U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Illuminating Engineering Society

A Technical Discussion of IES TM-30-15

DOE+IES Webinar | September 22, 2015

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A Brief Recap of *Understanding and Applying TM-30*

1. TM-30 follows 25+ years of committee work on color rendering, synthesizing previous research to produce a cohesive method for evaluating color rendering, vetted through the consensus process.
2. TM-30-15 addresses both the philosophical and technical limitations of CRI.
3. TM-30 helps specifiers better determine the most suitable source, and helps manufacturers differentiate their products.
4. Development of design guidance and establishment of specification criteria is an ongoing process.
5. The document and Excel tools are available from IES and can be used immediately!

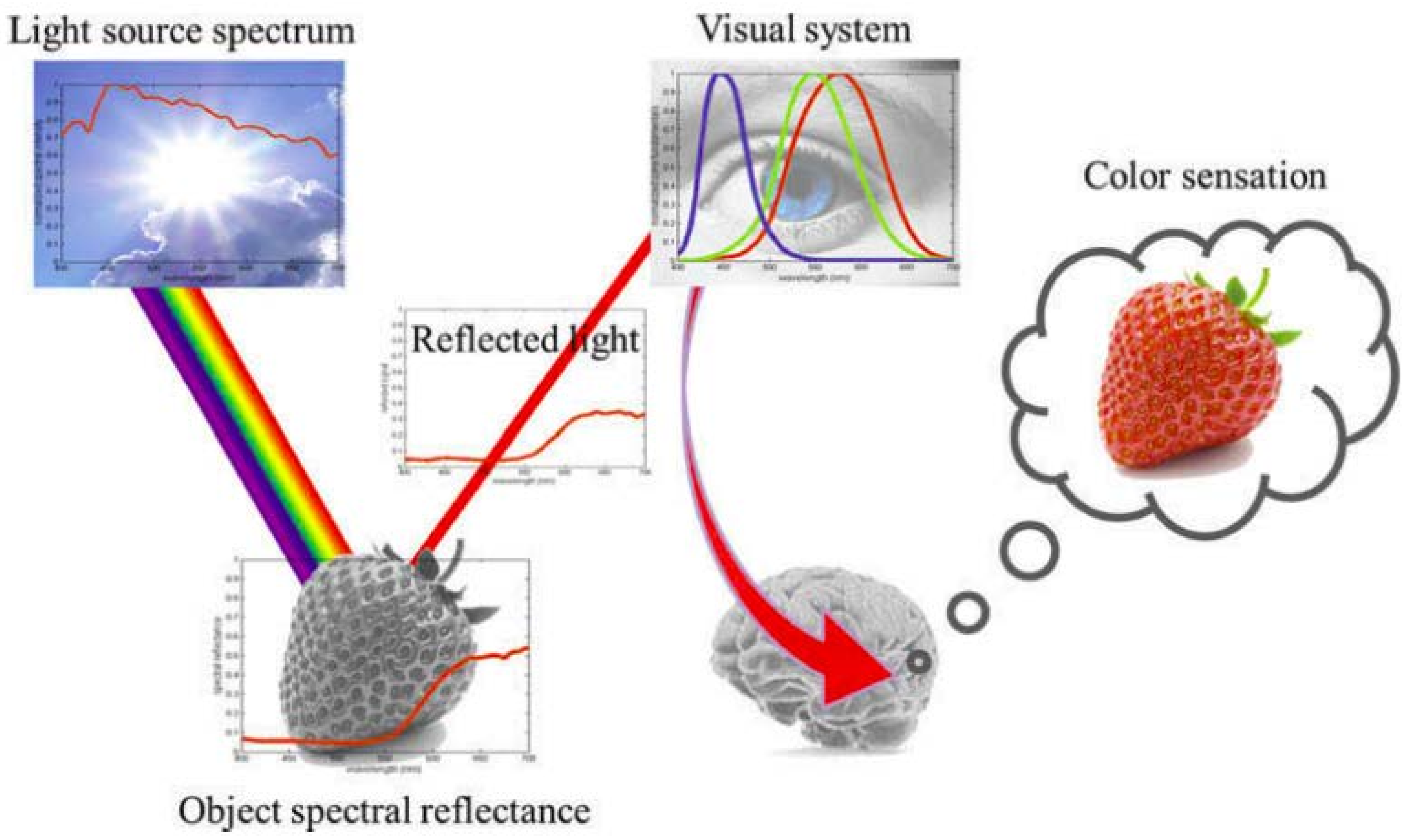
How and Why We Perceive Object Color

Most agree daylight shows true color…

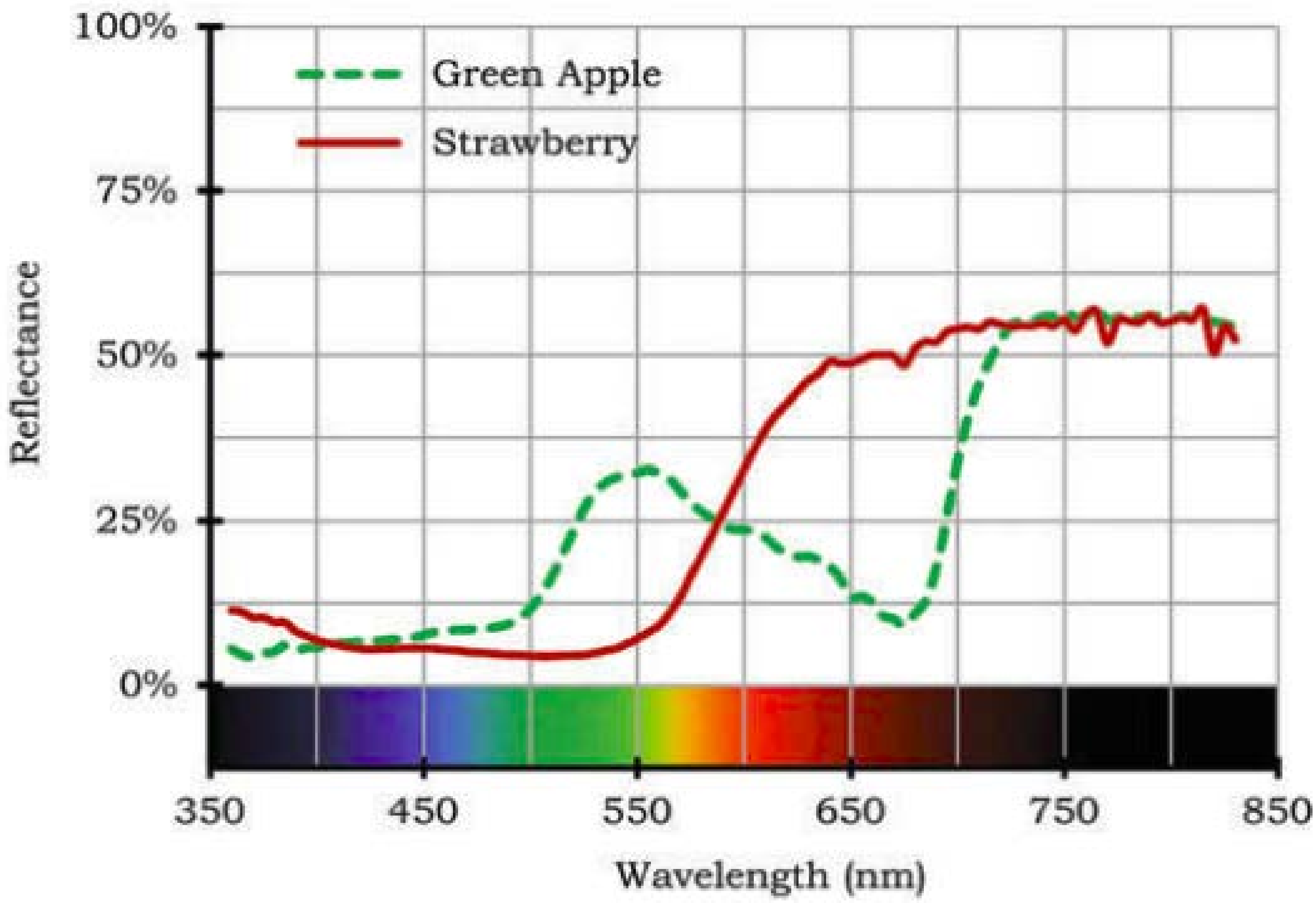
…and this is usually good for natural objects.

“Acceptable” error ?

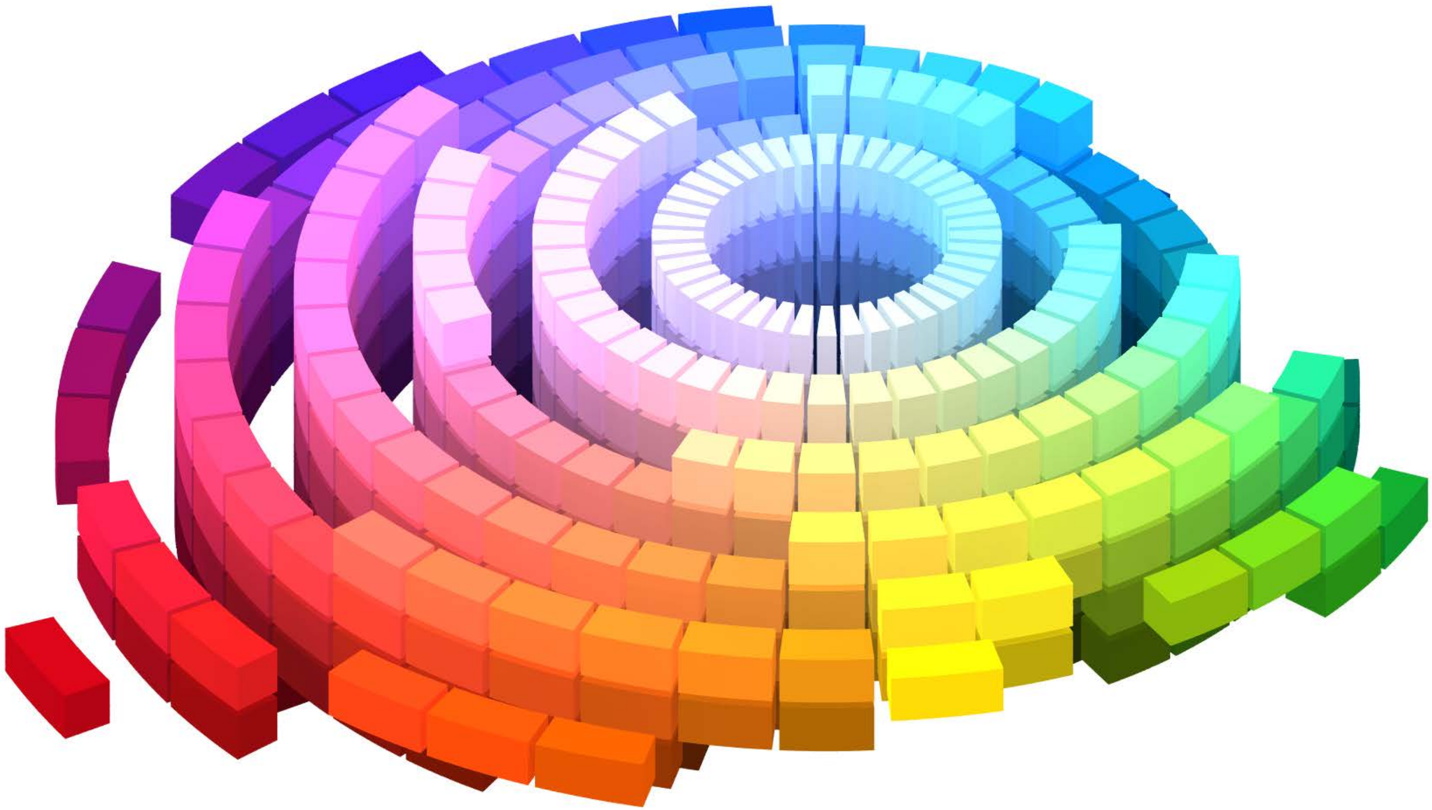
How and Why We Perceive Object Color



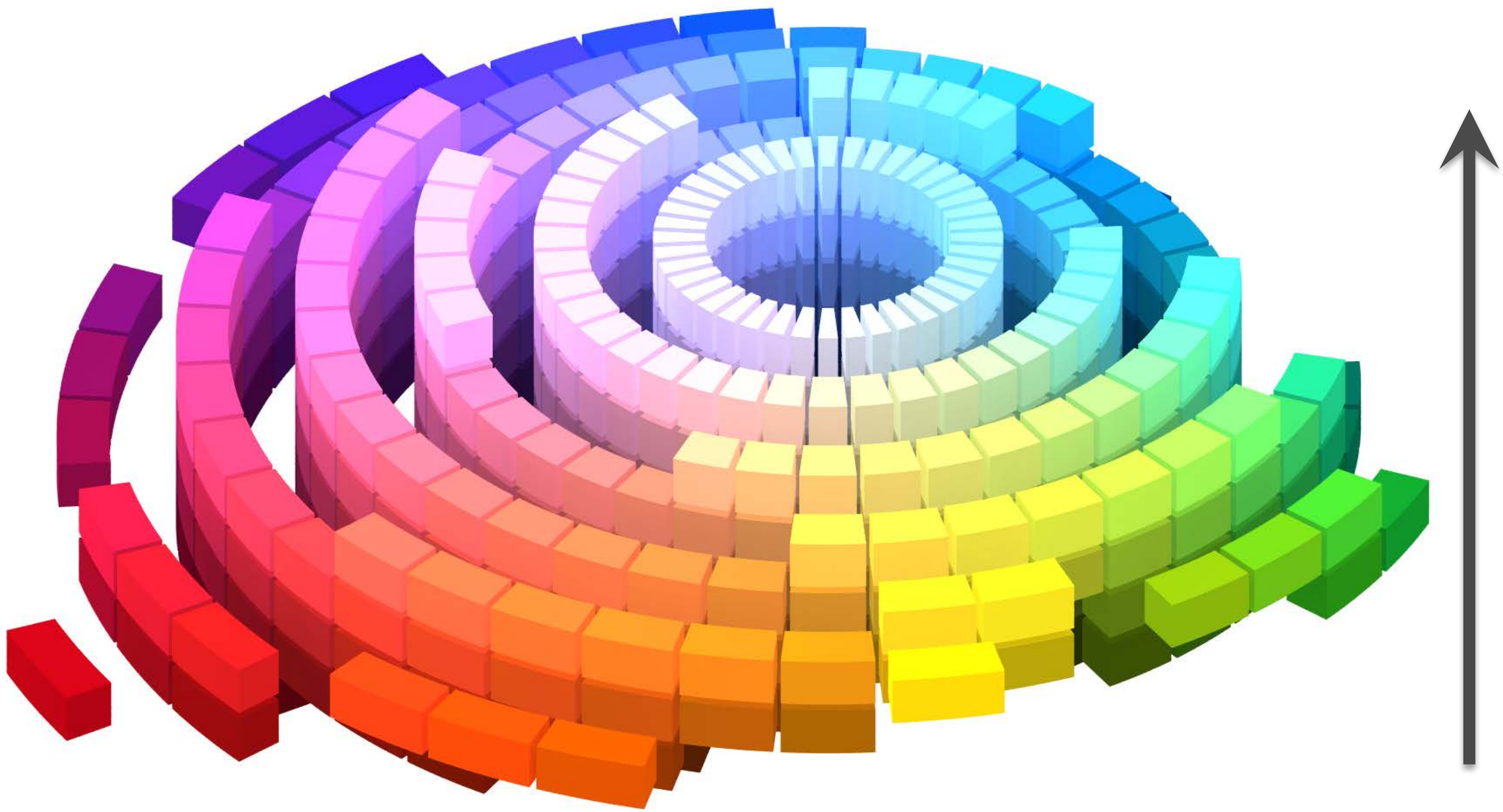
Spectral reflectance functions tell us about the molecules within objects, which is helpful.



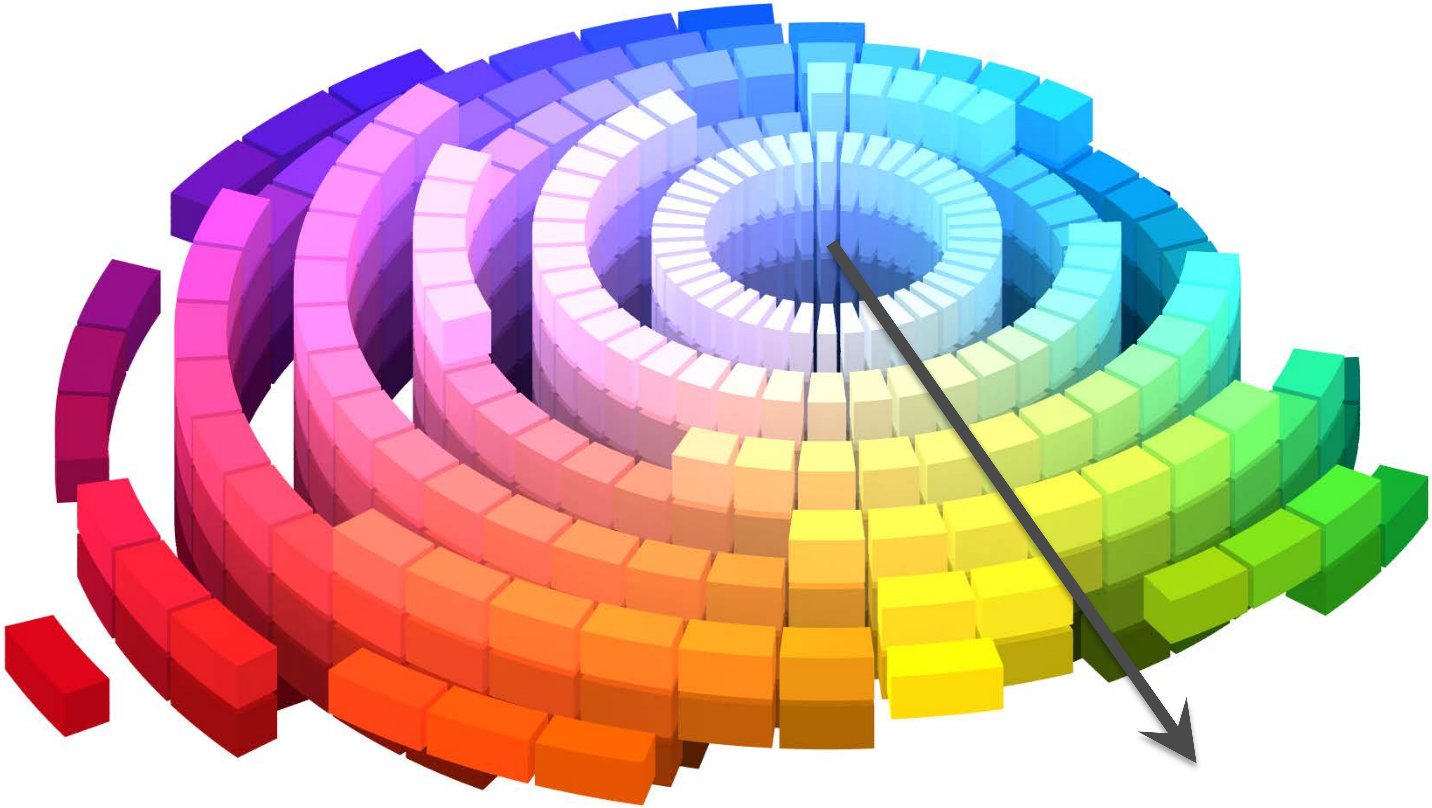
Organization Schemes for Object Colors



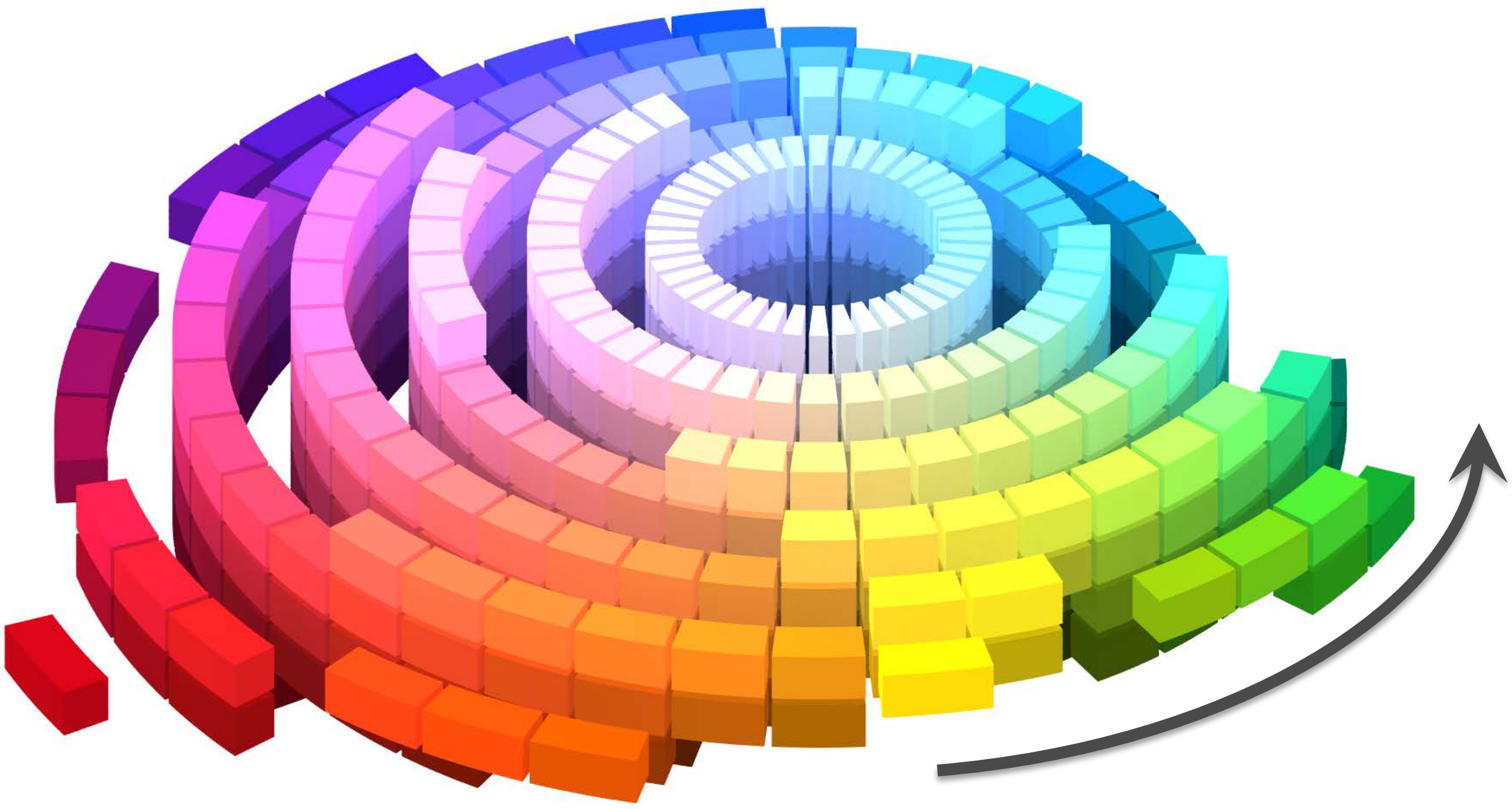
Lightness: The attribute by which a perceived color is judged to be closer to white than black.



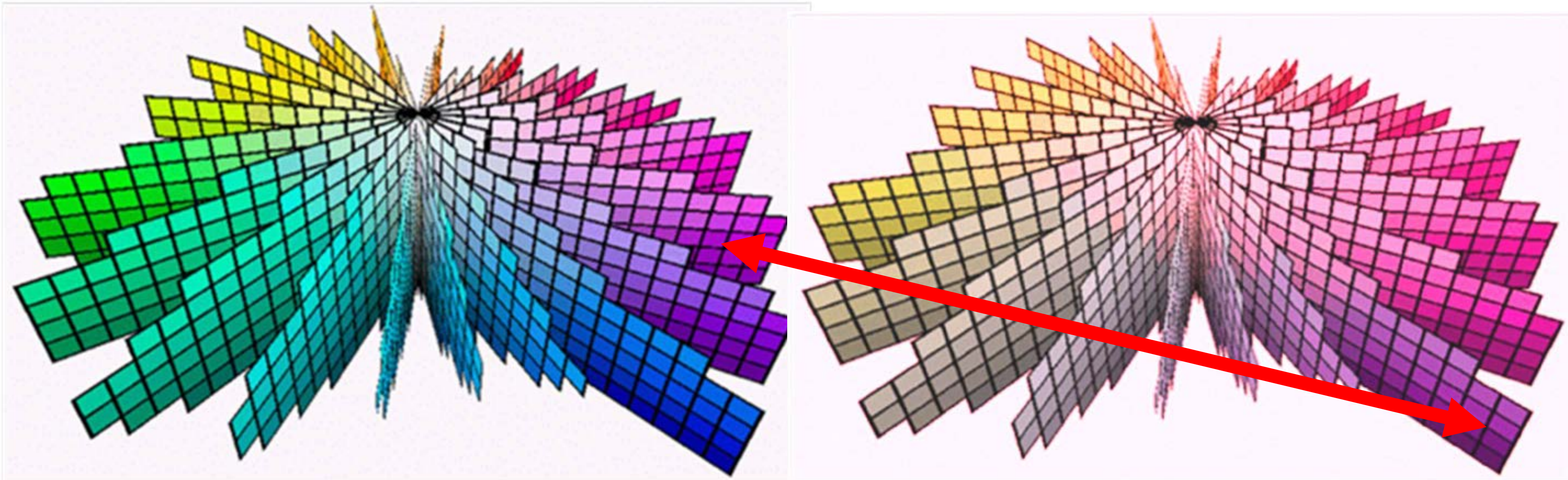
Saturation or Chroma: degree of departure from a gray of equal lightness (or neutral gray).



Hue: The perception of relative redness, blueness, greenness, or yellowness of a stimulus.



Reference Illuminant *Test Source*



It’s straightforward to predict the color shift for a color sample, but there are millions of samples, and each shifts differently.

Required – a metric producing ***useful summary information***.

We must accurately:
Calculate it, communicate it, specify it, and achieve it.

Today's Topics

1. **A Brief Review of CIE CRI**
2. **Use of Up-to-date Color Space**

   [Questions]

3. **Development of the TM-30-15 Color Evaluation Samples**
4. **Reference Illuminants**

   [Questions]

5. **TM-30-15 Calculation Procedure and Outputs**

   [Questions]

For more information on the use and application of IES TM-30-15, please see the DOE/IES Webinar from 9/15/2015, available at:
http://energy.gov/eere/ssl/webinar-understanding-and-applying-tm-30-15

Part 1:

A Brief Review of CIE CRI

CIE Method for Evaluating Color Rendition

For more see CIE 13.3-1995, or *[Tutorial: Color Rendering and Its Applications in Lighting]* (Houser et al. 2015).

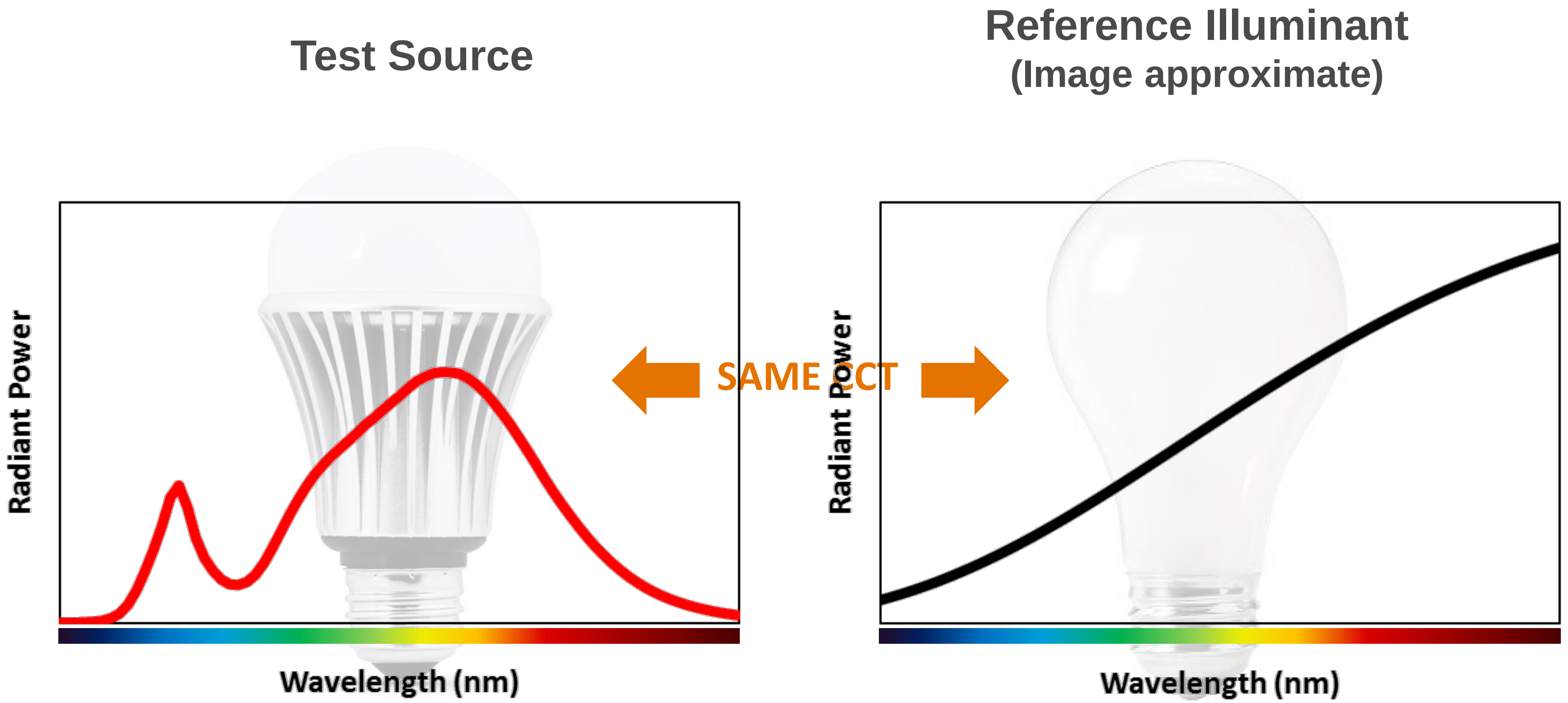
Determine the CCT of the test source.

Calculate a reference source at the same CCT

Calculate the chromaticity of color samples under the test and reference sources

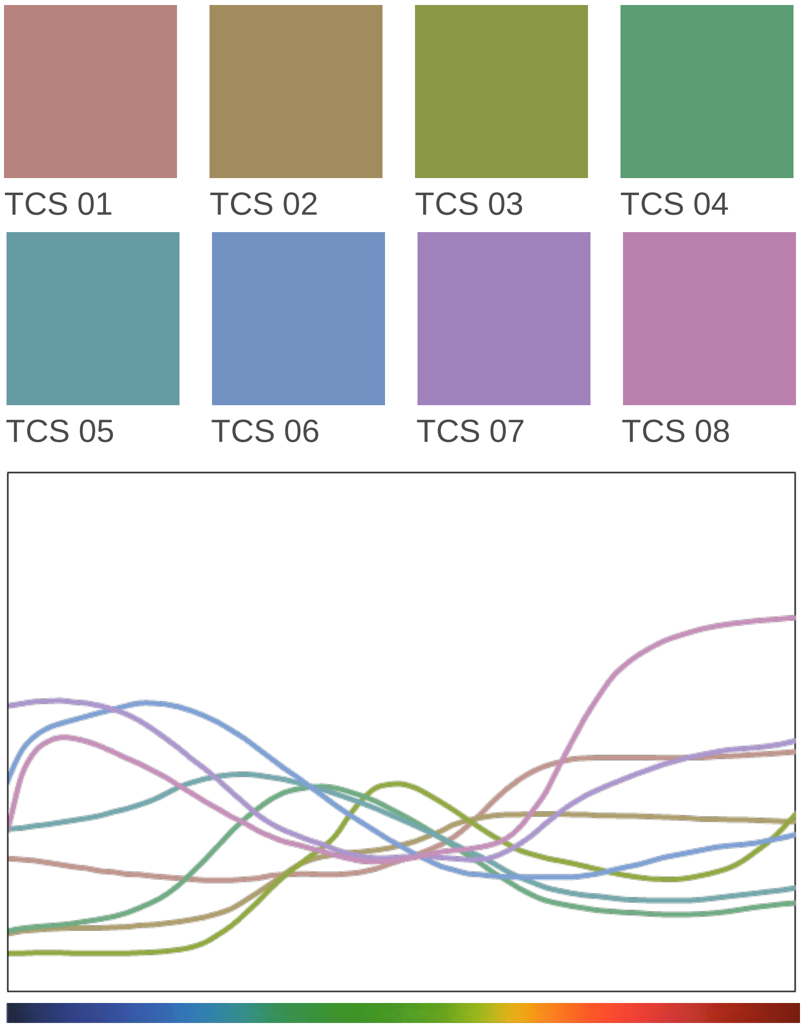
Determine the average difference in chromaticity for the two sets.

Determining CRI (Example)

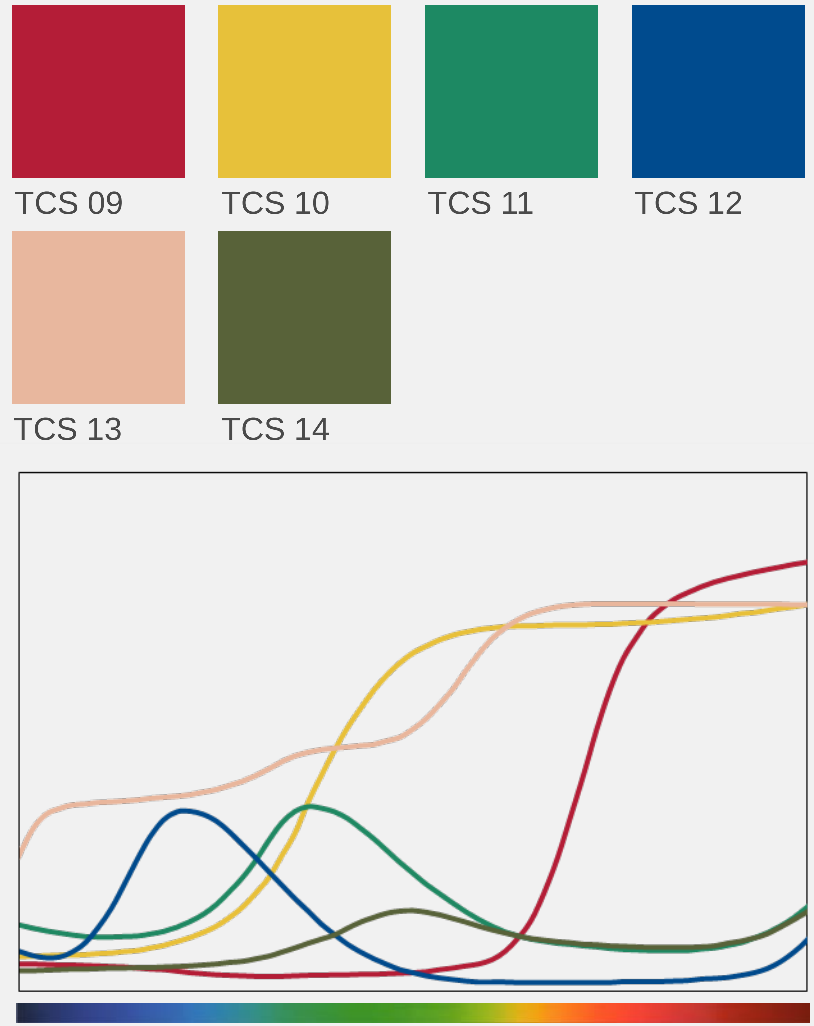


Determining CRI (Example)

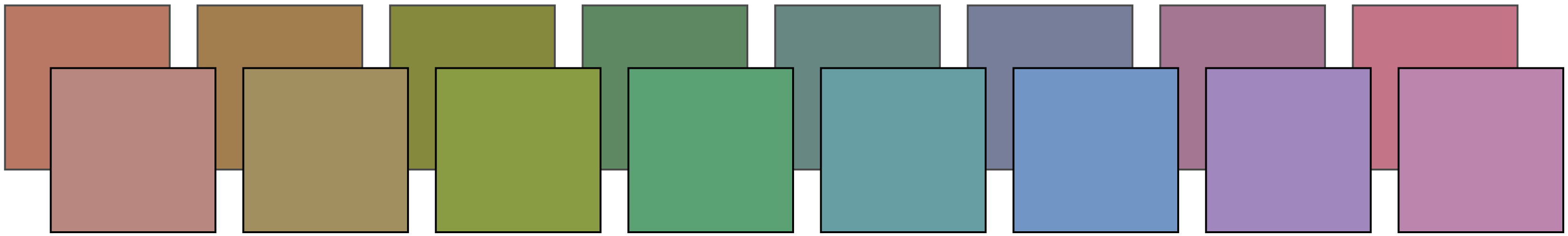
Approximation of Color Samples for R_a



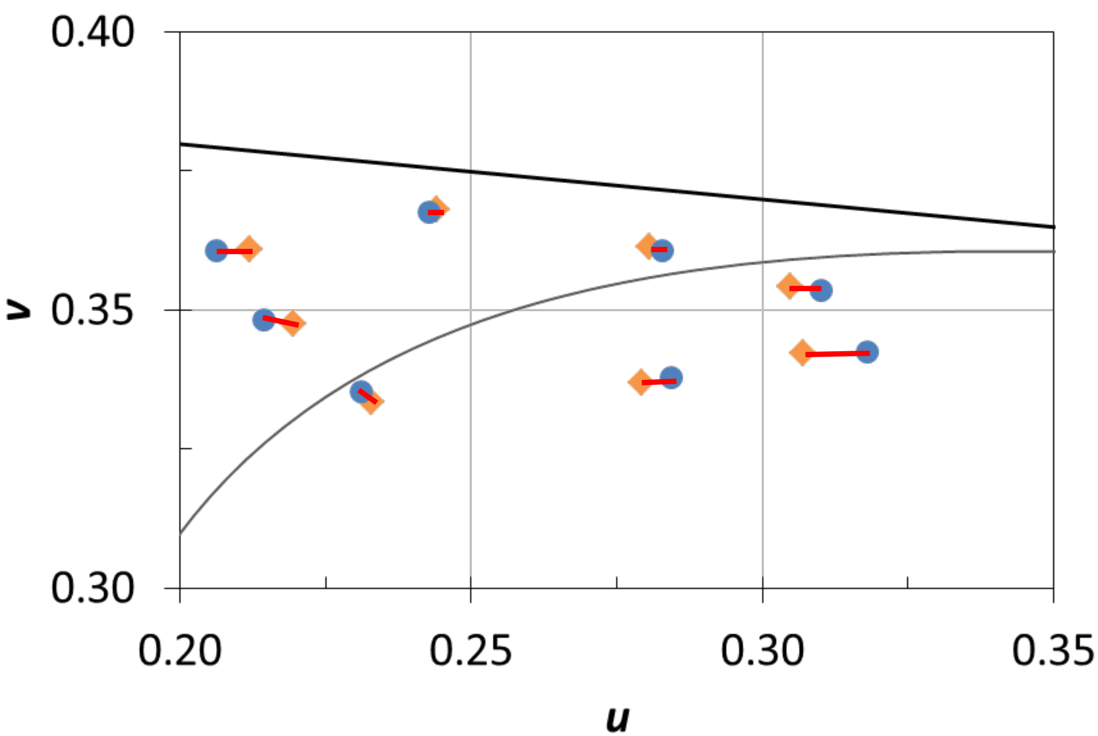
Color Samples for R_9–R_{14}



Determining CRI (Example)



(Illustration Only)



$$R_i = 100 - 4.6\mathrm{DE}_i$$

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

CIE CRI and TM-30-15

CRI Calculation Engine (1974)	TM-30 Calculation Engine (2015)
CIE 1964 U*V*W*	CAM02-UCS (CIECAM02)
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
Fidelity Metric Only	Fidelity, Gamut, Graphical, Detailed
Ref Illuminant Step Function	Ref Illuminant Continuous (Uses same reference sources, but blended between 4500 K and 5500 K)

CIE CRI Philosophical Limitations

Color Fidelity

Change in Saturation (Gamut)

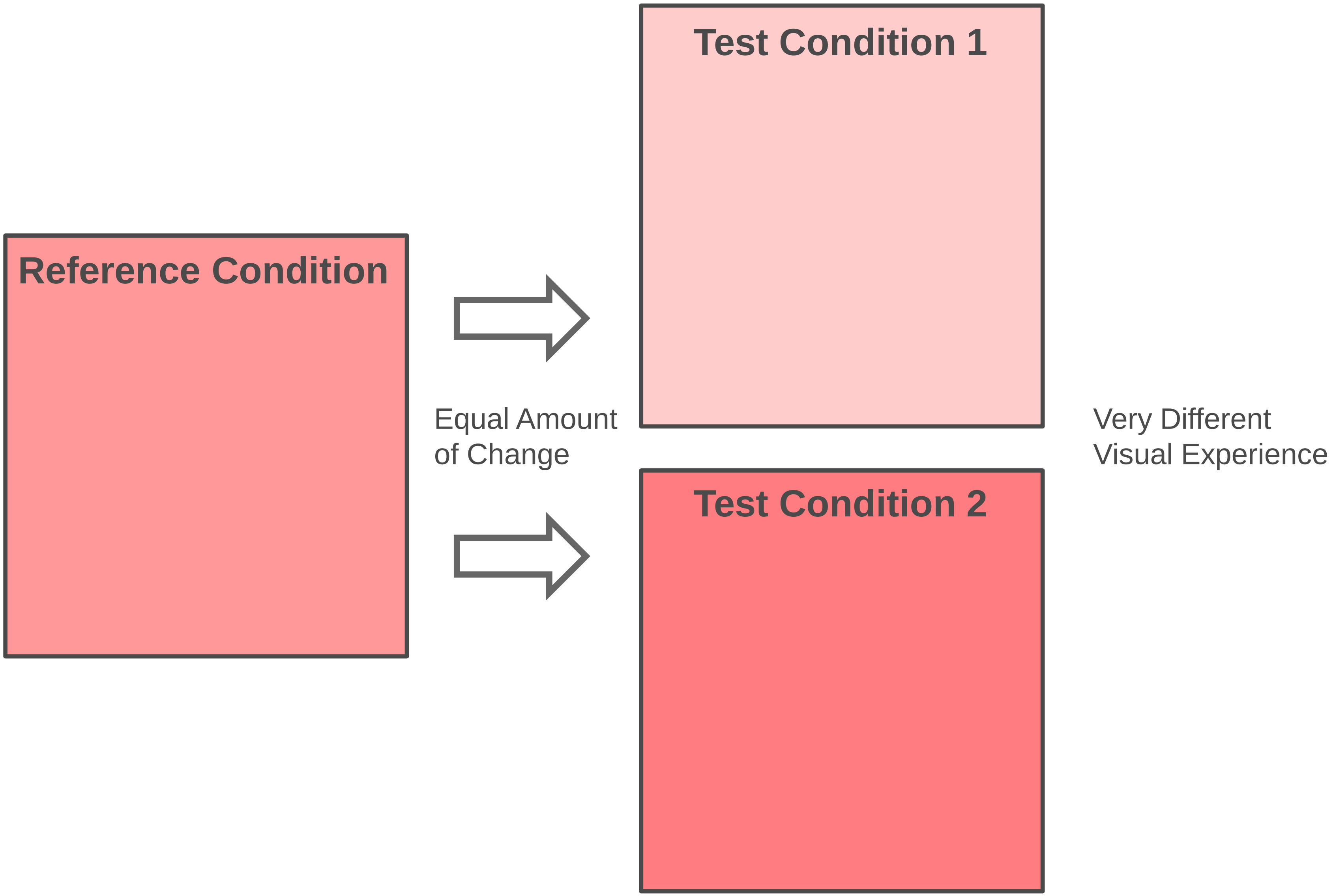
Color Preference

Color Discrimination

Hue-Specific Changes

Graphical Results

CIE CRI Philosophical Limitations



IES TM-30-15

Core Calculation Engine

Modern Color Science

New Color Samples

High Level Average Values

Fidelity Index (R_f)

Gamut Index (R_g)

Graphical Representations

Color Vector Graphic

Color Distortion Graphic

Detailed Values

Skin Fidelity ($R_{f,skin}$)

Fidelity by Hue ($R_{f,h\#}$)

Chroma Shift by Hue ($R_{g,h\#}$)

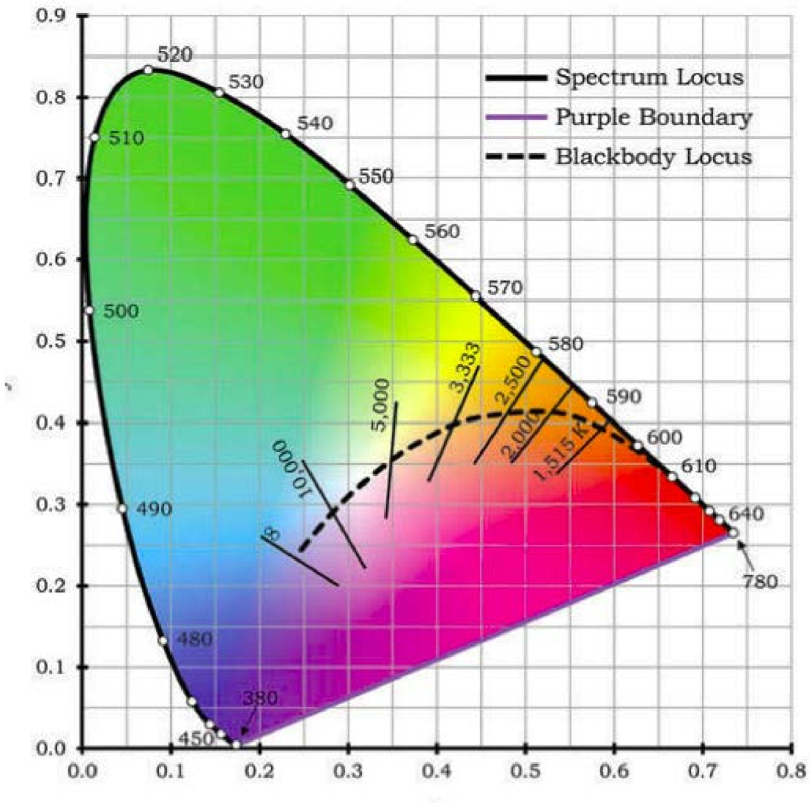
Fidelity by Sample ($R_{f,CES\#}$)

Part 2:

Use of Up-to-date Color Space

Color Space

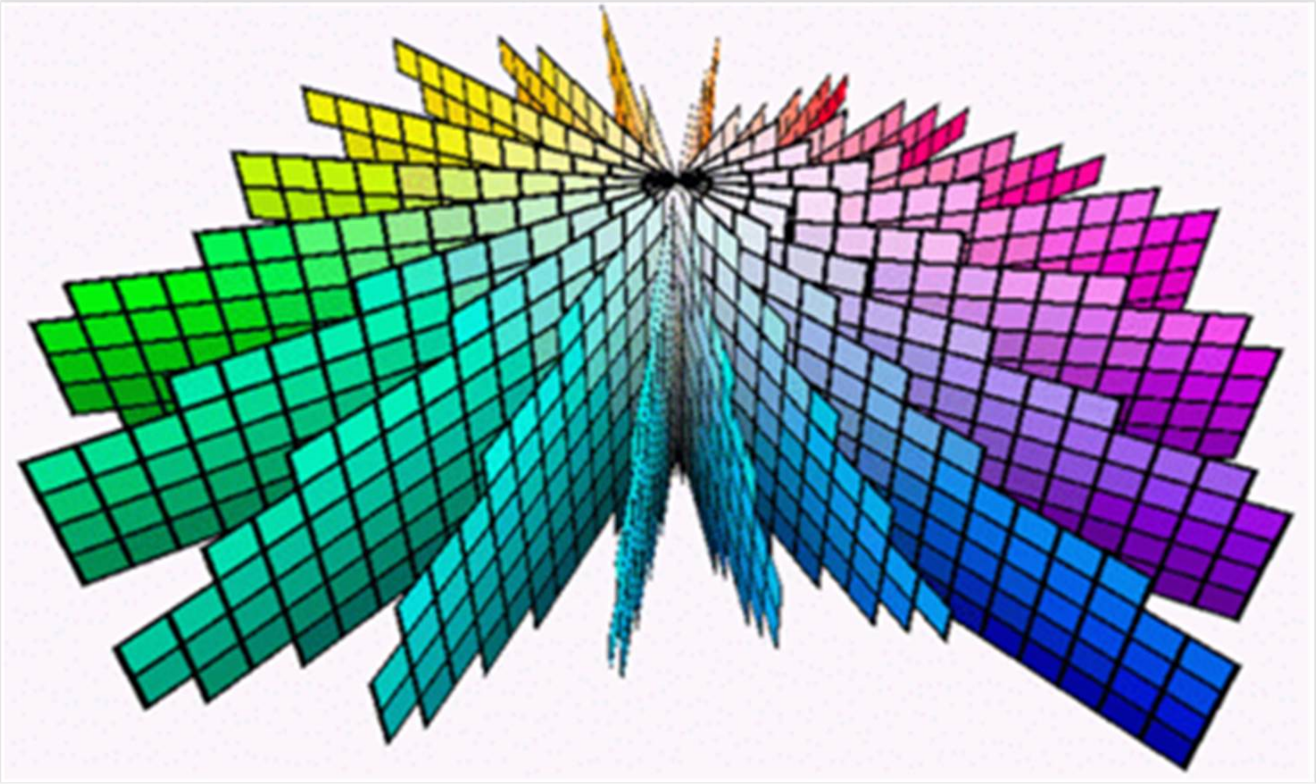
There are many mathematical color metrics.
One is the CIE xy chromaticity diagram.



It's a 2D system that can't begin to describe 3D object color.
For today, please fuhgeddaboudit ...

Color Space

The Munsell system is much more useful.



However it is difficult to compute the Munsell coordinates from the source SPD and sample spectral reflectance functions.

CAM02-UCS Introduction

CAMO2-UCS is the best solution to this so far.

It “eats” the illuminant SPD and a sample SRF
and calculates the three components of object color.

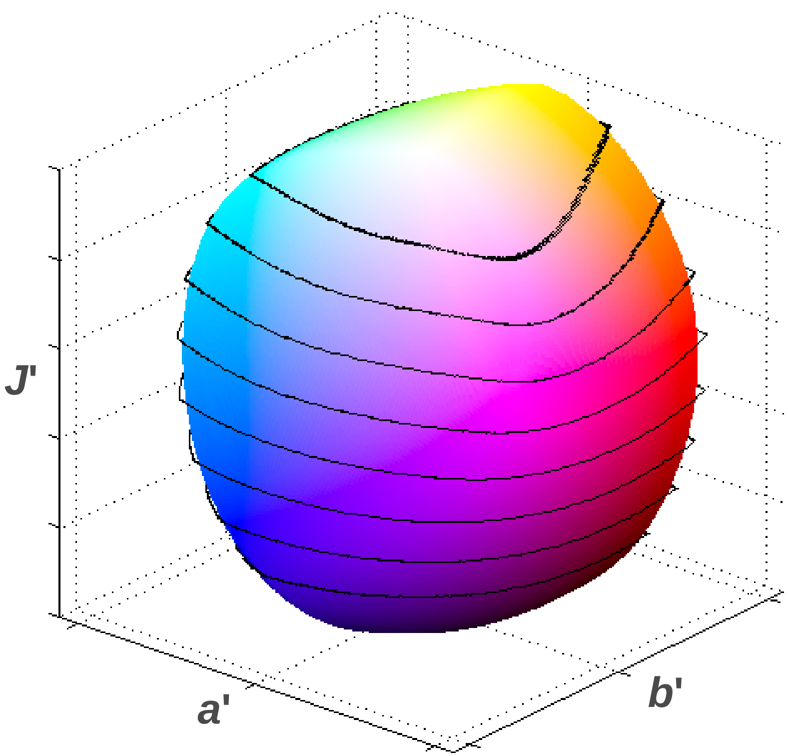
It does a good job of making distances in J',a',b' space proportional to perceived color differences, and actually corresponds to the Munsell system fairly well.

It is a complicated “looking” set of formulas, but it is a straightforward, practical computation and it is sufficiently accurate for the calculation of color differences.

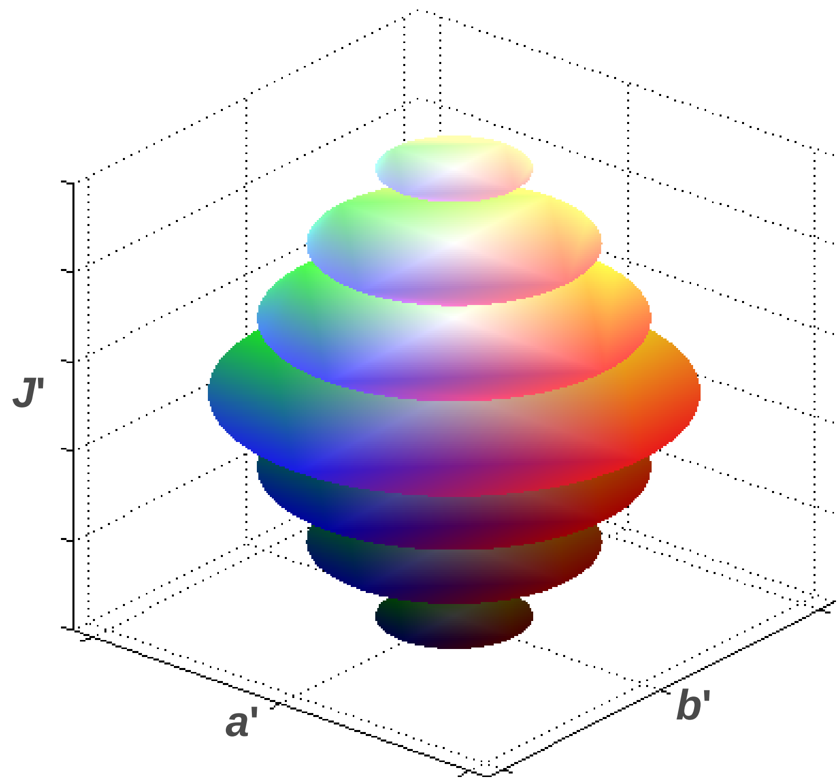
CAM02-UCS Desirable Properties

The color volume has a **regular shape** in CAM02-UCS

Color volume in CAM02-UCS
(all the colors our vision system can see)

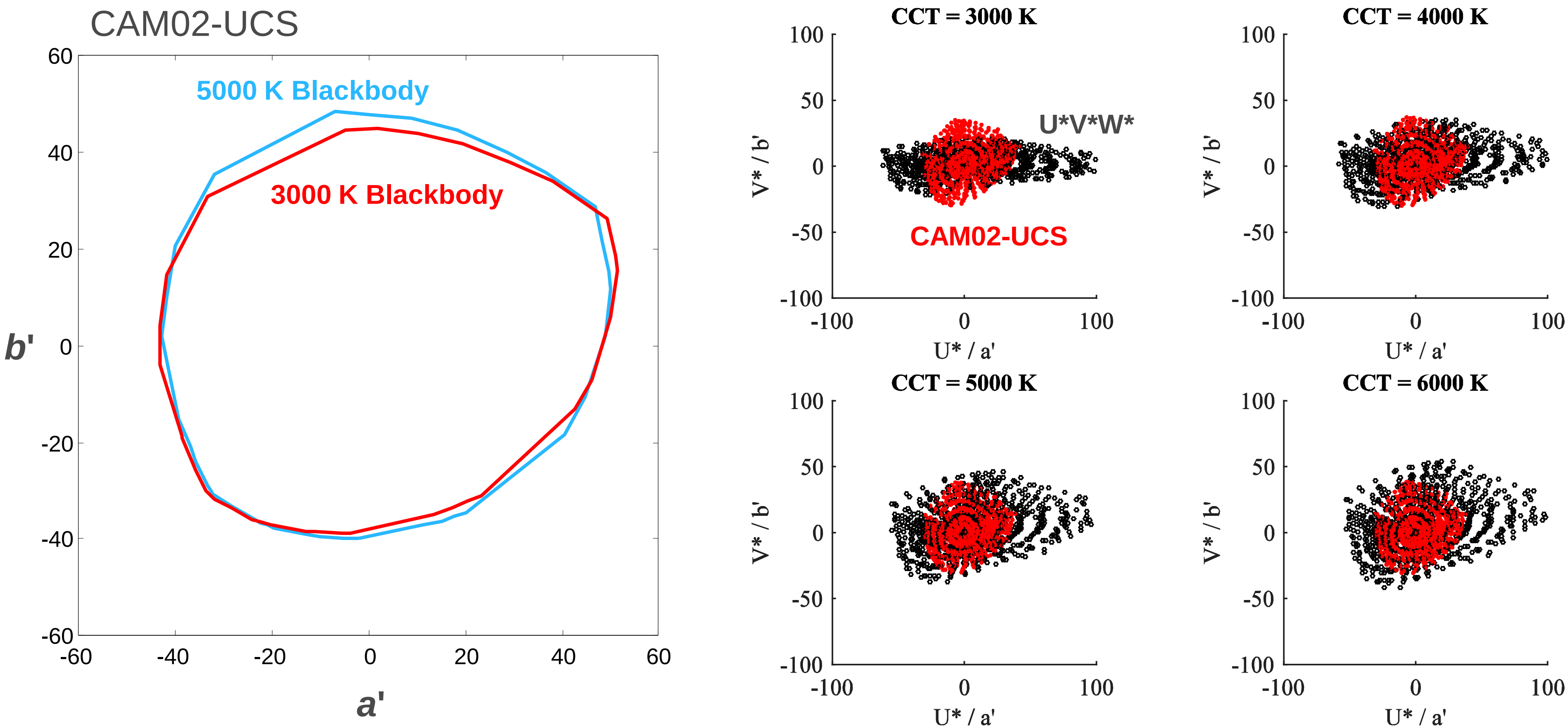


“slices” in the color volume (sketch!)



CAM02-UCS Desirable Properties

Color volume is stable at all CCTs
i.e. the colors of objects are approximately the same at all CCTs: reasonable!



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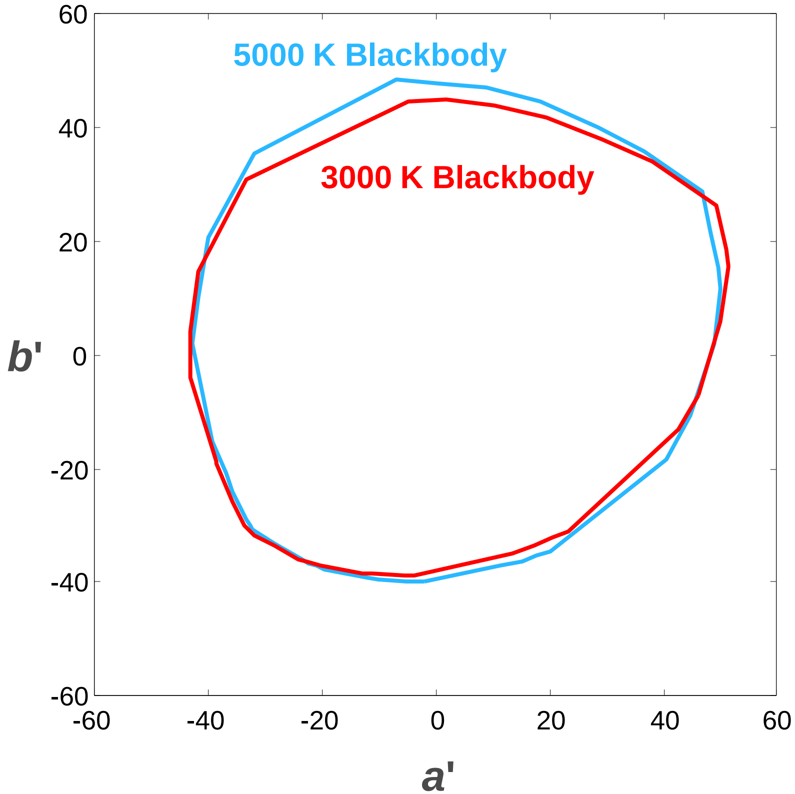
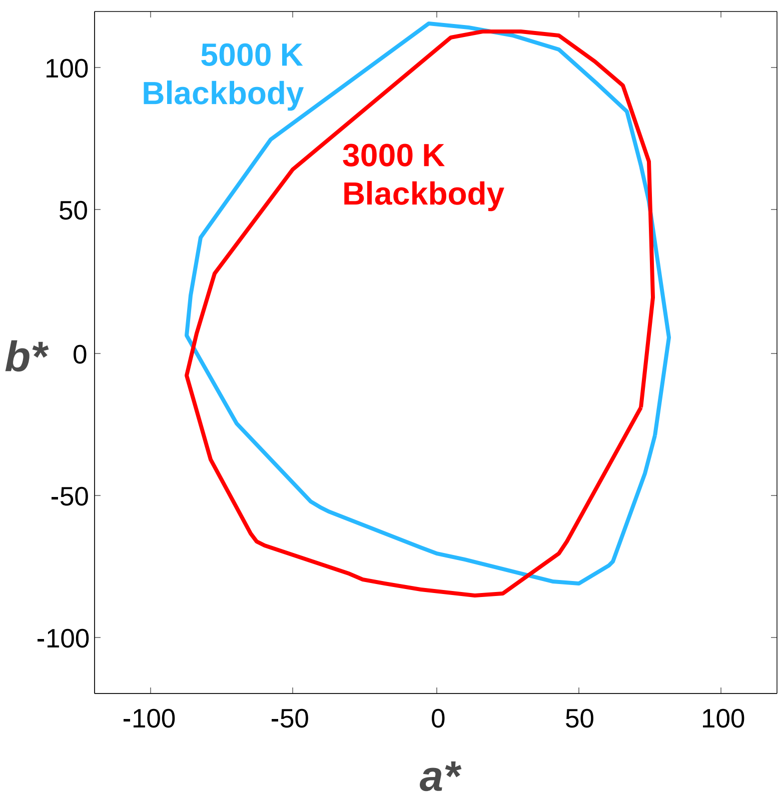
CAM02-UCS



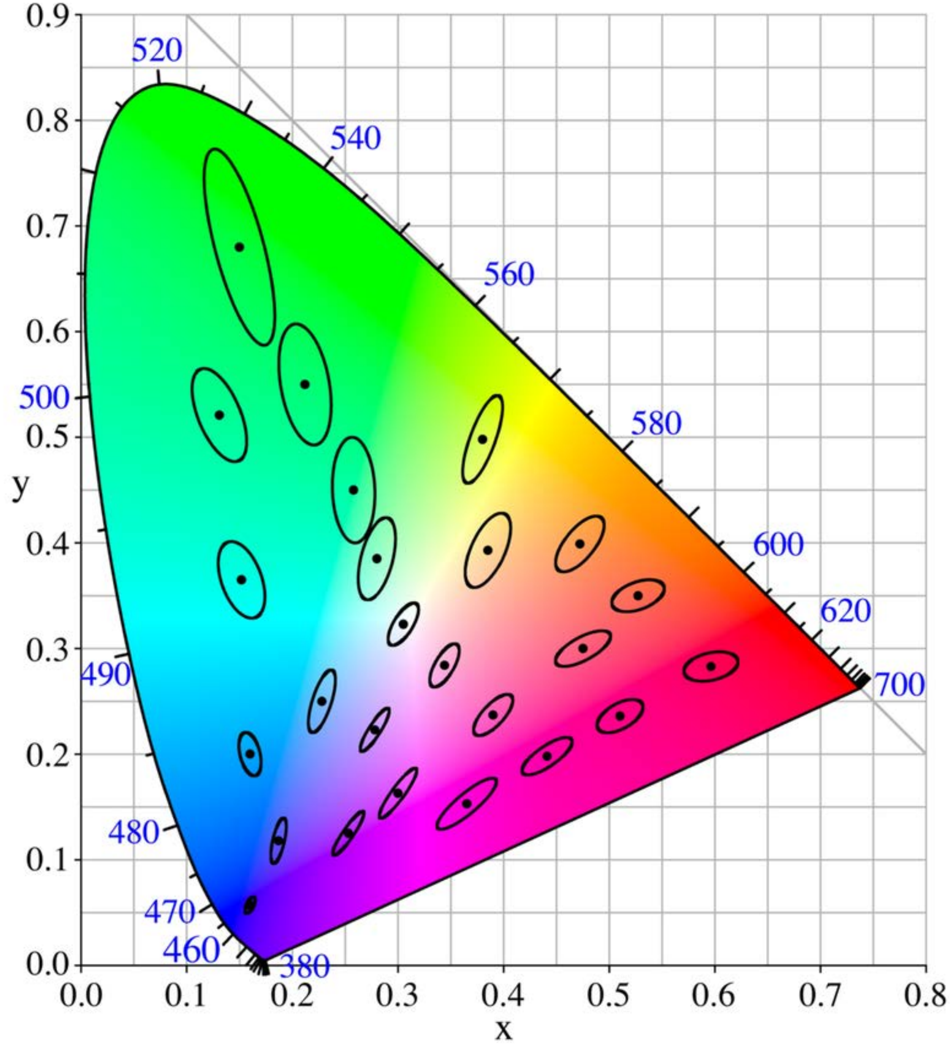
CIELAB



CAM02-UCS Desirable Properties

Color uniformity

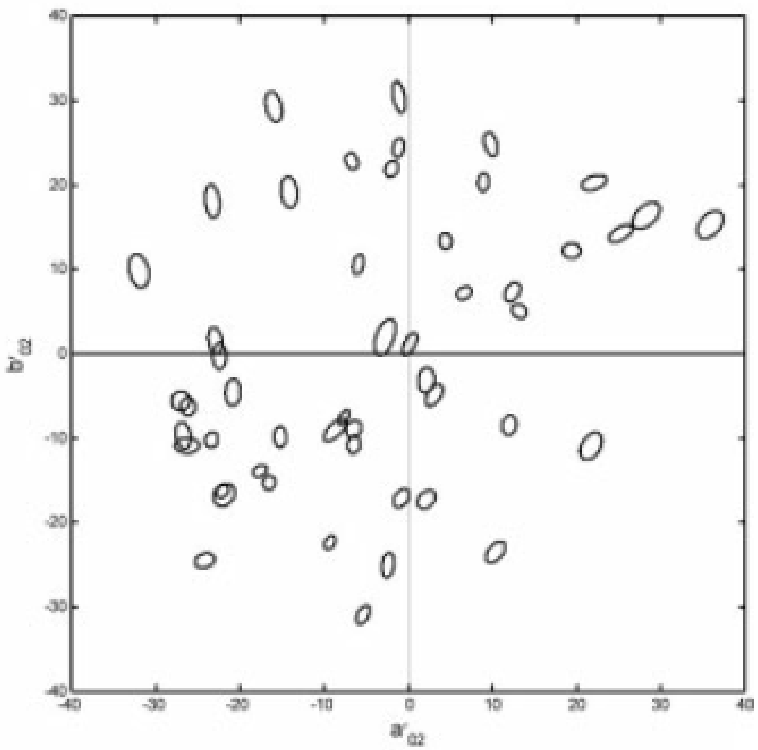
MacAdam ellipses should all be circular, have the same size…



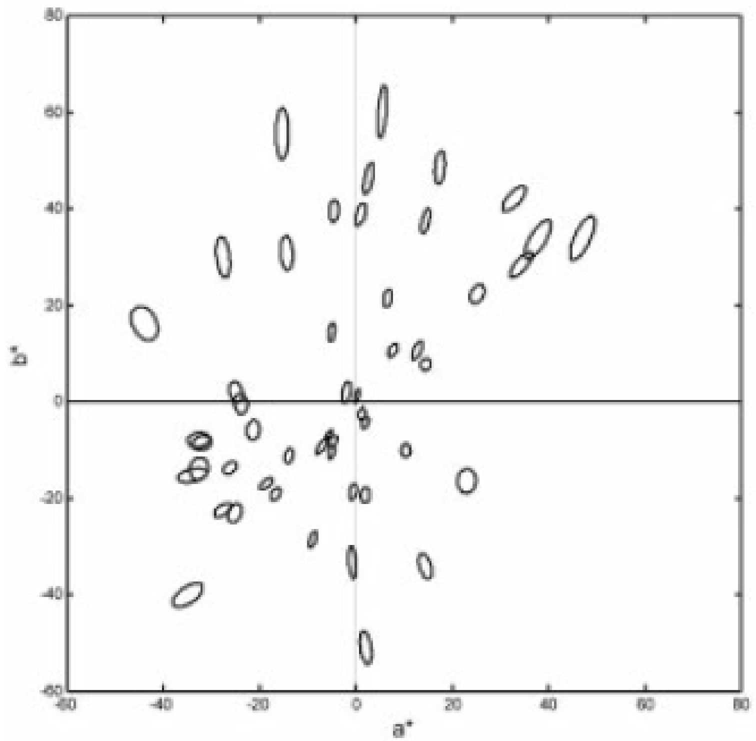
CAM02-UCS Desirable Properties

Color uniformity is very good – color shifts for various colors are equally scaled.

CAM02-UCS



CIELAB



“Uniform Colour Spaces Based on CIECAM02 Colour Appearance Model”, Luo et al. CRA 2006

Questions?

Part 3:

Development of the IES TM-30-15 Color Evaluation Samples (CES)

Test Samples

Test samples are a contentious issue!

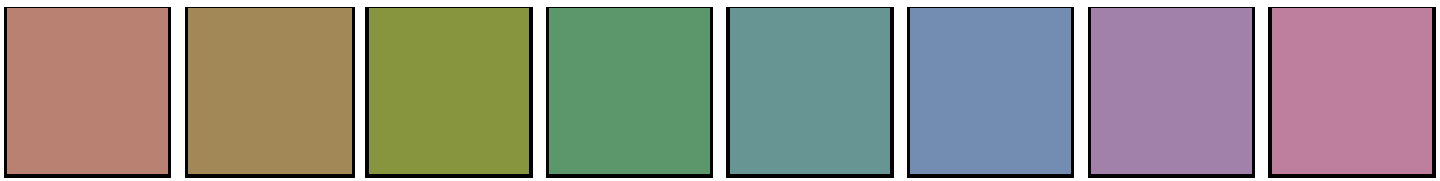
CRI: 8 samples (+6)
Other methods (CQS, nCRI) ~ 15-20 samples

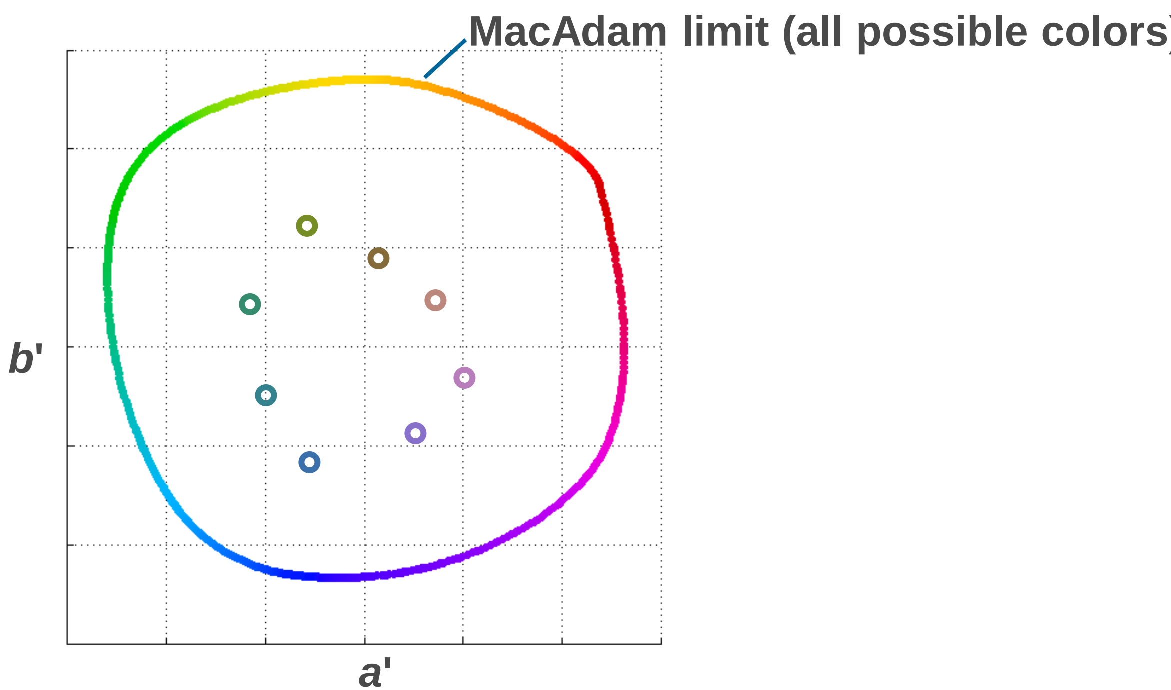
Desirable properties considered in TM-30:

- Use only real, measured samples
- Use samples from a variety of objects
- Use a variety of colors, including saturated samples
- Treat all wavelengths of light equally (no bias)
- Use enough samples for high accuracy, but not too many

Test Samples – Distribution in Color Space

CRI TCS only correspond to a few unsaturated colors, unrepresentative of the variety of colors in a real environment. The absence of saturated samples (especially deep red) is a common complaint.

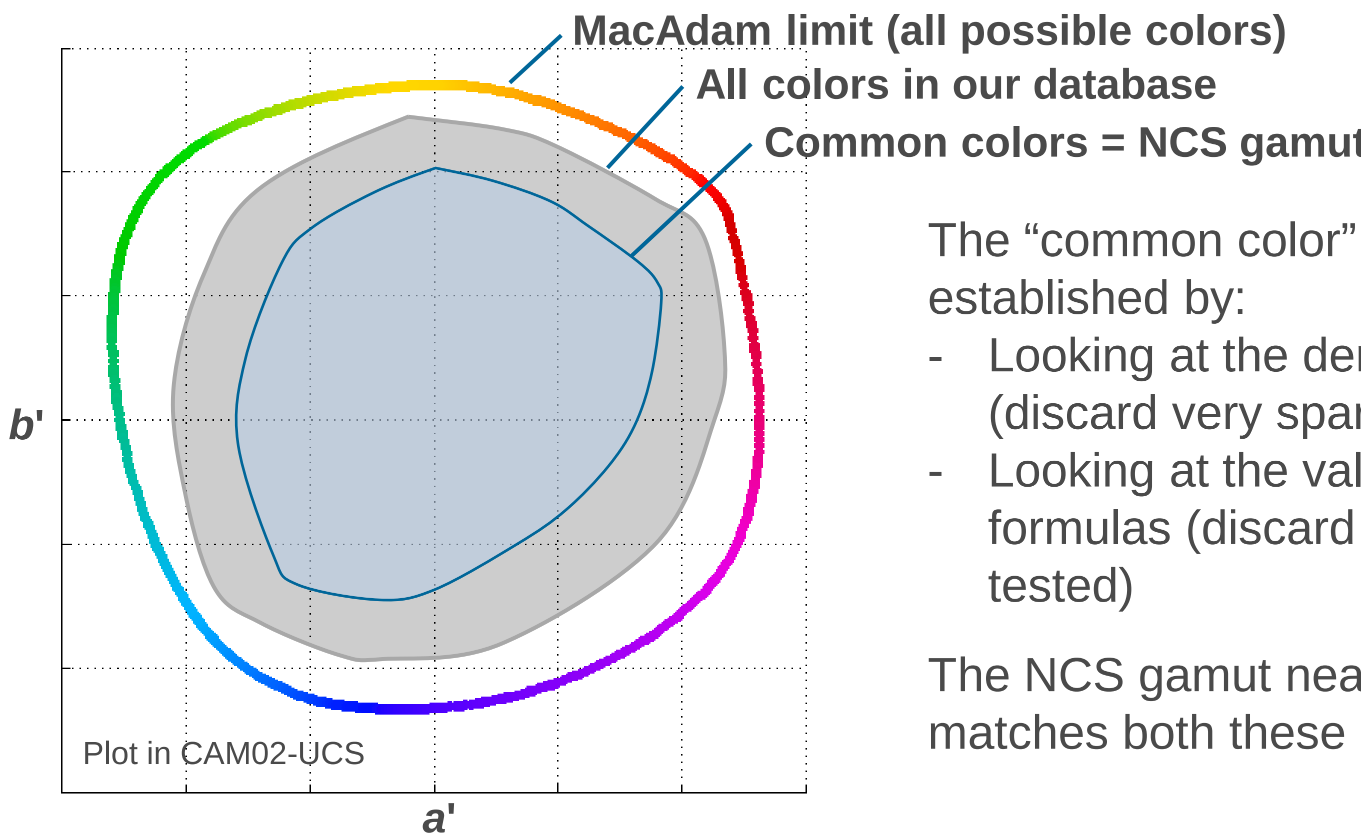




Test Samples – Distribution in Color Space

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

1) Gather a large database of samples (~100,000)
2) Define a gamut of "common colors", keep samples within



The "common color" gamut is established by:

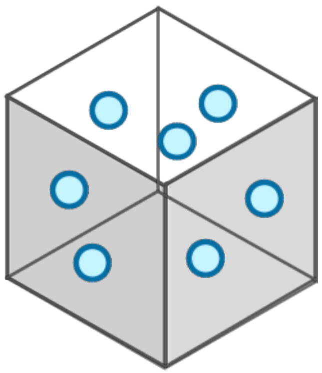
- Looking at the density of samples (discard very sparse regions)
- Looking at the validity of color error formulas (discard areas where not tested)

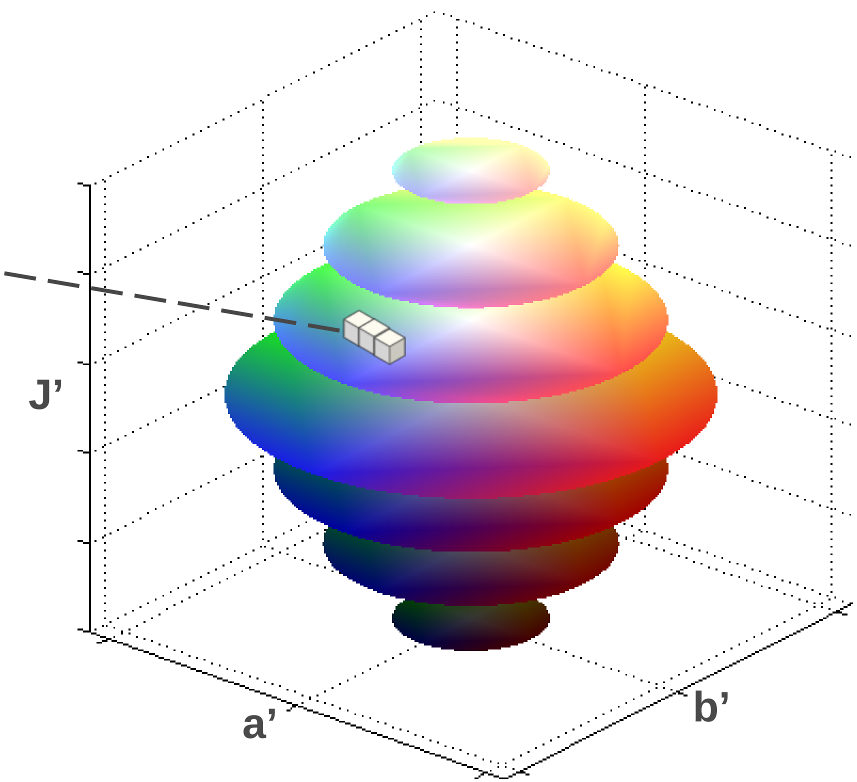
The NCS gamut nearly perfectly matches both these conditions.

Test Samples – Distribution in Color Space

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

→ “one sample per color”



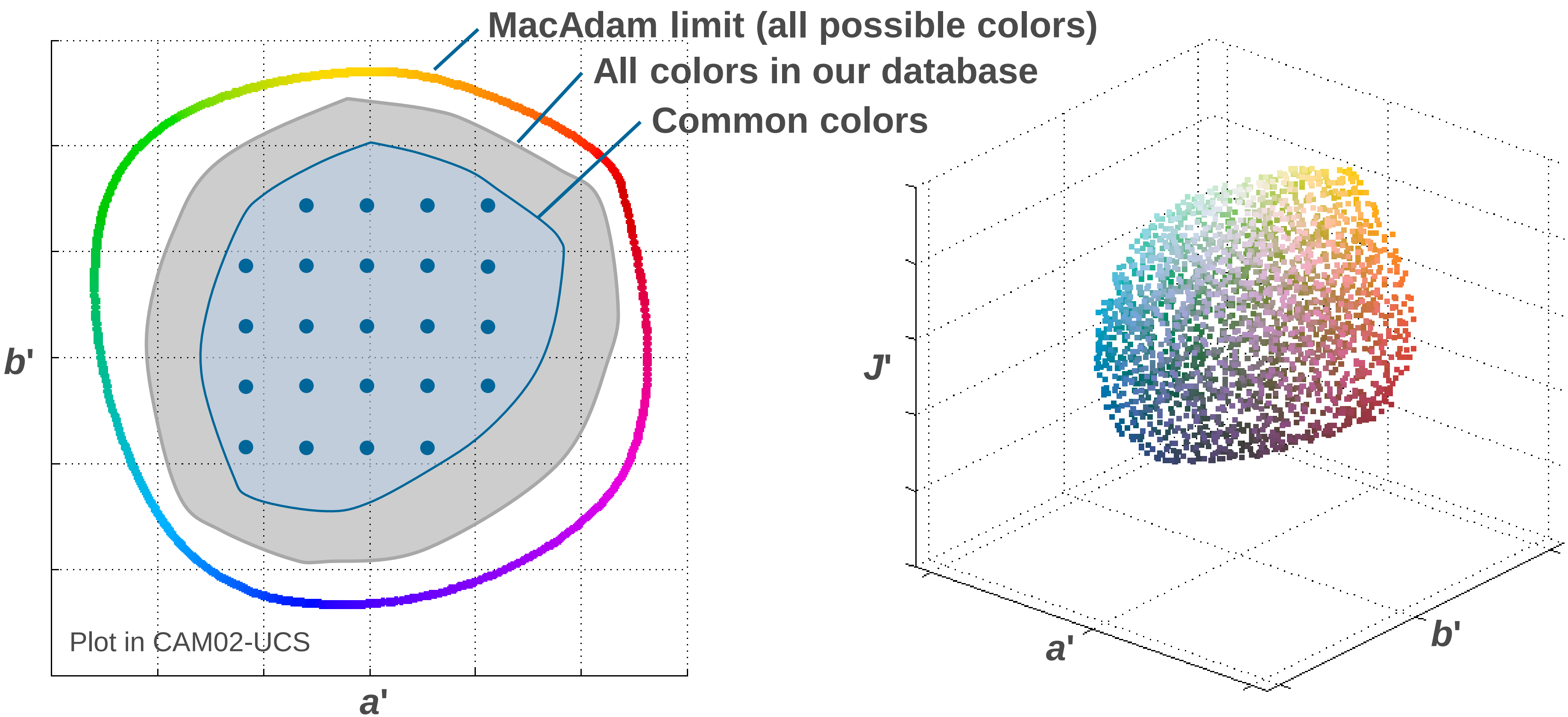


We keep one sample per pixel
Argument: 1 pixel = 1 color

Test Samples – Distribution in Color Space

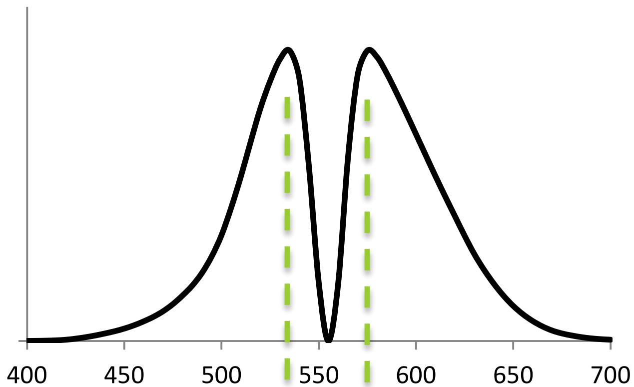
TM-30: select a gamut of “common colors” in color space and span it uniformly.

→ “one sample per color”

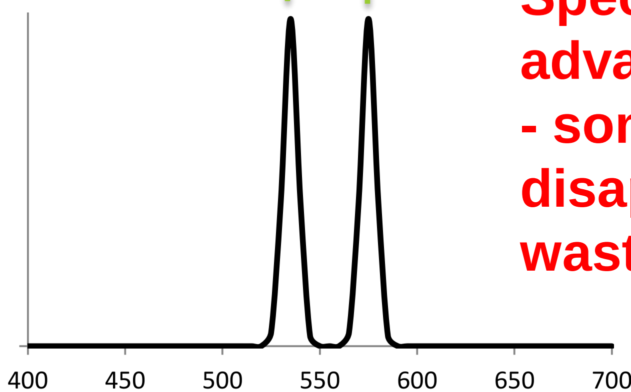


Test Samples – Wavelength Uniformity

Suppose a measurement error had distorted *V*λ but no one knew:



With the advent of narrow band LEDs, SPD's would trend to this:



Spectral manipulation to take advantages of errors
- sometimes called "gaming" - disappoints consumers and wastes energy.

Test Samples – Wavelength Uniformity

With the CRI there actually is a similar, but more subtle problem, and it definitely creates errors and thus wastes energy:

The CRI R_a function responds to sharp spectral features, and the sensitivity with which it does so depends on wavelength.

Ideally this wavelength dependence should arise only from the response functions of the human visual system, which vary smoothly with wavelength.

However the wavelength dependence is not smooth, because the CRI samples were not selected to achieve this.

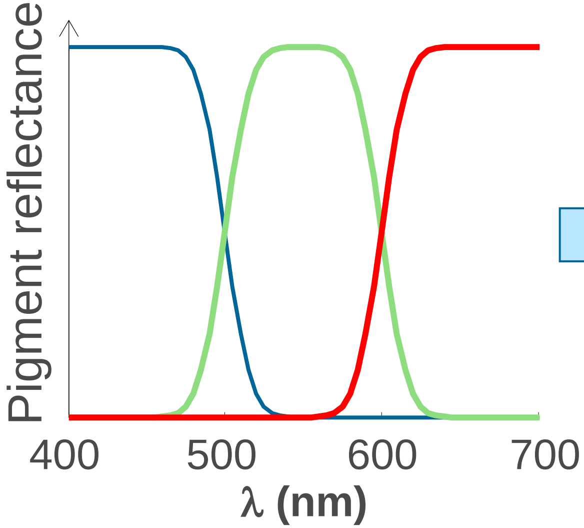
This is an understandable oversight arising from the practical challenges of the pre-computer era.

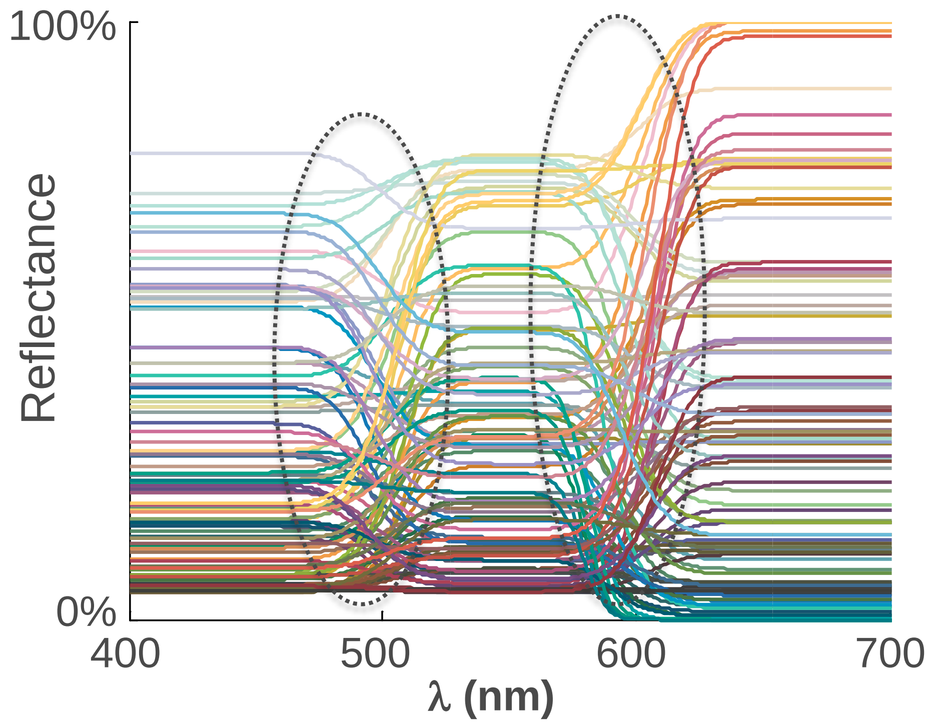
We can and must do better now, or LED “gaming” will occur.

Test Samples – Wavelength Uniformity Implementation

An extreme example of a sample set with wavelength bias…

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

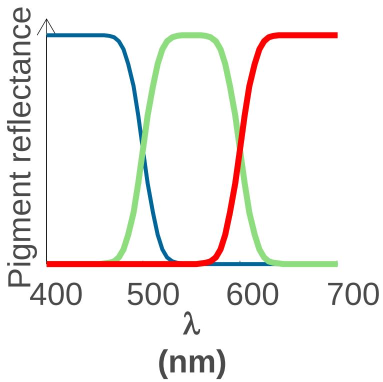


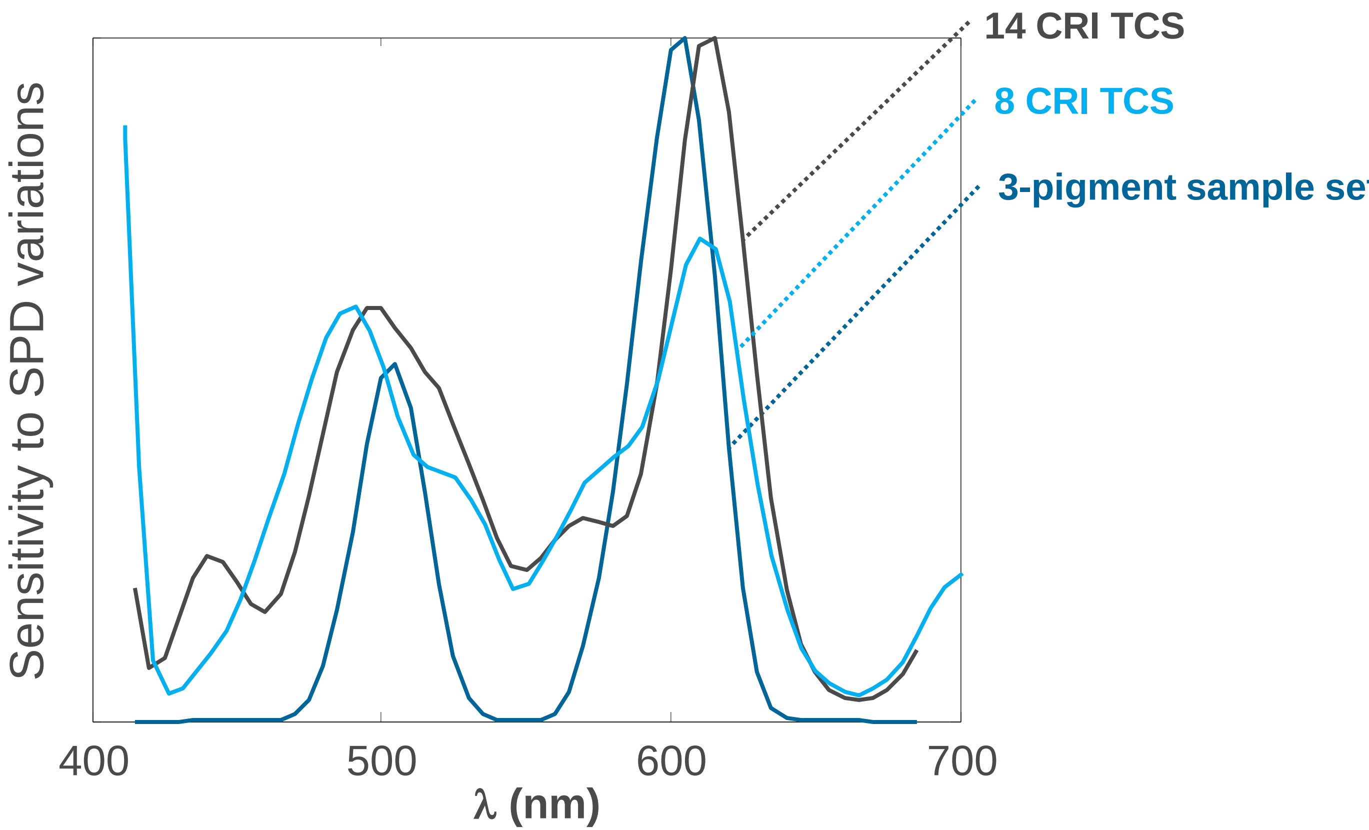


But the corresponding samples are mostly sensitive to a few wavelengths

Test Samples – Wavelength Uniformity Implementation

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





In general, sample sets suffer from some wavelength bias…

Test Samples – Wavelength Uniformity Implementation

Color shifts are caused by variations in reflectance:

→ Color shifts are controlled by the various derivatives of the test sample's reflectance: r', r''…

We can compute the "wavelength bias" for a sample set (r'^2, r''^2…)

$$F = k_1 \int \left| (r')^2 - \left\langle (r')^2 \right\rangle \right| d\lambda + k_2 \int \left| (r'')^2 - \left\langle (r'')^2 \right\rangle \right| d\lambda$$

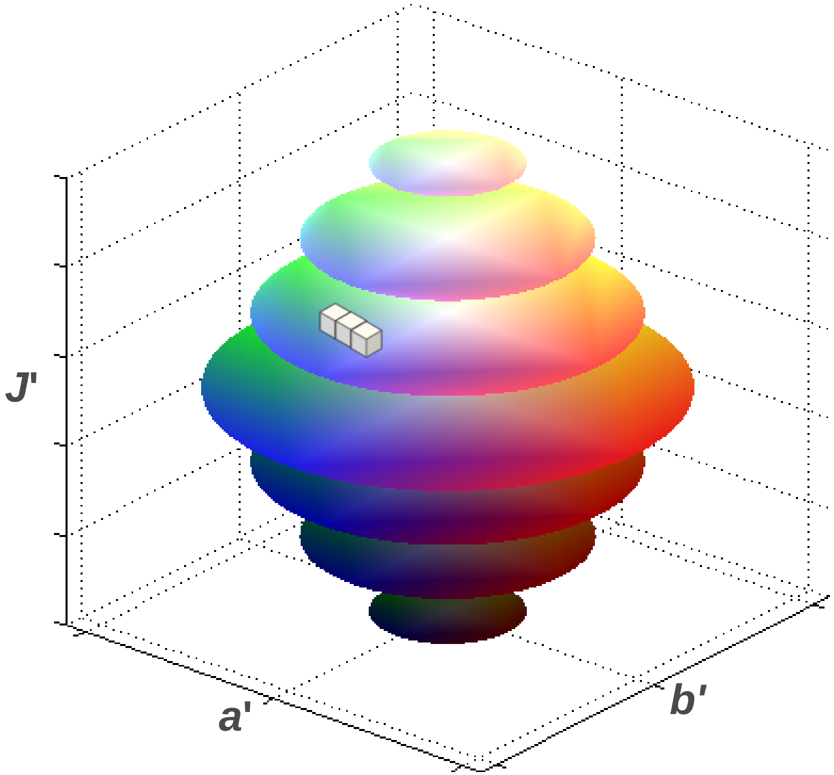
First derivative term   Second derivative term

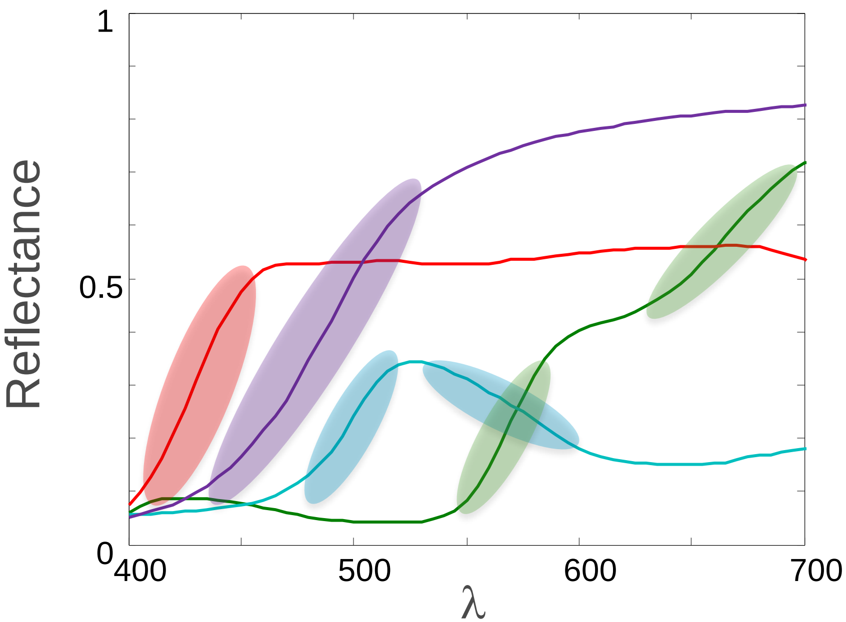
F should be minimized, e.g. the derivatives should be constant at all wavelengths when averaged over all samples

Test Samples – Wavelength Uniformity Implementation

To solve this, we select one sample per pixel **while minimizing the wavelength bias F**

→ Select samples not only based on their color but also on their **reflectance features!**

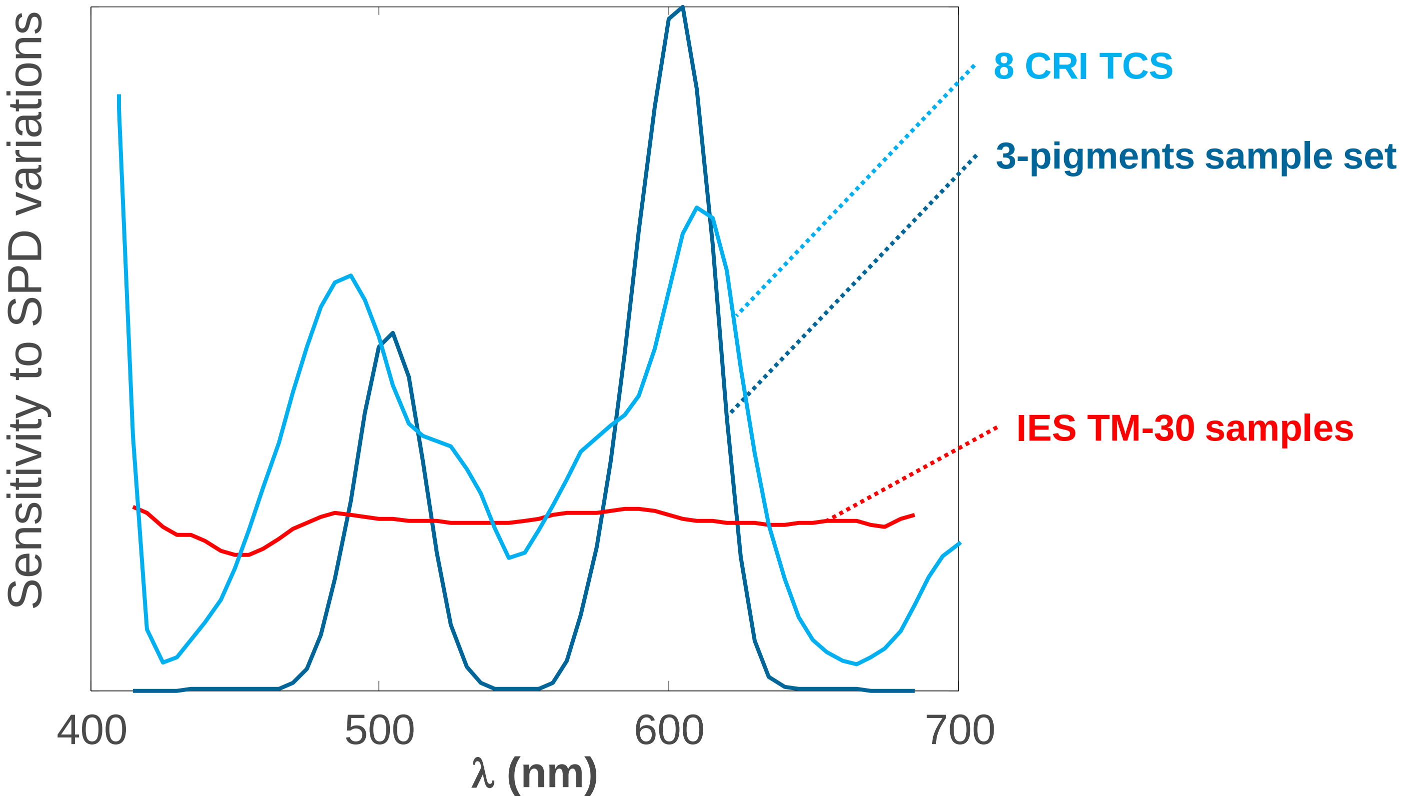




Spectral features are evenly distributed across wavelengths on average

Test Samples – Wavelength Uniformity Implementation

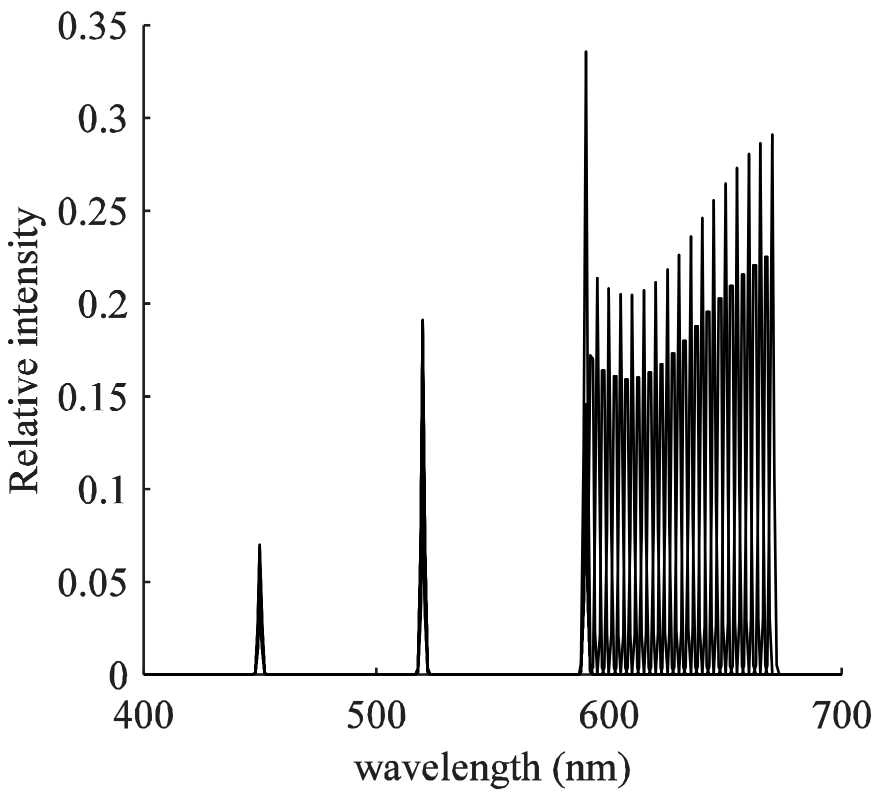
We can compute the “wavelength sensitivity” for a sample set (r'^2, r''^2…)

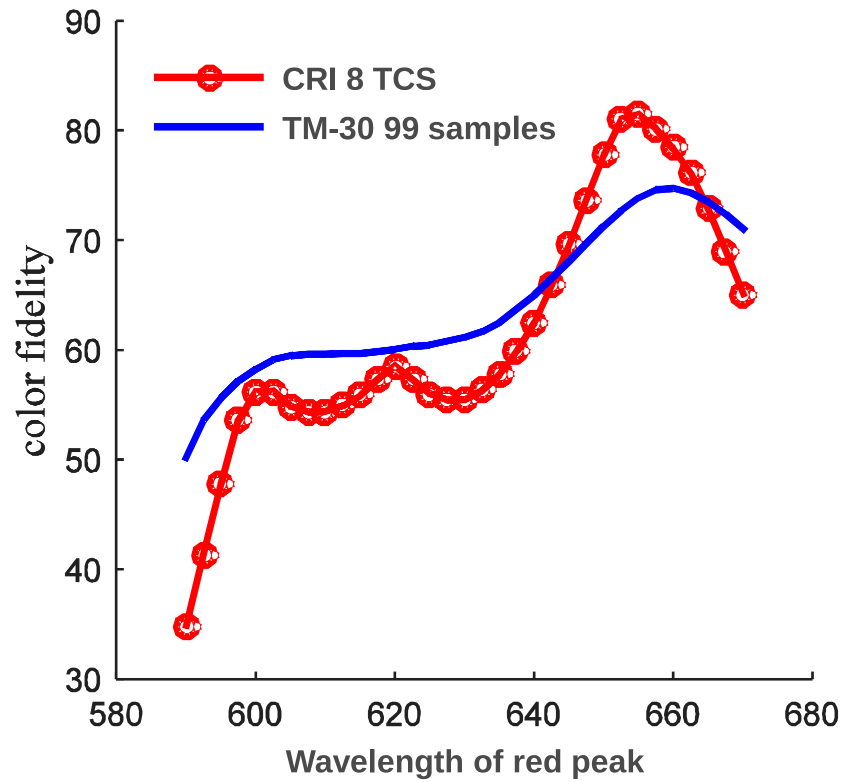


→ We select samples to make the samples equally sensitive to all wavelengths
Same concept as CRI2012, but using real samples only

Impact of wavelength uniformity on spikey SPDs

Consider a series of 3-peak SPDs:

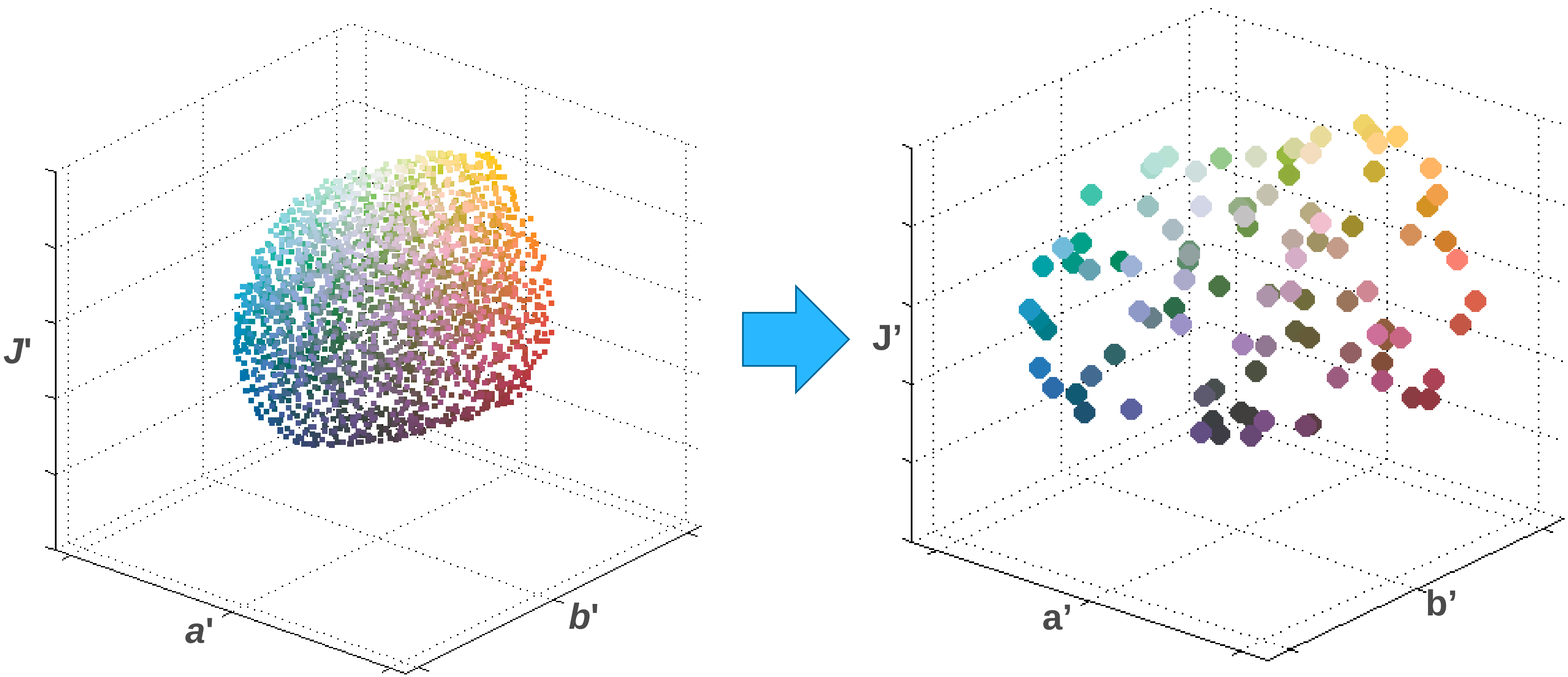




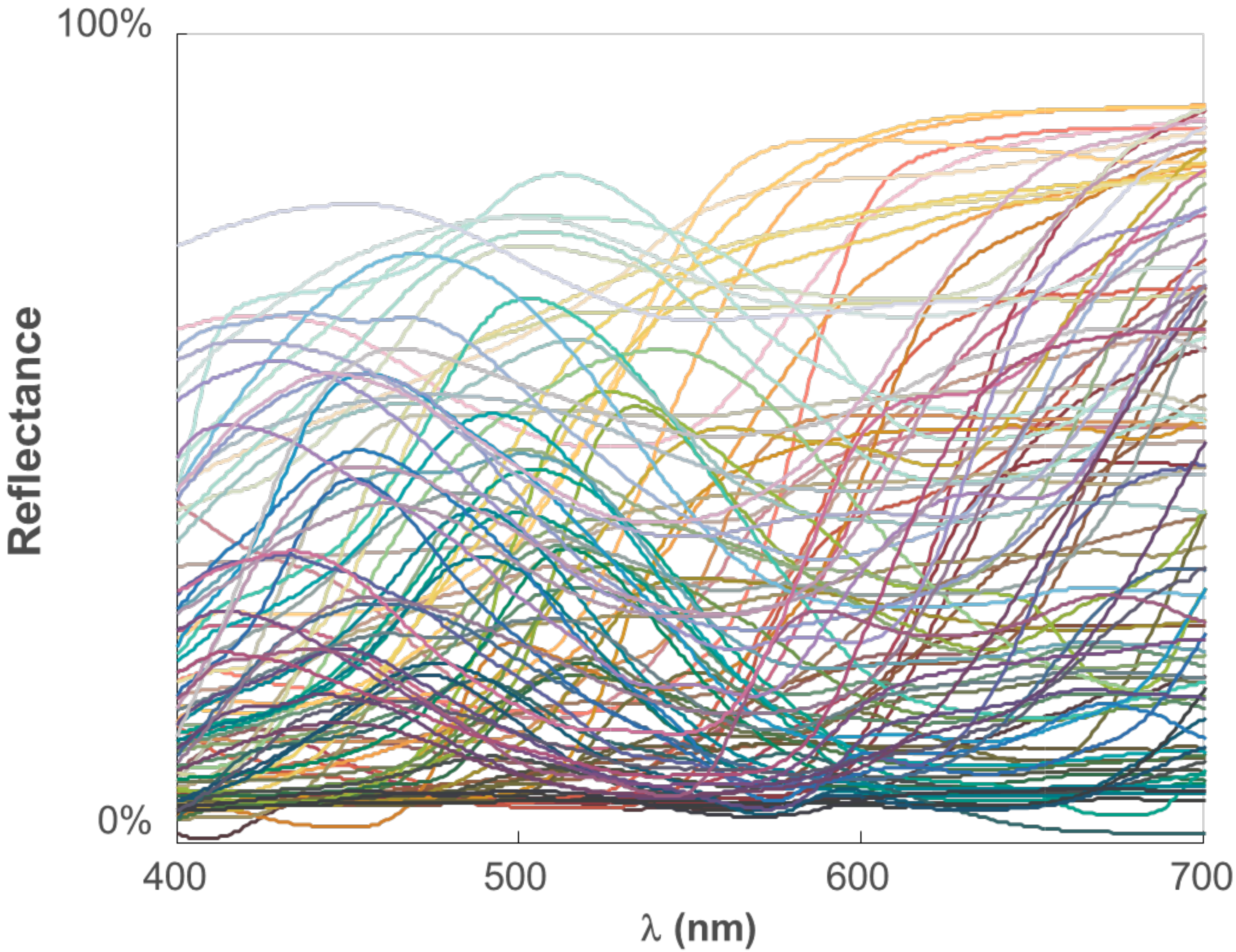
The artificial sensitivity of the CRI TCS is removed with TM-30 samples

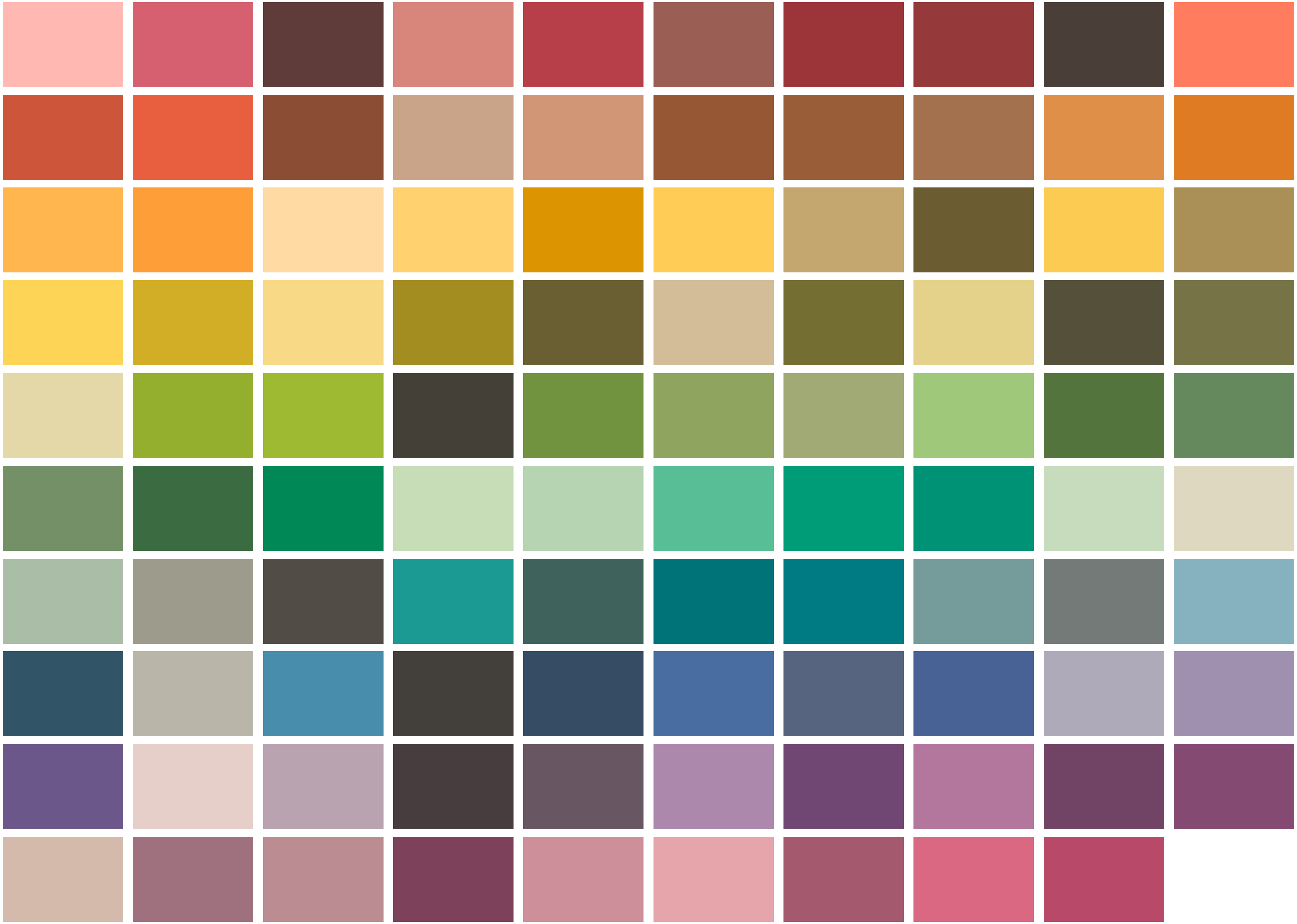
Reduction in sample size

Minimize sample count while maintaining accuracy
→ 99 samples



Test samples – The Result!





Part 4:
Reference Illuminants

Reference Illuminants

TM-30, like CRI, uses reference illuminants:
blackbody radiators and daylight phases.

Daylight is universally available and by definition it produces the “true color” of natural objects.

Some dispute blackbody radiators as a reference for low CCT

They say “standard of convenience” but not so – consider HPS

Blackbody light enables people to judge objects’ daylight color, because both spectra are quite smooth

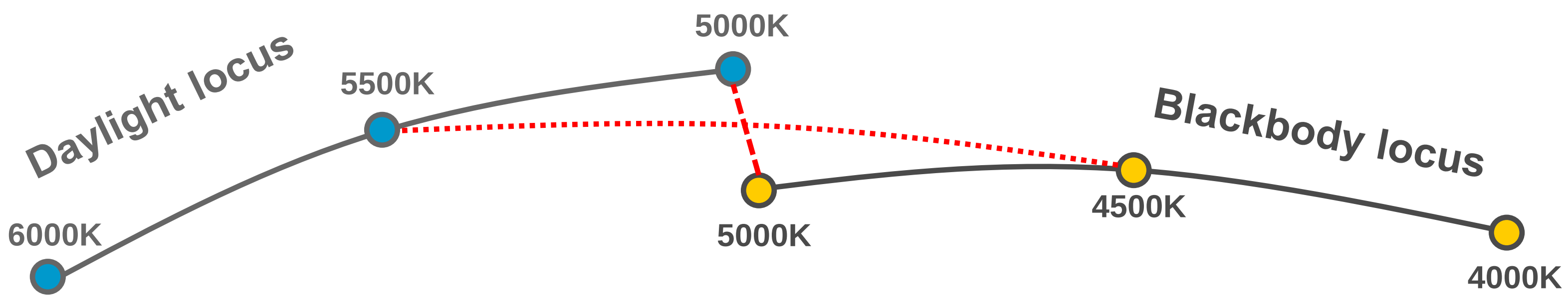
Sources can deviate from the blackbody curve and score well, because of the chromatic adaptation calculation of CIECAM02.

Reference Illuminants

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

CIE D Series
(Model of Daylight)

Planckian Radiation
(Think Incandescent)



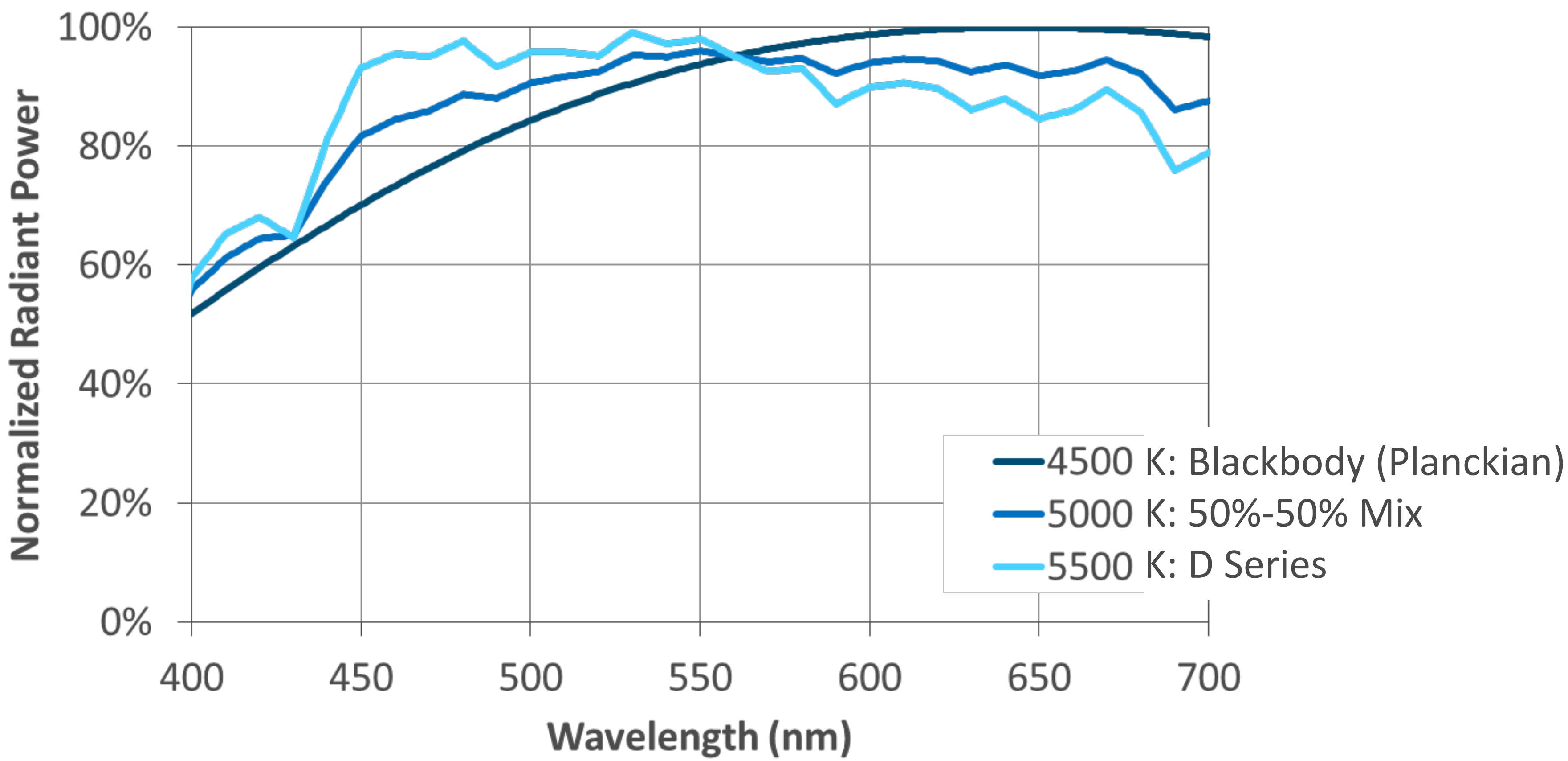
TM-30: **CCT ≥ 5500 K** | **5500 K > CCT > 4500 K** | **CCT ≤ 4500 K**

CIE D Series
(Model of Daylight)

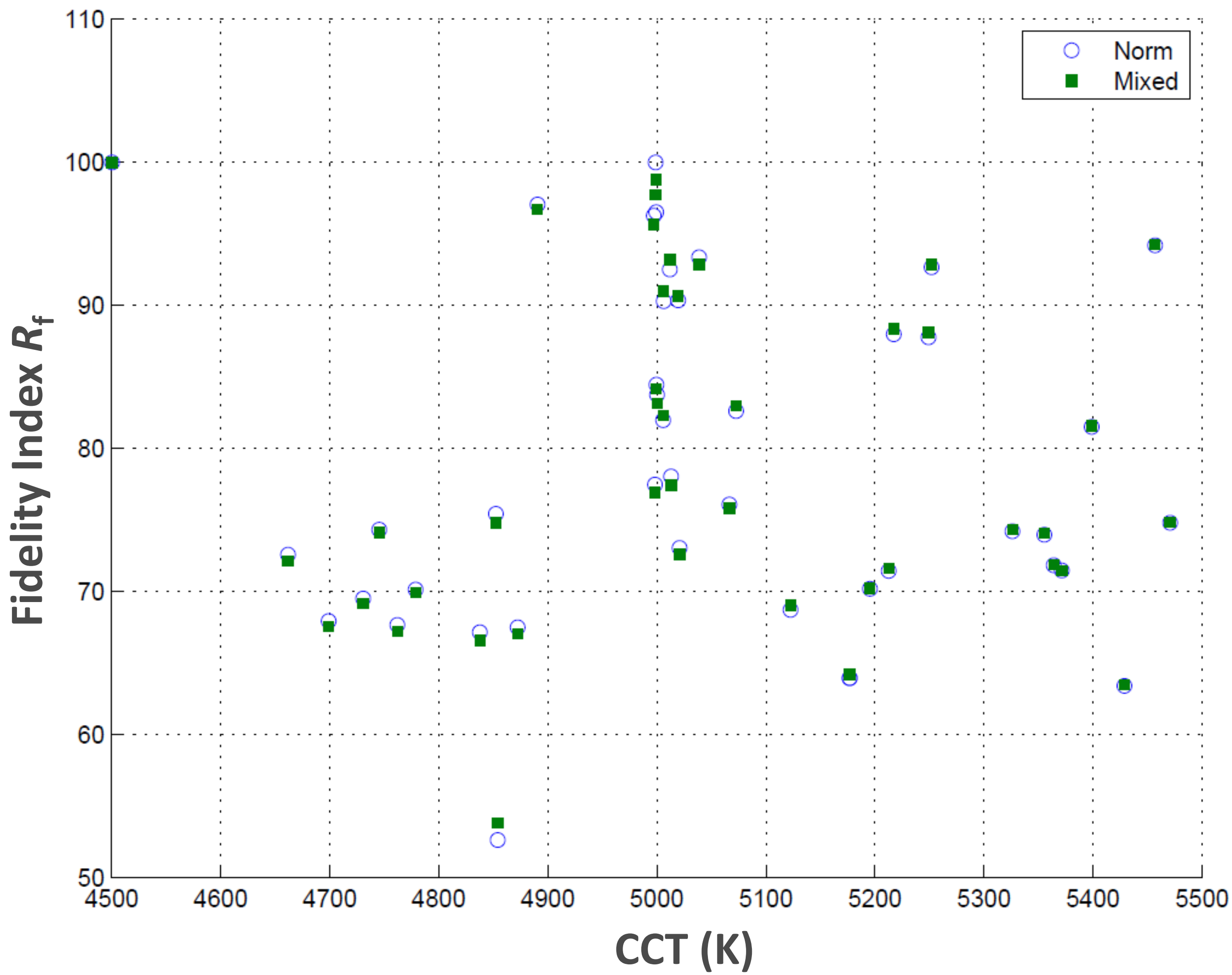
Proportional blend of
D Series and Planckian

Planckian Radiation
(Think Incandescent)

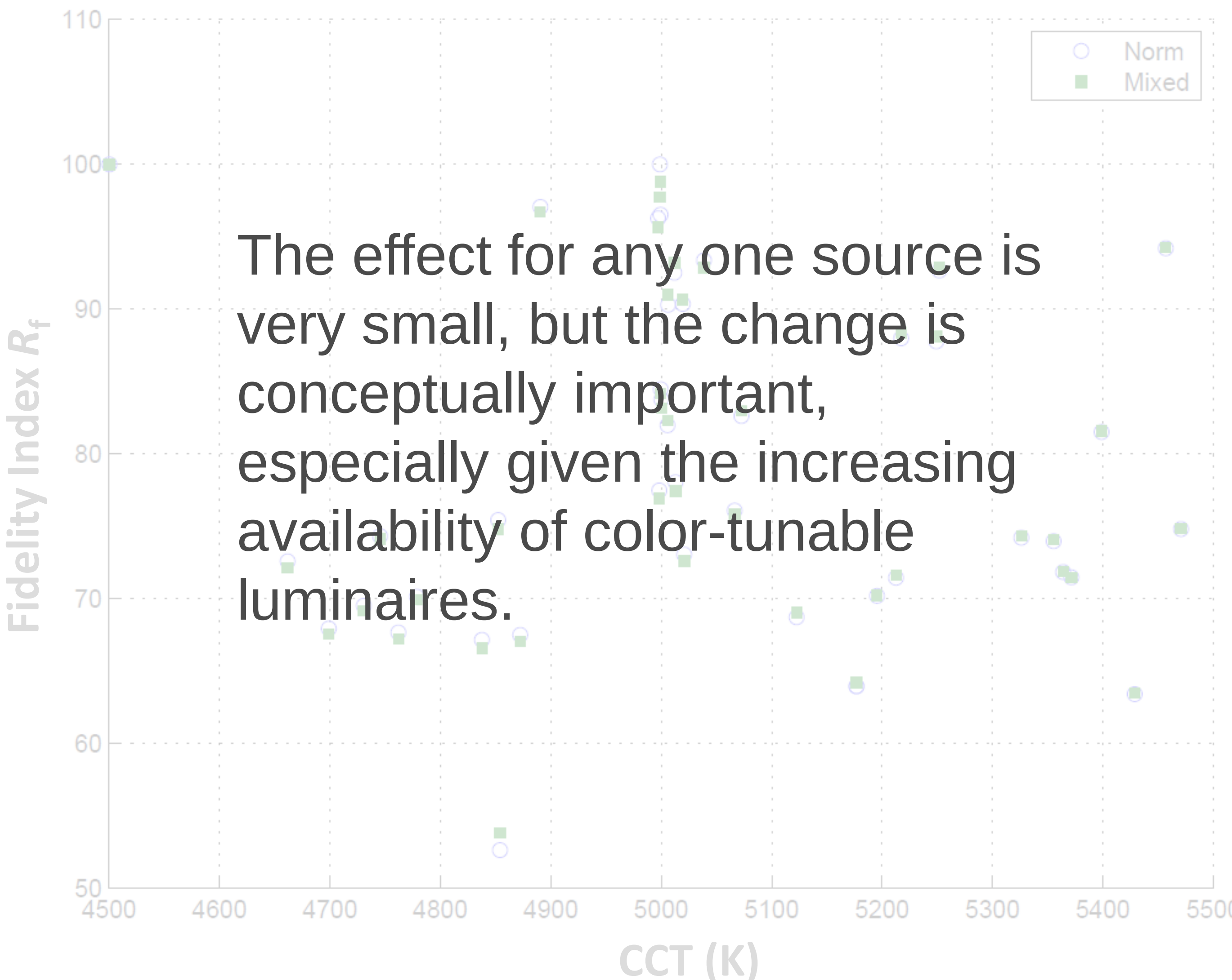
Reference Illuminants



Mixed Reference: Minimal Effect on Fidelity Values



Mixed Reference: Minimal Effect on Fidelity Values



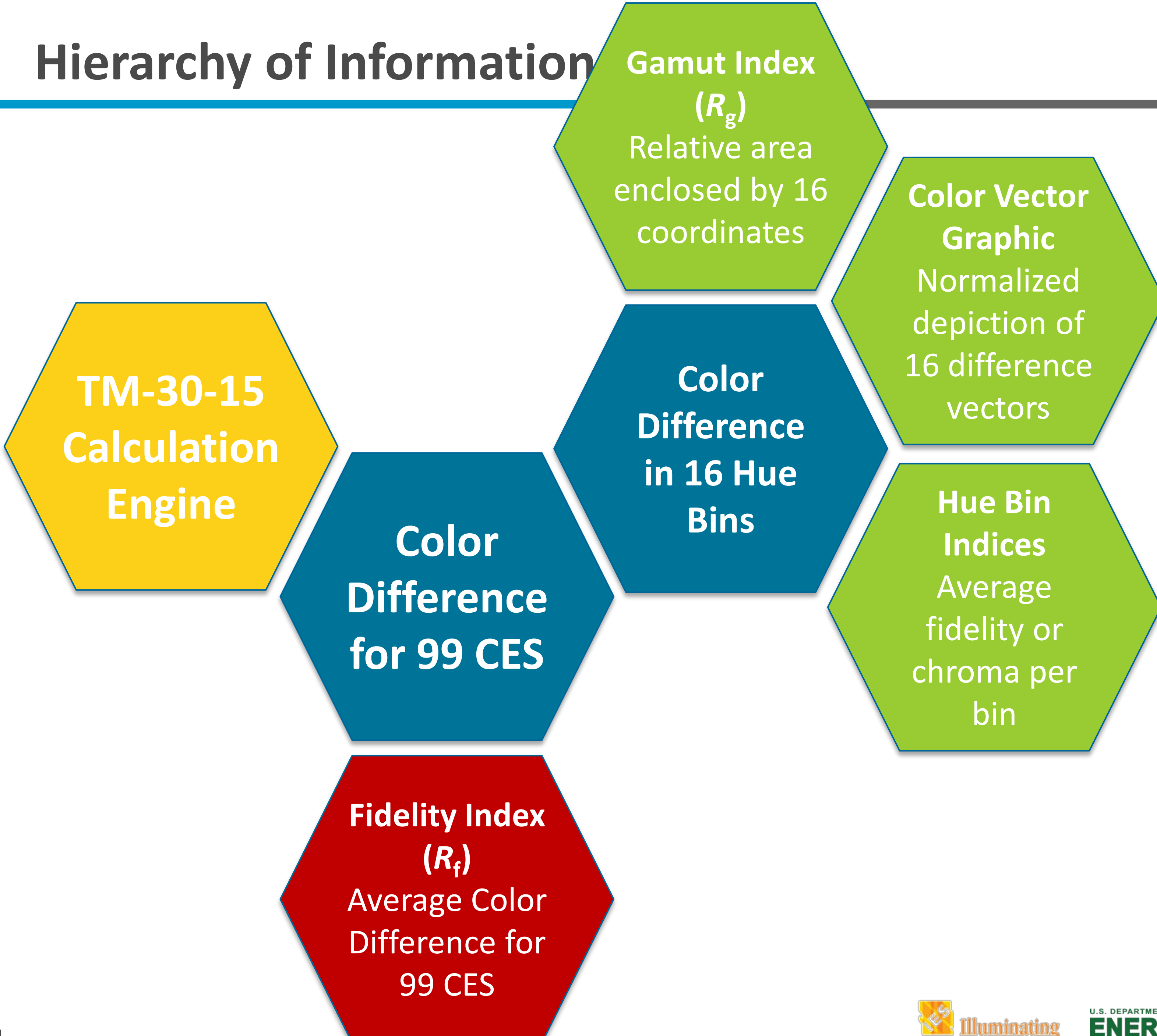
The effect for any one source is very small, but the change is conceptually important, especially given the increasing availability of color-tunable luminaires.

Questions?

Part 5:

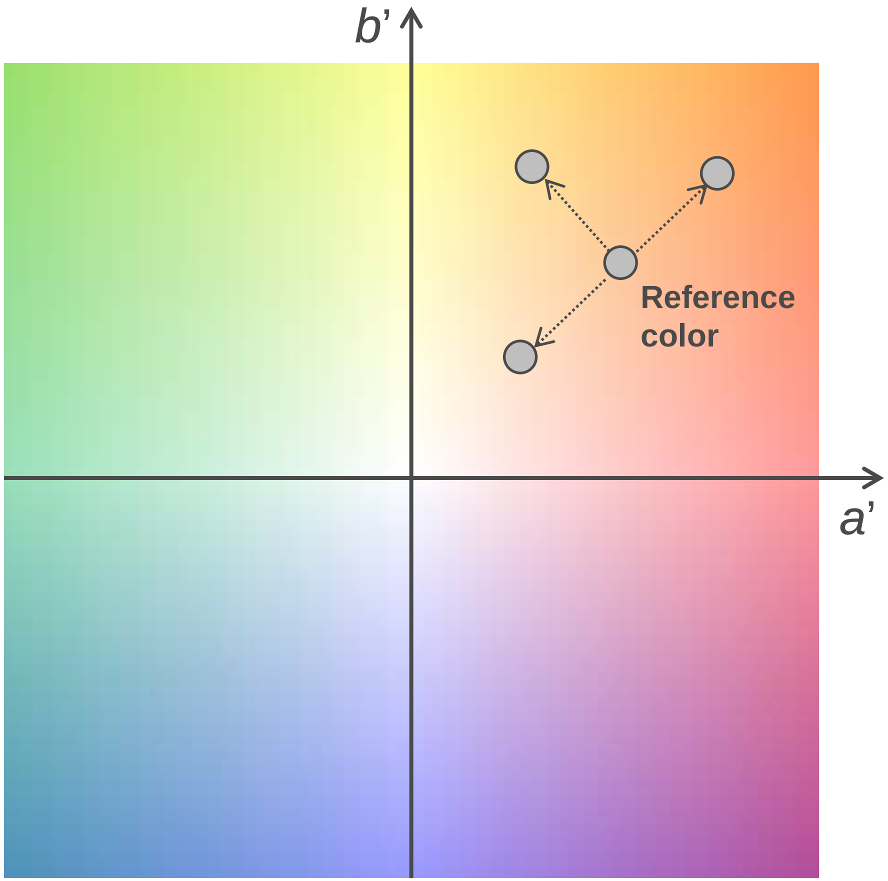
Calculation Procedure and Outputs

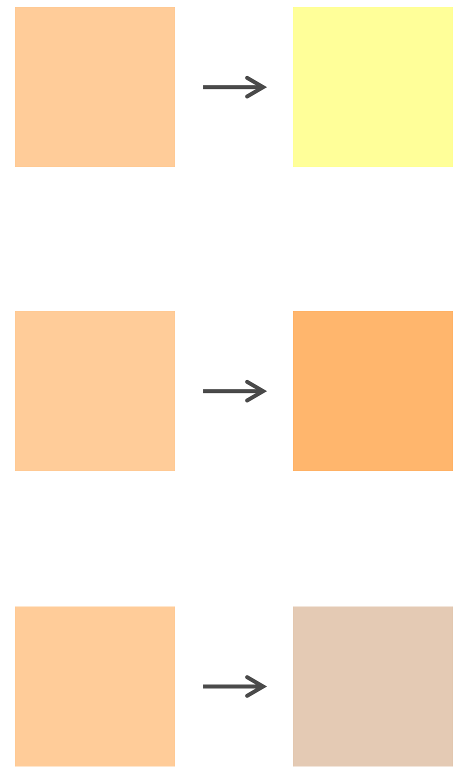
Hierarchy of Information



Color Difference

A light source can induce various kinds of color distortions:





Hue shift

Saturating shift

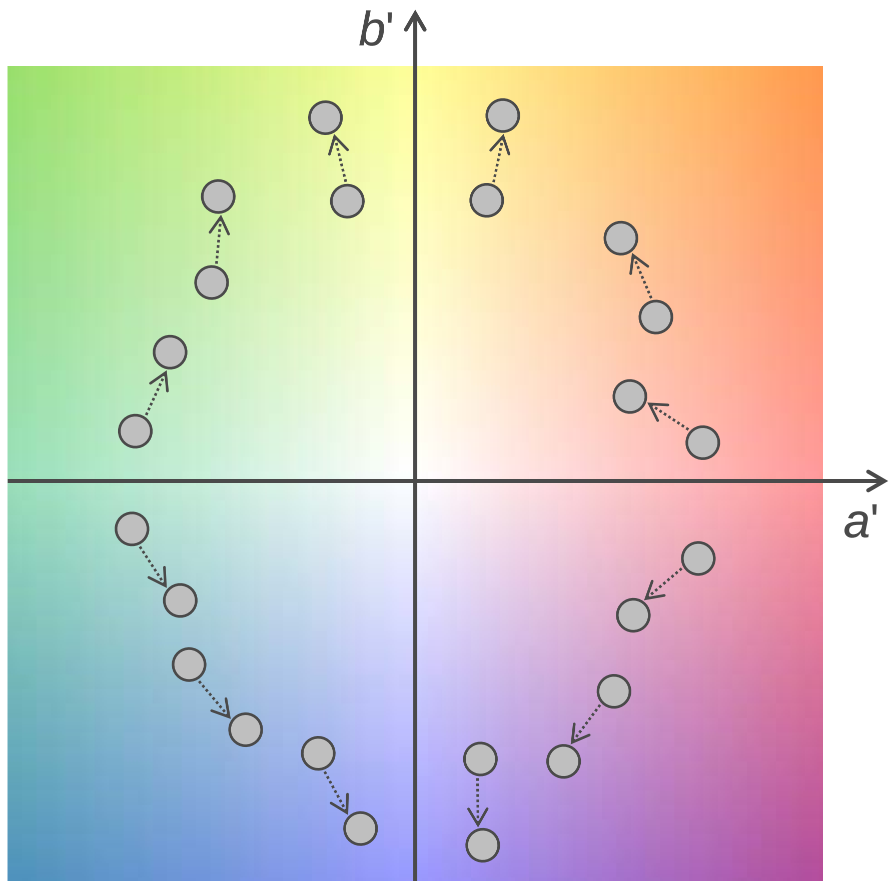
Desaturating shift

Color Difference

TM-30-15 Calculation Engine

Color Difference for 99 CES

To compute the color rendition metrics, we compute the color of each test sample under the test source and the reference illuminant



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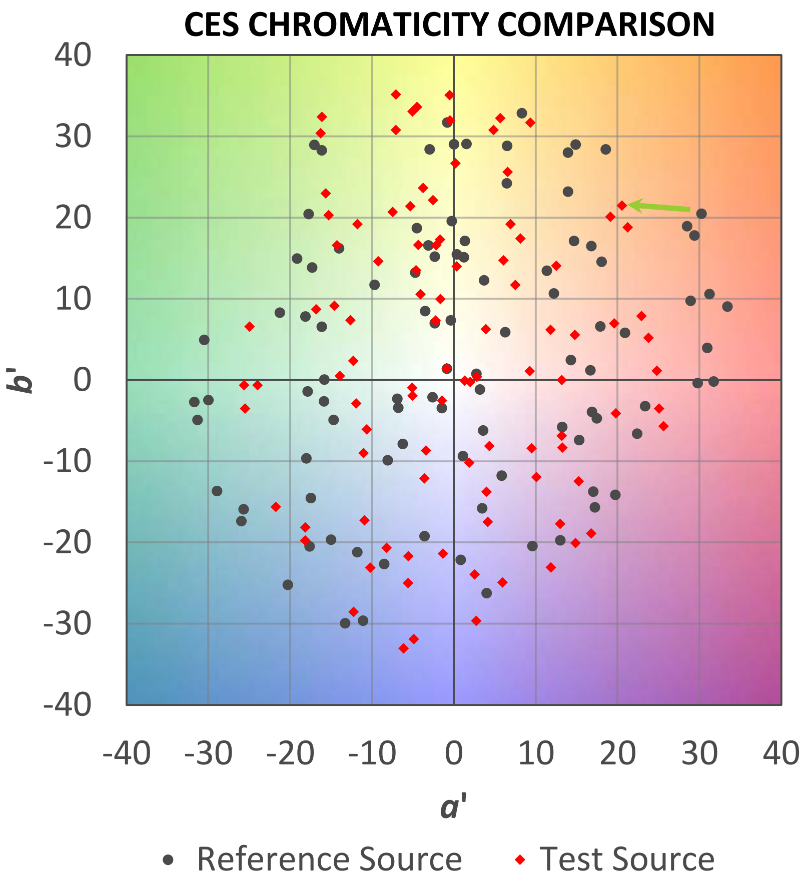
Color Difference – TM-30-15

TM-30-15 Calculation Engine

Color Difference for 99 CES



[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

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

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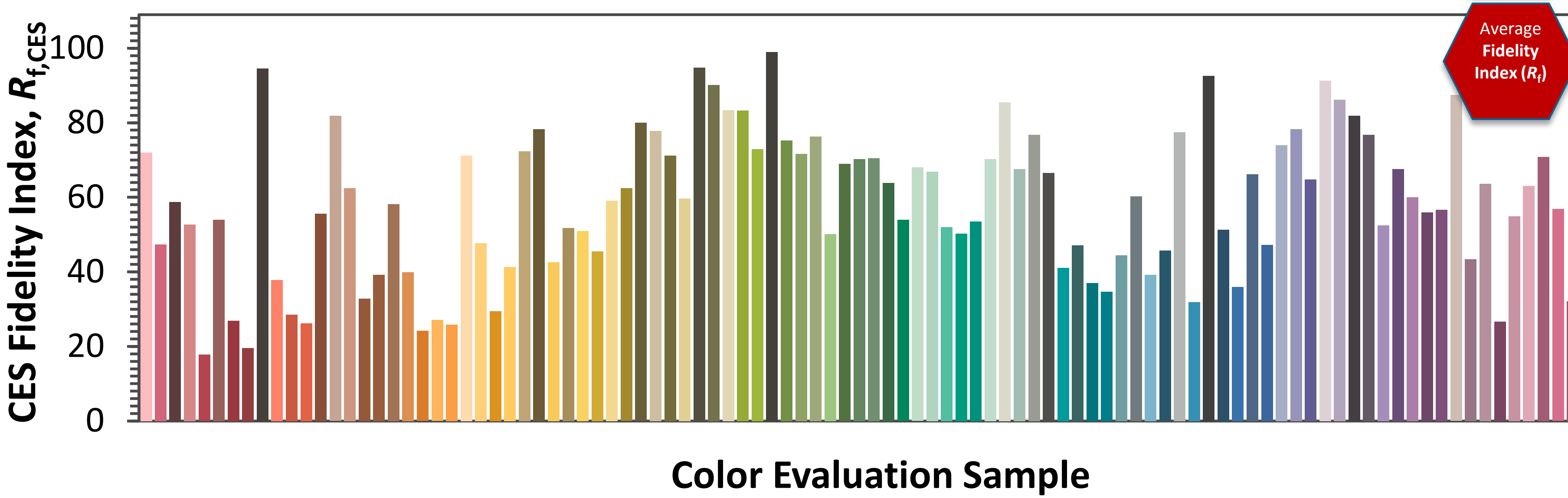
TM-30-15 Fidelity (Each CES)

TM-30-15 Calculation Engine

Color Difference for 99 CES

Average Fidelity Index (R_f)



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

Scaling Factor

Maximum value of 100

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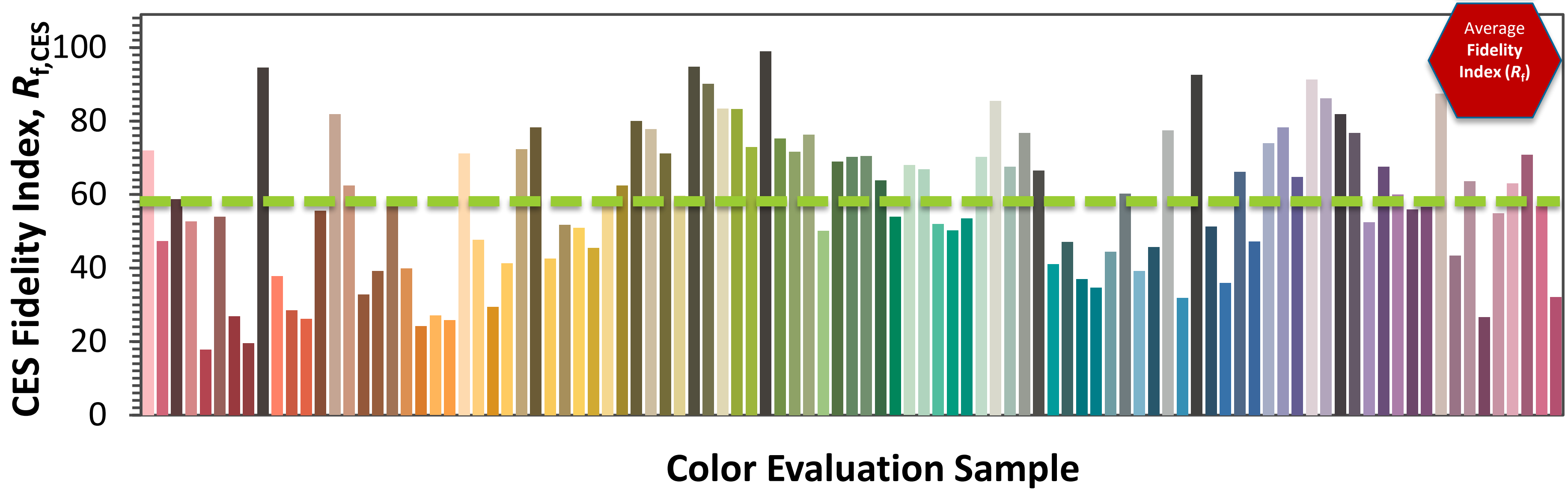
TM-30-15 Fidelity (Average)

TM-30-15 Calculation Engine

Color Difference for 99 CES

Average Fidelity Index (R_f)



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

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

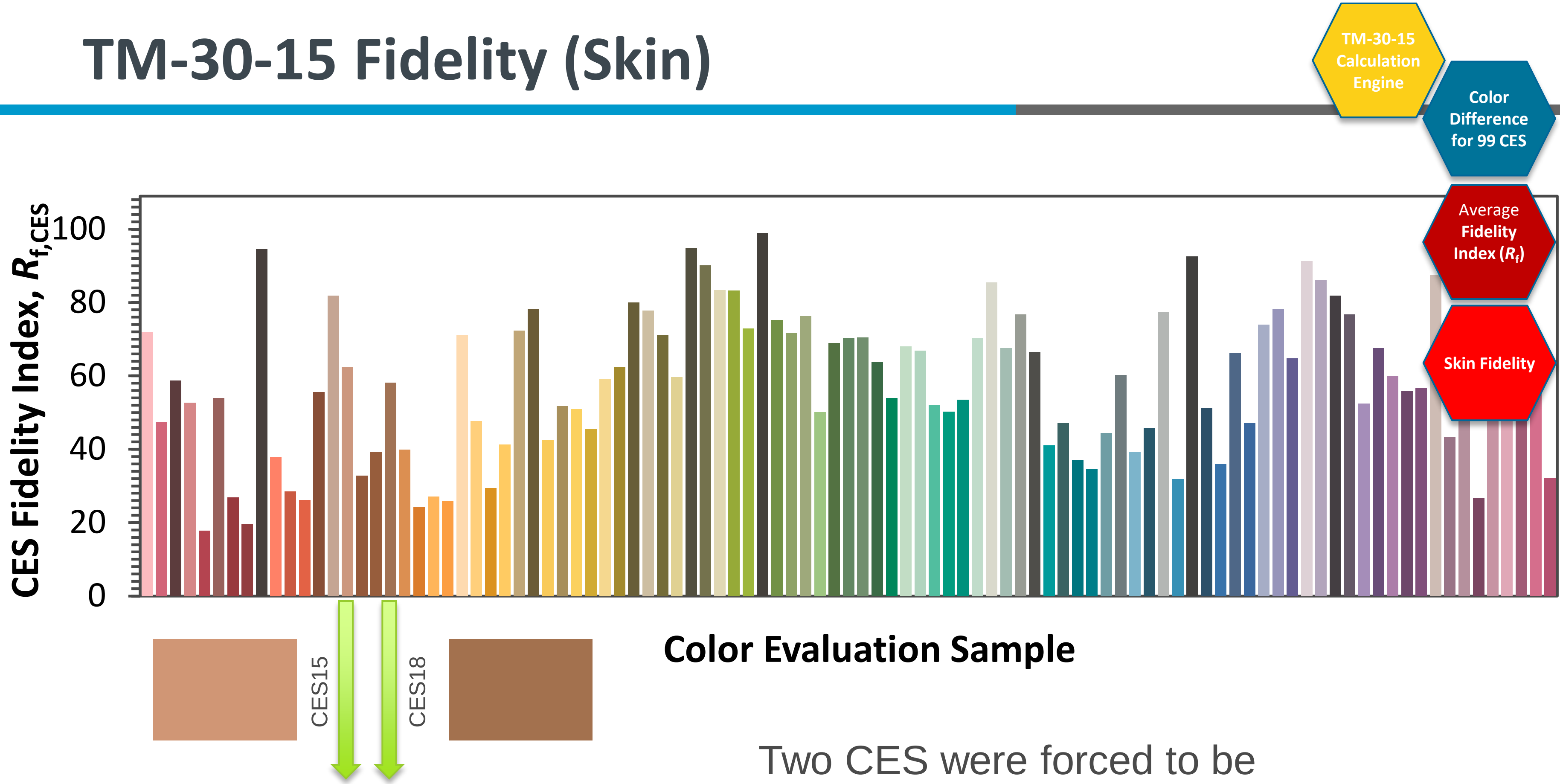
Arithmetic Mean

Scaling Factor

Maximum value of 100

Lower limit = 0

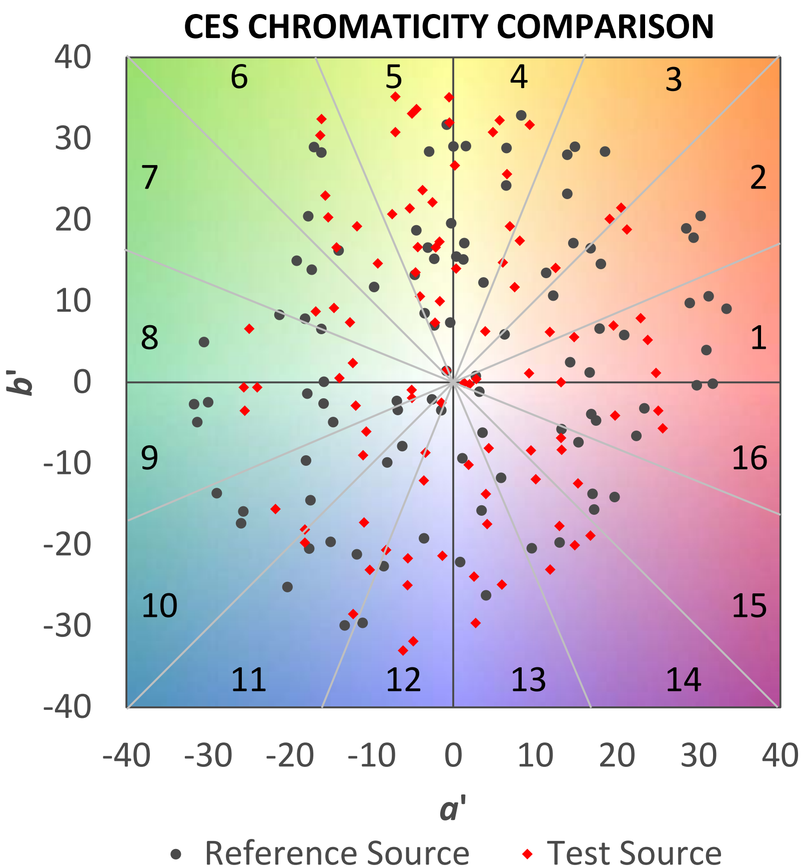
TM-30-15 Fidelity (Skin)

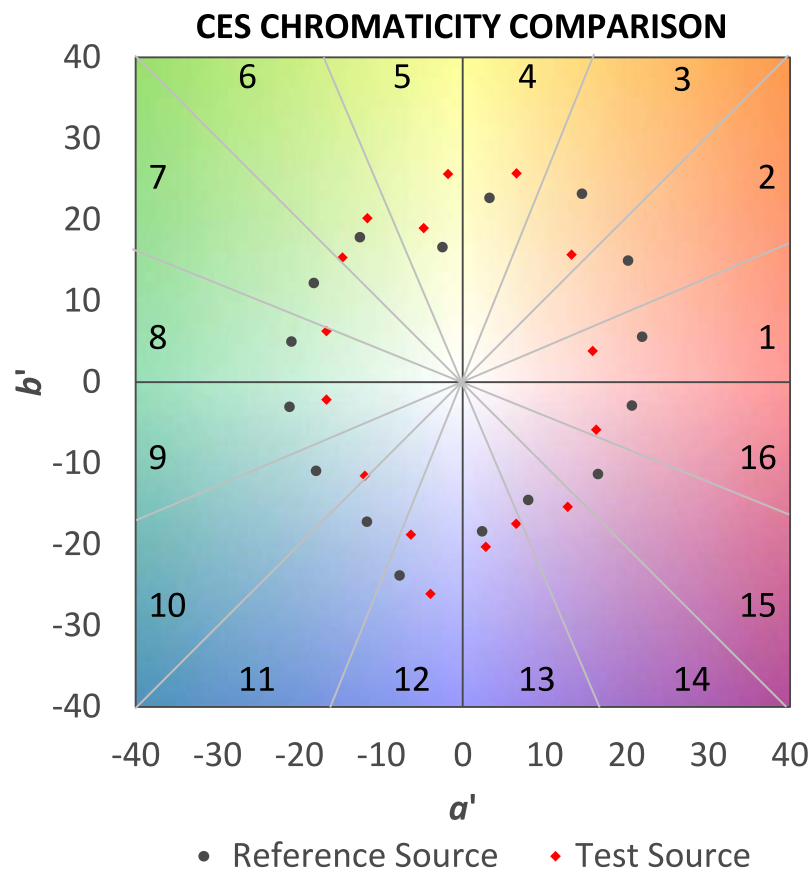


$$R_{f,skin} = \frac{R_{\mathrm{f,CES15}} + R_{\mathrm{f,CES18}}}{2}$$

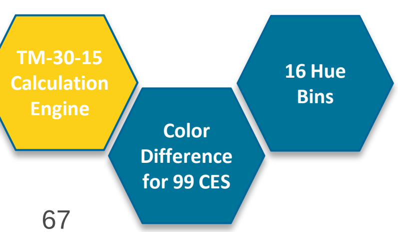
Two CES were forced to be measurements of human skin. The two samples lead to the highest correlation in R_f compared the full set of thousand of measured skin samples.

TM-30-15 Hue Bins



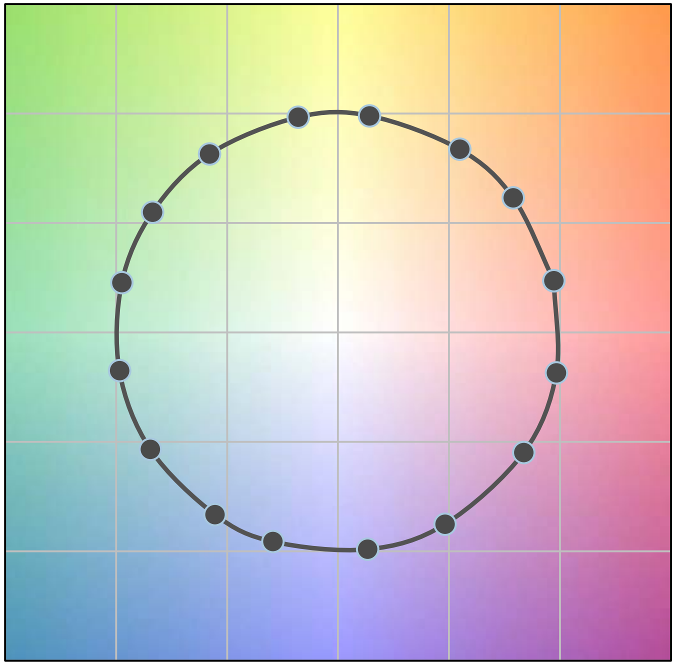


Average (*a*', *b*') chromaticity coordinates in each bin (binned by <u>reference</u> condition).

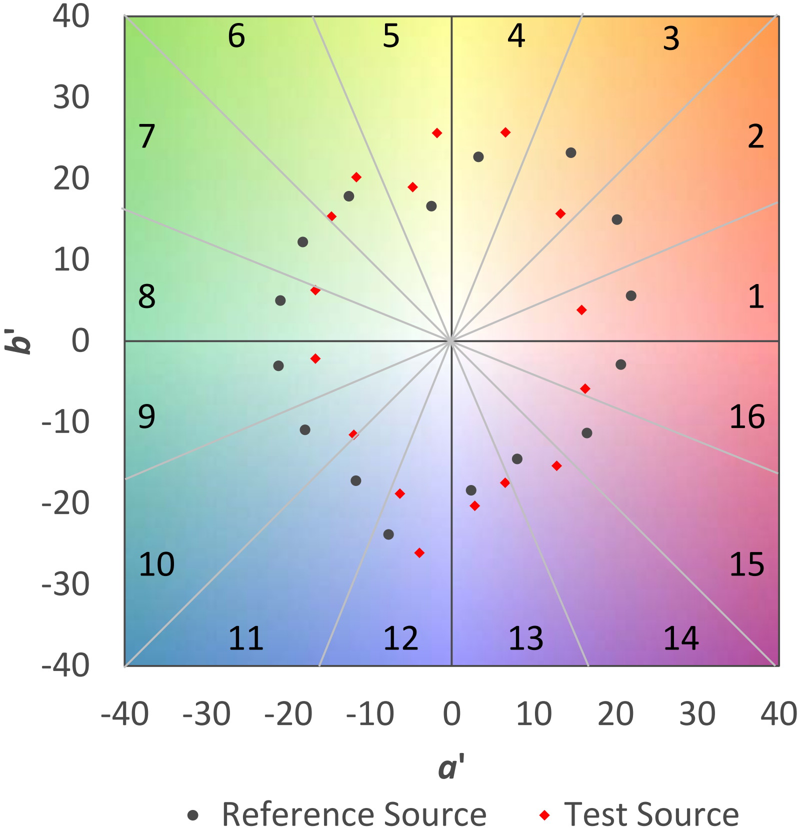


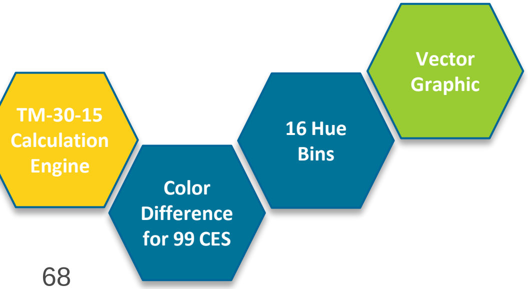
TM-30-15 Vector Graphics

COLOR VECTOR GRAPHIC

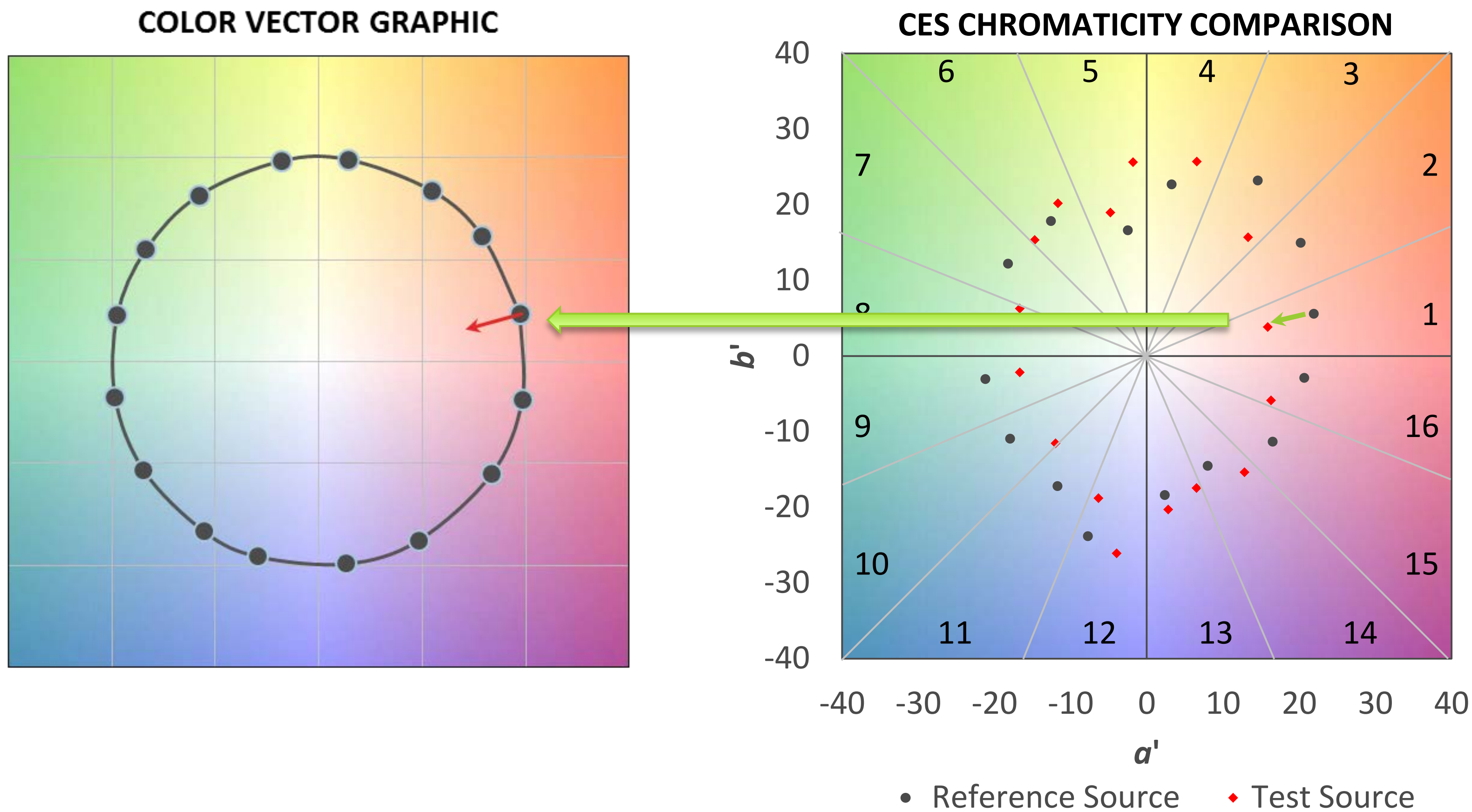


CES CHROMATICITY COMPARISON

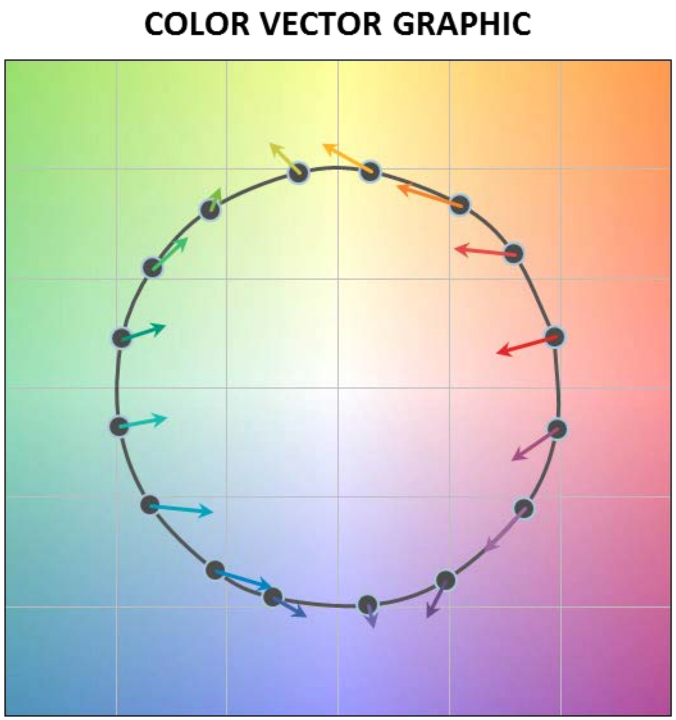


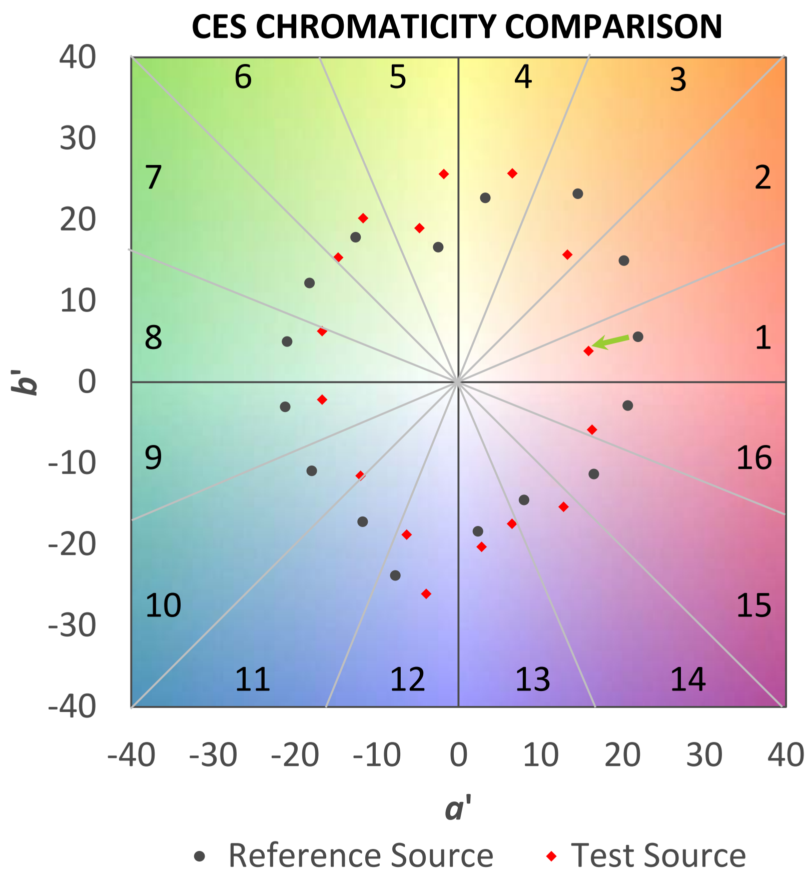


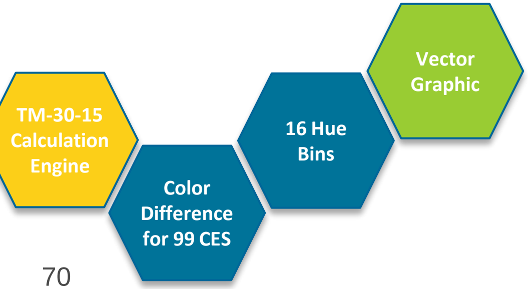
TM-30-15 Vector Graphics



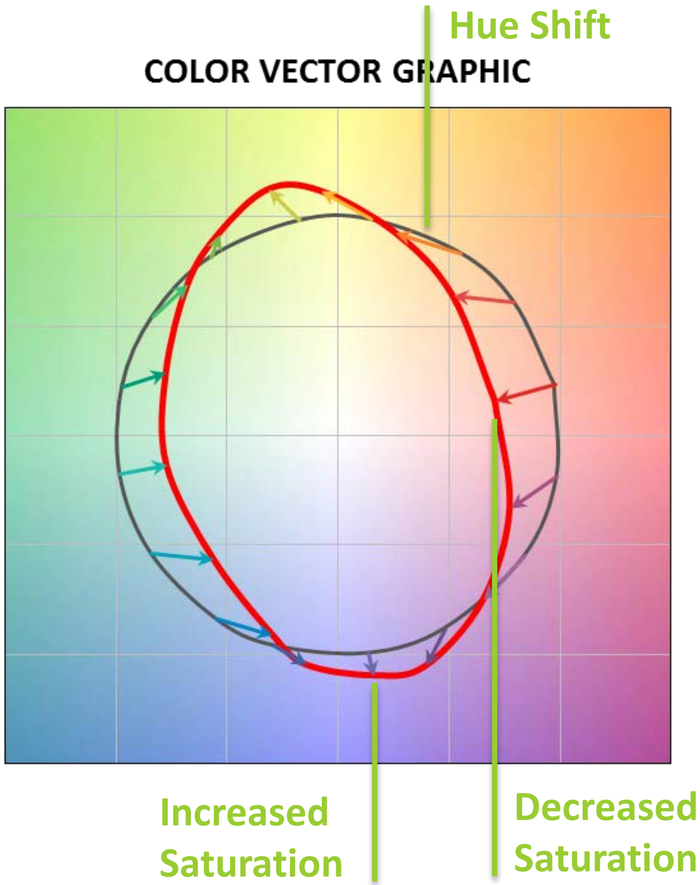
TM-30-15 Vector Graphics

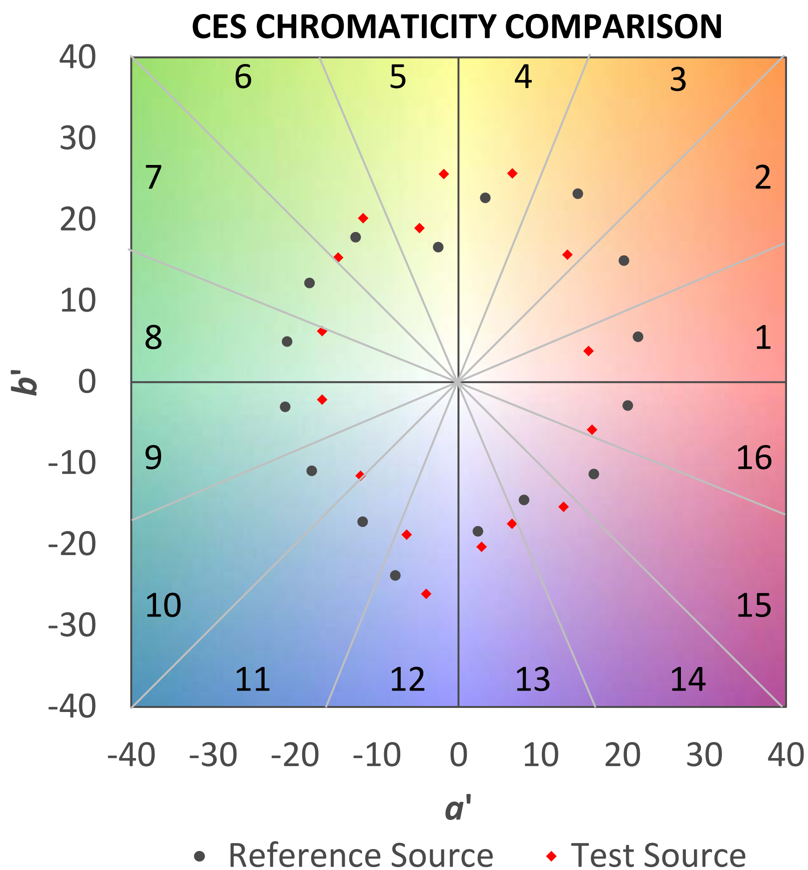


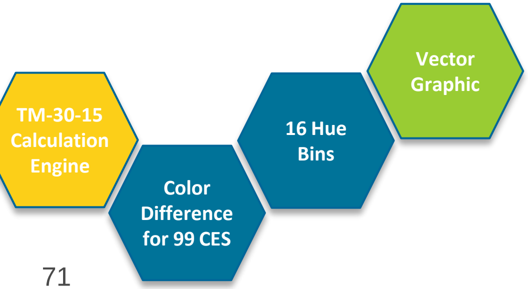




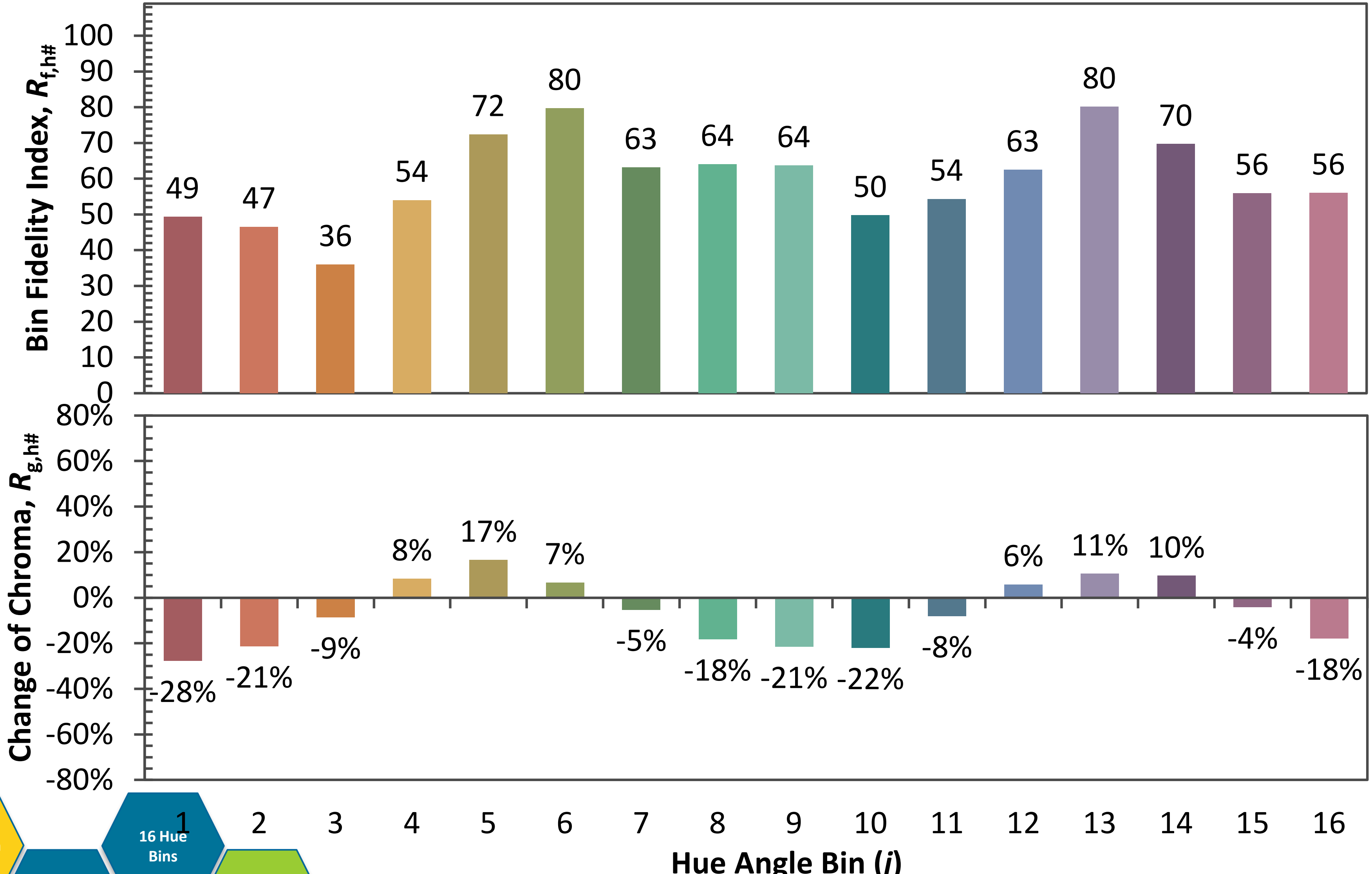
TM-30-15 Vector Graphics

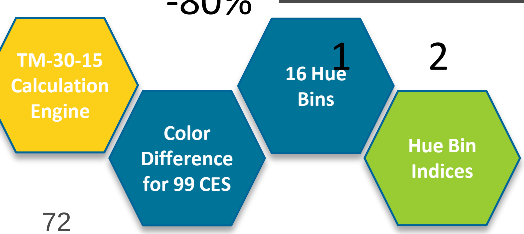






TM-30-15 Hue Bin Indices



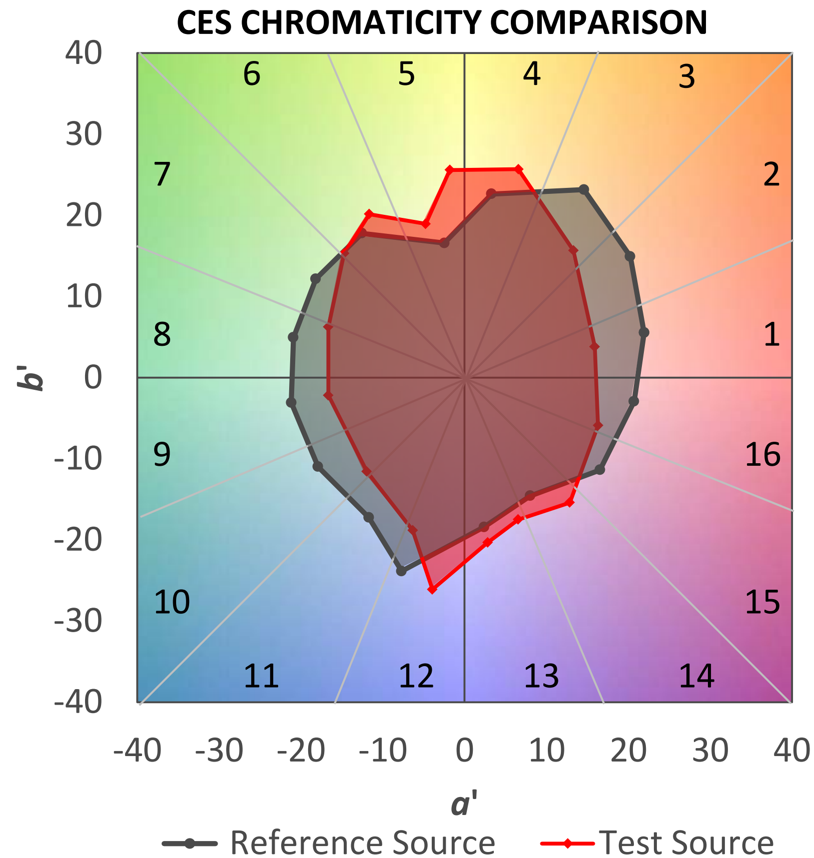


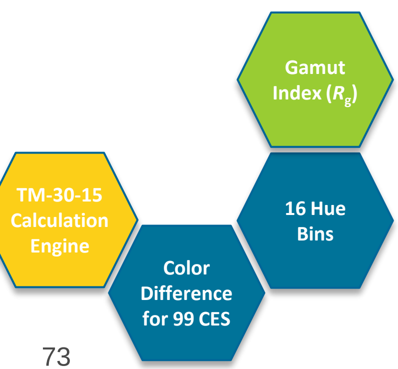
TM-30-15 Relative (Average) Gamut

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

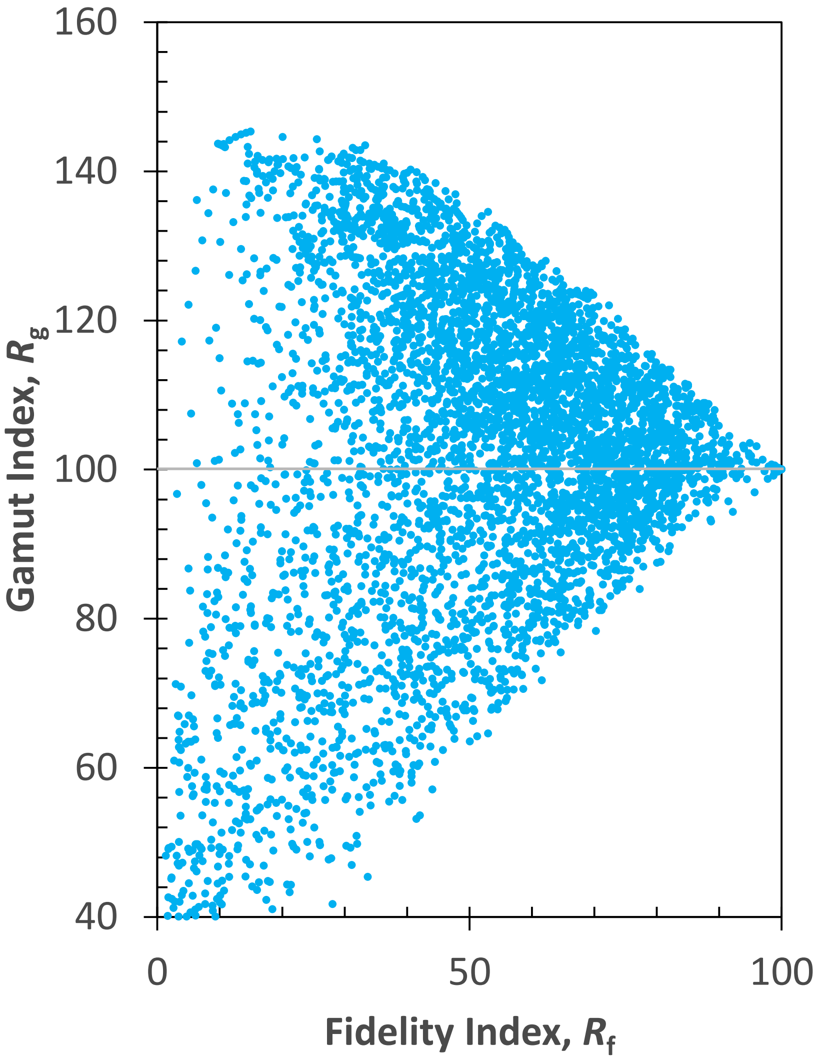
R_g > 100: Average increase in saturation

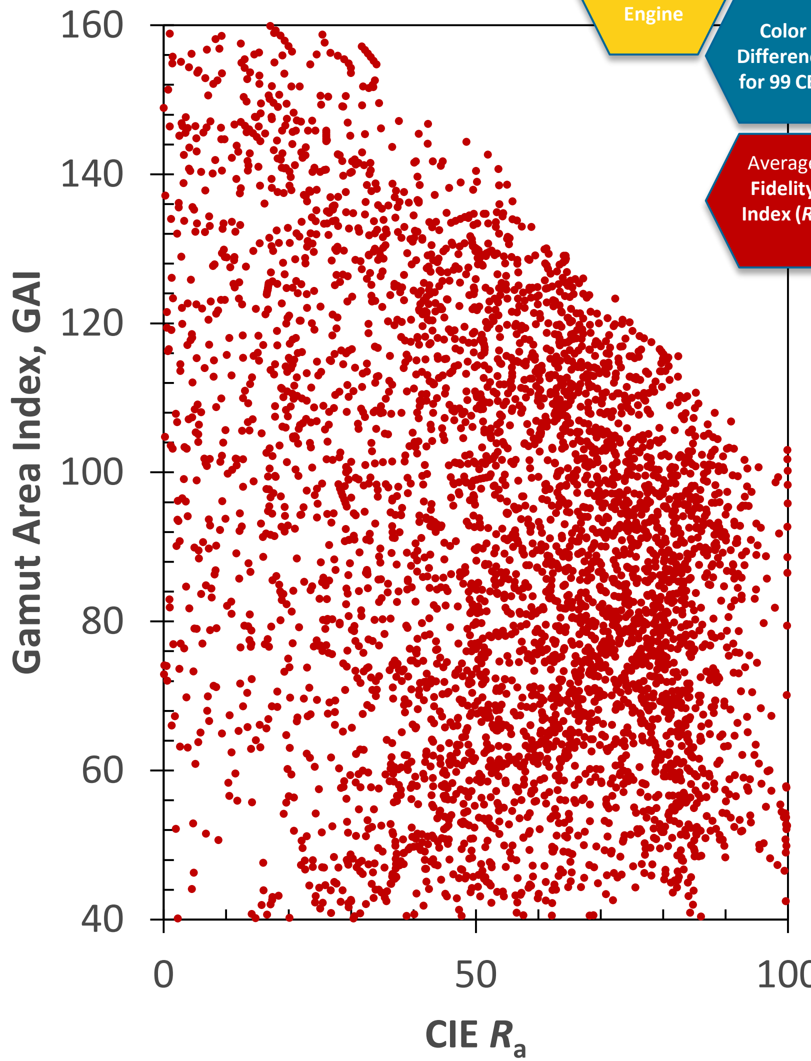
R_g < 100: Average decrease in saturation

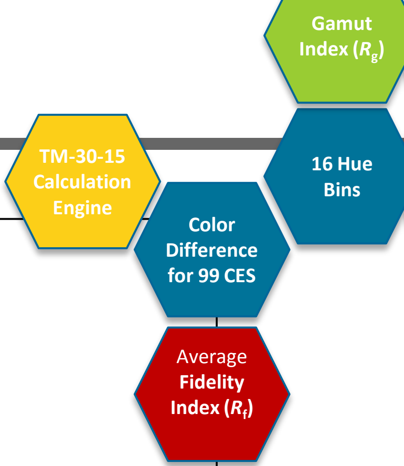




A Cohesive Two-Axis System







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Conclusions

- TM-30 is ready and available for use! Try it out and share your experiences.
- TM-30 offers substantial technical improvements via a new set of color samples and updated color science, each contributing to improved accuracy/usefulness.
- TM-30 greatly expands the scope of available information on color rendering, eliminating the limitations of considering a fidelity metric alone.
- TM-30 offers a single, cohesive method that includes a variety of measures suitable for various needs.
- The measures can be used together (and in combination with other important lighting metrics) to determine the most suitable source for a given application/user group.

Additional Resources

IES Technical Memorandum (TM) 30-15 (includes link to download calculator tools):
IES Method for Evaluating Light Source Color Rendition
http://bit.ly/1IWZxVu

LEUKOS editorial about adoption of TM-30-15 and next steps:
IES TM-30-15 is Approved—Now What?
Available soon at http://www.tandfonline.com/toc/ulks20/current

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

LEUKOS journal article that describes improved accuracy:
Of Why Color Space and Spectral Uniformity Are Essential for Color Rendering Measures
Available soon at http://www.tandfonline.com/toc/ulks20/current