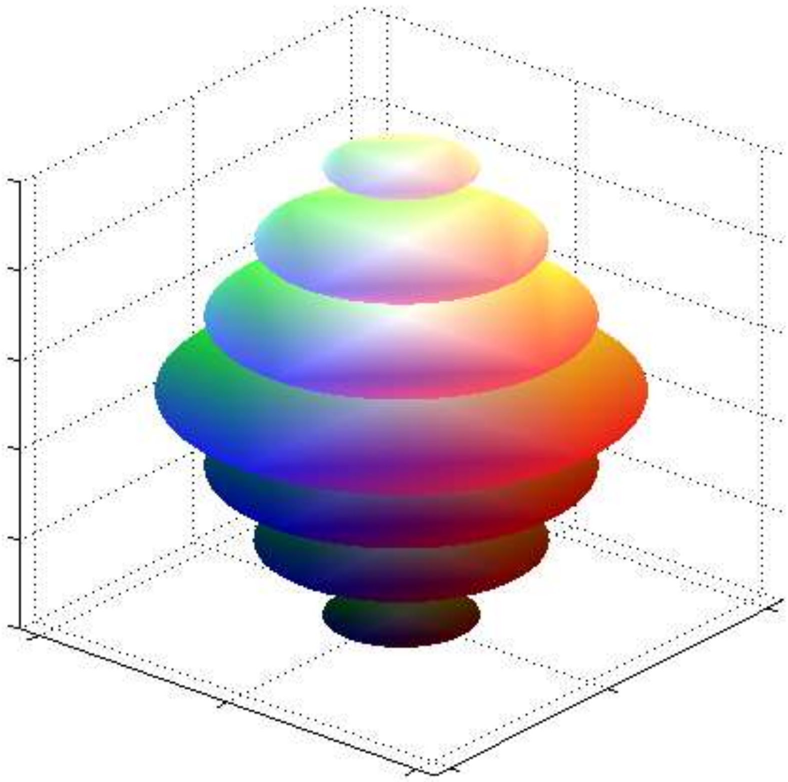
Color Space: CAM02-UCS

CAM02-UCS is a state-of-the art color space

Color volume



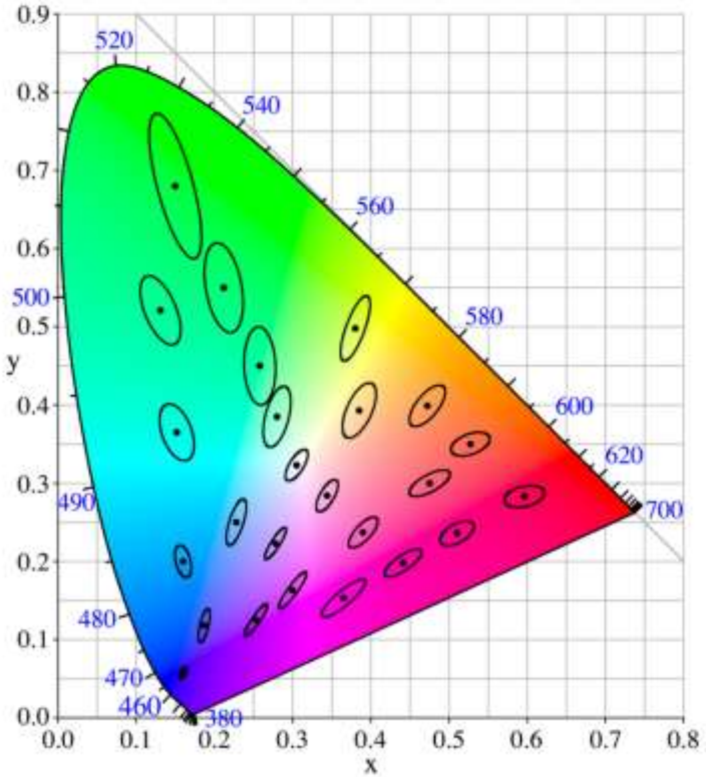
“slices” in the color volume



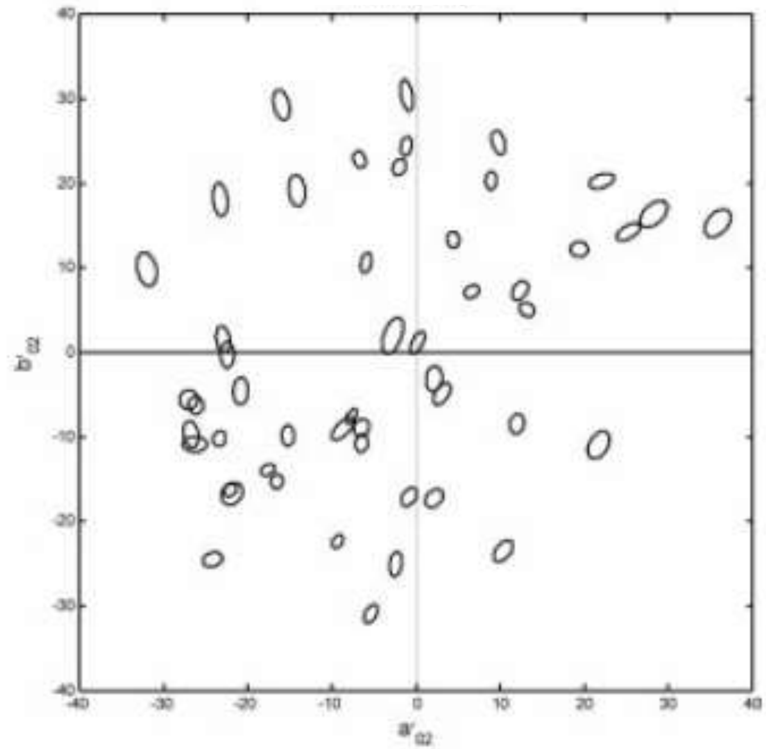
Color Space: CAM02-UCS

Color uniformity:

CIEXYZ



CAM02-UCS



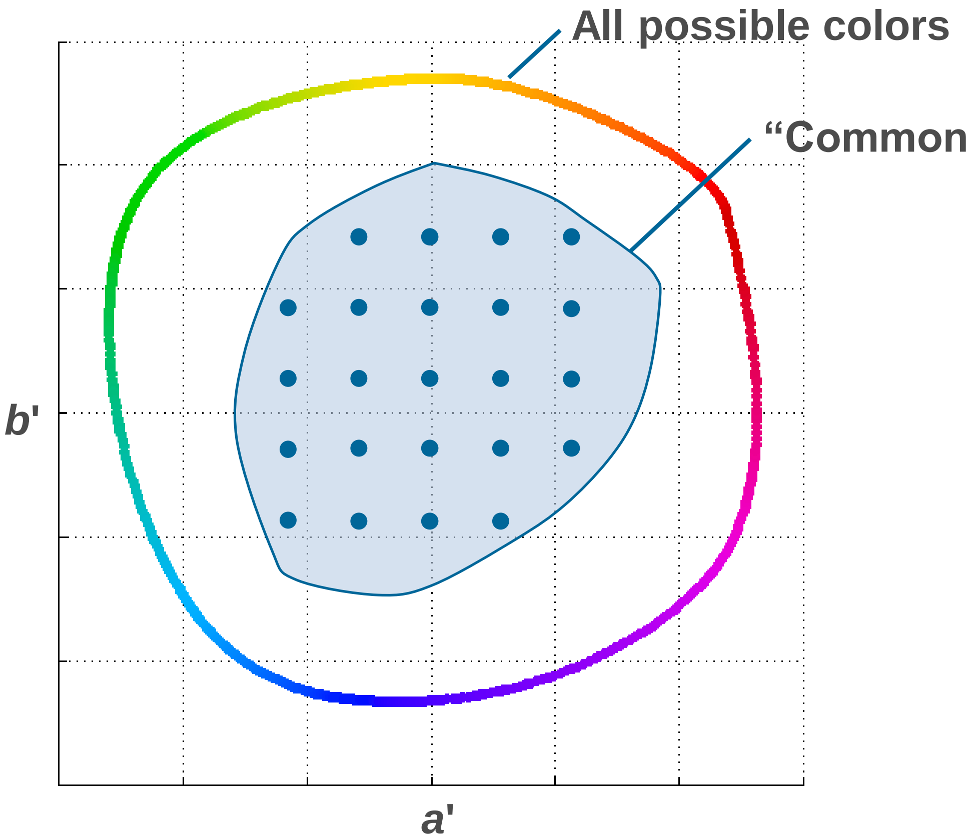
Color-error ellipses are nearly circular and of even size

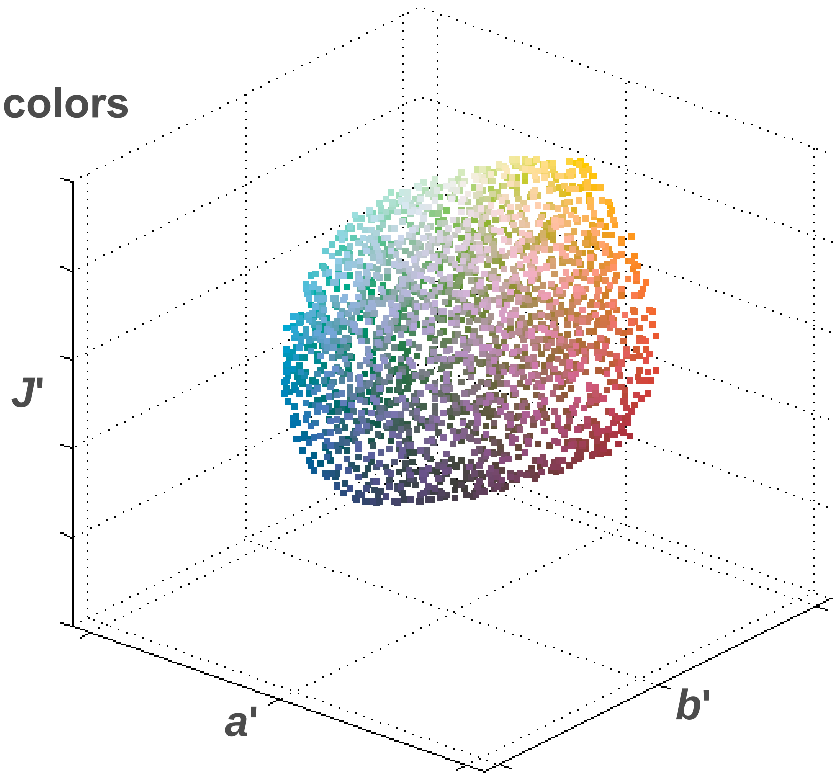
→ color distortions for different colors can be compared

Test samples: color space uniformity

TM-30: select a gamut of "common colors" in color space and span it uniformly.

→ "one sample per color"

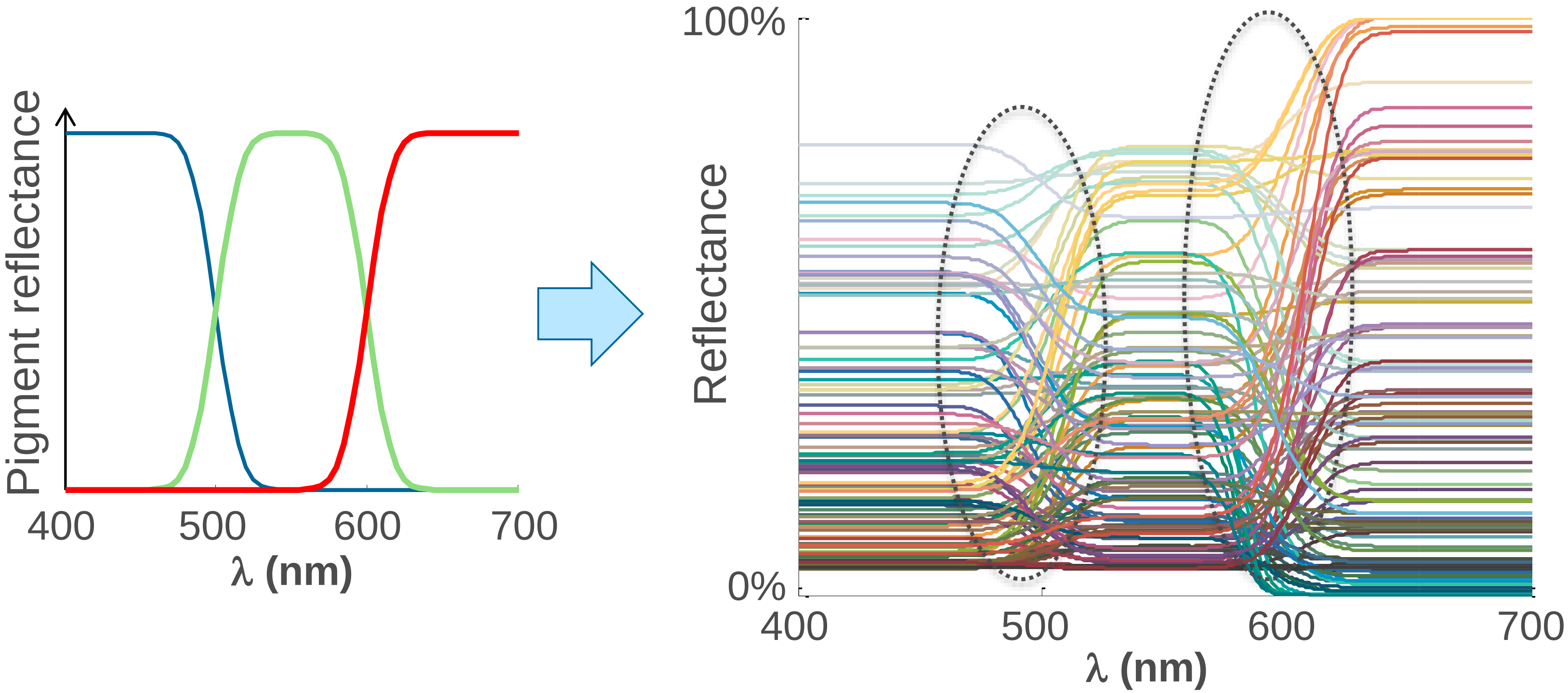




Test samples: wavelength uniformity

An extreme example of a sample set with wavelength bias…

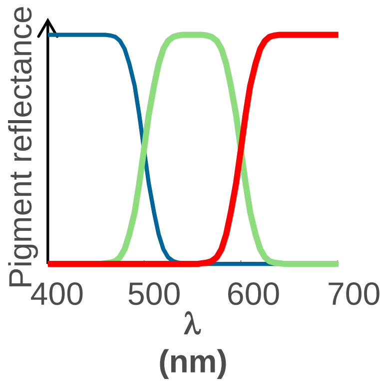
It is possible to generate many colors with only 3 “pigments”!

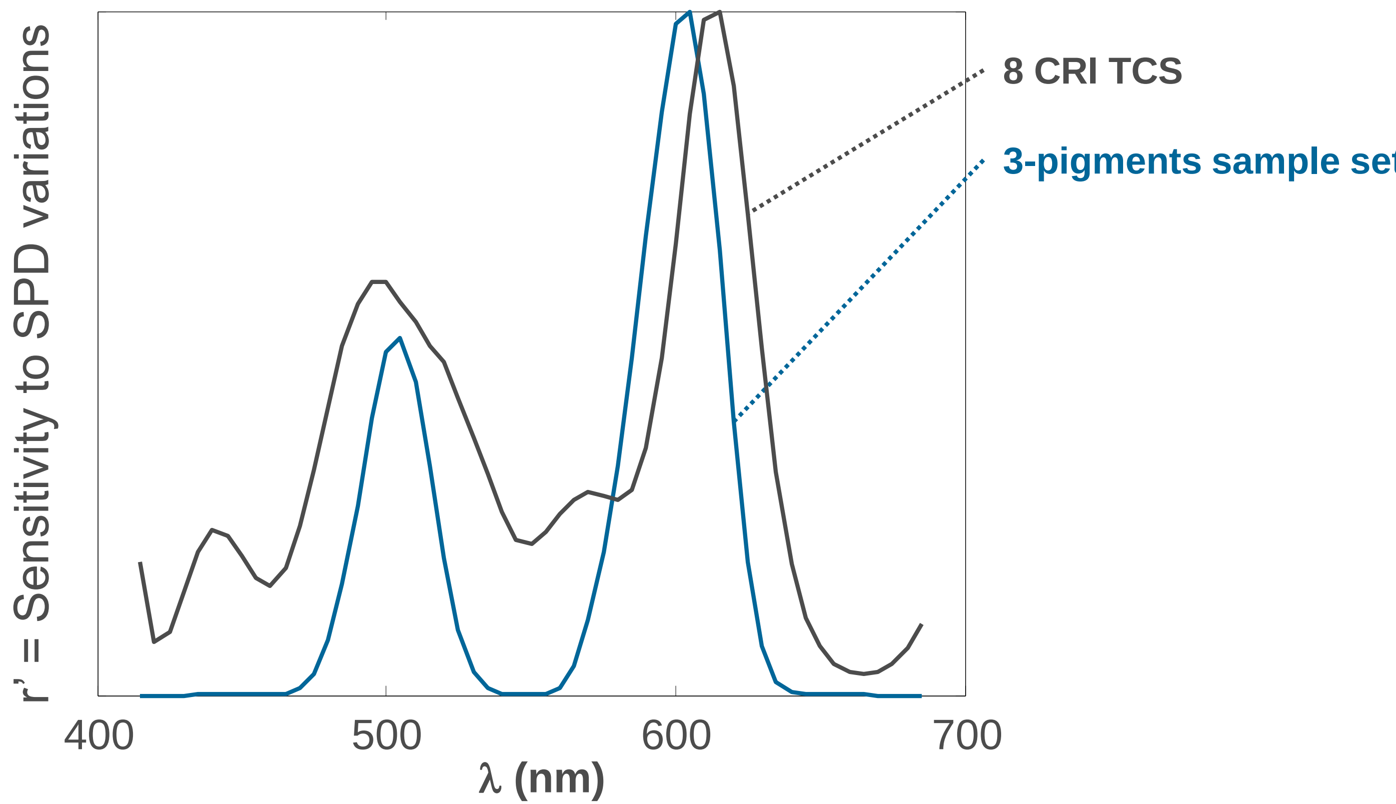


But the corresponding samples are mostly sensitive to a few wavelengths

Test samples: wavelength uniformity

We can compute the “wavelength sensitivity” for a sample set (r'^2, r''^2…)



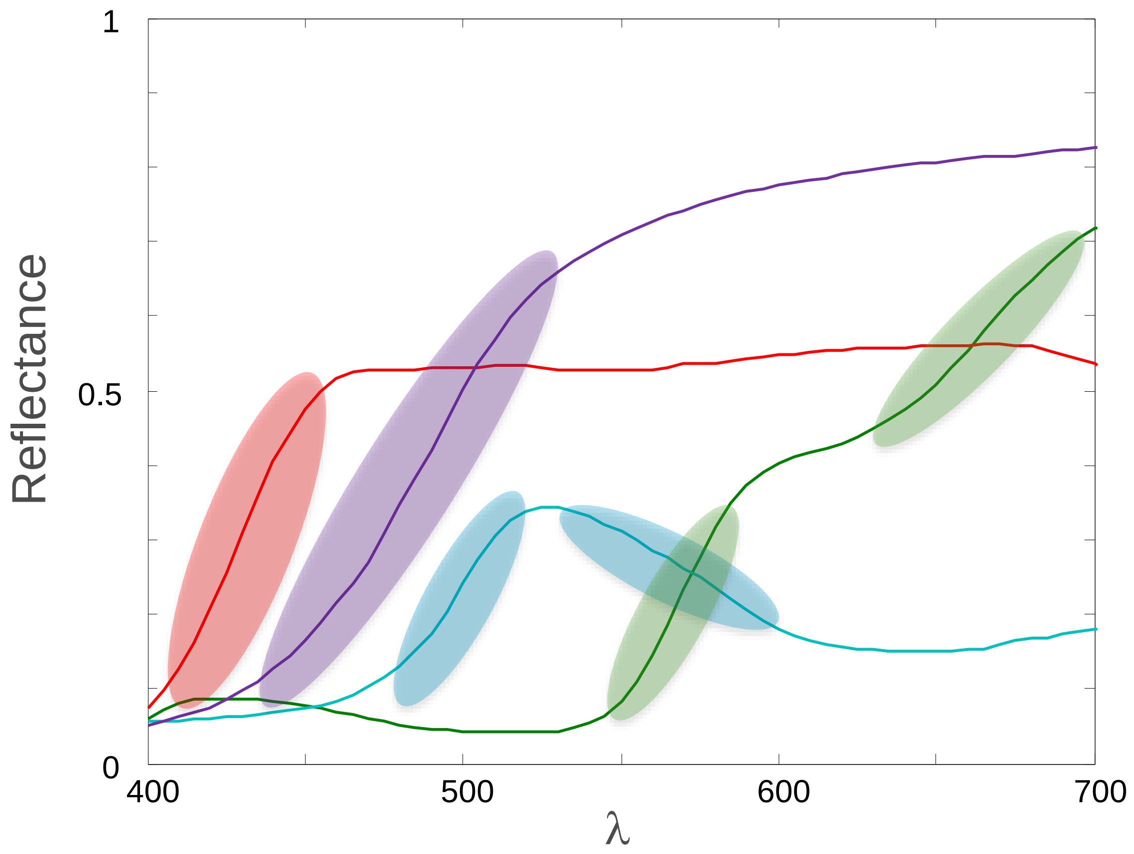


In general, sample sets suffer from some wavelength bias…

They “care more” about some wavelengths than others

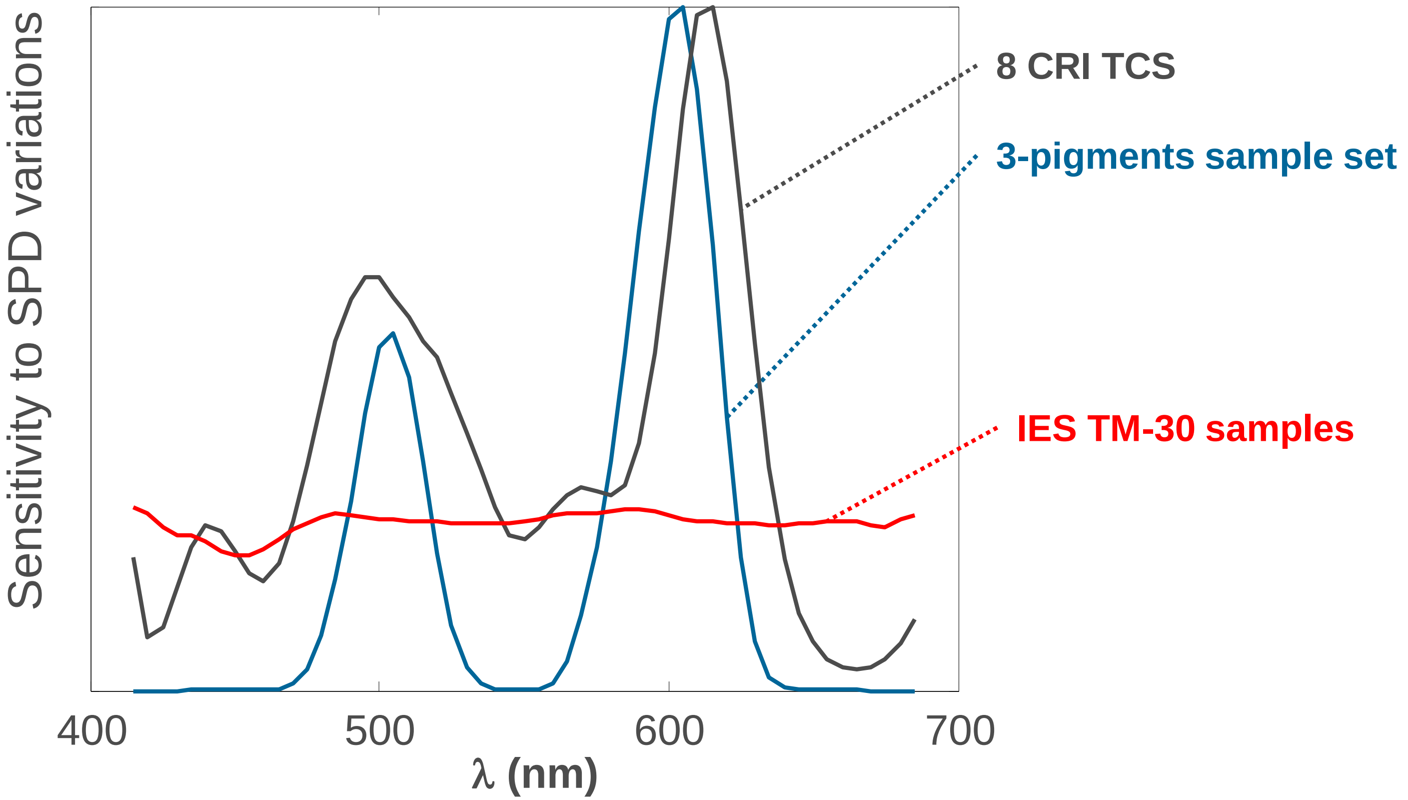
This is because reflectance variations happen preferentially at some wavelengths

Test samples: wavelength uniformity



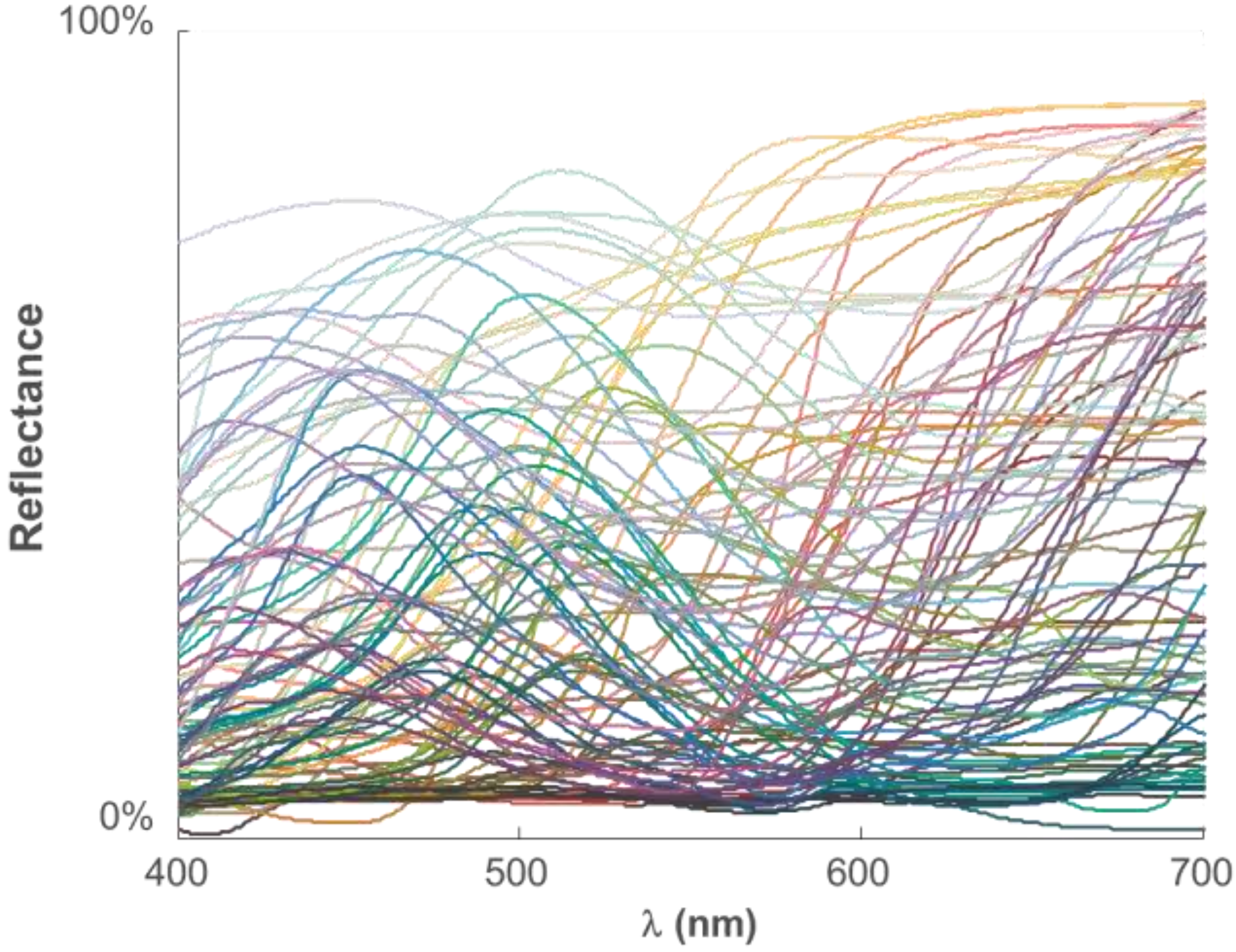
In TM30 test samples, reflectance variations are evenly distributed across wavelengths

Test samples: wavelength uniformity

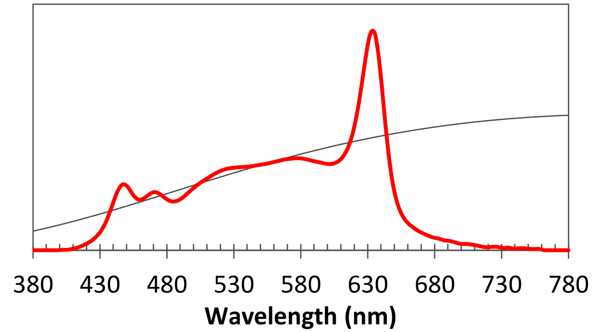


The result: test samples which can not easily be “tricked” by moving SPD peaks around

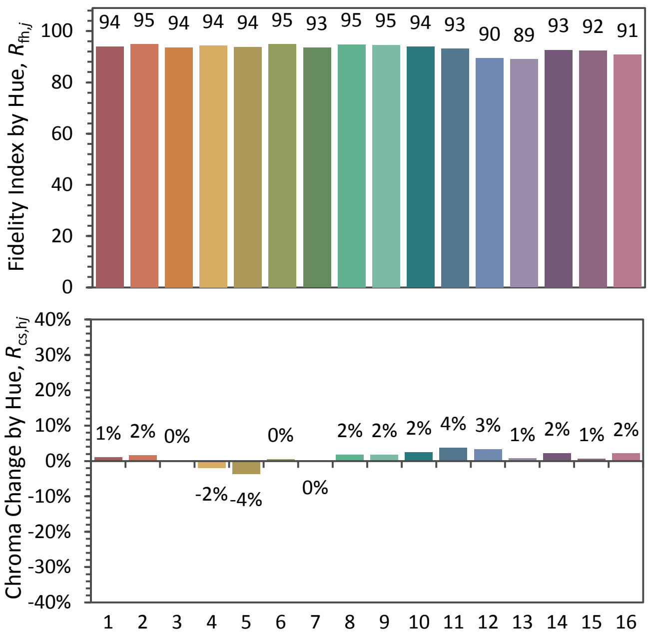
Test samples: wavelength uniformity



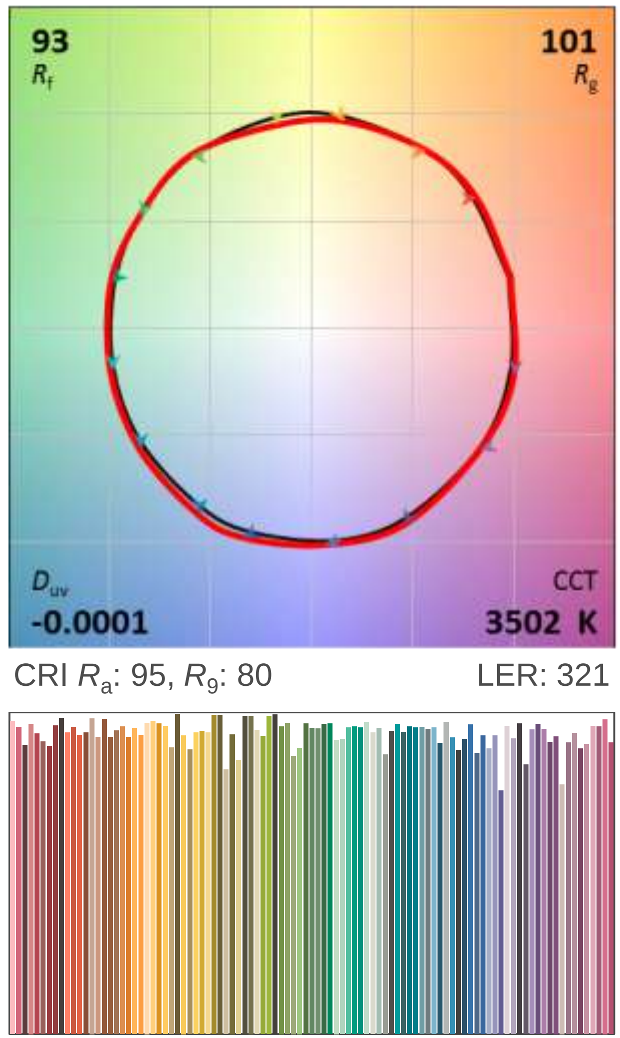
Part 4:
Demonstration and Latest Research Results



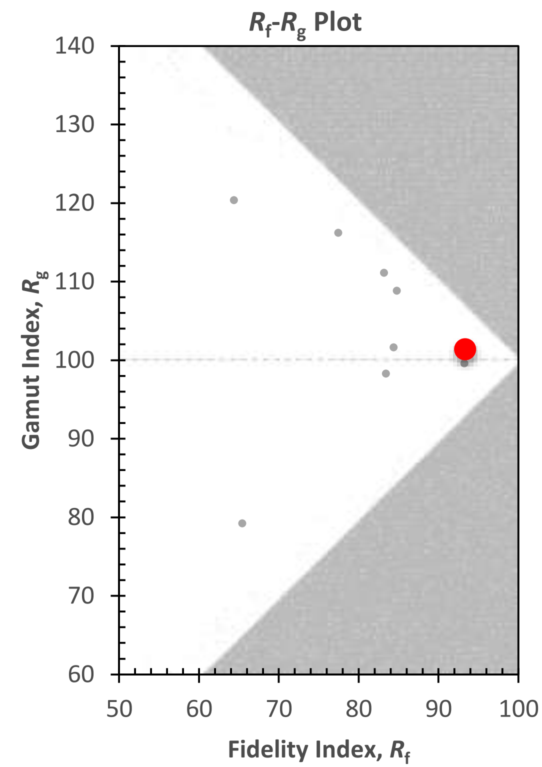
380 430 480 530 580 630 680 730 780
Wavelength (nm)



Fidelity Index by Hue, $R_{f,hj}$
94 95 94 94 94 95 93 95 95 94 93 90 89 93 92 91
Chroma Change by Hue, $R_{cs,hj}$
1% 2% 0% -2% -4% 0% 0% 2% 2% 2% 4% 3% 1% 2% 1% 2%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

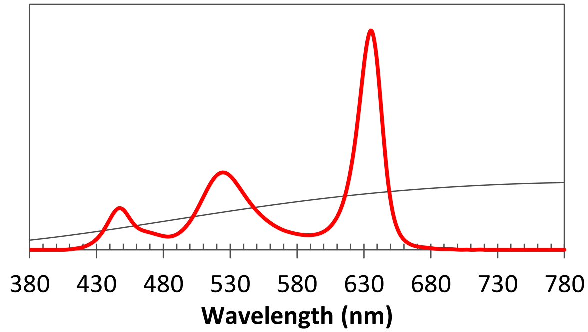


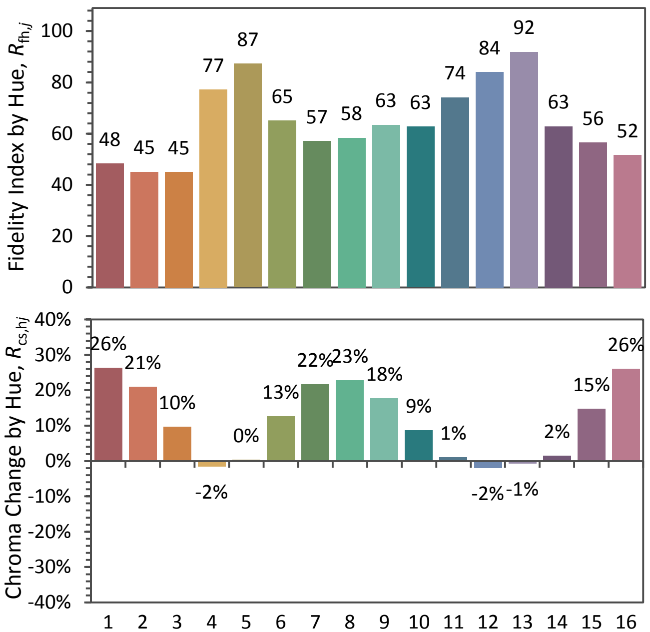
93
R_f
101
R_g
D_{uv}
-0.0001
CCT
3502 K
CRI R_a: 95, R_9: 80
LER: 321

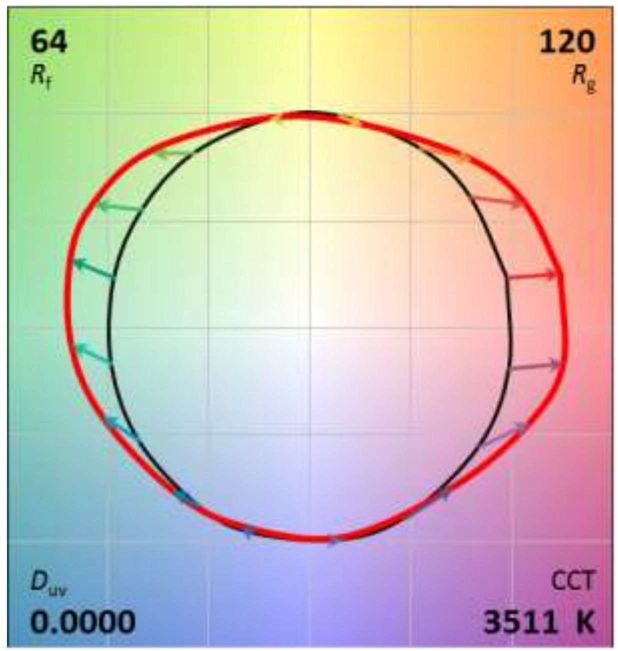


R_f-R_g Plot
Gamut Index, R_g
Fidelity Index, R_f

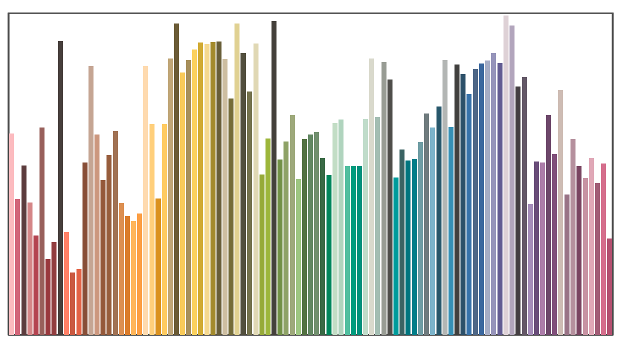
10

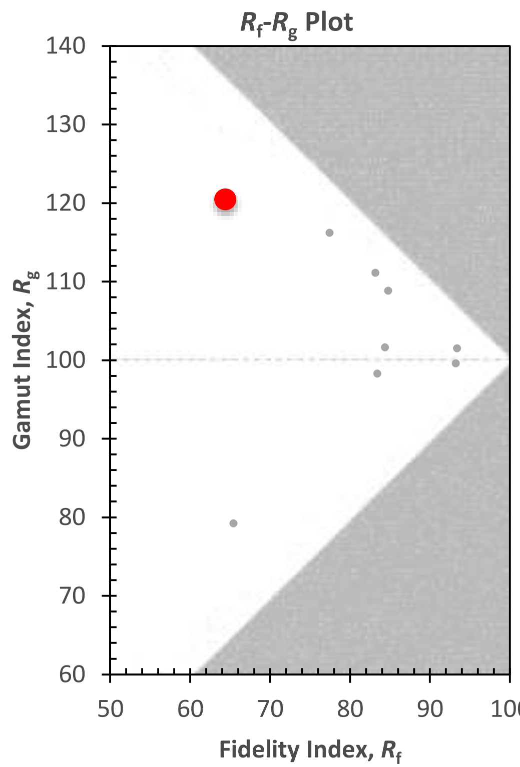




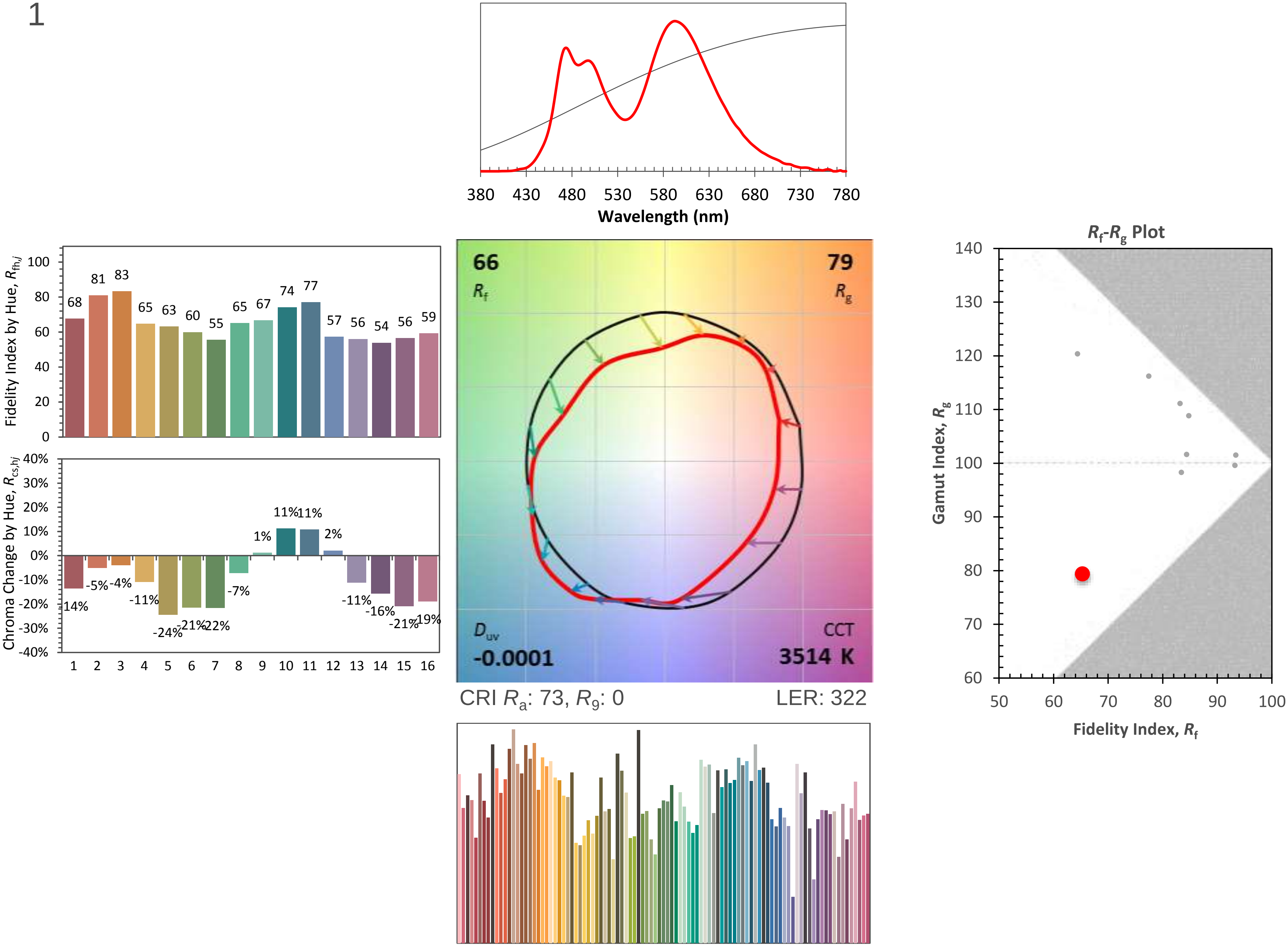


CRI R_a: 43, R_9: -120 LER: 287

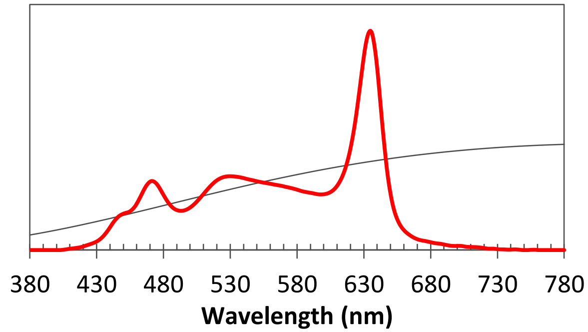


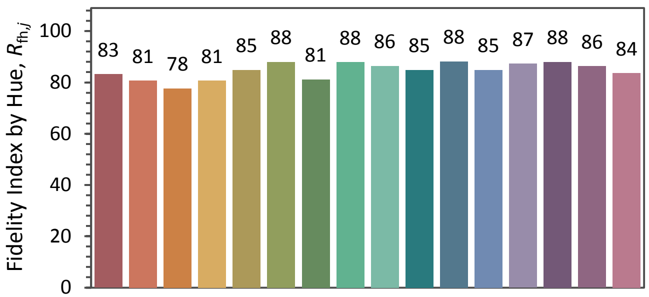


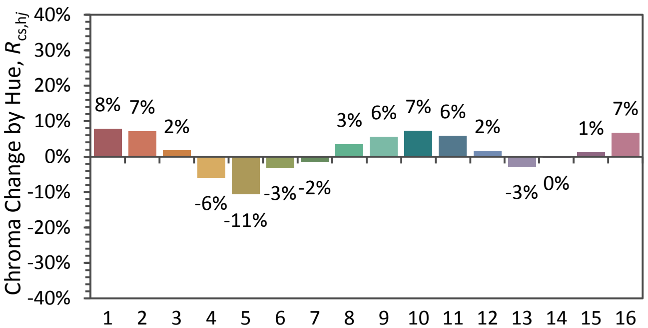
1

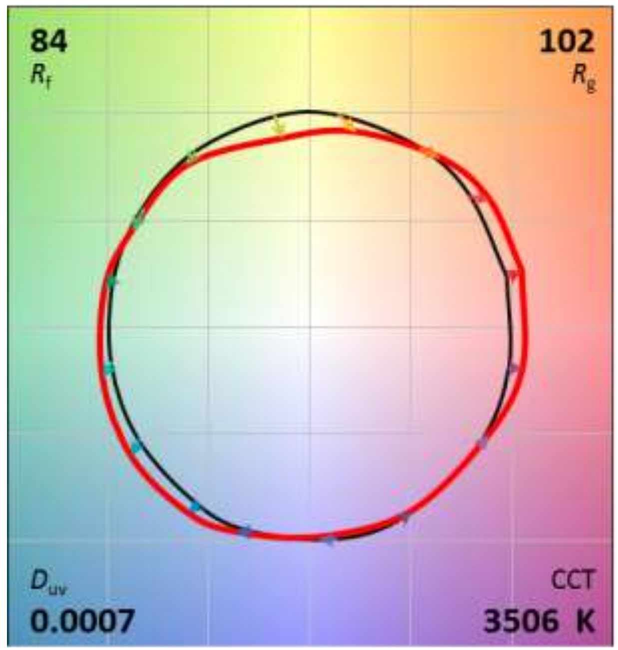


380
430
480
530
580
630
680
730
780
Wavelength (nm)
Fidelity Index by Hue, $R_{f,hj}$
68 81 83 65 63 60 55 65 67 74 77 57 56 54 56 59
Chroma Change by Hue, $R_{cs,hj}$
-14% -5% -4% -11% -24% -21% -22% -7% 1% 11% 11% 2% -11% -16% -21% -19%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
66
R_f
79
R_g
D_{uv}
-0.0001
CCT
3514 K
CRI R_a: 73, R_9: 0
LER: 322
R_f-R_g Plot
Gamut Index, R_g
Fidelity Index, R_f

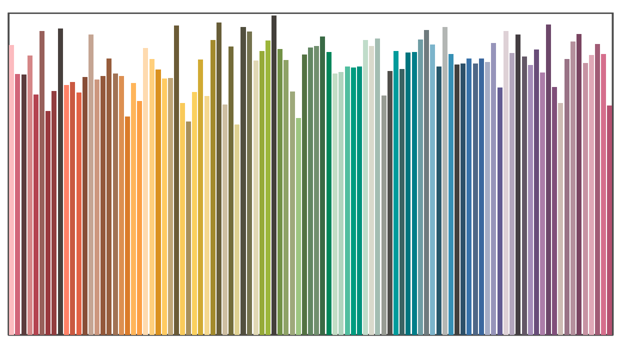


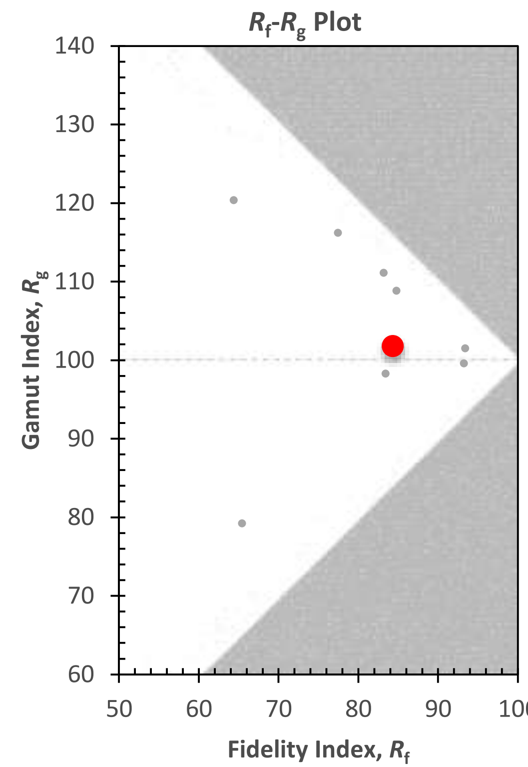


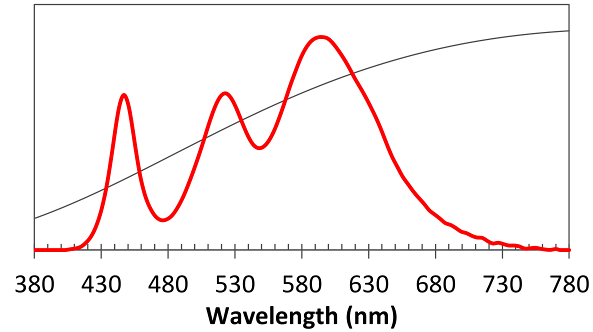


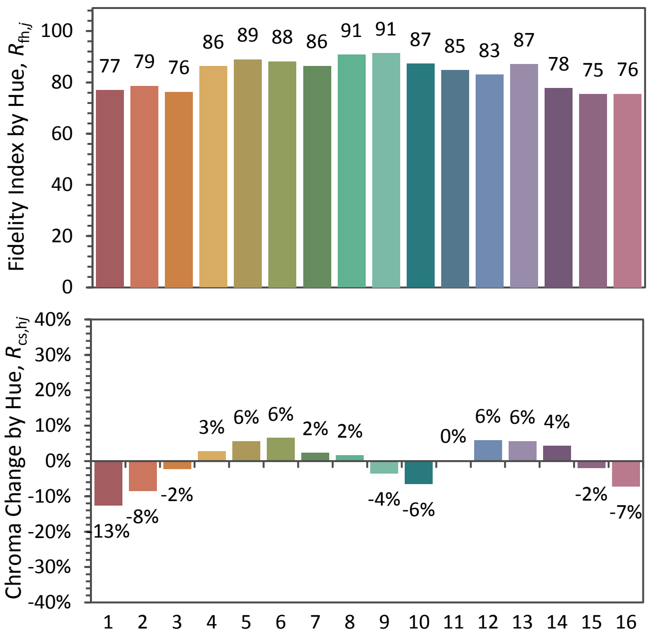


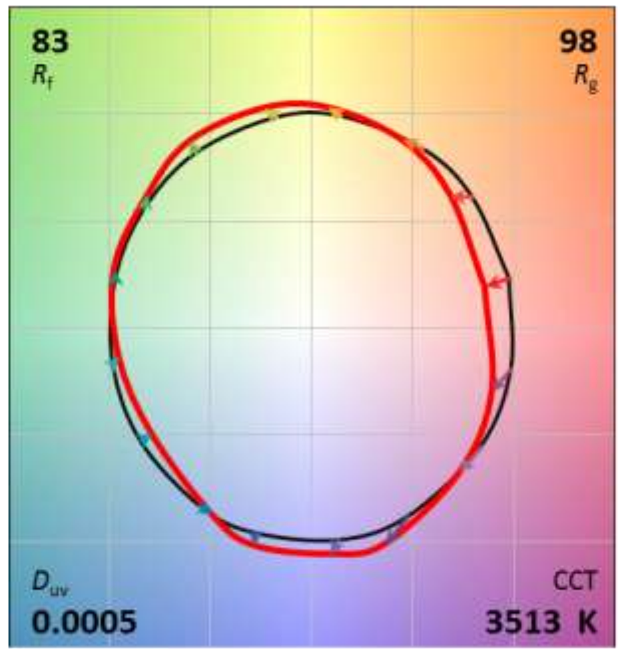
CRI R_a: 83, R_9: 21 LER: 311



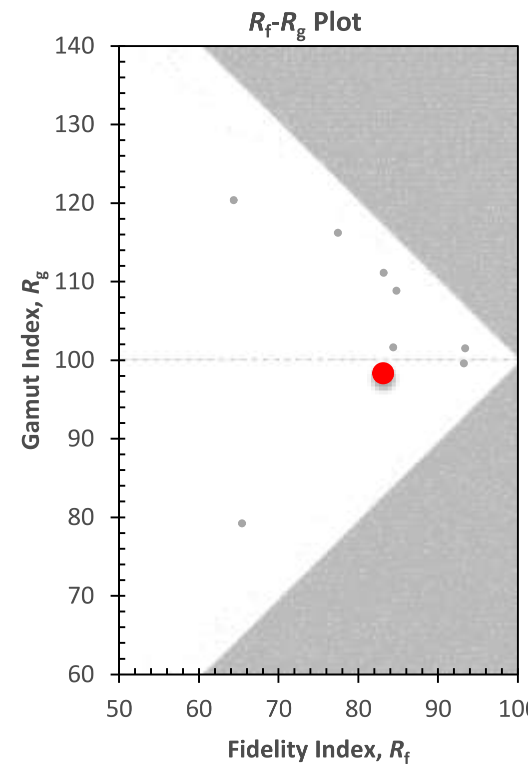


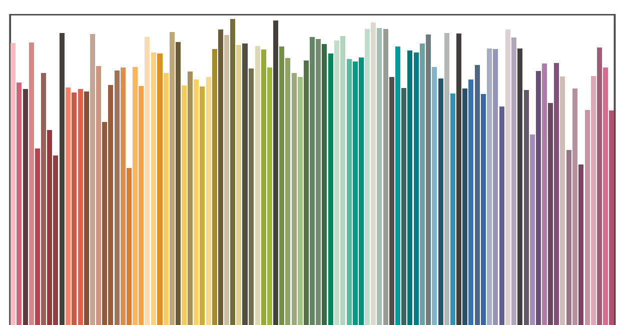




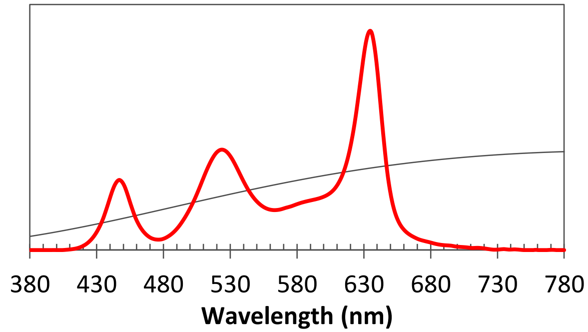


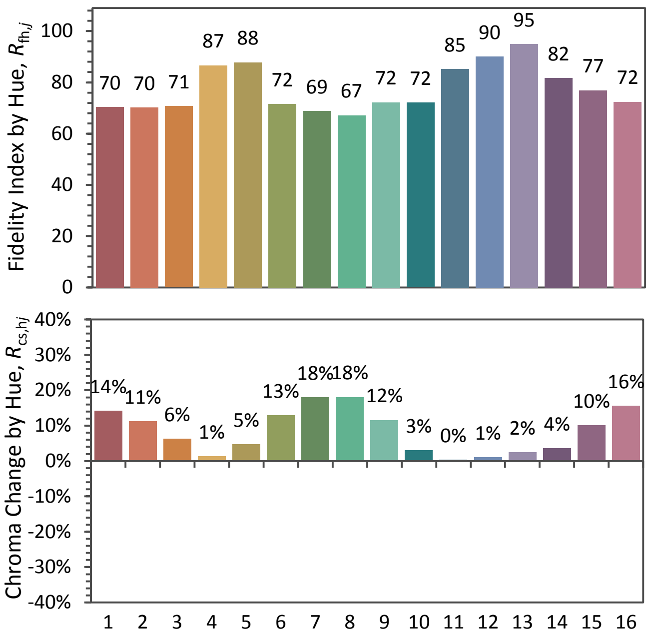
CRI R_a: 84, R_9: -7 LER: 343

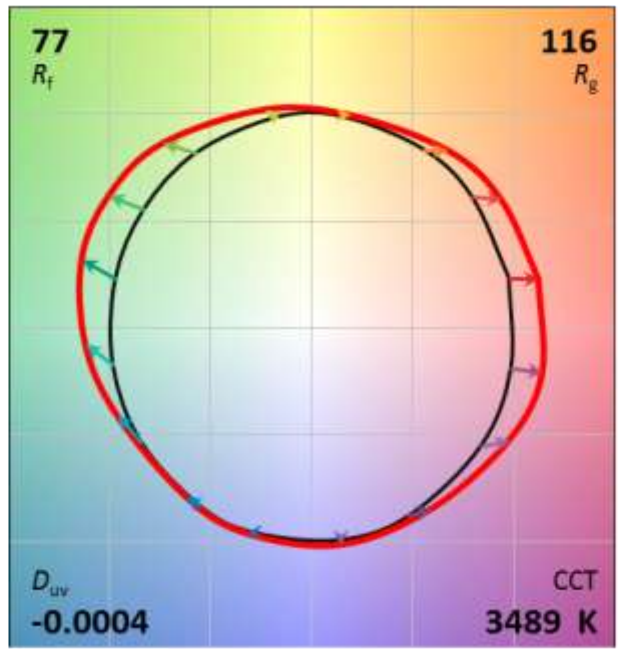




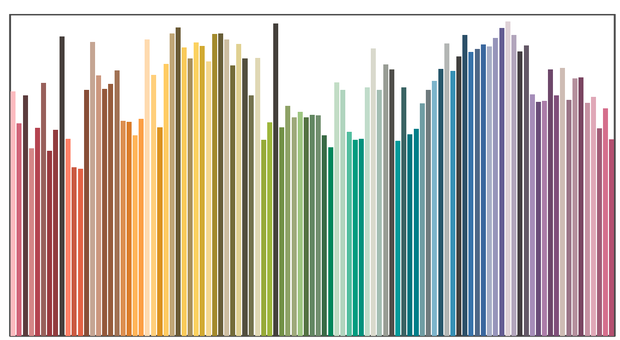
17

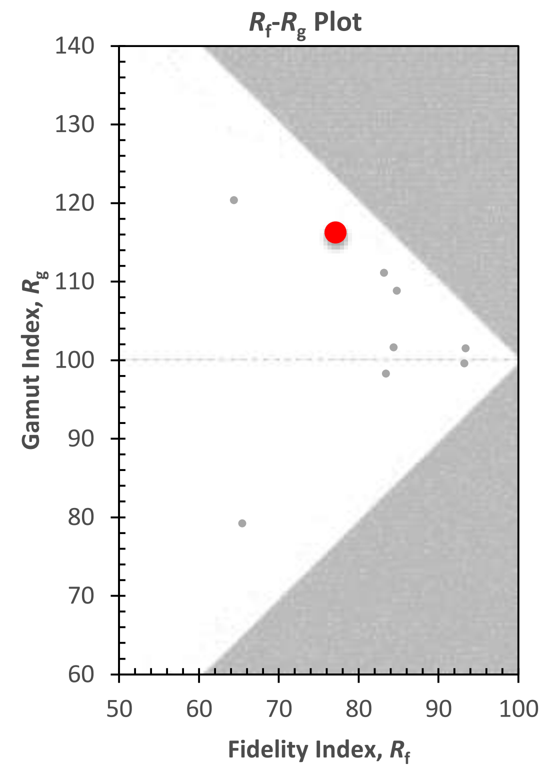


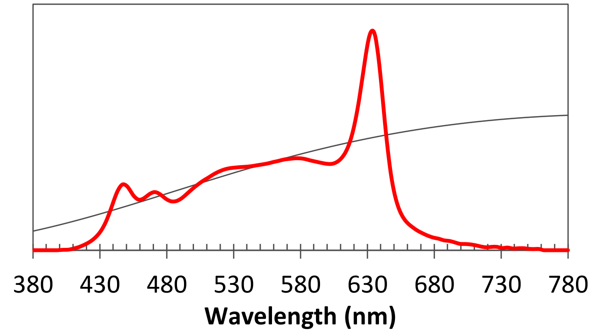


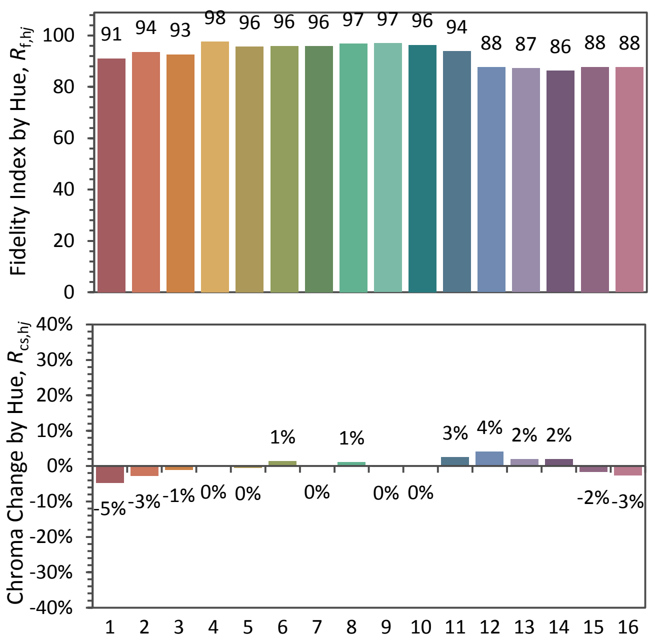


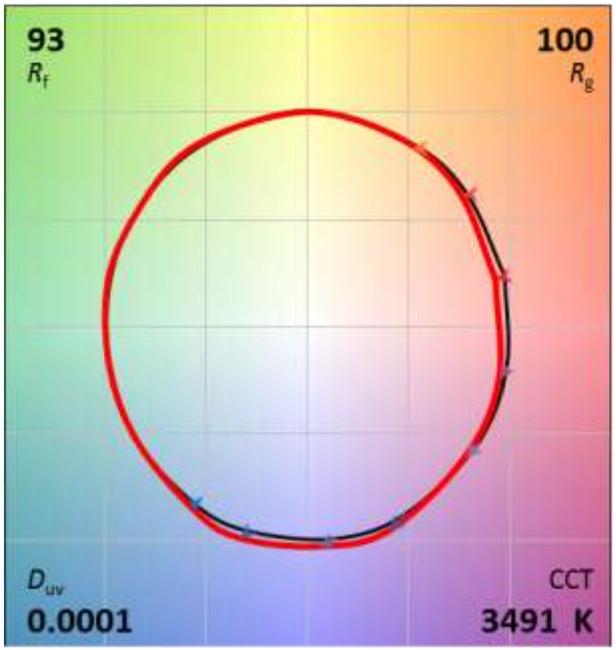
CRI R_a: 68, R_9: -12 LER: 305



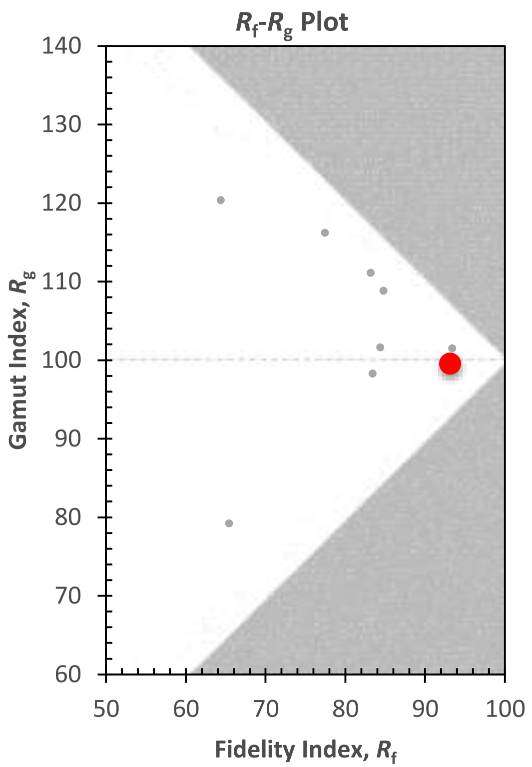


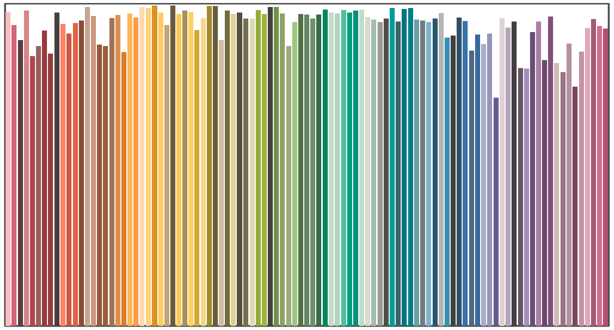


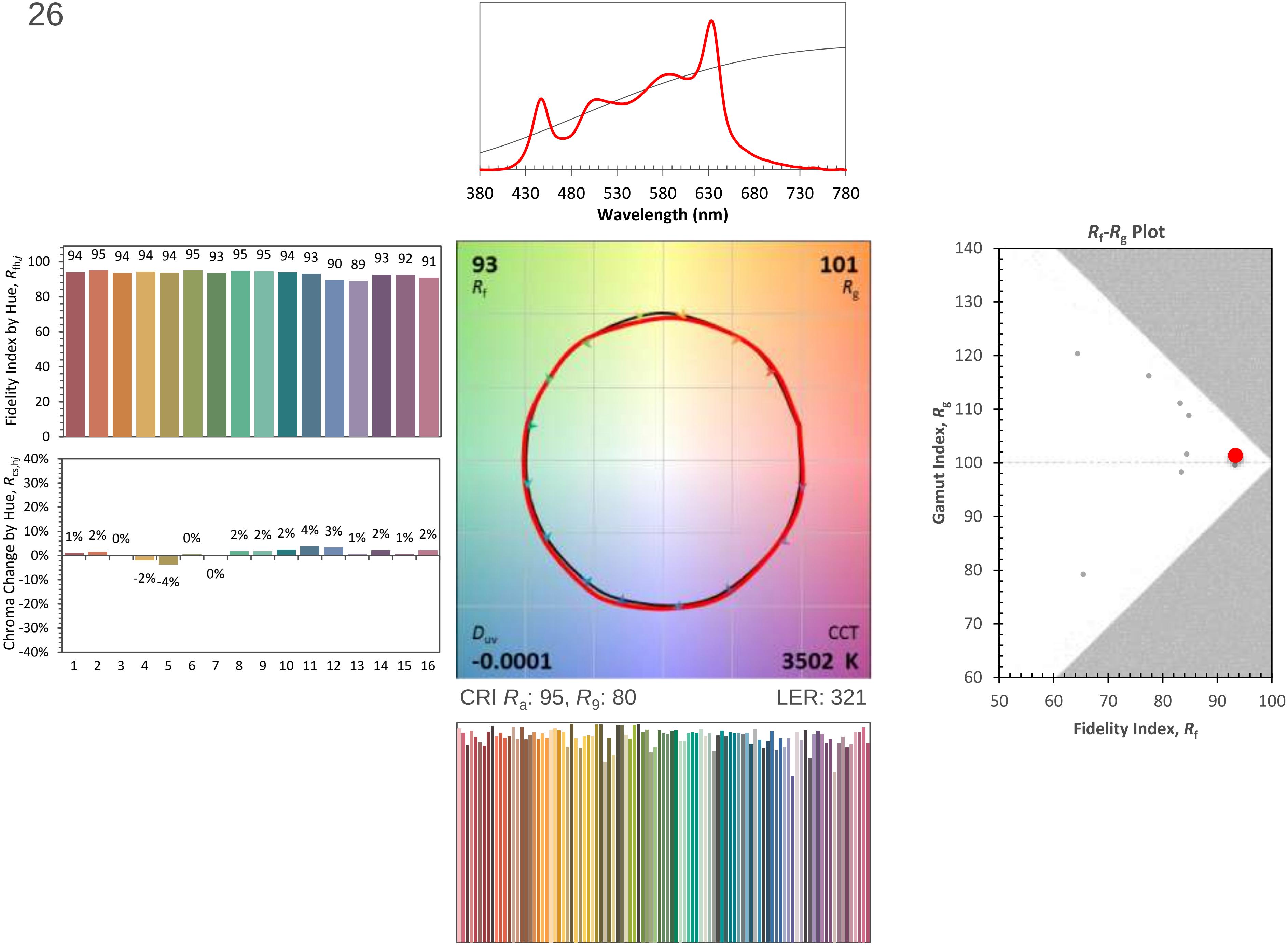




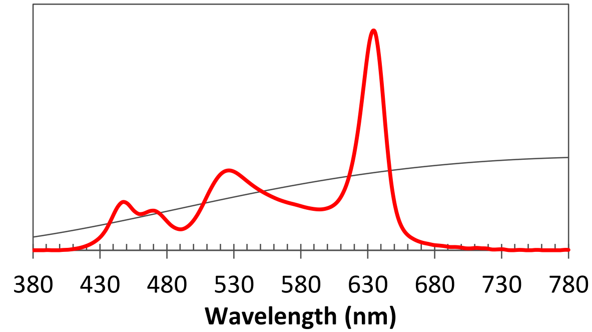
CRI R_a: 95, R_9: 68 LER: 328

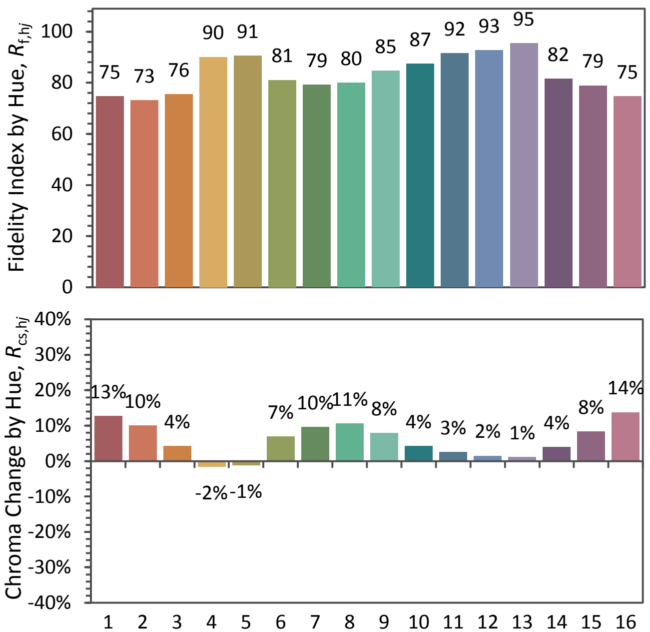


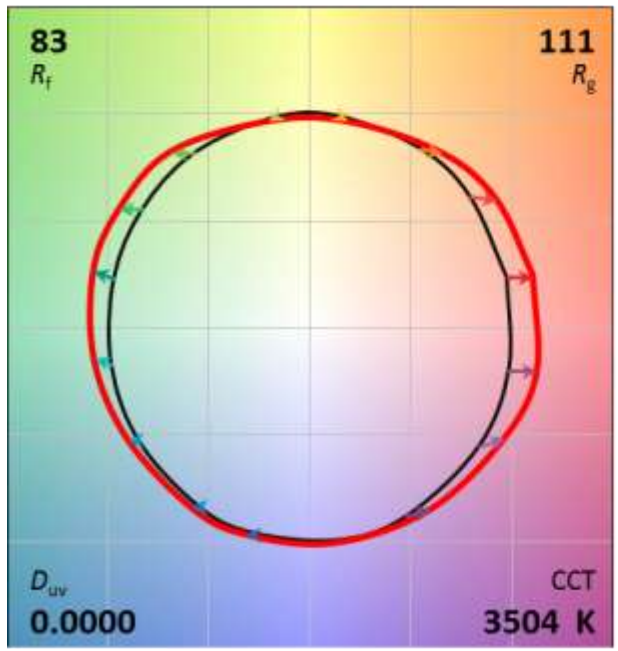



380
430
480
530
580
630
680
730
780
Wavelength (nm)
Fidelity Index by Hue, $R_{f,h,j}$
94 95 94 94 94 95 93 95 95 94 93 90 89 93 92 91
100
80
60
40
20
0
Chroma Change by Hue, $R_{cs,hj}$
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
1% 2% 0% -2% -4% 0% 0% 2% 2% 2% 4% 3% 1% 2% 1% 2%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
93
R_f
101
R_g
D_{uv}
-0.0001
CCT
3502 K
CRI R_a: 95, R_9: 80
LER: 321
R_f-R_g Plot
Gamut Index, R_g
140
130
120
110
100
90
80
70
60
50
60
70
80
90
100
Fidelity Index, R_f

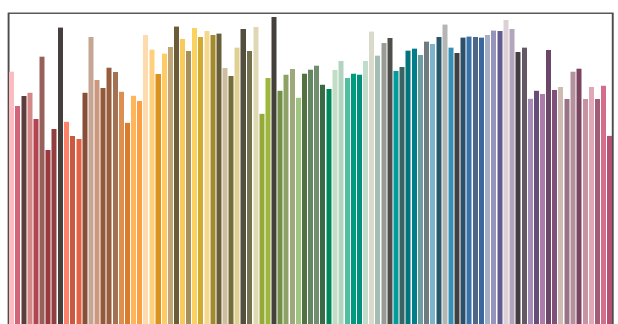
23

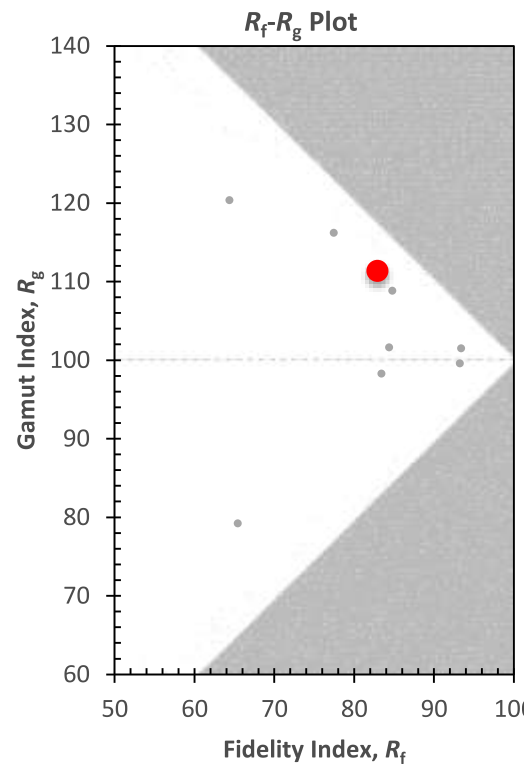


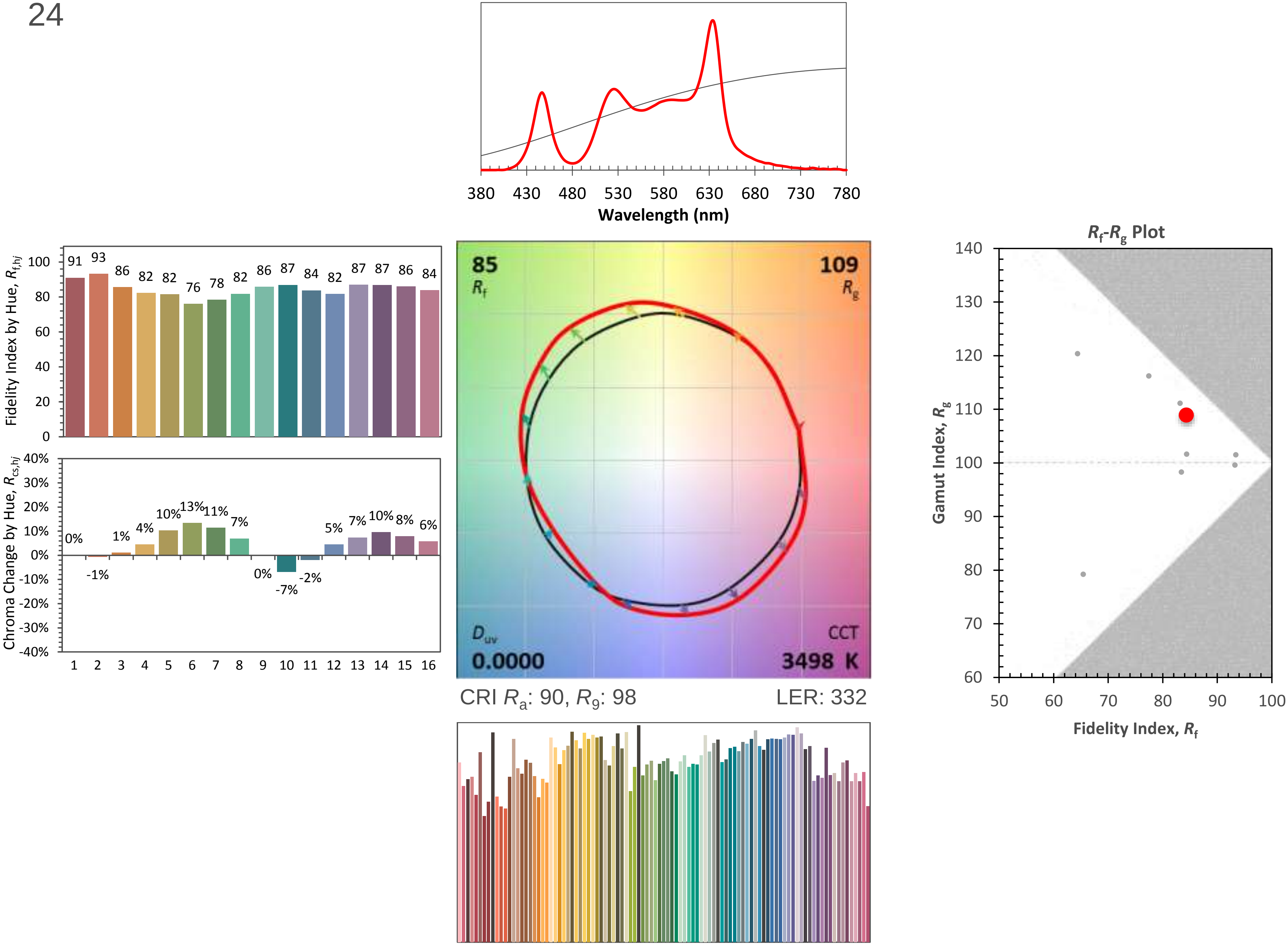




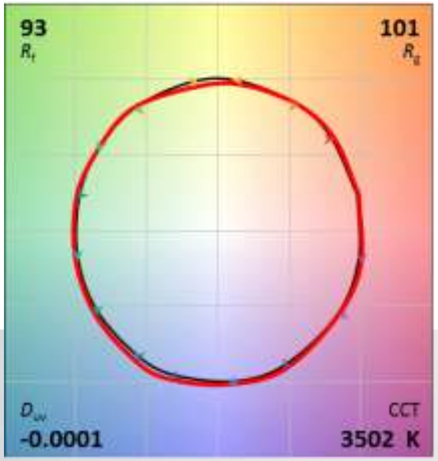
CRI R_a: 73, R_9: -14 LER: 309



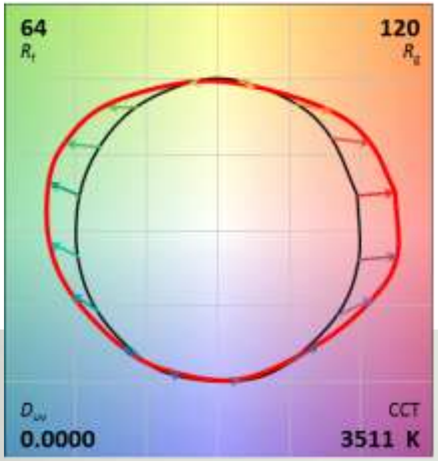




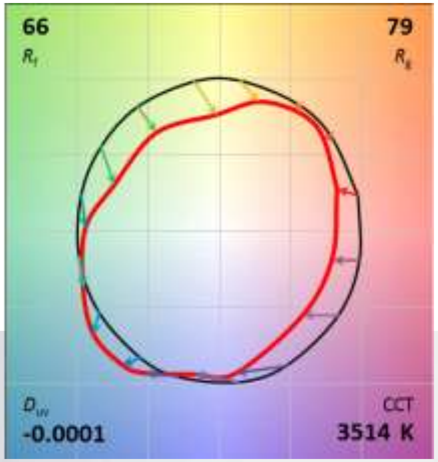
380 430 480 530 580 630 680 730 780
Wavelength (nm)
Fidelity Index by Hue, $R_{f,hj}$
91 93 86 82 82 76 78 82 86 87 84 82 87 87 86 84
Chroma Change by Hue, $R_{cs,hj}$
0% -1% 1% 4% 10% 13% 11% 7% 0% -7% -2% 5% 7% 10% 8% 6%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
85
R_f
109
R_g
D_{uv}
0.0000
CCT
3498 K
CRI R_a: 90, R_9: 98
LER: 332
R_f-R_g Plot
Gamut Index, R_g
Fidelity Index, R_f


93
Rf
101
Rg
Duv
-0.0001
CCT
3502 K

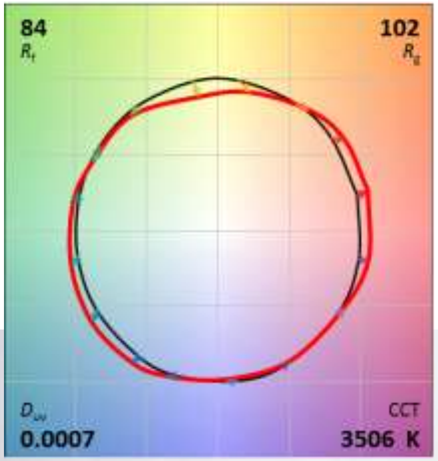

Dr Pepper


64
R_f
120
R_g
D_uv
0.0000
CCT
3511 K


Dr Pepper

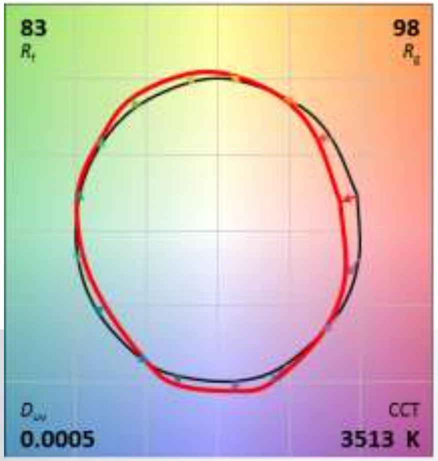

66
R_f
79
R_g
D_{uv}
-0.0001
CCT
3514 K

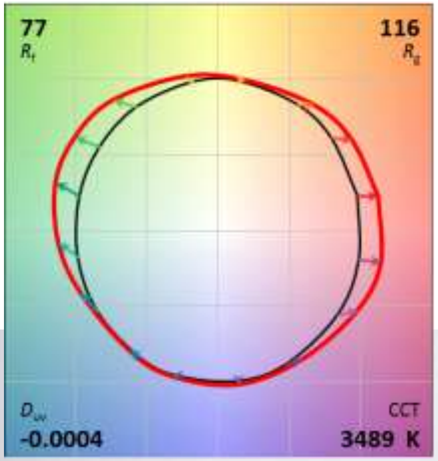

Dr Pepper



84
R_f
102
R_g
D_uv
0.0007
CCT
3506 K

Dr Pepper

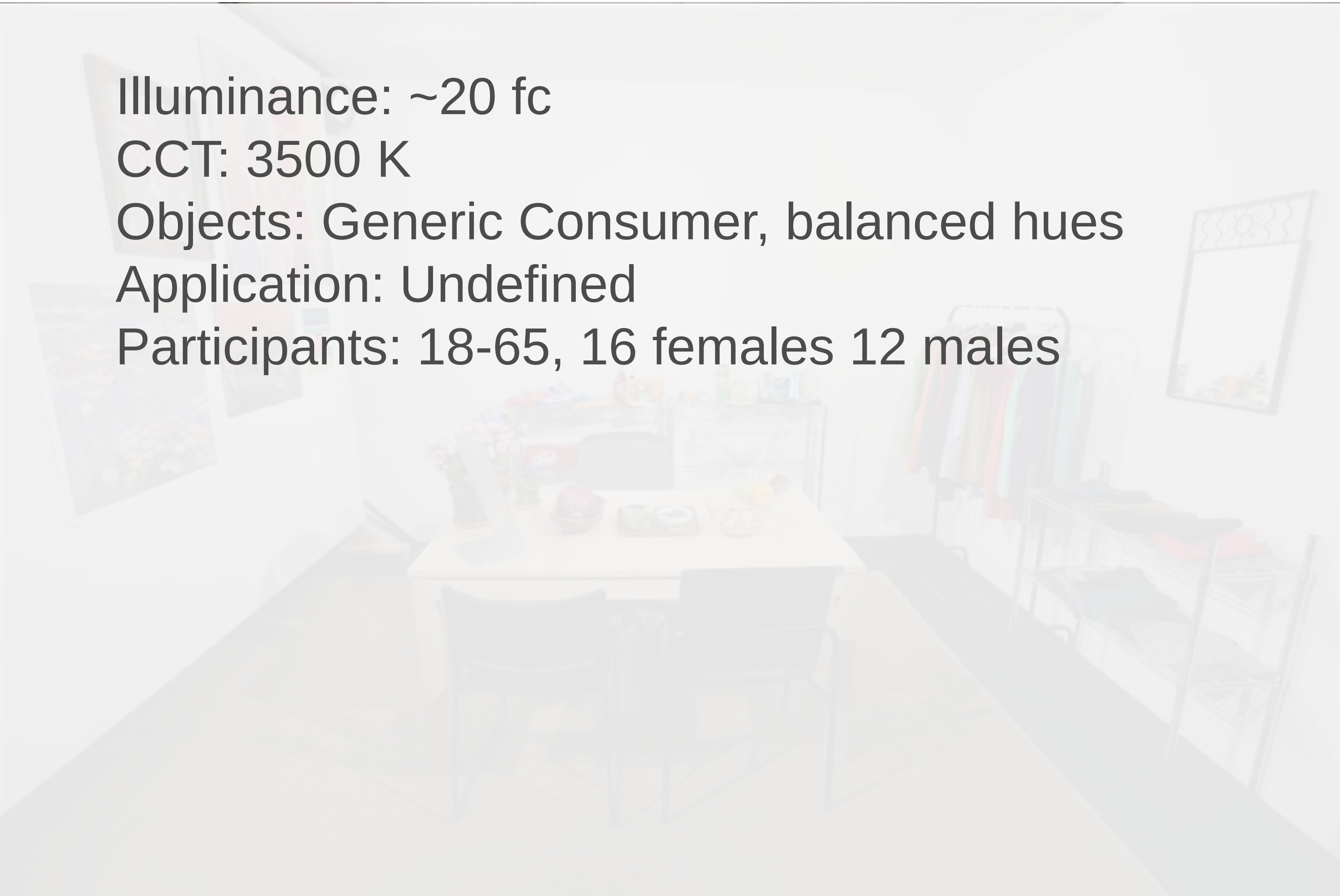

83
R_f
98
R_g
D_{uv}
0.0005
CCT
3513 K


77
R_f
116
R_g
D_{uv}
-0.0004
CCT
3489 K


Dr Pepper

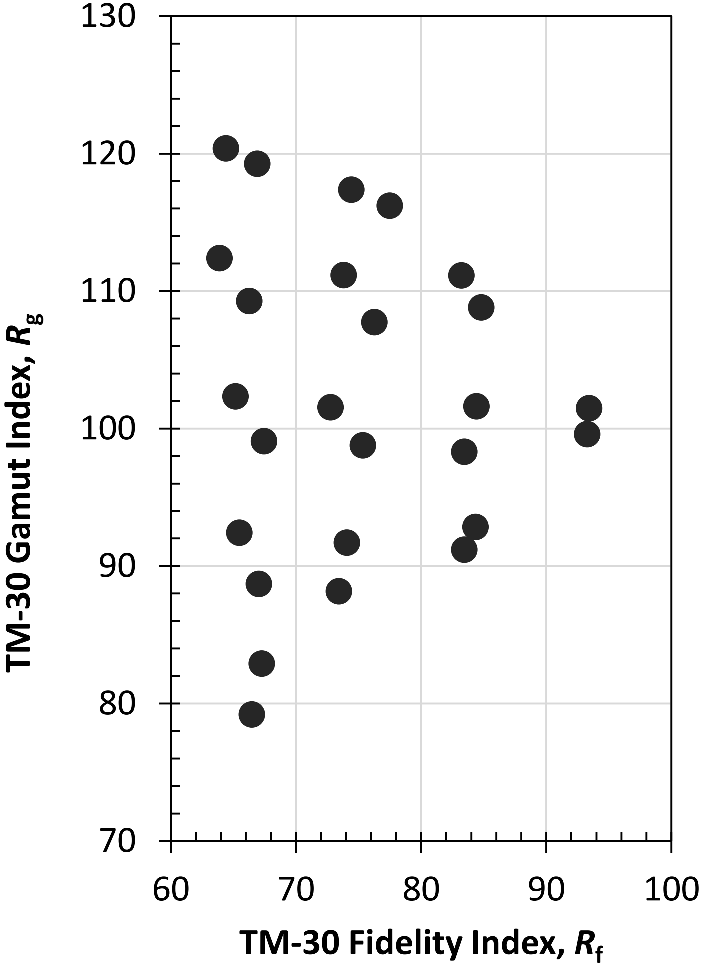
Experimental Room

Experimental Room: Context

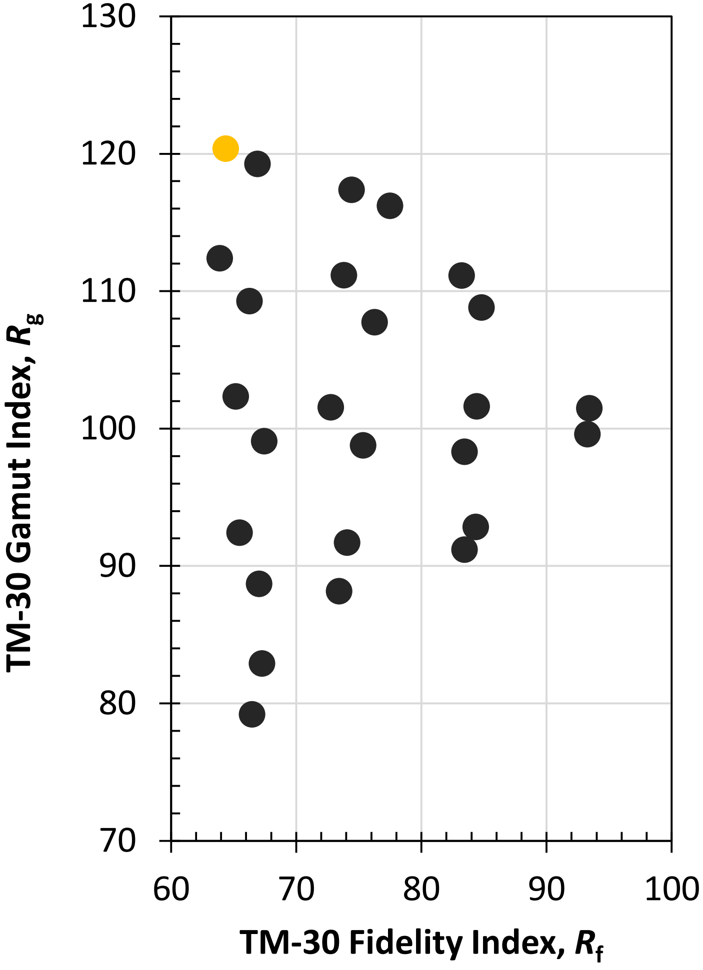


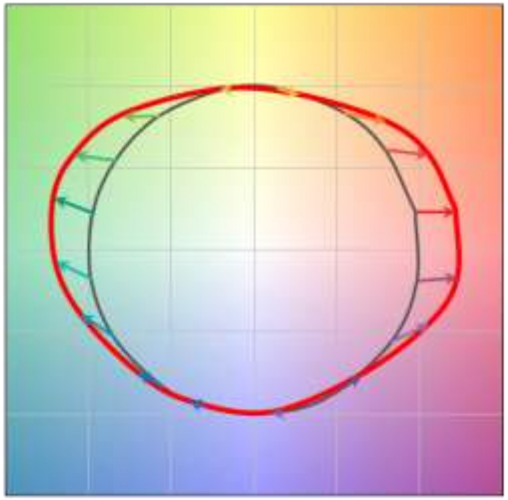
Illuminance: ~20 fc
CCT: 3500 K
Objects: Generic Consumer, balanced hues
Application: Undefined
Participants: 18-65, 16 females 12 males

Experimental Conditions

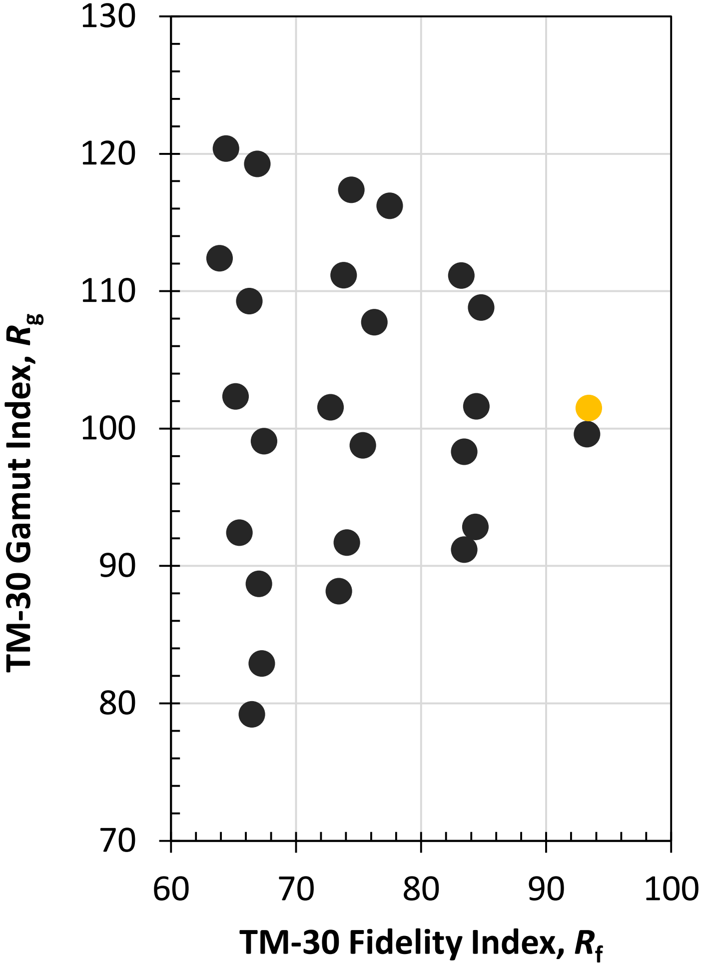


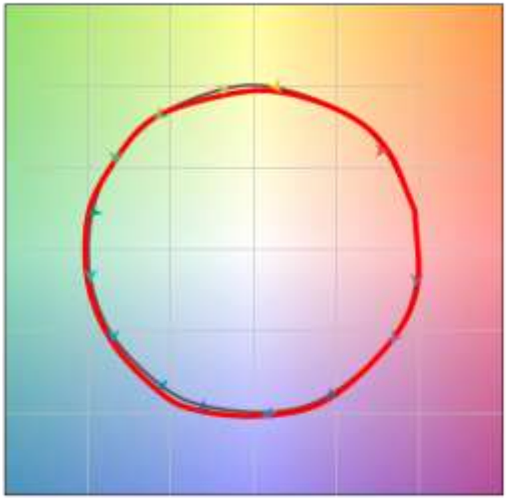
Experimental Conditions



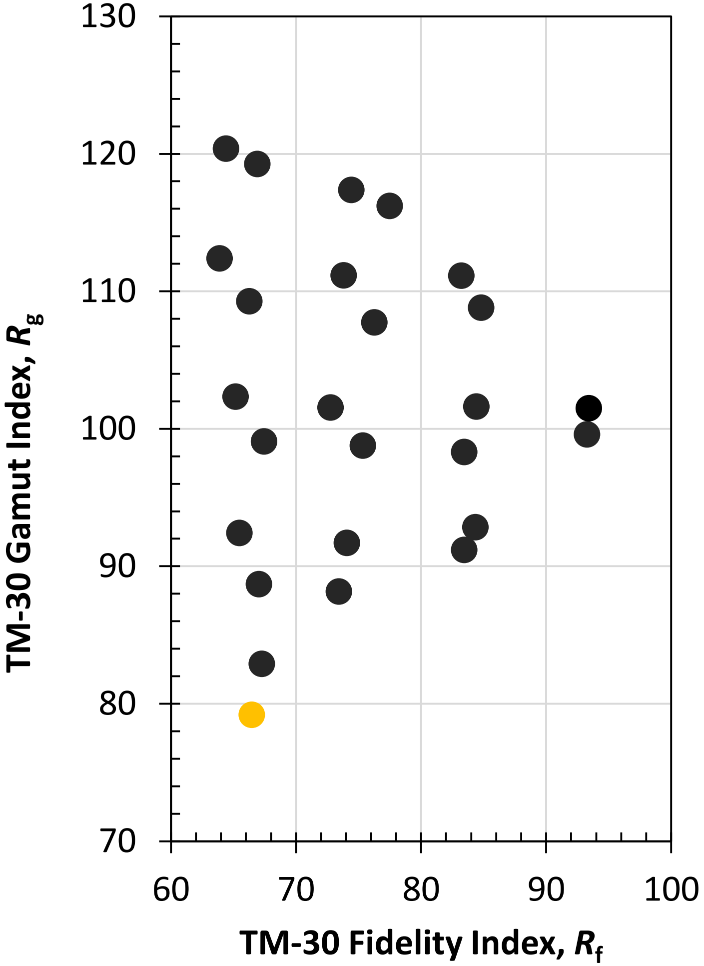


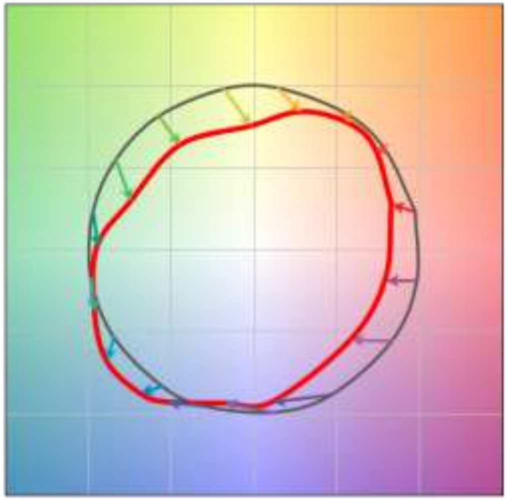
Experimental Conditions



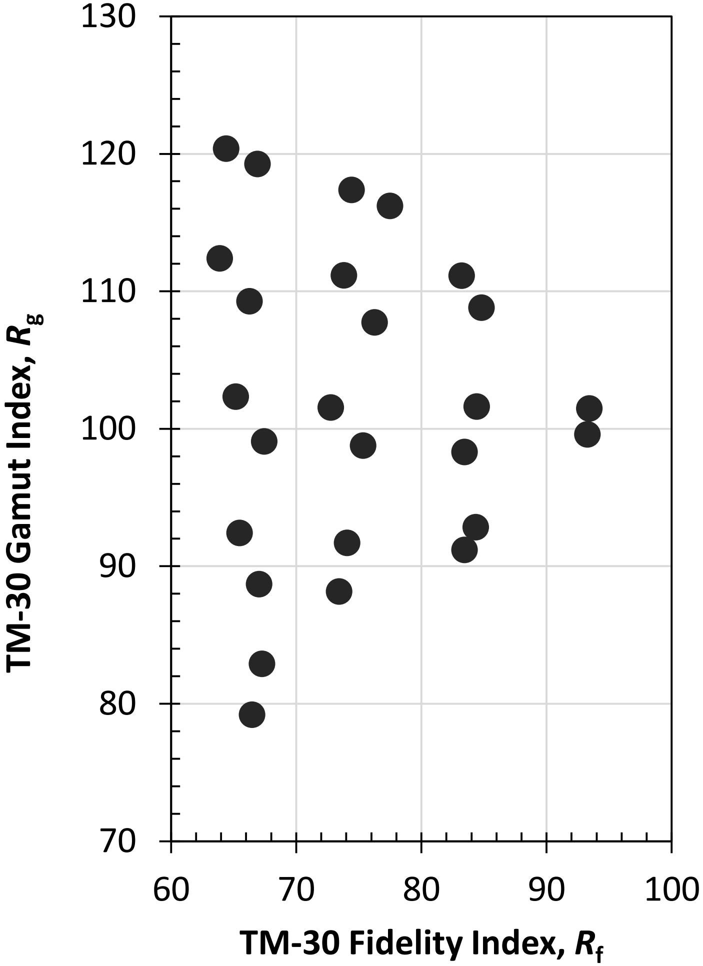


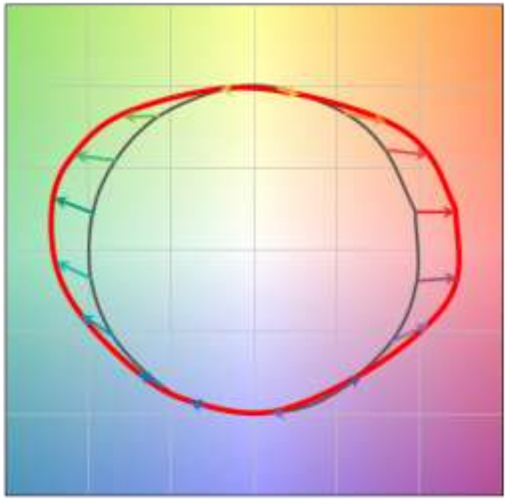
Experimental Conditions

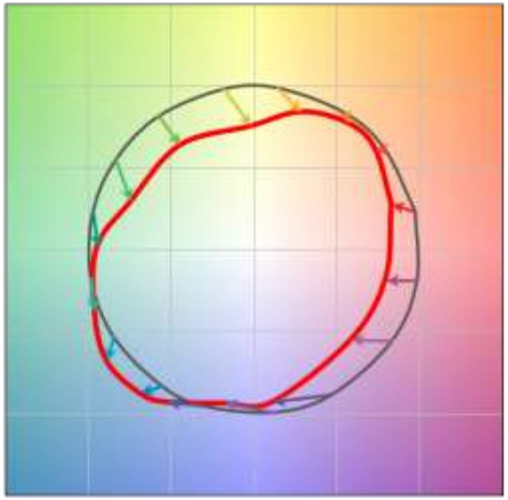


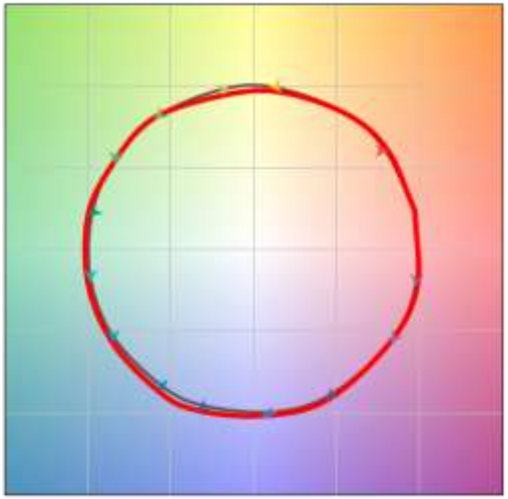


Experimental Conditions

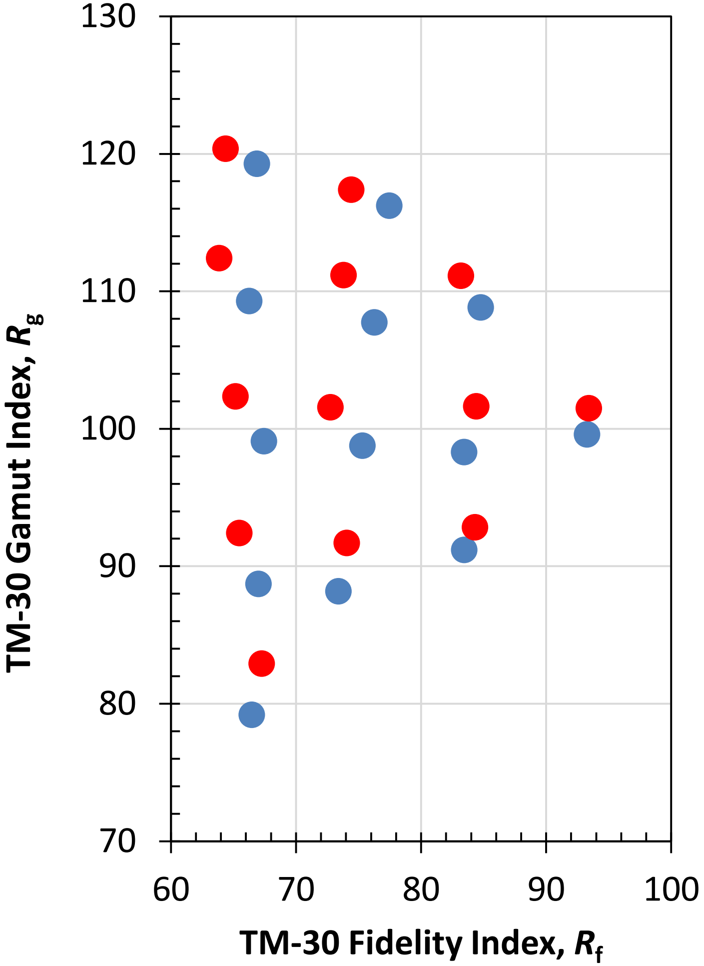




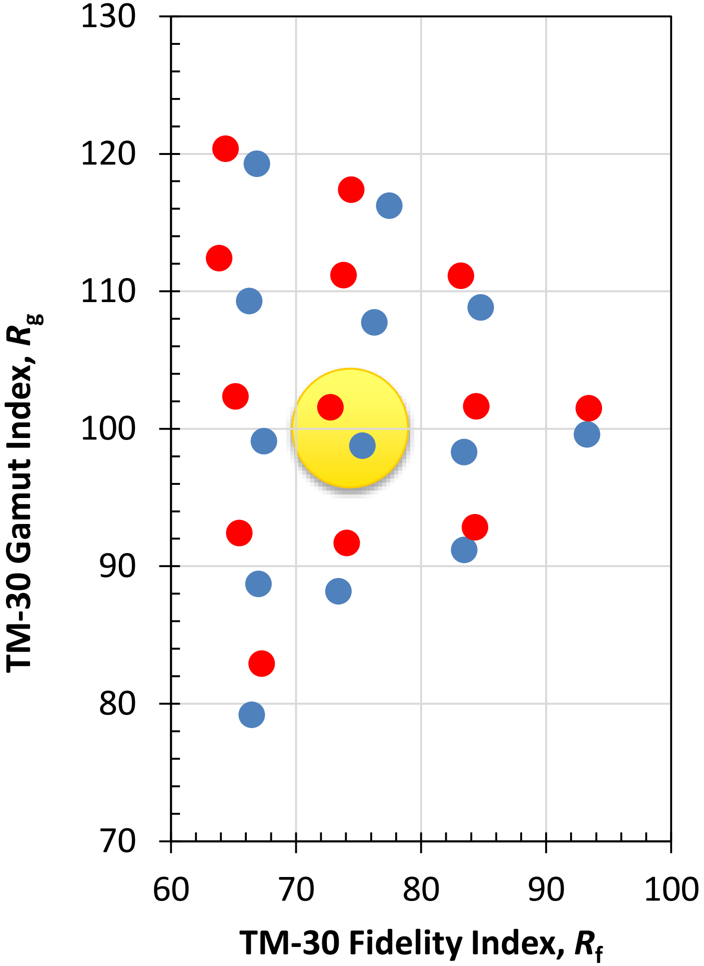


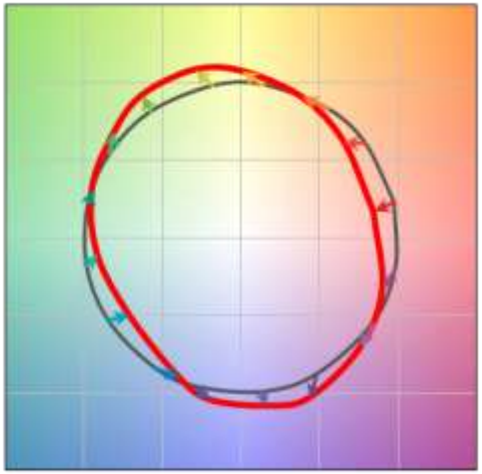


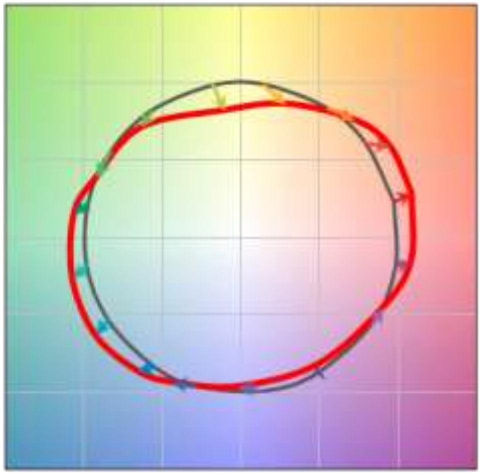
Experimental Conditions



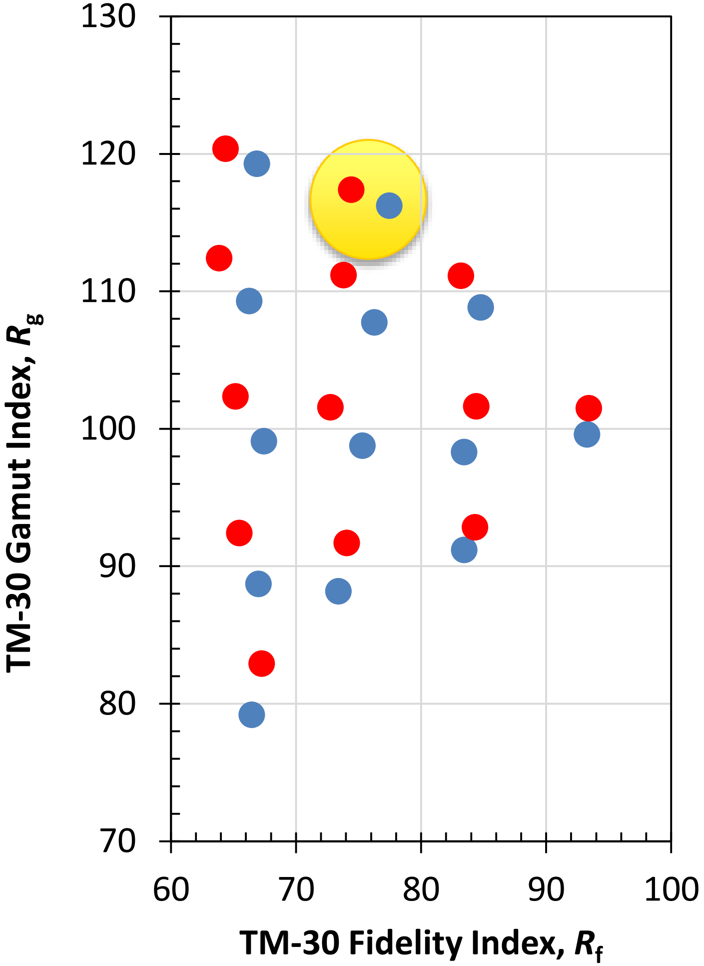
Experimental Conditions

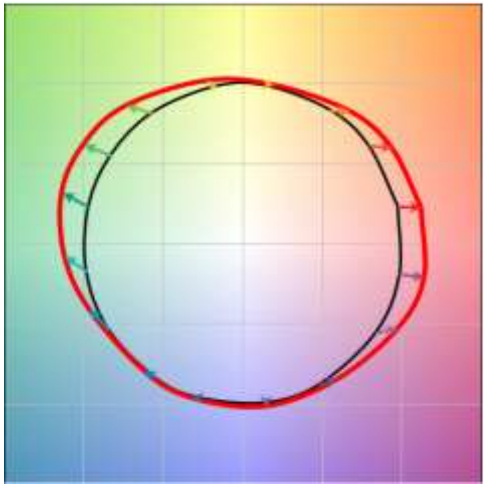


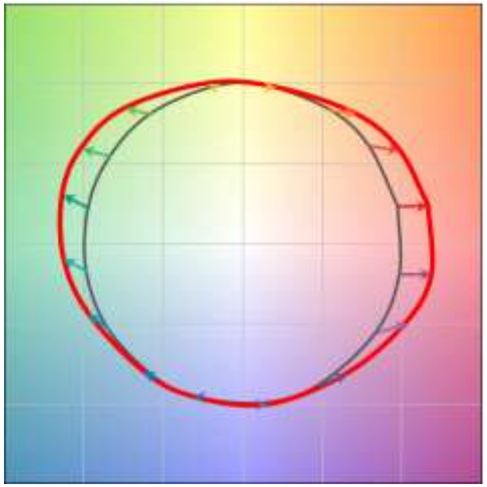




Experimental Conditions







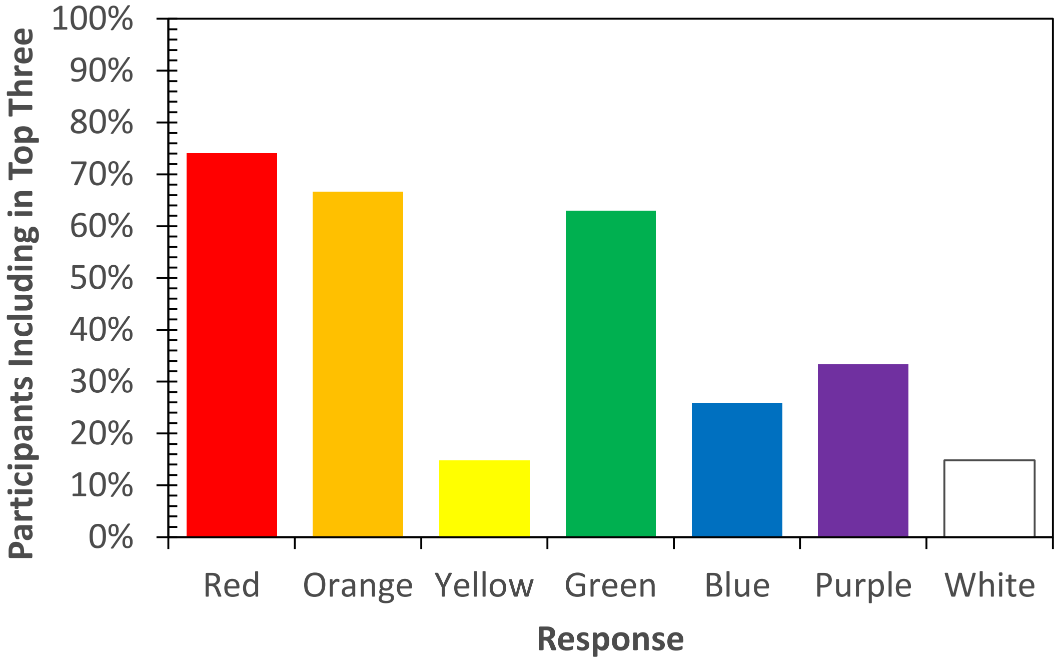
We’re going to look at averages (means)….

…but the person to person differences are substantial!

Almost every source received ratings across the full range for each question. (Normalness, Saturation, Like)

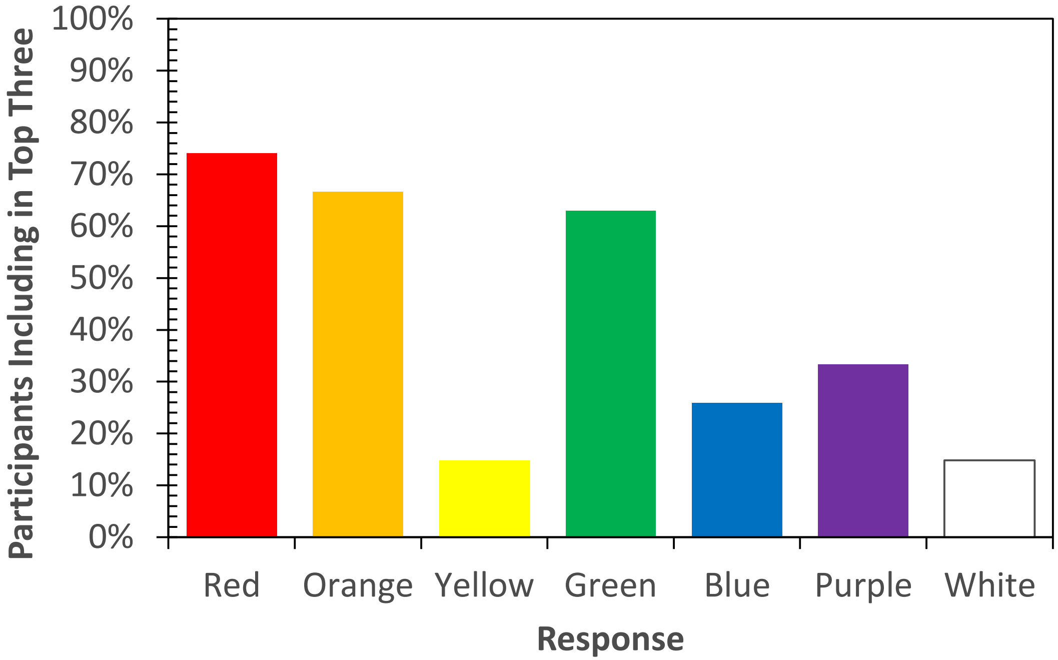
If you’re a specifier, you get to decide what you like for the given space!

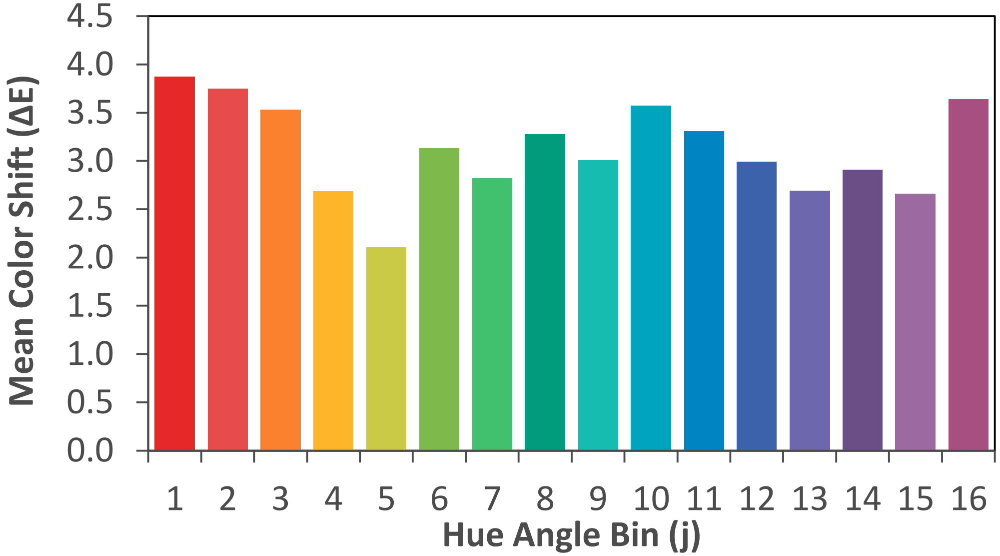
Most Influential Colors



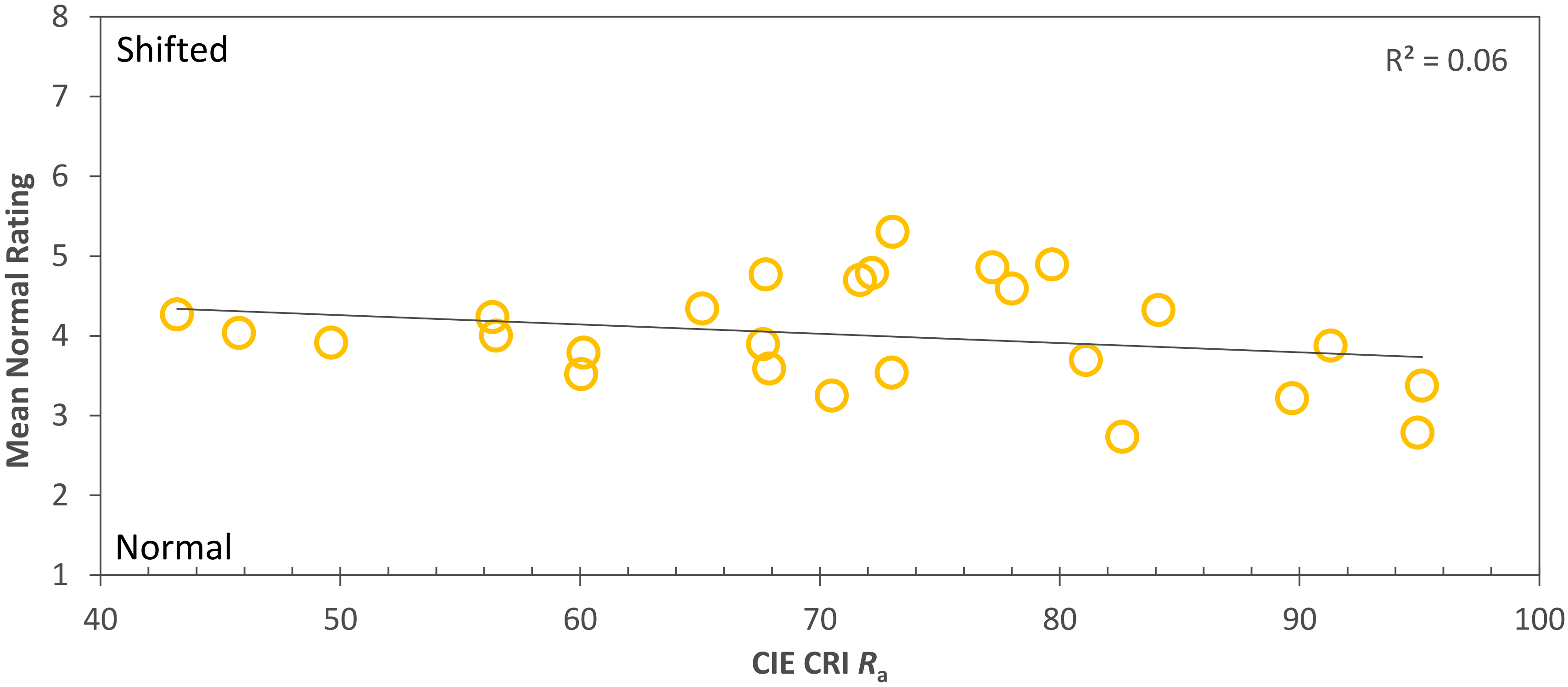
Flowers Reese's Pepper Flowers
Coke

Most Influential Colors

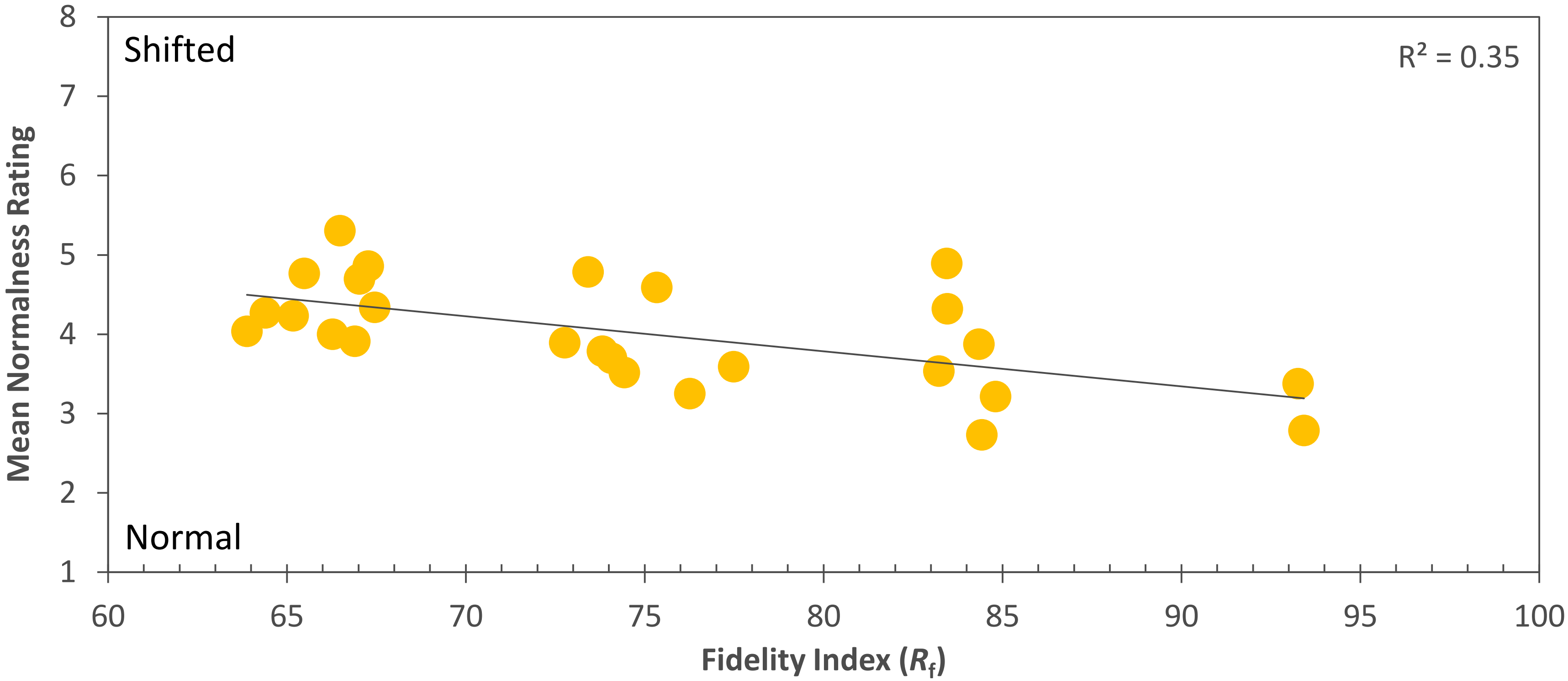




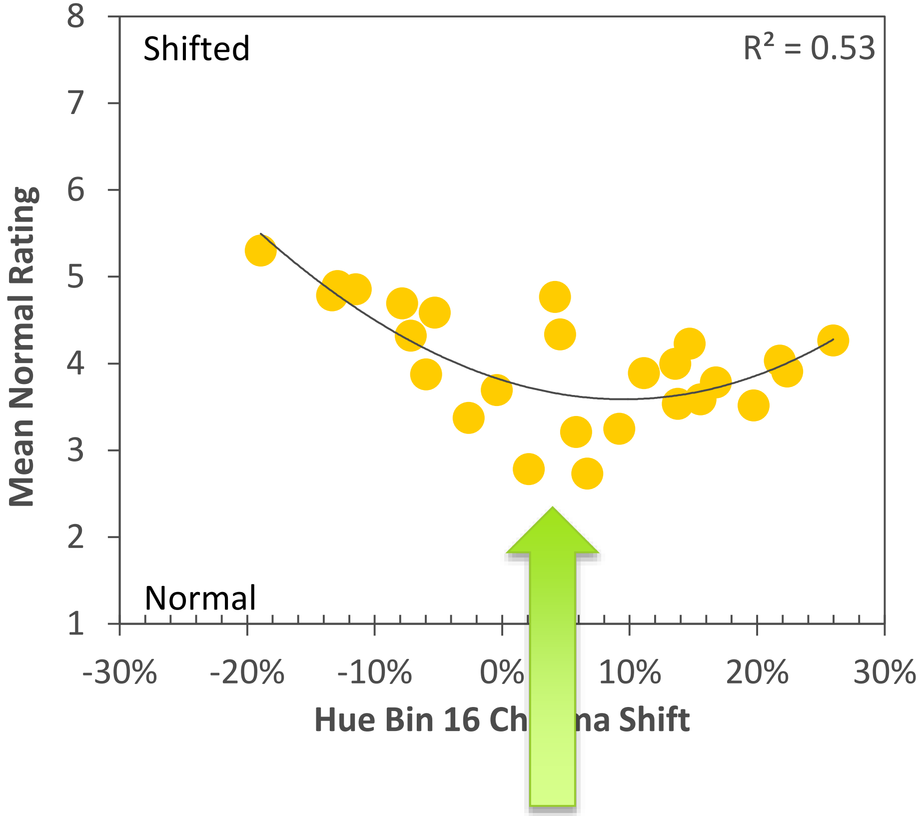
Normalness vs. Fidelity

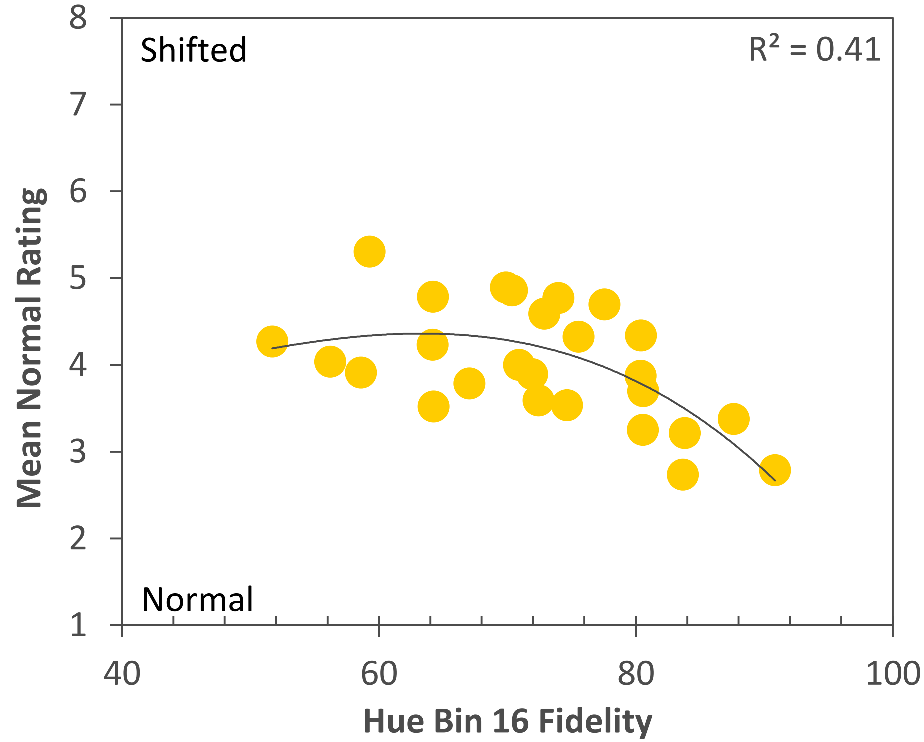


Normalness vs. Fidelity



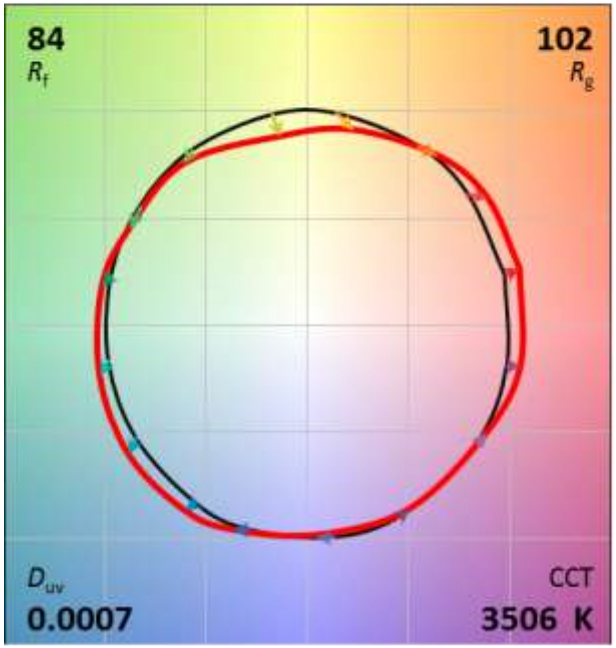
Normalness vs. Red Rendering





Rated Most Normal

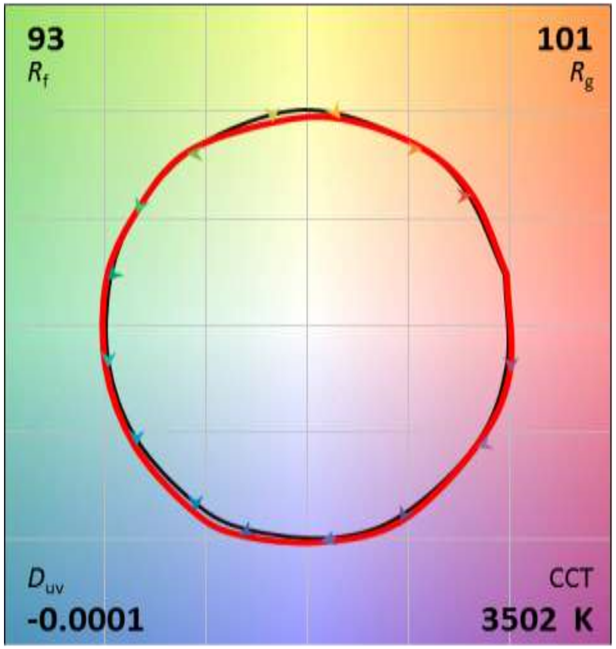
1



$R_{f,h1}$ = 83
$R_{cs,h1}$ = 8%

$R_{f,h16}$ = 84
$R_{cs,h16}$ = 7%

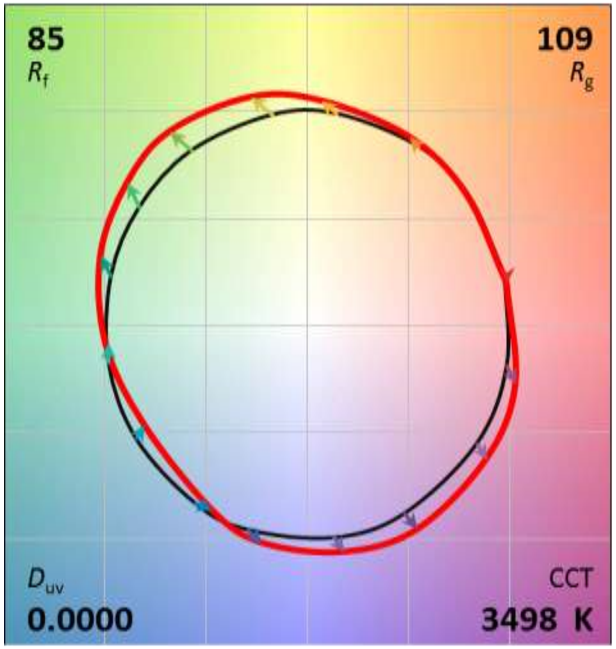
2



$R_{f,h1}$ = 94
$R_{cs,h1}$ = 1%

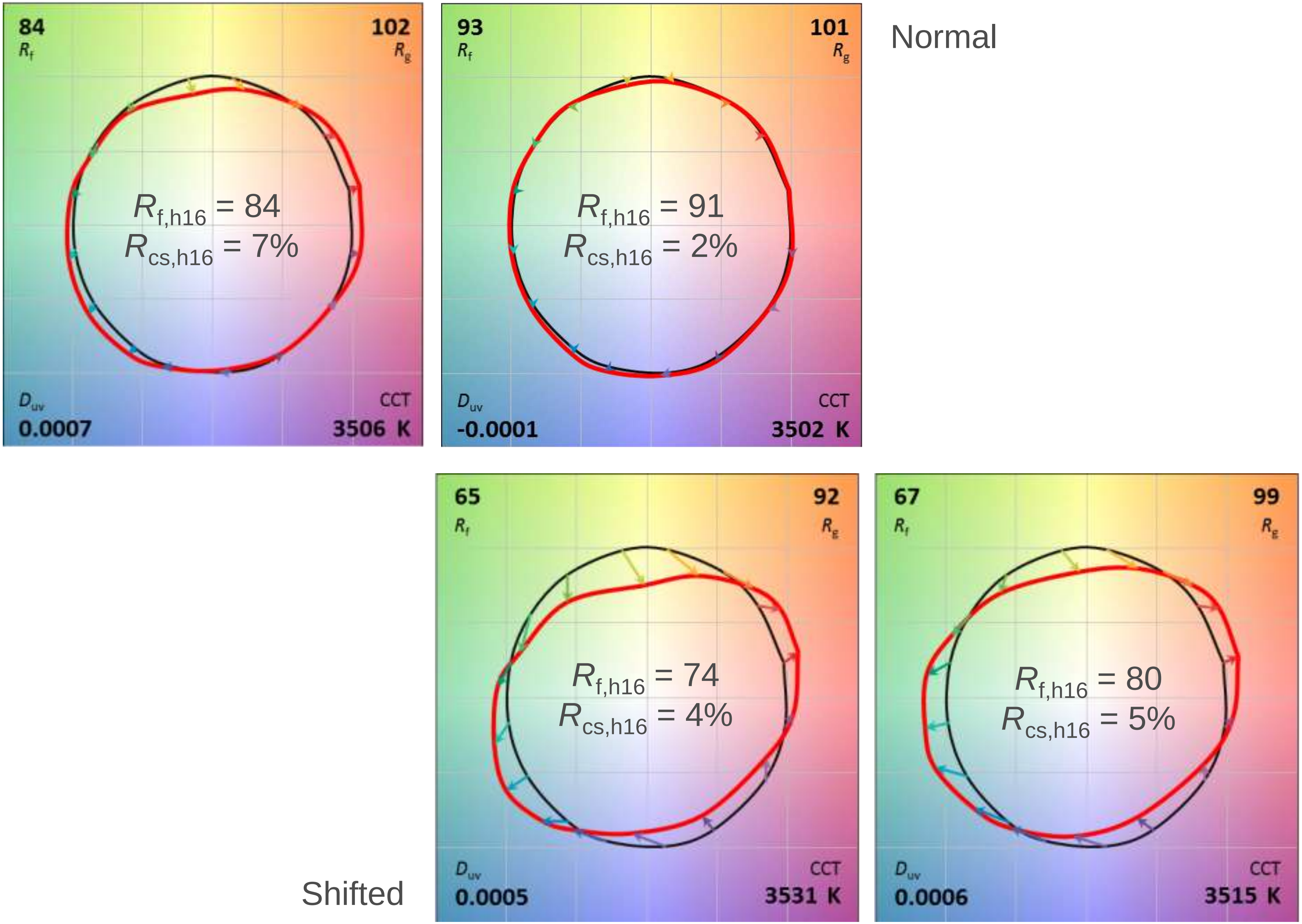
$R_{f,h16}$ = 91
$R_{cs,h16}$ = 2%

3



$R_{f,h1}$ = 91
$R_{cs,h1}$ = 0%

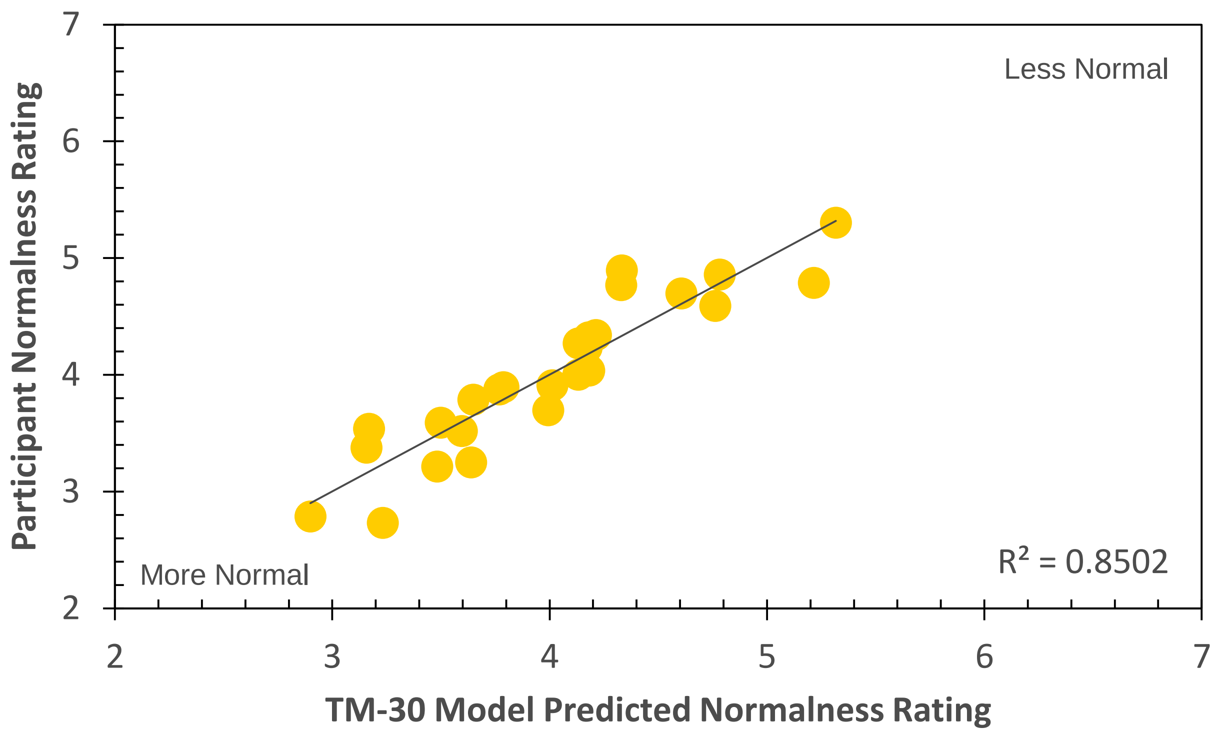
$R_{f,h16}$ = 84
$R_{cs,h16}$ = 6%



84
R_f
102
R_g
$R_{f,h16}$ = 84
$R_{cs,h16}$ = 7%
D_{uv}
0.0007
CCT
3506 K
93
R_f
101
R_g
$R_{f,h16}$ = 91
$R_{cs,h16}$ = 2%
D_{uv}
-0.0001
CCT
3502 K
Normal
65
R_f
92
R_g
$R_{f,h16}$ = 74
$R_{cs,h16}$ = 4%
D_{uv}
0.0005
CCT
3531 K
67
R_f
99
R_g
$R_{f,h16}$ = 80
$R_{cs,h16}$ = 5%
D_{uv}
0.0006
CCT
3515 K
Shifted

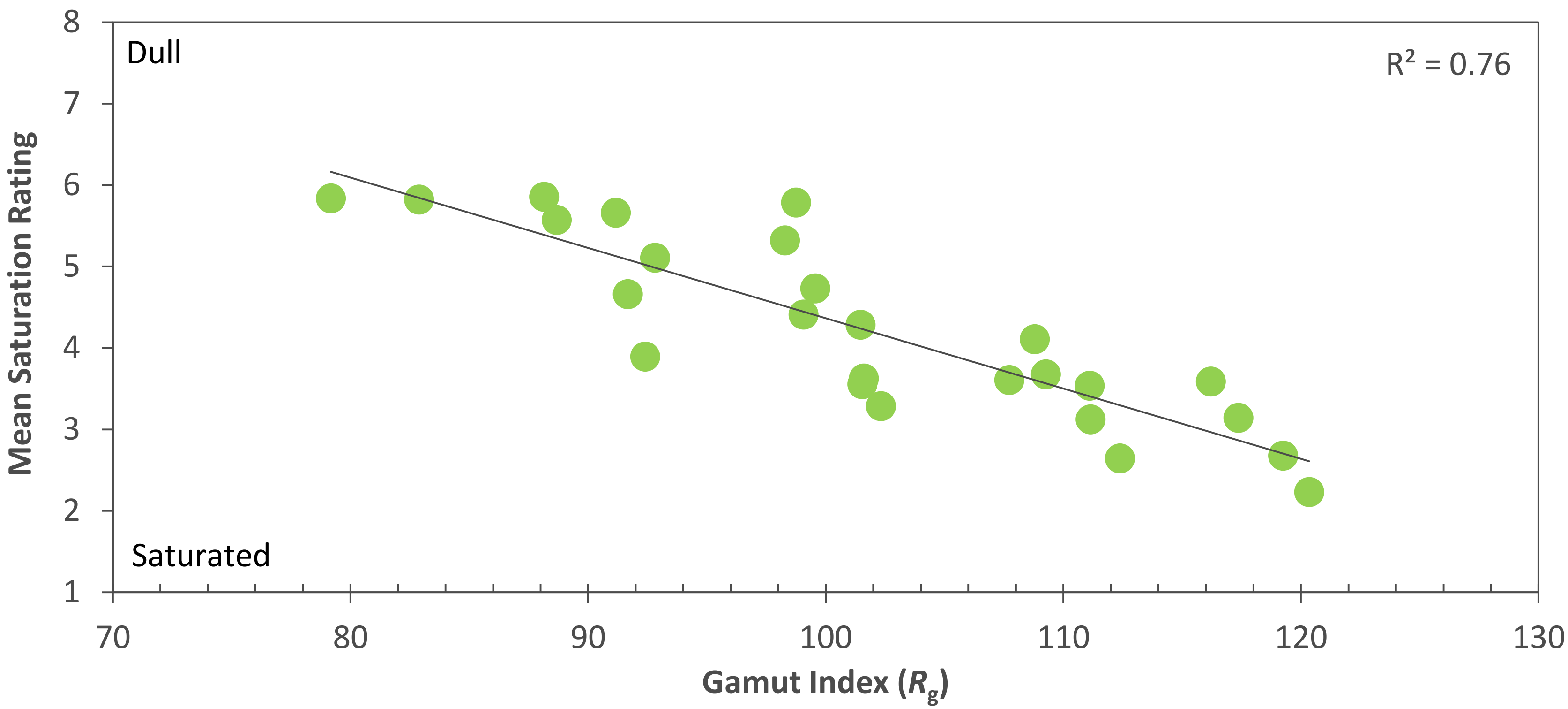
Normalness Model for this Experiment

Need to look at more than one measure!

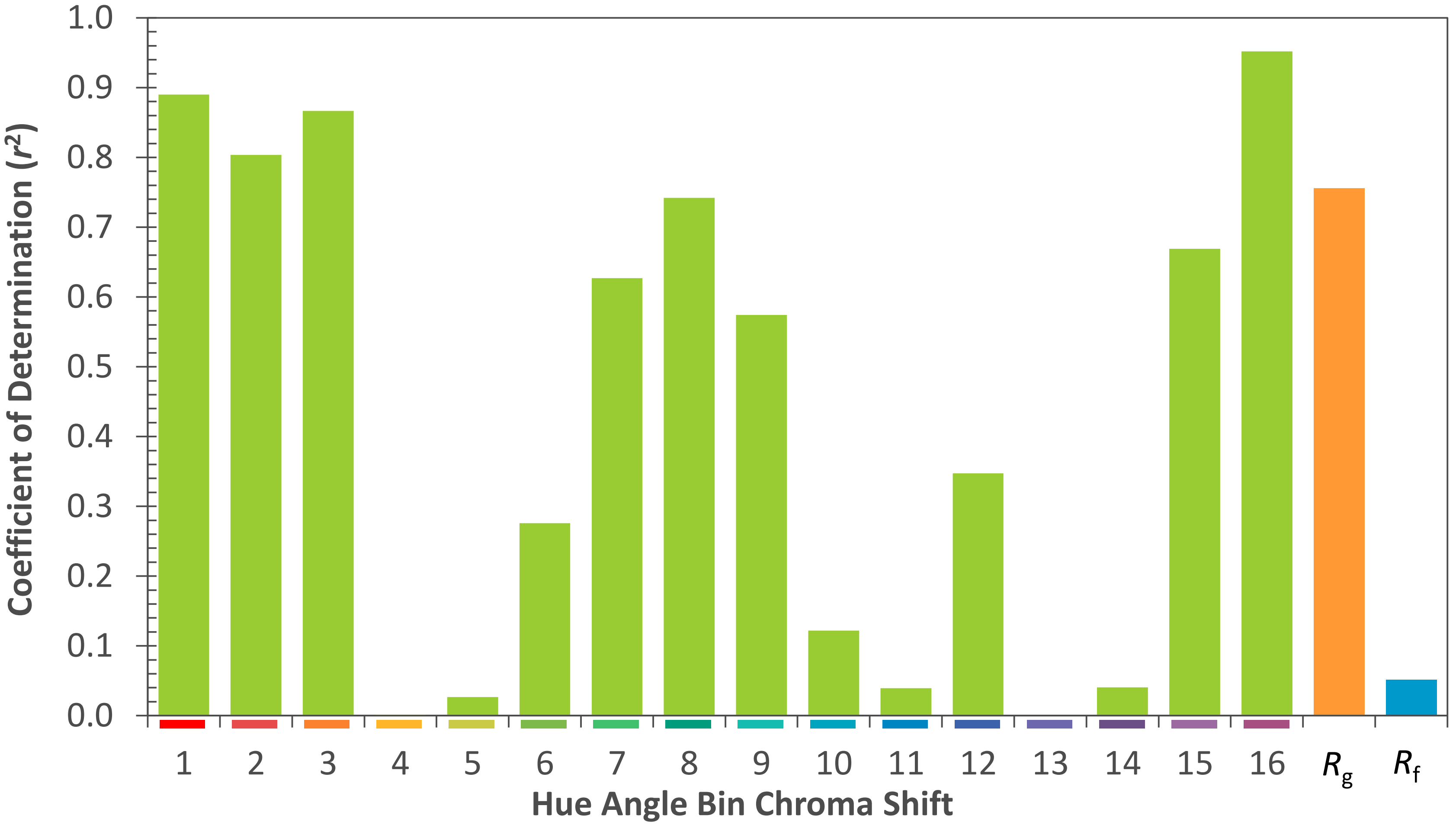


$$\text{Normal-Shifted} = 8.877 - 0.06354(\boldsymbol{R_f}) - 4.068(\boldsymbol{R_{cs,h1}}) + 6.04(\boldsymbol{R_{cs,h1}}^2)$$

Saturation vs. Gamut

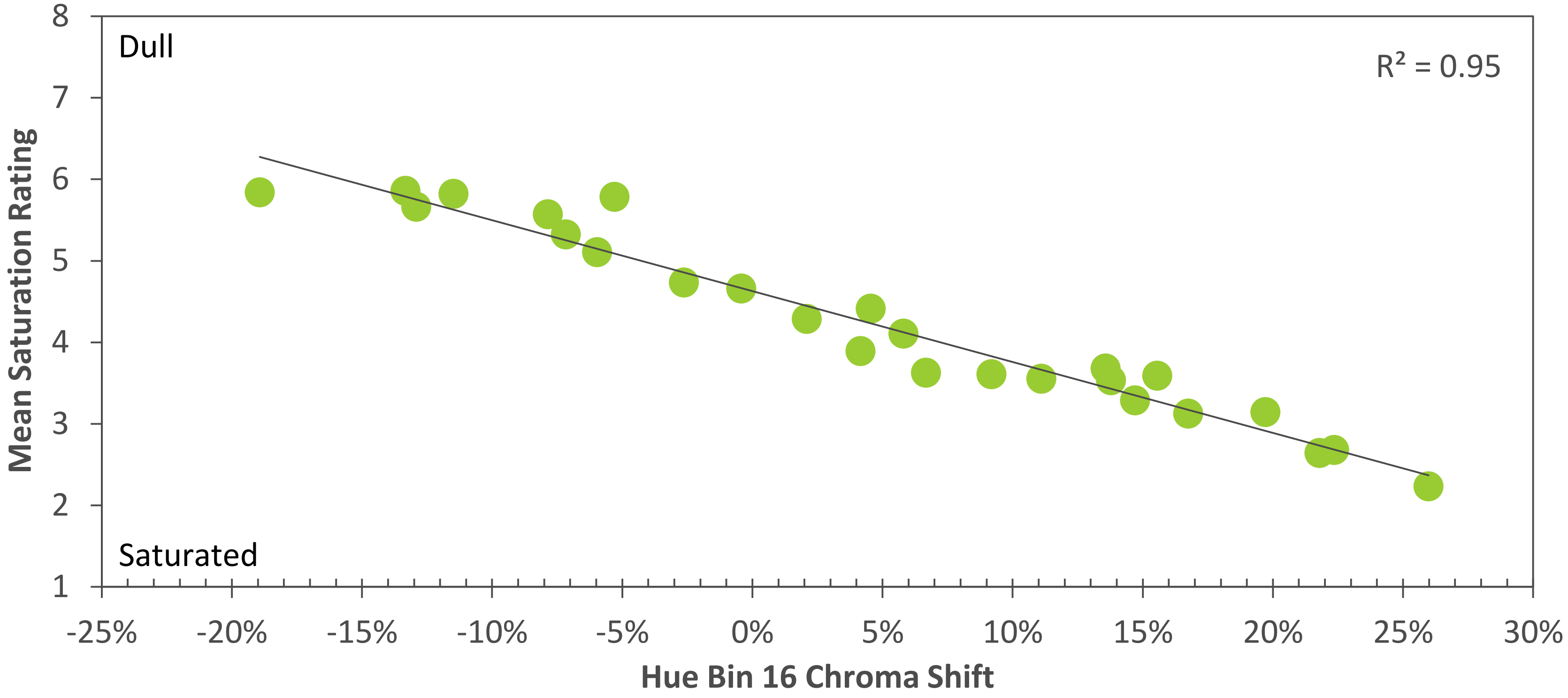


Saturation

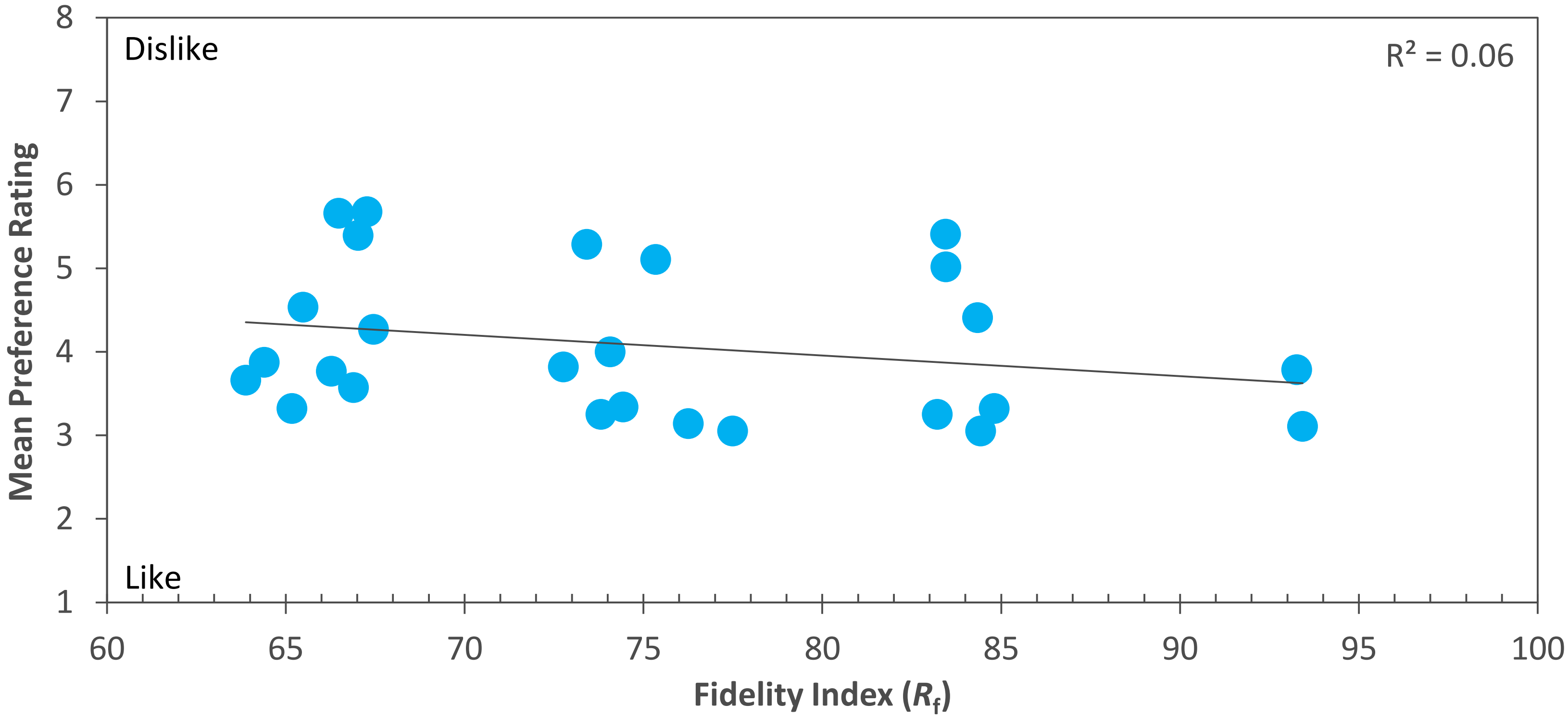


Coefficient of Determination (r^2)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
R_g
R_f
Hue Angle Bin Chroma Shift

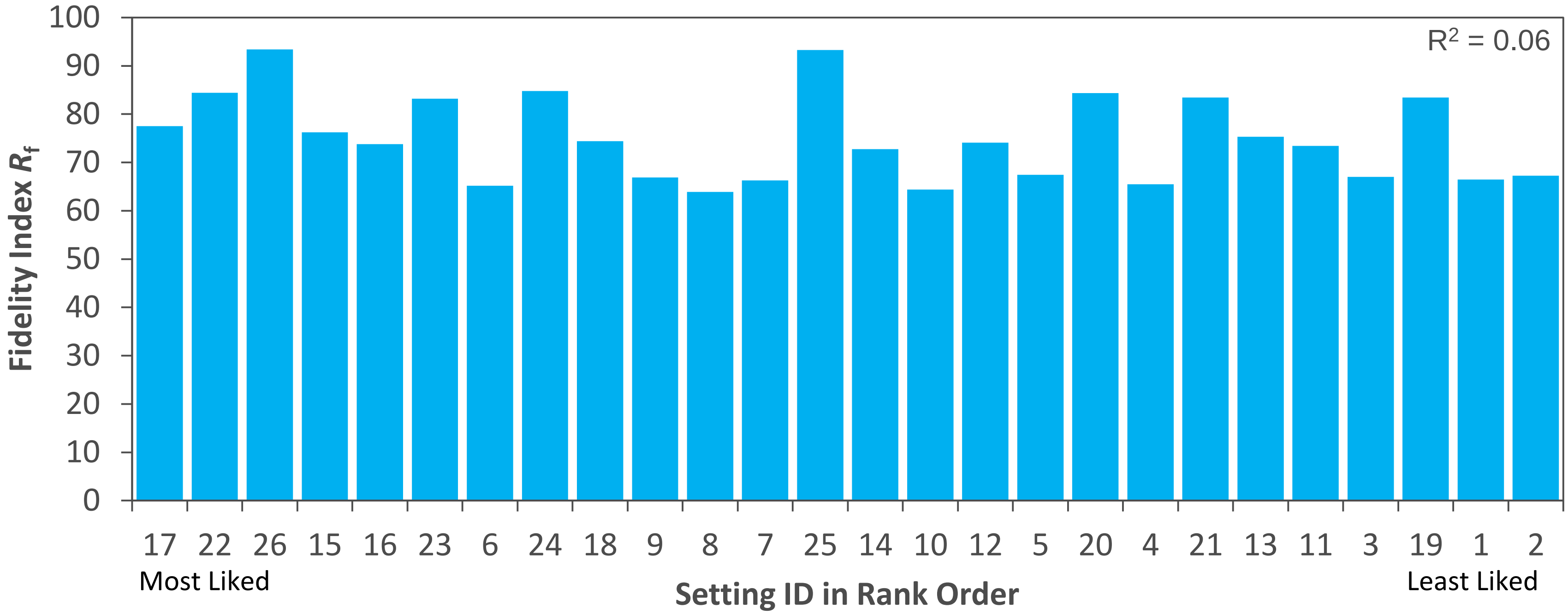
Saturation vs. Red Chroma Shift



Preference vs. Fidelity

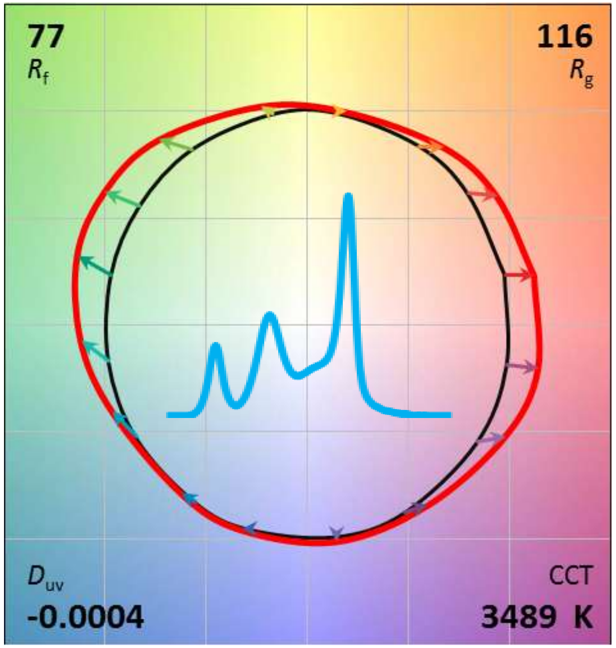


Preference vs. Fidelity

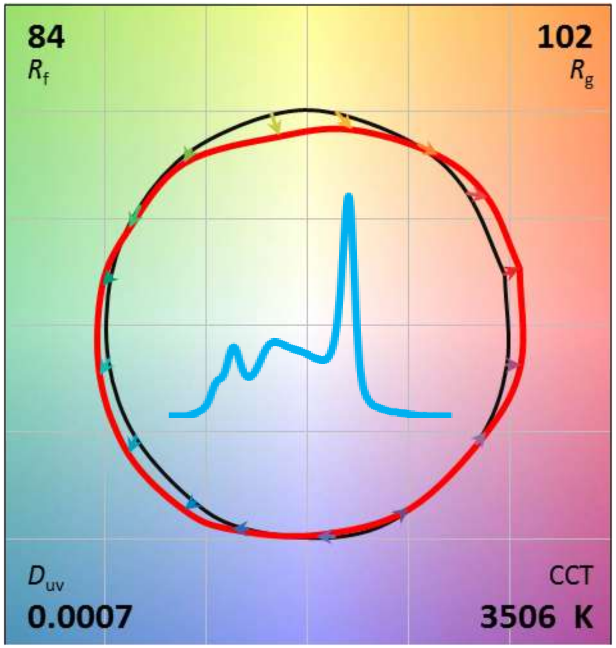


Rated Most Preferred

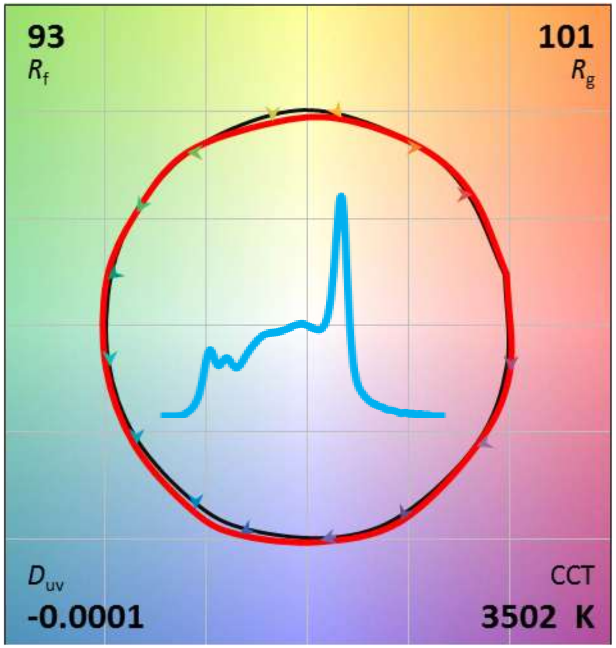
1



2

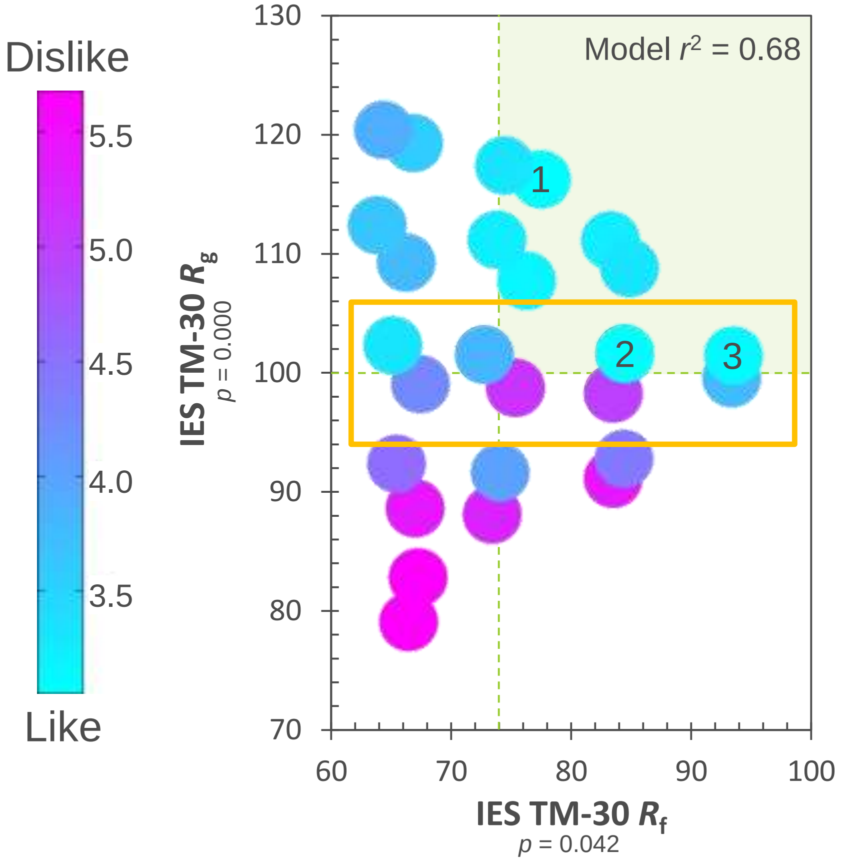


3

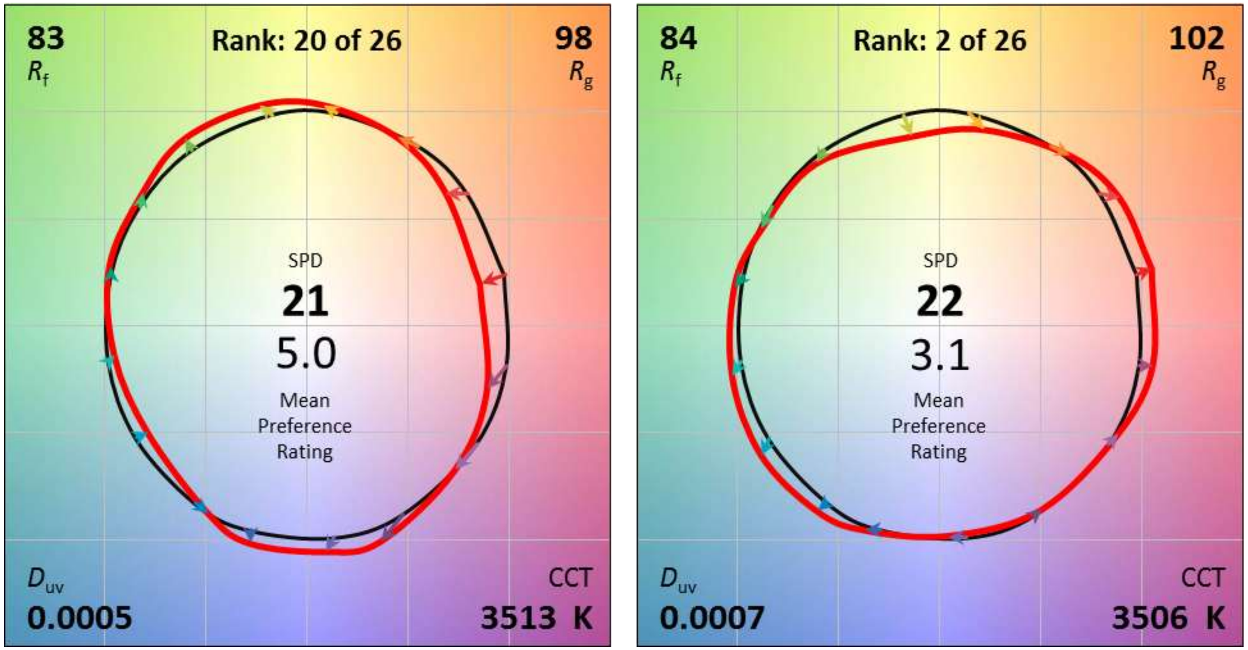


(These aren't necessarily the most preferred sources possible, just the most preferred sources from this experiment).

Preference vs. Fidelity/Gamut

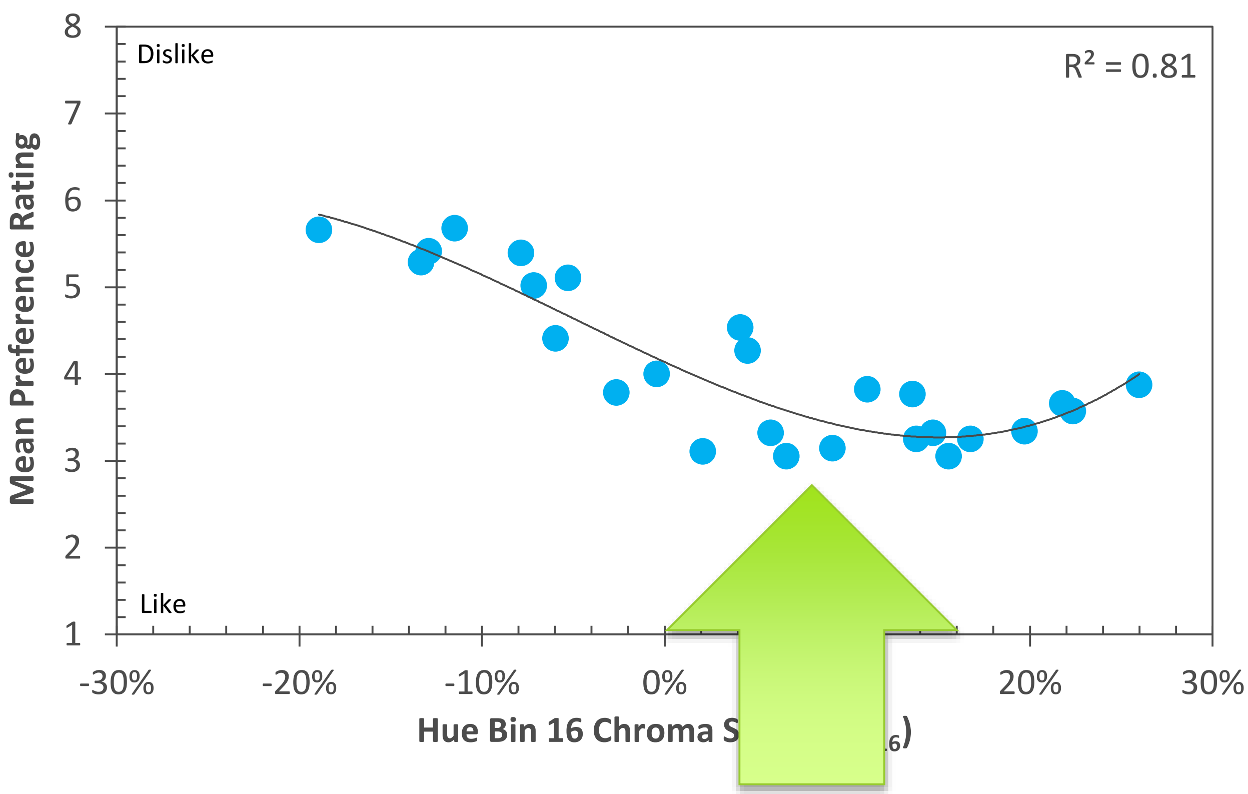


Gamut Shape/Red Rendering

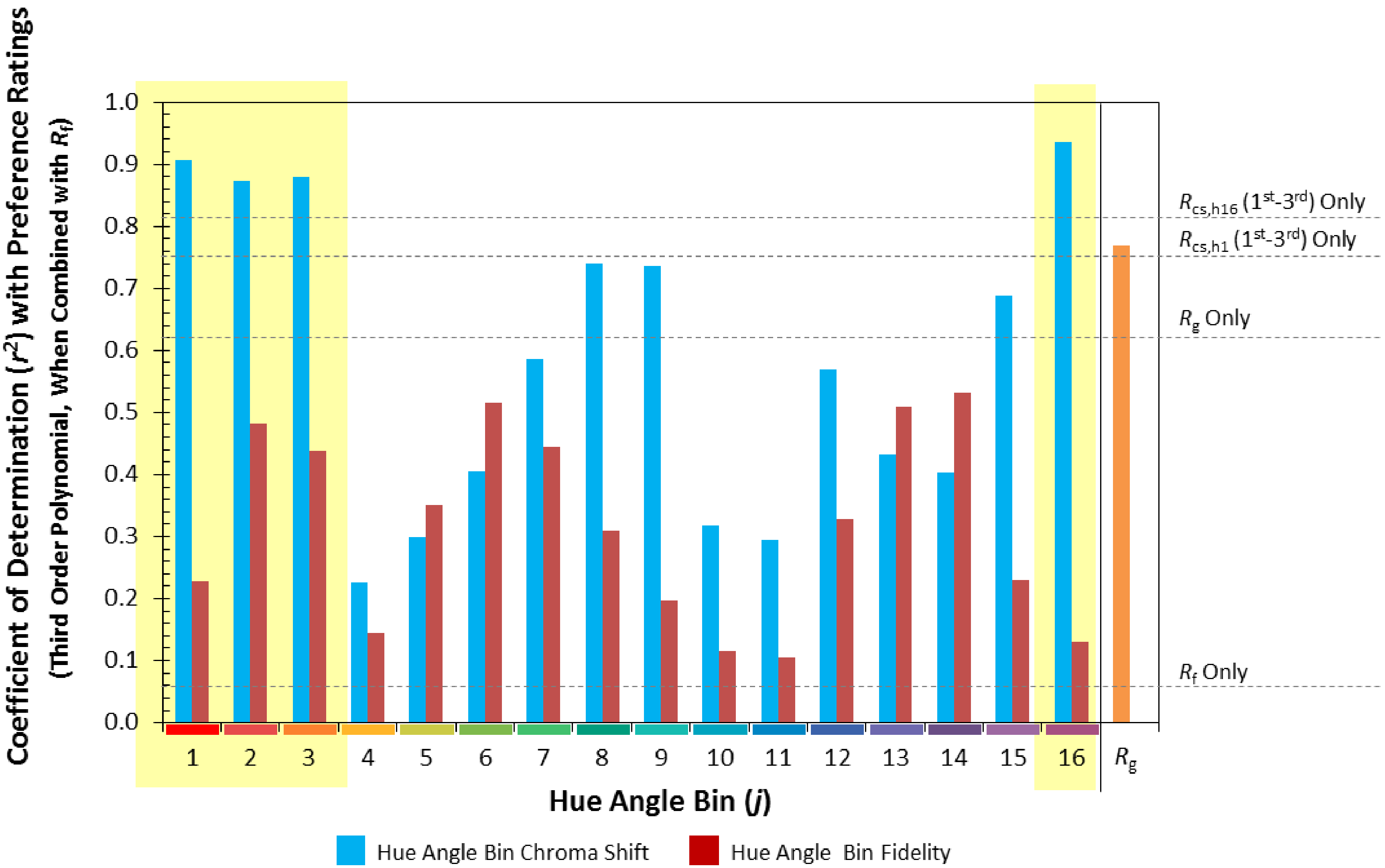


Same Fidelity, Same Gamut, Significantly Different Rating.

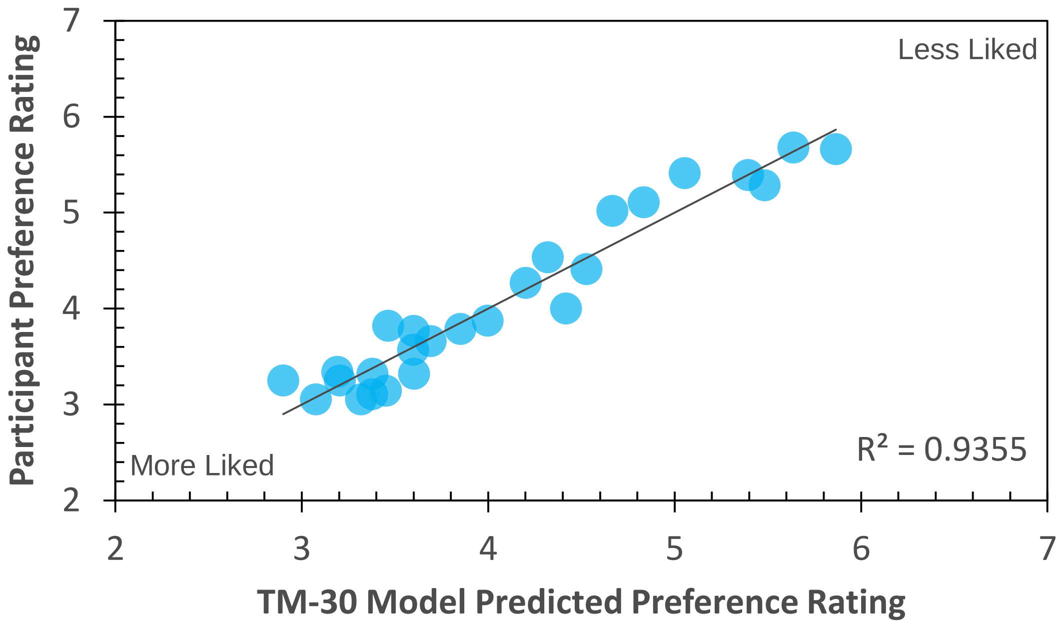
Preference for Increased Red Saturation…with limits.



Preference Correlated with Red Saturation



Preference Model for this Experiment



Best Model for Preference:
Like-Dislike = 7.396 - 0.0408($\boldsymbol{R}_{\mathbf{f}}$) + 103.4($\boldsymbol{R}_{\mathbf{cs,h16}}^{3}$) - 9.949($\boldsymbol{R}_{\mathbf{cs,h16}}$)

Summary

Context = 

Normalness = Fidelity + Red Fidelity/Saturation

$R_f > 80$ $R_{f,h1} > 80$ $0\% < R_{cs,h1} < 8\%$

Saturation = Red Saturation

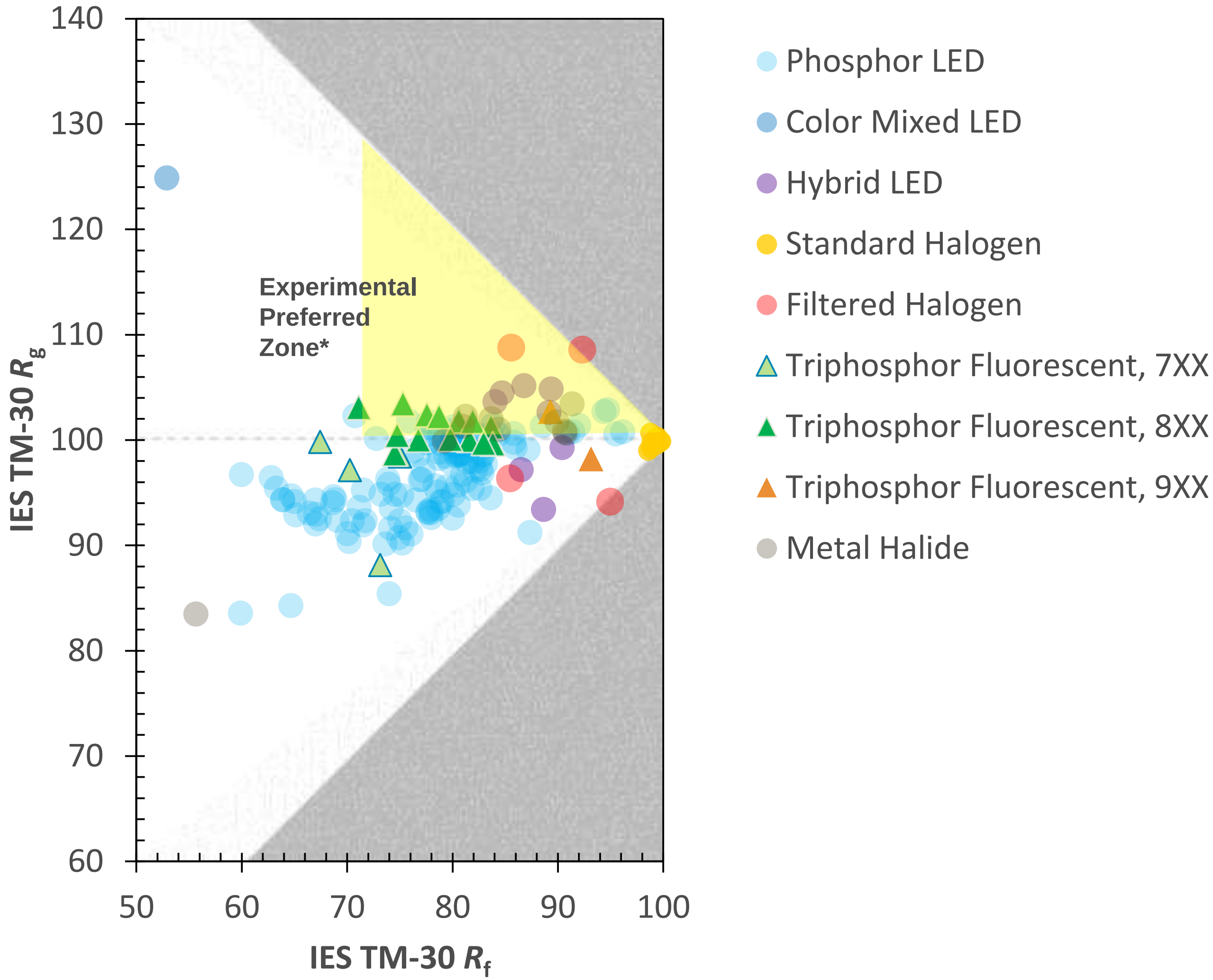
Maximize $R_{cs,h16}$, $R_{cs,h1}$

Preference = Fidelity + Red Saturation

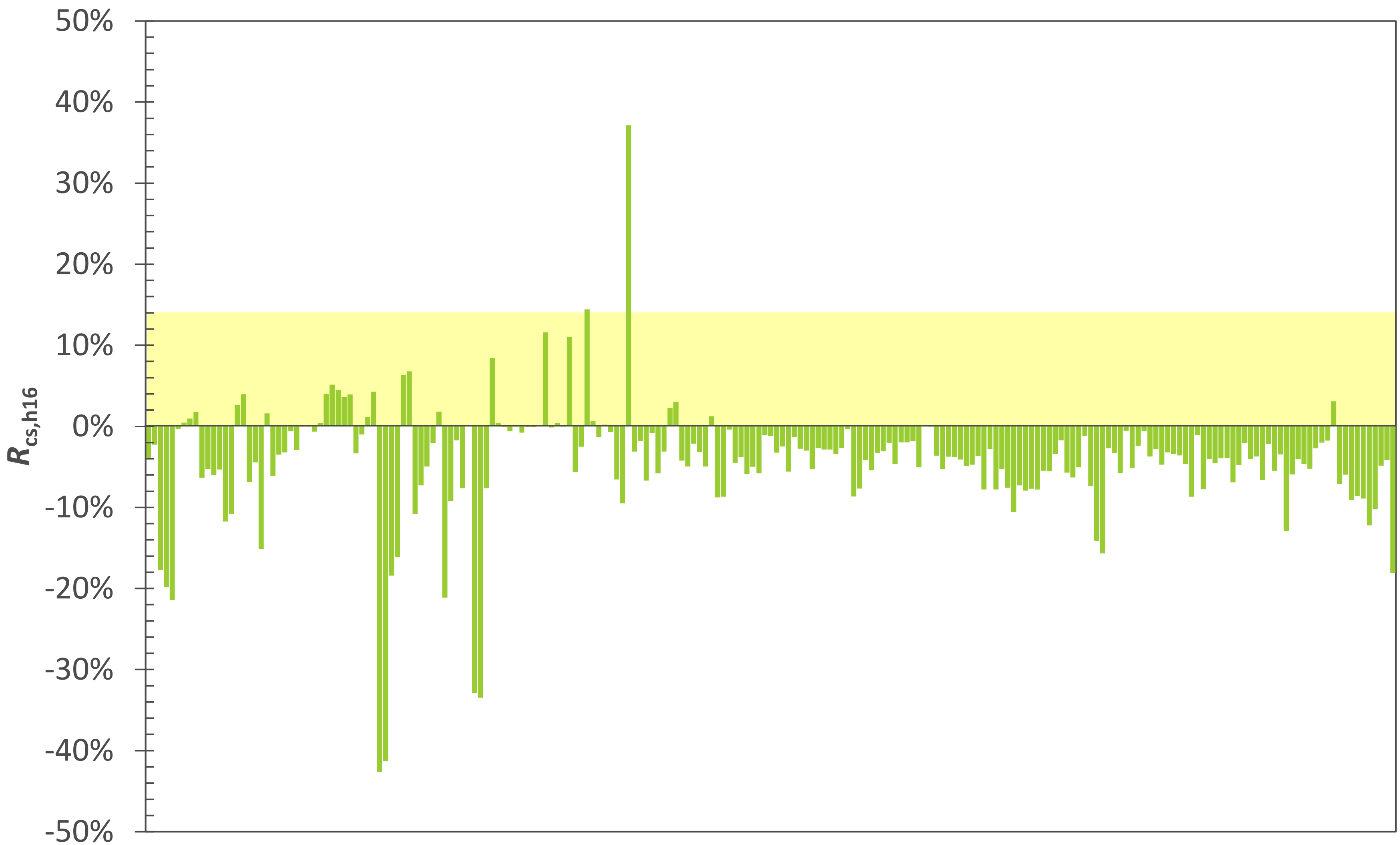
$R_f > 74$ $0\% < R_{cs,h16} < 15\%$ $(R_g > 100)$

$0\% < R_{cs,h1} < 15\%$

A Look at Existing Sources



A Look at Existing Sources

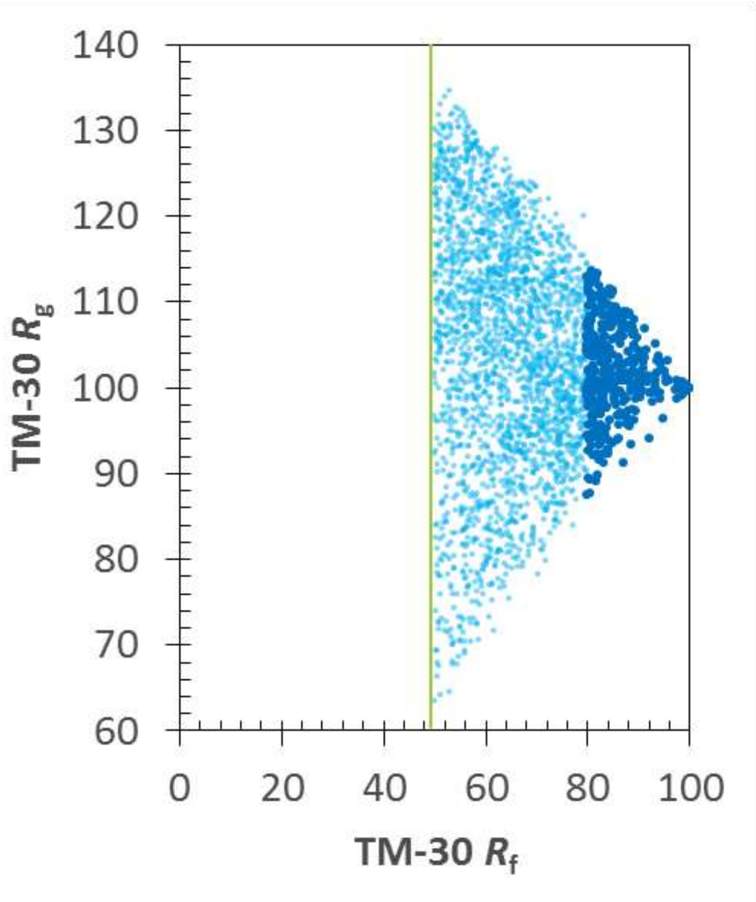


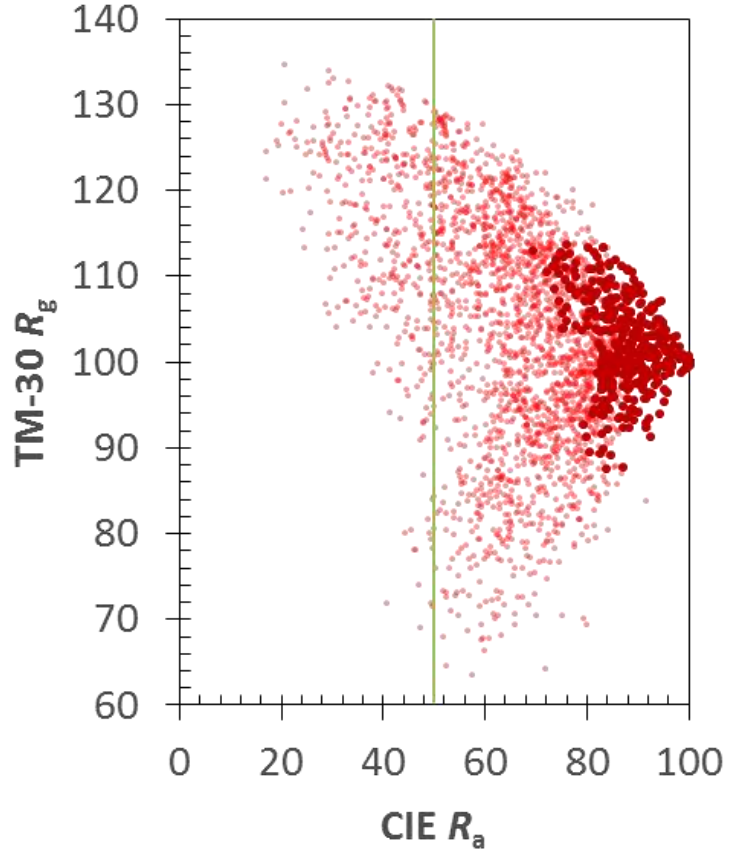
A Look at Existing Sources

- 212 Commercially-Available Sources in TM-30 Library
- 157 Have $R_f > 74$
- 63 Have $R_f > 74$, $R_g > 100$
- 24 Have $R_f > 74$, $R_g > 100$, $R_{cs,h16} > 0\%$
    - Some Fluorescent
    - Some LED
    - Neodymium Incandescent

Why so Few Red-Enhancing Sources?

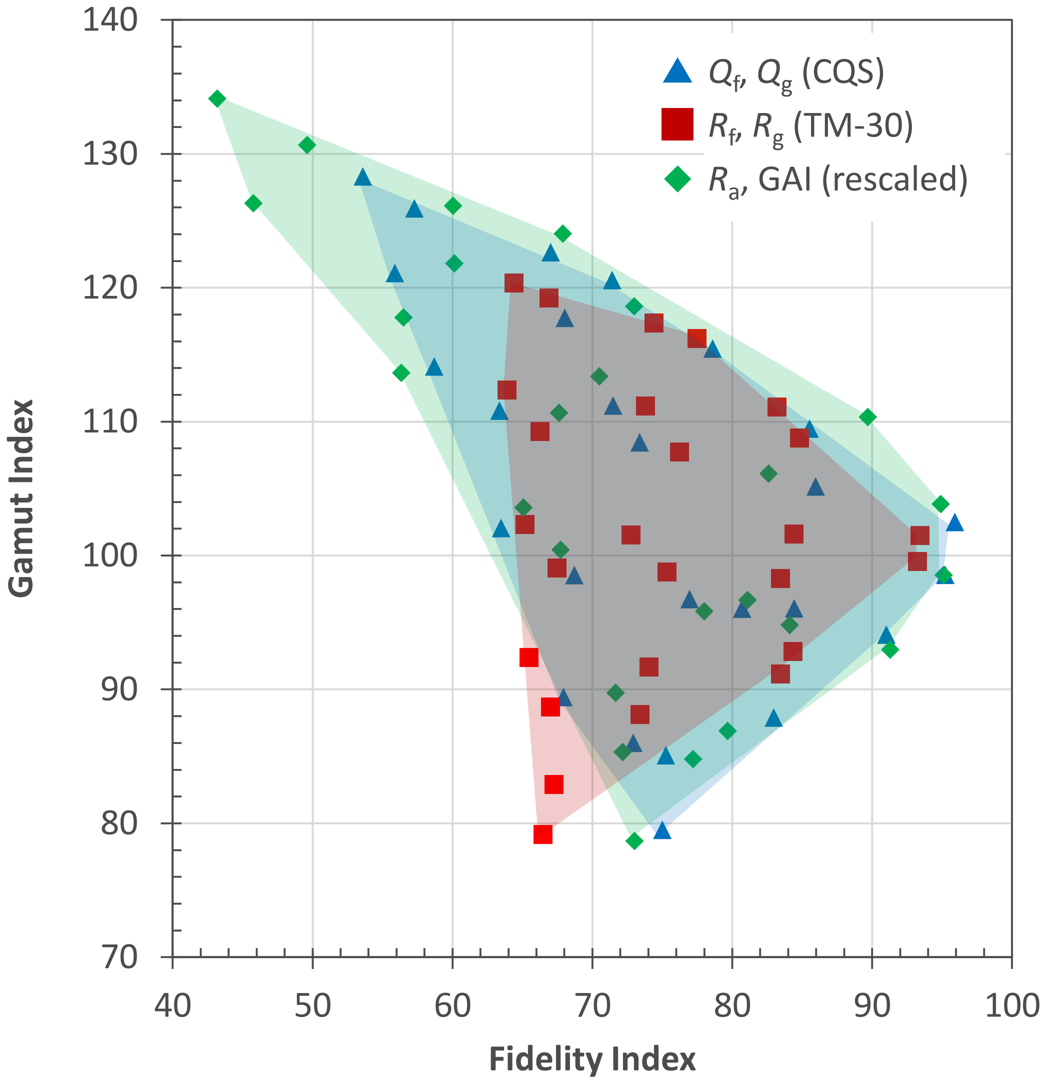
1. Penalization by CRI





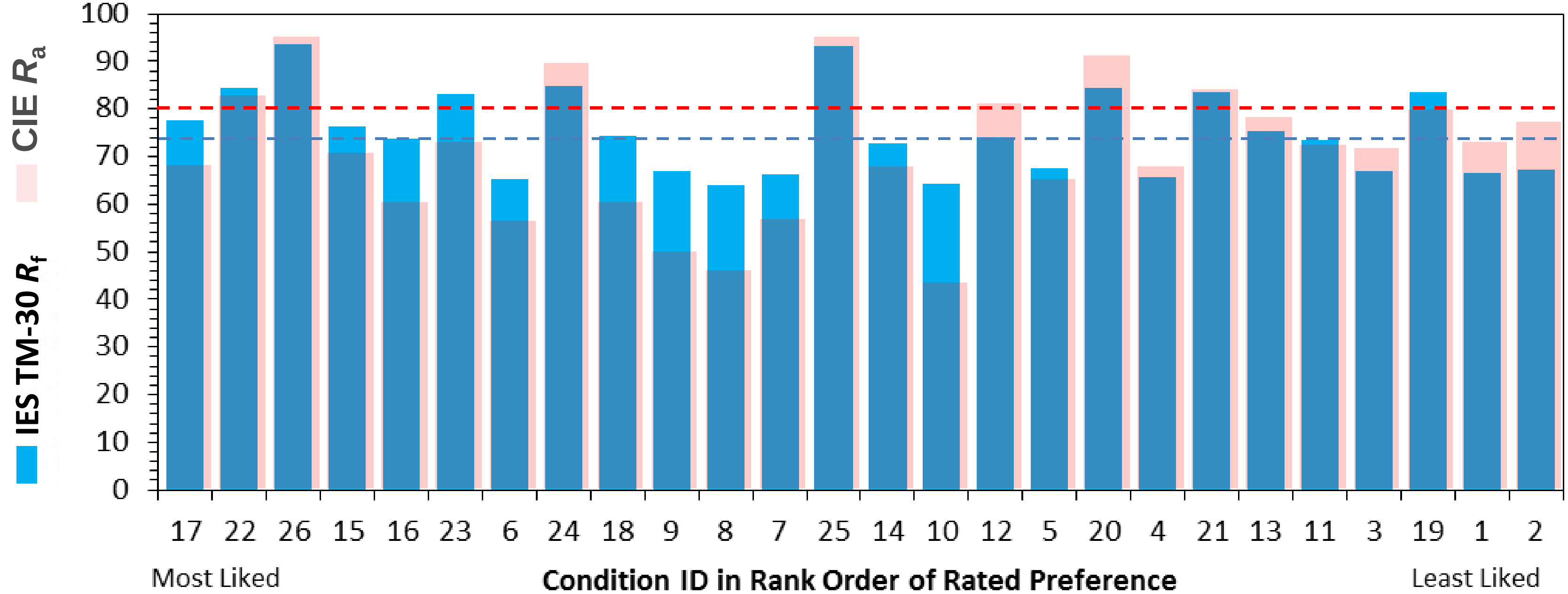
Why so Few Red-Enhancing Sources?

1. Penalization by CRI



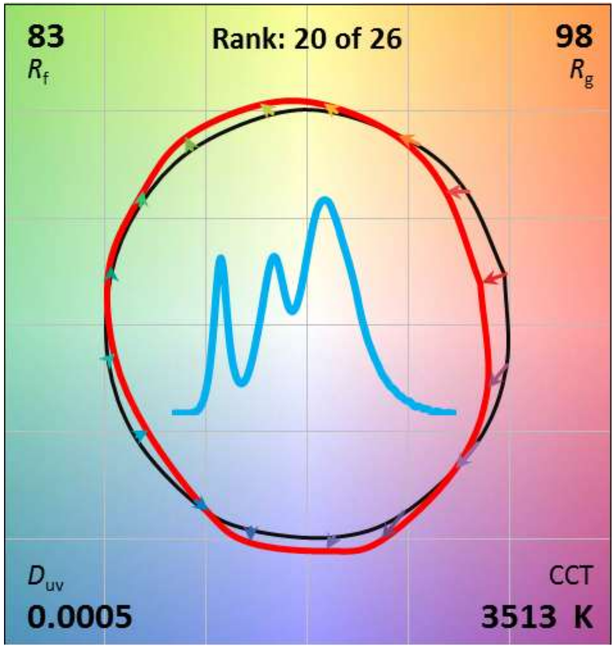
Why so Few Red-Enhancing Sources?

1. Penalization by CRI

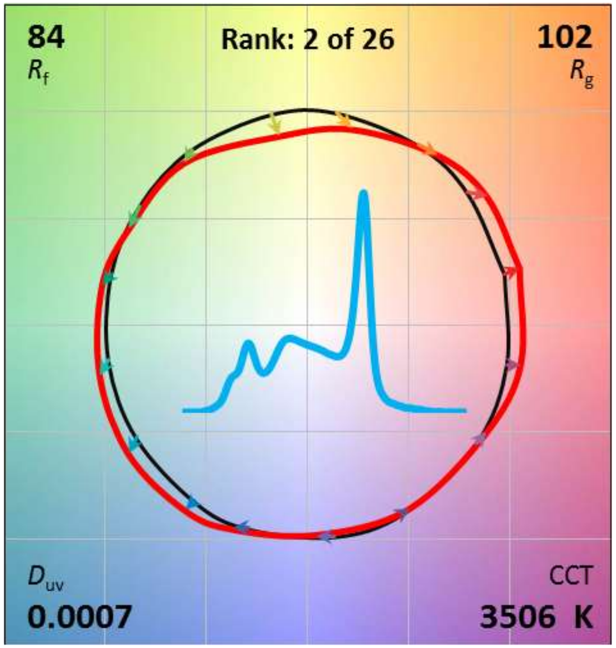


Why so Few Red-Enhancing Sources?

2. Efficiency Considerations



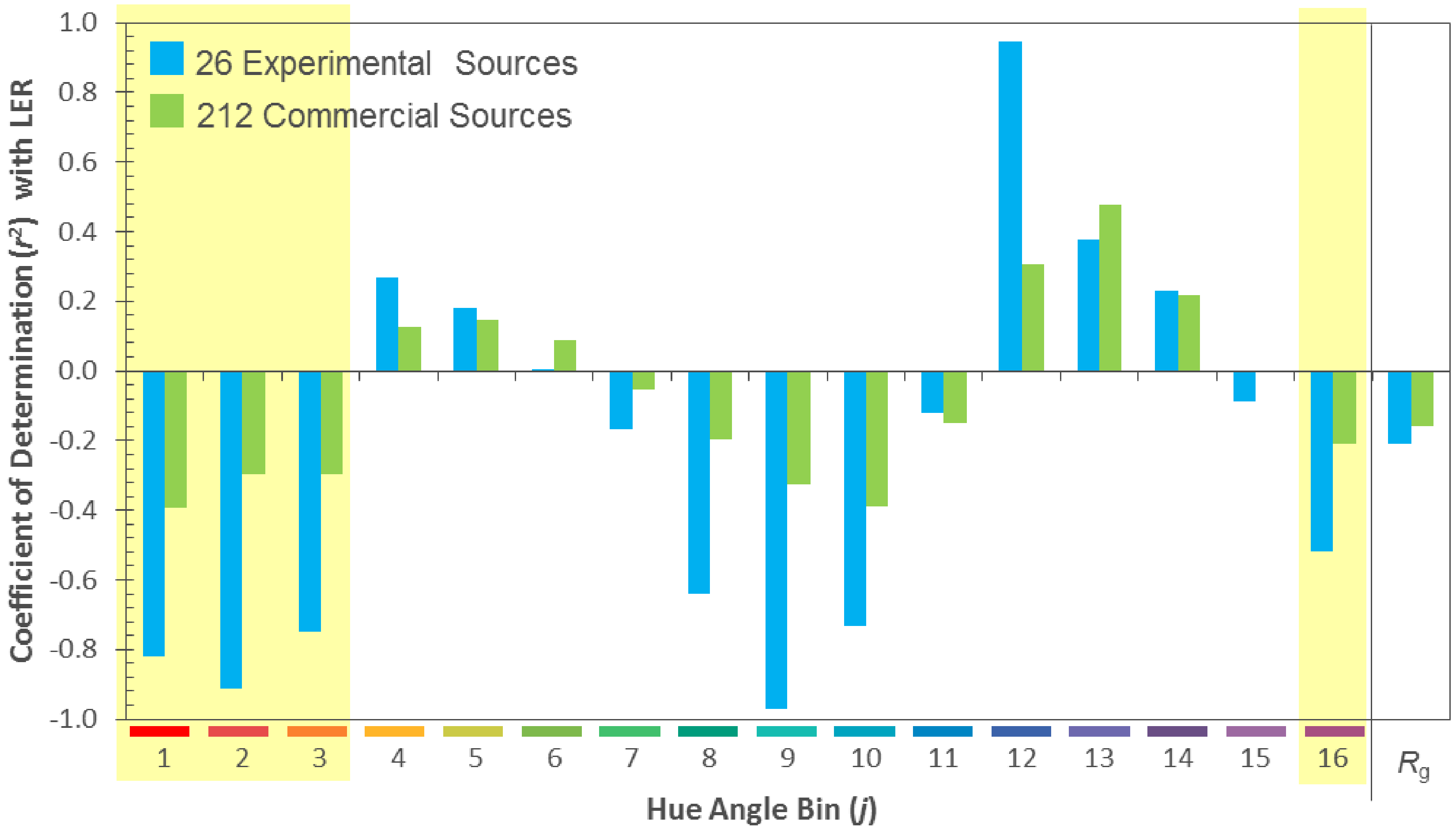
R_a 84, R_9 = -7, **LER 343**



R_a 83, R_9 = 21, **LER 311**

Why so Few Red-Enhancing Sources?

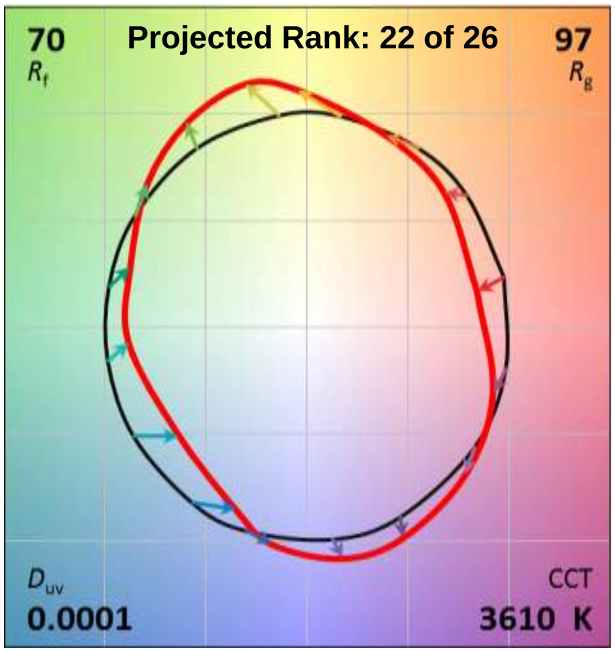
2. Efficiency Considerations



Common Commercially Available Sources

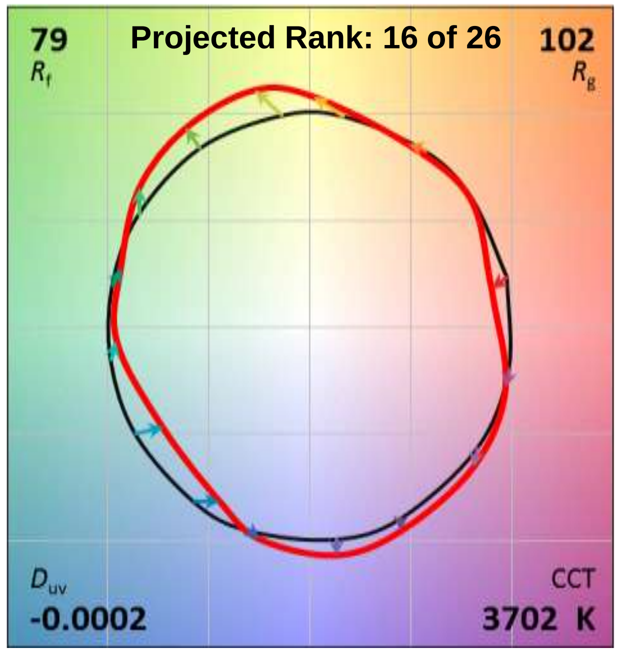
(Developed for CRI R_a):

F32T8/735



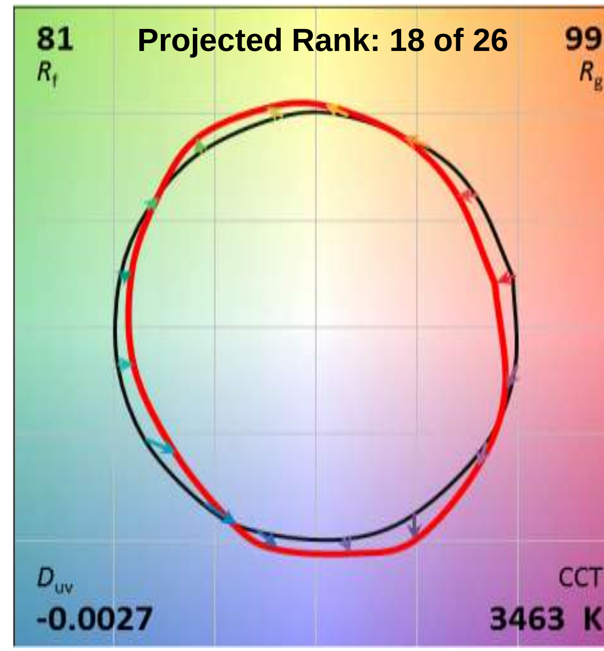
R_a 74, LER 348

F32T8/835



R_a 85, LER 343

Blue-Pump Phosphor LED (81 CRI)

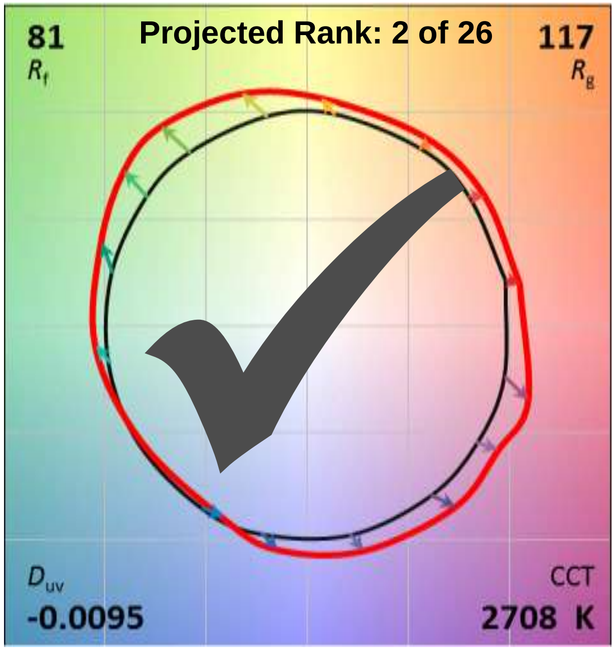


R_a 83, LER 309

Enhanced Sources

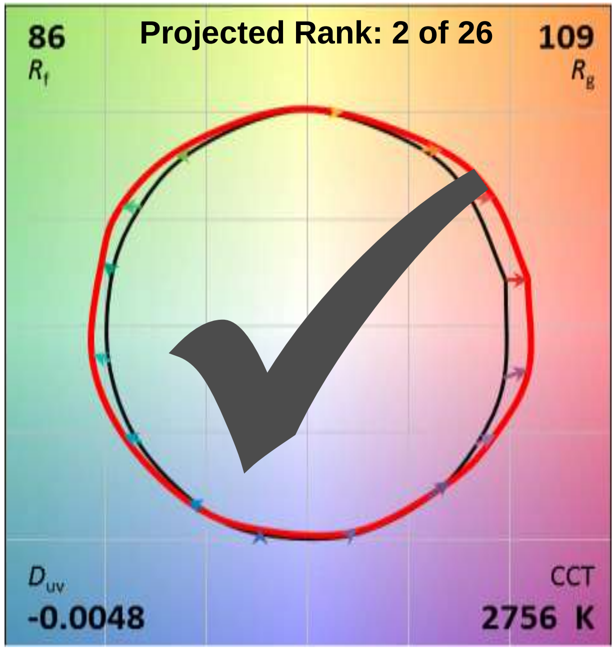
(Developed for CRI R_a and/or Gamut Area)

LED (Patent Application)



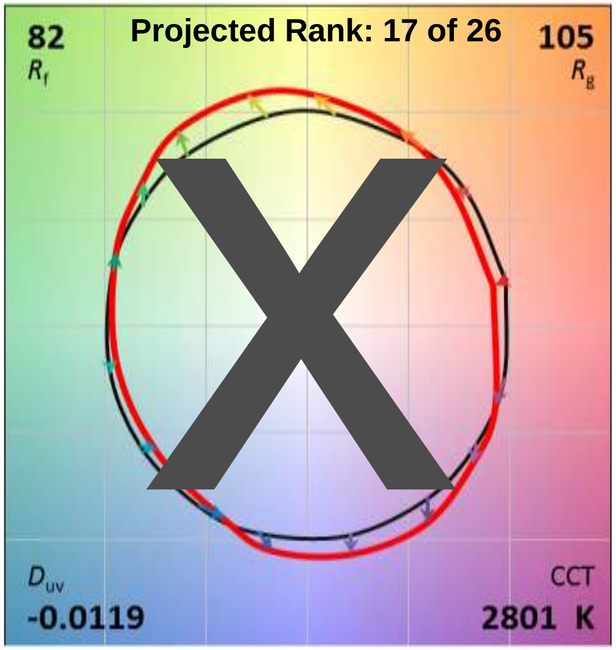
R_a 80, LER 272

Neodymium Incandescent



R_a 77, LER 136

LED (Available Product)



R_a 87, LER 295

(Might be perfect for a different application!)

Enhanced Sources Using TM-30

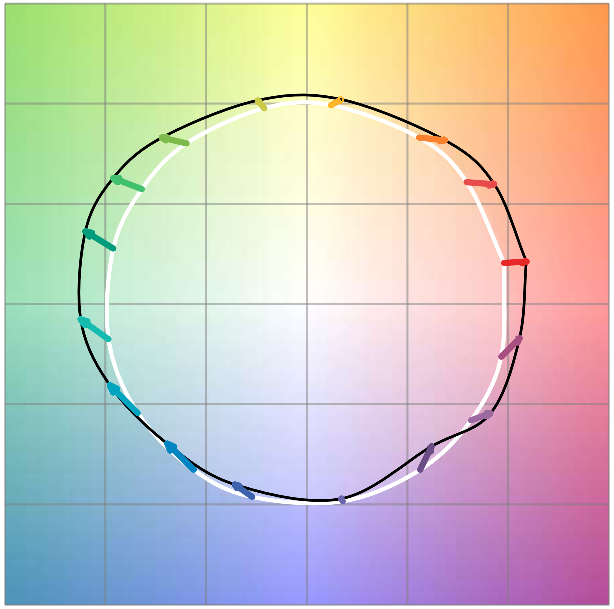
A commercial color-enhancing source designed with TM30:

Rf=78

Rg=110, red-enhancing

CCT=3000K

Duv~0

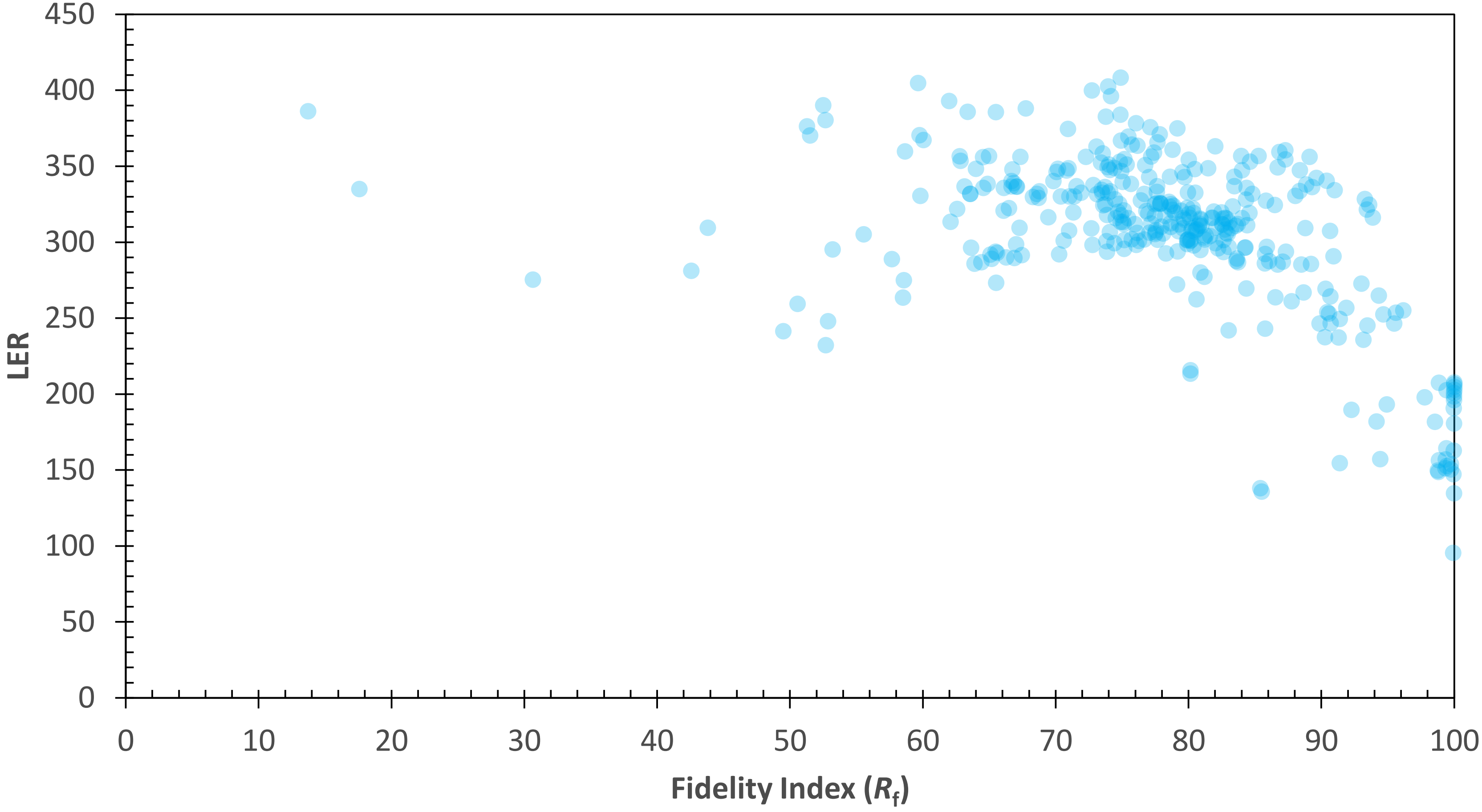


Using a different color metric leads to a different product!

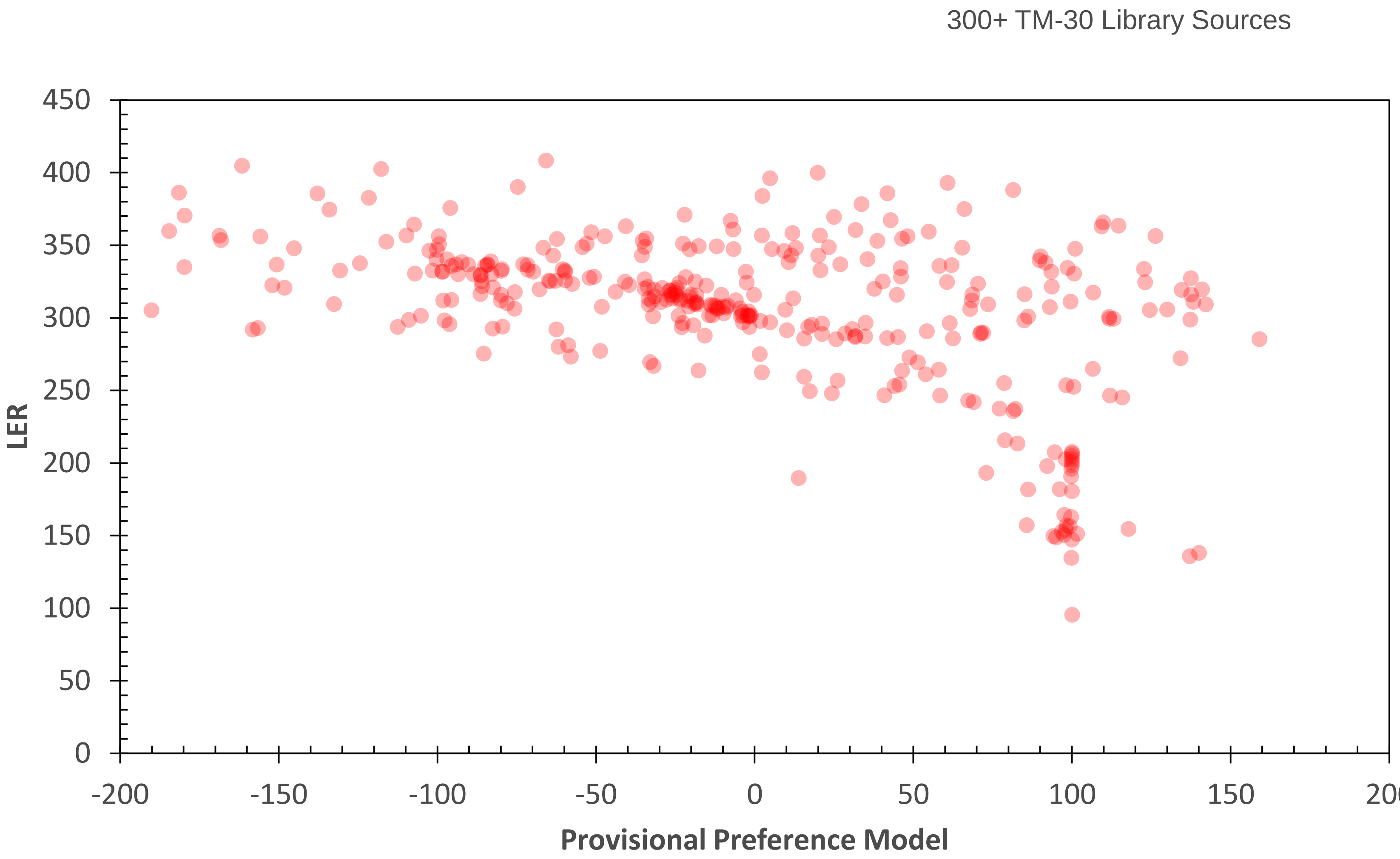
Here: no chromaticity bias, no “blue-rich” bias

Efficiency versus Fidelity

300+ TM-30 Library Sources



Efficiency versus Preference



Part 5:

TM-30 Use and Case Studies

Getting Started With TM-30

1. Read up and learn what the new metrics mean and how they are calculated. {Links at end of presentation}

2. Download and use the calculator tool.
   a) Examine sources in the library. How do they match your experience?
      i. If you liked a source before, new numbers won't change anything.
   b) Enter your own data.

3. Get access to a tunable source. Play with it to understand how changing different color rendering attributes makes things look.

Adoption Stakeholders

SPECIFIERS

Evaluate Sources
Philosophical Changes
Help Develop Criteria
“Pull”

MANUFACTURERS

Provide Data
Engineer New Sources
Marketing Advantages
“Push”

RESEARCHERS

Help Develop Criteria
Continue Improving Science

CODES AND PROGRAMS

Implement New Criteria

Specifiers

- TM-30-15 is an approved method: USE IT!
- Choosing a “better” light source may be more challenging, but also more rewarding.

Specifiers

1. What is the context?
   a) What kind of space?
   b) What objects are important?
   c) Illuminance level?
   d) Culture/expectations of occupants?
   e) Color temperature?

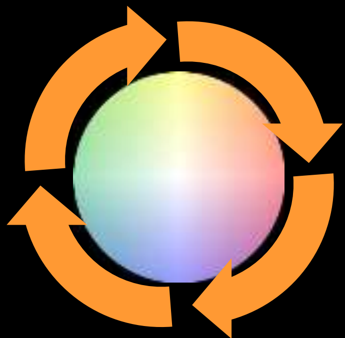
2. Understand your goals.
   a) Energy efficiency or color rendering?
   b) Matching other sources?
   c) Cost?

3. Develop a plan.
   a) Think about the mood/impression/theme, not about the numbers.

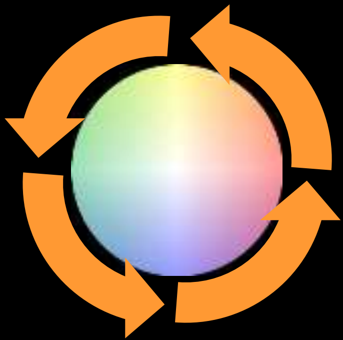
“Original” Baseline

Image courtesy of Randy Burkett Lighting Design

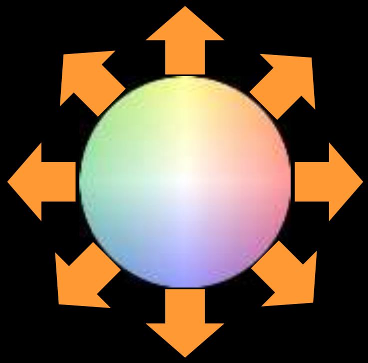
“CRI = 80” + Hue Shift



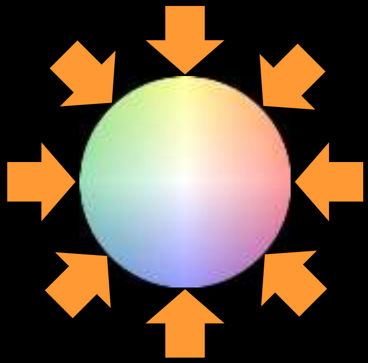
“CRI = 80” - Hue Shift



"CRI = 80" Saturated



“CRI = 80” Desaturated



Manufacturers

Manufacturers have explored tradeoffs between fidelity and gamut in the past.

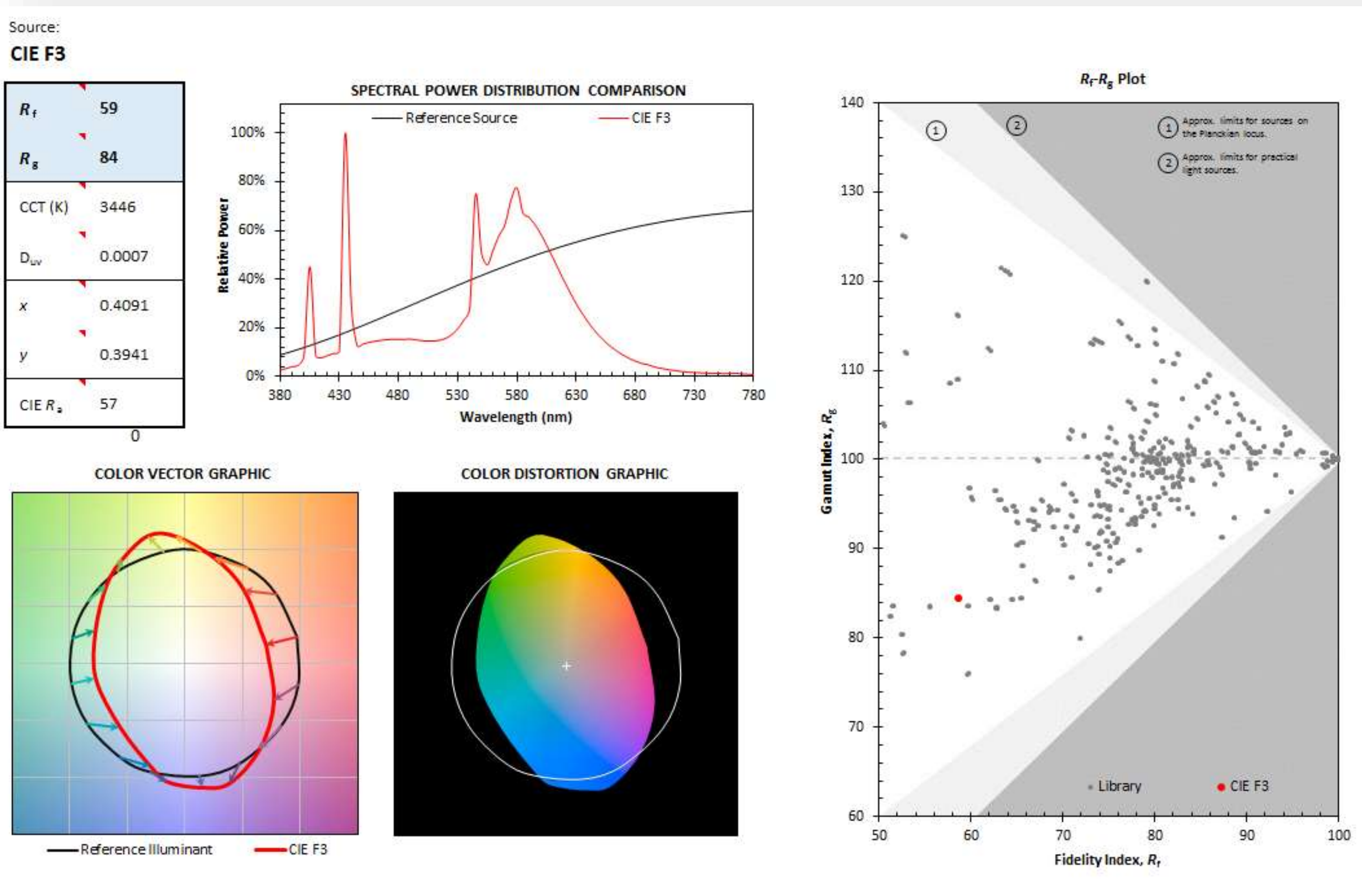
Manufacturers

1. Understand your goals.
   a) Energy efficiency or color rendering?
   b) Color enhancement?
   c) Matching other sources?
   d) Cost?

2. Respond to customers or develop original research?

Manufacturers

Data Availability.



Research

Research

Other Contexts?

Application/Objects
Observers/Culture/Age/Gender
Chromaticity
Illuminance Level
Gamut Shapes

Efficiency and Incentive Programs

1. **Keep using CRI?**
   - \- Uses an inaccurate metric, higher values not always better
   - \+ No disruption to existing system

2. **Replace CRI R_a with R_f, do not specify other limits?**
   - \- Higher R_f not always better
   - \+ Relatively easy implementation, but not a direct change

     Mandatory reporting of R_g? Color Graphics?

     What about R_9?

3. **Replace CRI R_a with both R_f and R_g limits (& specifics)?**
   - \- May start to regulate quality/preference
   - \+ More thorough specification. Limits for R_g could only preclude extreme sources (e.g., ≤70, ≥130)

4. **Include nothing on color rendition?**
   - \- Will most likely lead to reduce color quality, given inherent relationships
   - \+ Avoids any decisions

Case Studies

BRIGHTER
than the rest
we believe in:
RULES BEING
BROKEN,
REWRITTEN, and
BROKEN OVER again.


HUSSMANN


BLACK 1175
© Christina Chung


BARBARA STANWYCK
GEORGE SANDERS-GARY MERRILL
TEMOIN DE CE MEURTRE
DAVID FARRAR
DAVID KNIGHT
JULIA ARNALL
LA PAGE ARRACHÉE
"LOST"
EASTMANCOLOR
MGM
Graine de Violence
(BLACKBOARD JUNGLE)
LE TOUBIB DU GANG
RACKET DANS LA COUTURE
BRANDO
"THE BIG HEAT"
ALEXANDER SCOURBY
JEANETTE NOLAN
ENQUÊTE À VENISE
RICHARD TODD-EVA BARTOK
JAMES CAGNEY
Le Bagarreur N°1
LE FAUVE EN LIBERTÉ
LE GANTELET VERT
ANNE BAXTER
STERLING HAYDEN
infamie
SLIGHTLY SCARLET
DOROTHY McGUIRE
STEPHEN McNALLY
Make Haste to Live
MARY MURPHY
LINDA
DARNELL

Conclusions

- IES TM-30-15 offers substantial improvement over CRI, both in terms of technical accuracy and in providing a more complete representation of color rendering.
- TM-30 is available and ready for use. Try it out an provide feedback. With time, industry consensus and standardization can happen.
- TM-30 can be as simple or as complicated as you want it to be; it’s more than just two average measures.
- TM-30 provides benefits for manufacturers, specifiers, researchers, and energy efficiency programs.
- TM-30 is a tool, not an answer. You must understand it to be able to use it effectively.
- Color quality is more than just TM-30: keep an eye on other metrics.

Additional Resources

IES Technical Memorandum (TM) 30-15 (Includes Excel Calculators):
IES Method for Evaluating Light Source Color Rendition
http://bit.ly/1IWZxVu

Optics Express journal article that provides overview of the IES method:
Development of the IES method for evaluating the color rendition of light sources
http://bit.ly/1J32ftZ

Application webinar co-sponsored by US Department of Energy and Illuminating Engineering Society:
Understanding and Applying TM-30-15: *IES Method for Evaluating Light Source Color Rendition*
http://1.usa.gov/1YEkbBZ

Technical webinar co-sponsored by US Department of Energy and Illuminating Engineering Society:
A Technical Discussion of TM-30-15: Why and How it Advances Color Rendition Metrics
http://1.usa.gov/1Mn15LG

LEUKOS journal article supporting TM-30's technical foundations:
Smet KAG, David A, Whitehead L. 2015. **Why Color Space and Spectral Uniformity Are Essential for Color Rendering Measures.** *LEUKOS*. 12(1,2):39-50.
http://dx.doi.org/10.1080/15502724.2015.1091356

LEUKOS editorial discussing next steps:
Royer MP. 2015. **IES TM-30-15 Is Approved—Now What? Moving Forward with New Color Rendition Measures.** *LEUKOS*. 12(1,2):3-5.
http://dx.doi.org/10.1080/15502724.2015.1092752

Lighting Research and Technology, Open Letter:
Correspondence: In support of the IES method of evaluating light source colour rendition (More than 30 authors)
http://dx.doi.org/10.1177/1477153515617392

DOE Fact Sheet on TM-30
http://energy.gov/eere/ssl/downloads/evaluating-color-rendition-using-ies-tm-30-15

DOE TM-30 FAQs Page:
http://energy.gov/eere/ssl/tm-30-frequently-asked-questions

Questions?