Great promise, few options: Can advances in color science shift the market?

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Tony Esposito

LIGHTING RESEARCH SOLUTIONS

Michael Royer

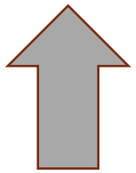
Pacific Northwest NATIONAL LABORATORY

Lorne Whitehead

UBC

Optimizing Illumination's Joy per Joule

human impact | well-being



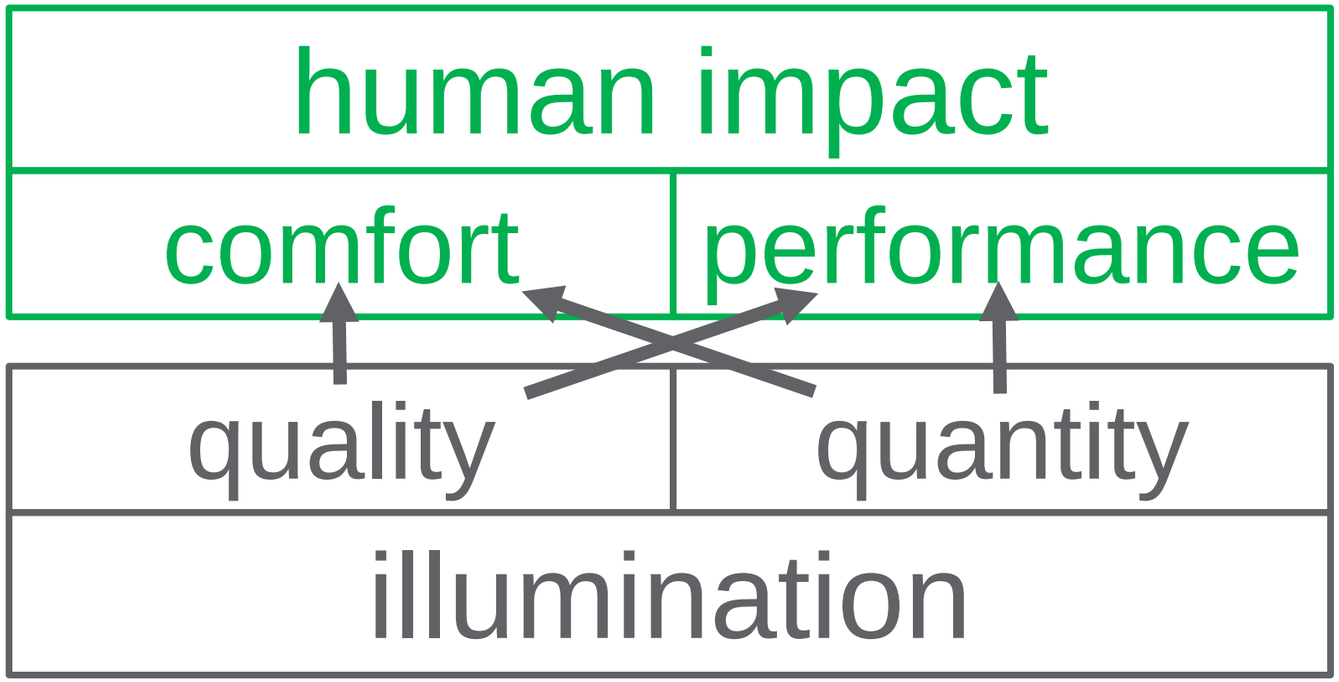
illumination

$$\frac{\text{well-being}}{\text{watt}}$$

"joy per joule"

electricity | watt

Optimizing Illumination's Joy per Joule



human impact	
comfort	performance

quality	quantity
illumination	

human impact

comfort

performance

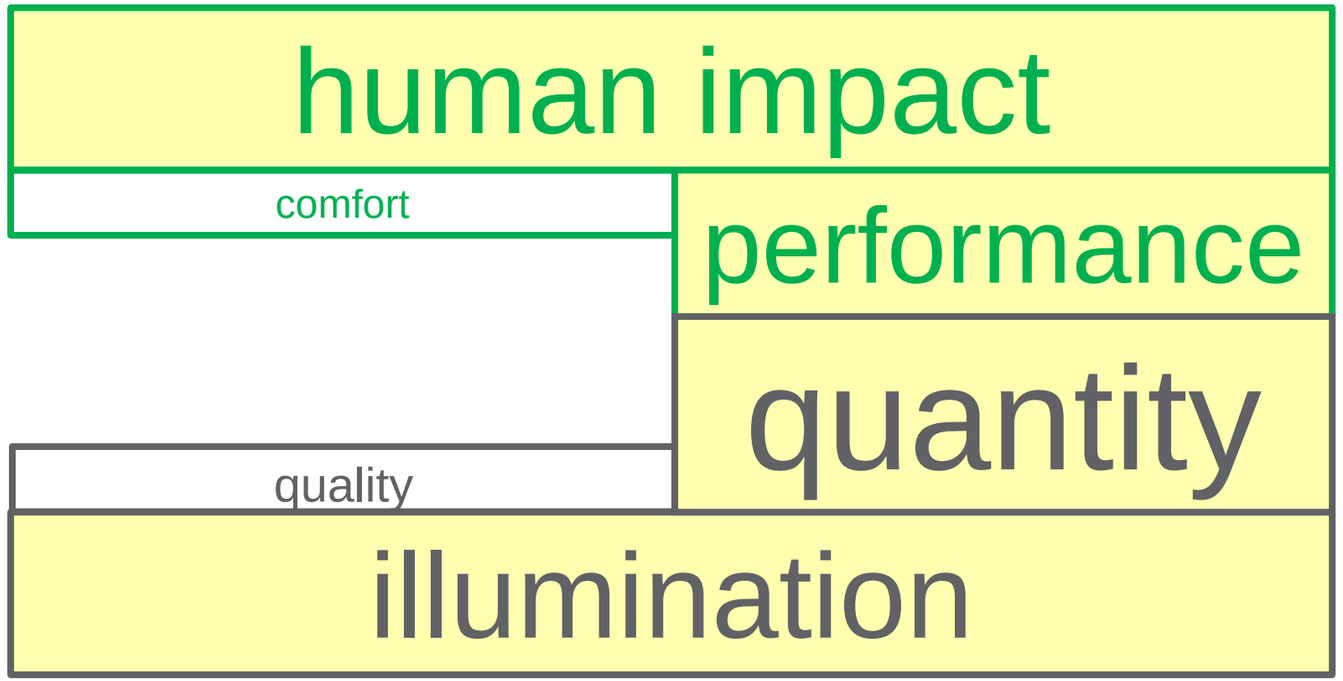
quantity

quality

illumination

Over-Emphasizing the Easily-Measured

- a lingering problem from the 20th century -



Over-Emphasizing the Easily-Measured

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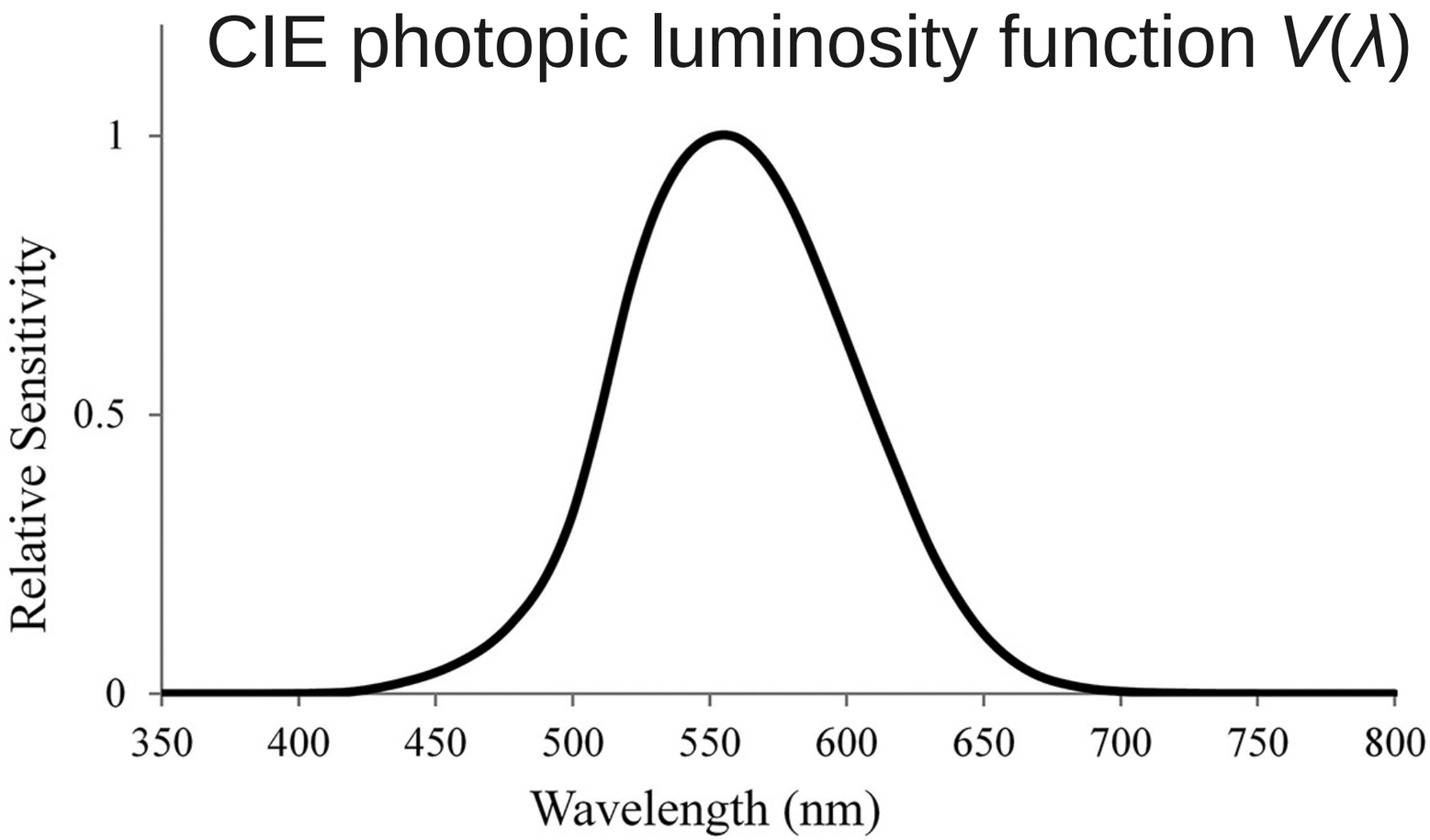

Over-Emphasizing the Easily-Measured

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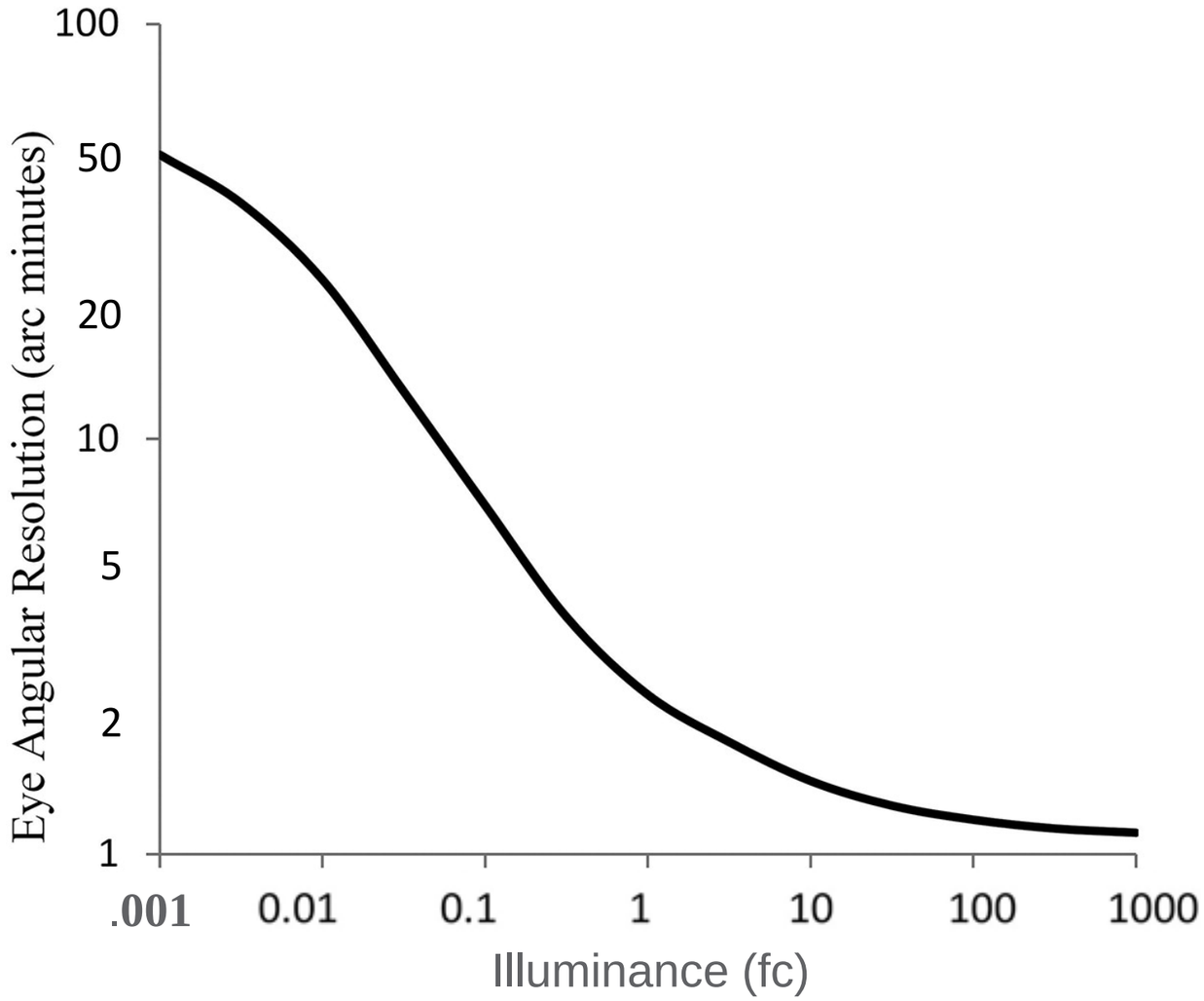

Location

Quantity

Spectrum

Timing

Control

Location

Quantity

Spectrum

Timing

Control

SPD

Match
Duv
Chromaticity
CCT
S/P
Relative Photoreceptor Stimulation
M/P
Pupil
Visual Perf.
Circa -dian
Fidelity
Hue
Shifts
Color Rendition
Chroma
White- ness
Match
LER
LPW

SPD

Match

Duv

Chromaticity

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Visual Perf.

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Relative Photoreceptor Stimulation

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Fidelity

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Color Rendition

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Match

LER

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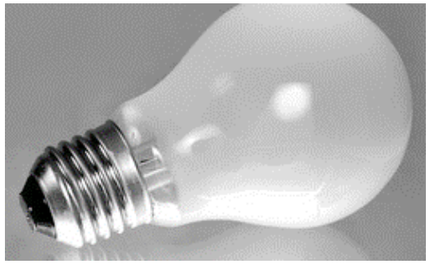
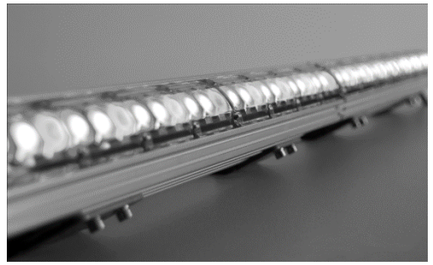
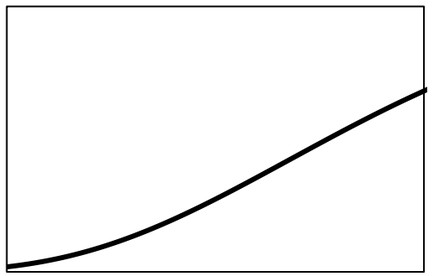
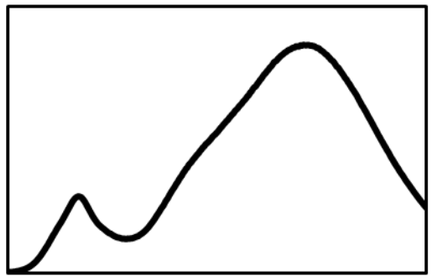
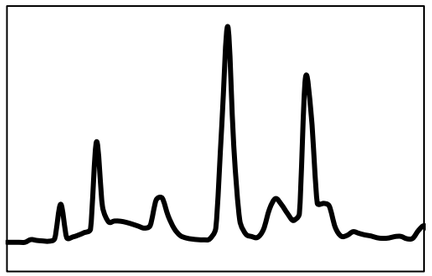
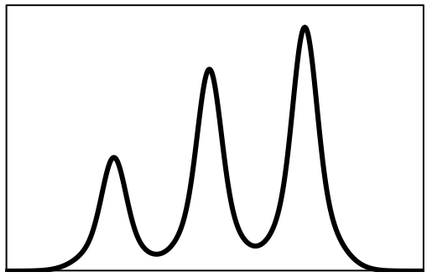
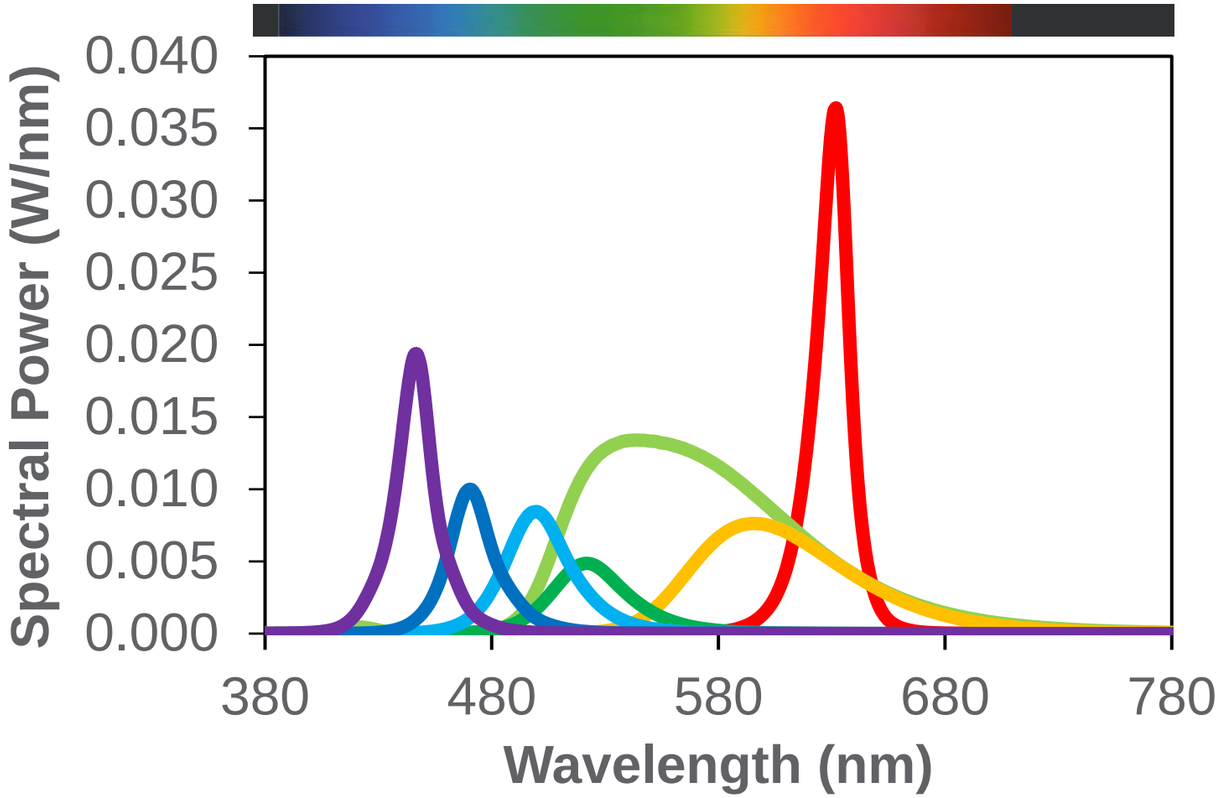
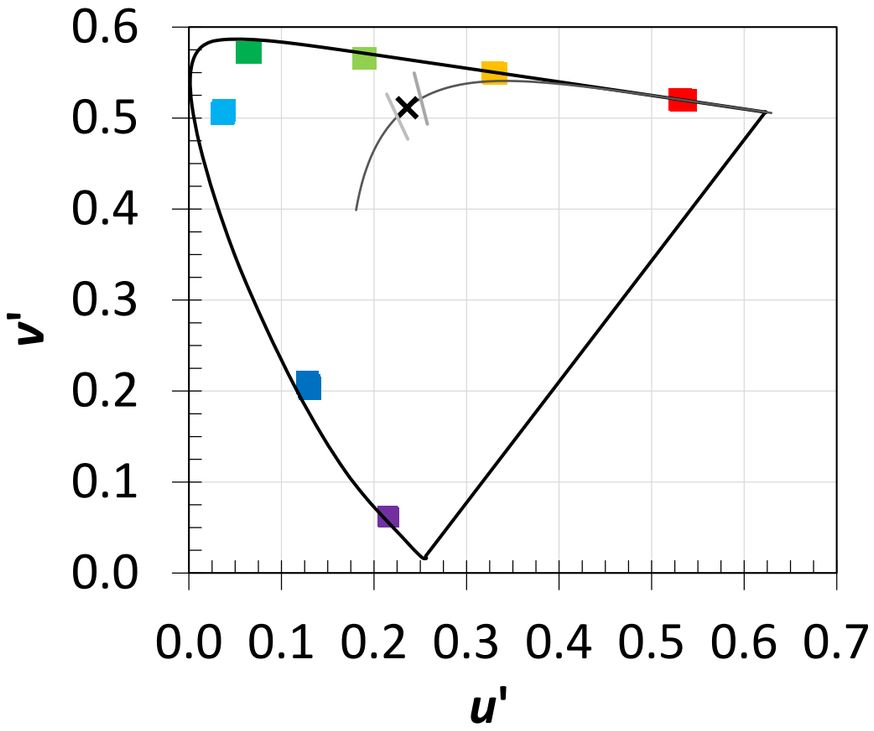


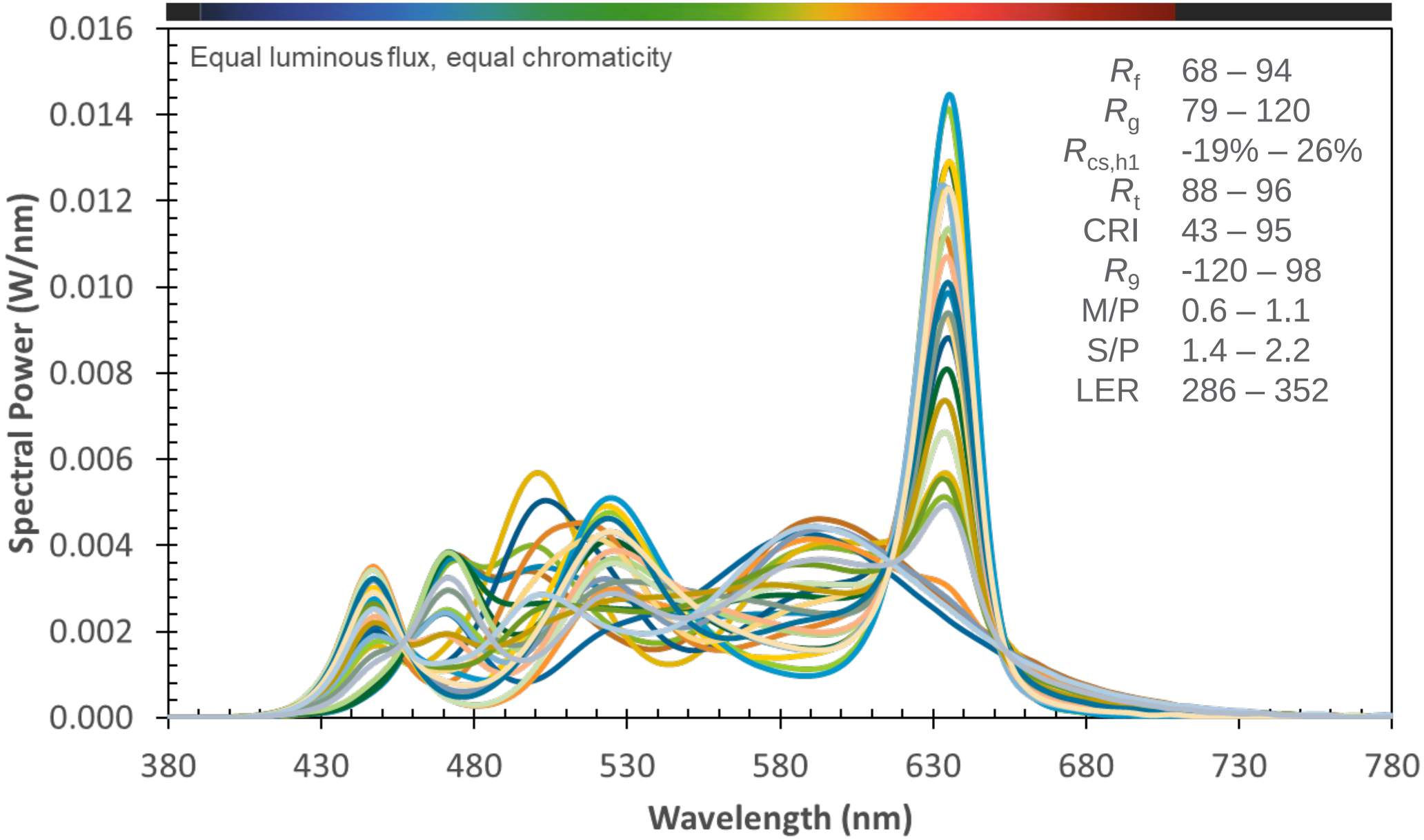








Spectral Power (W/nm)
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
380
480
580
680
780
Wavelength (nm)

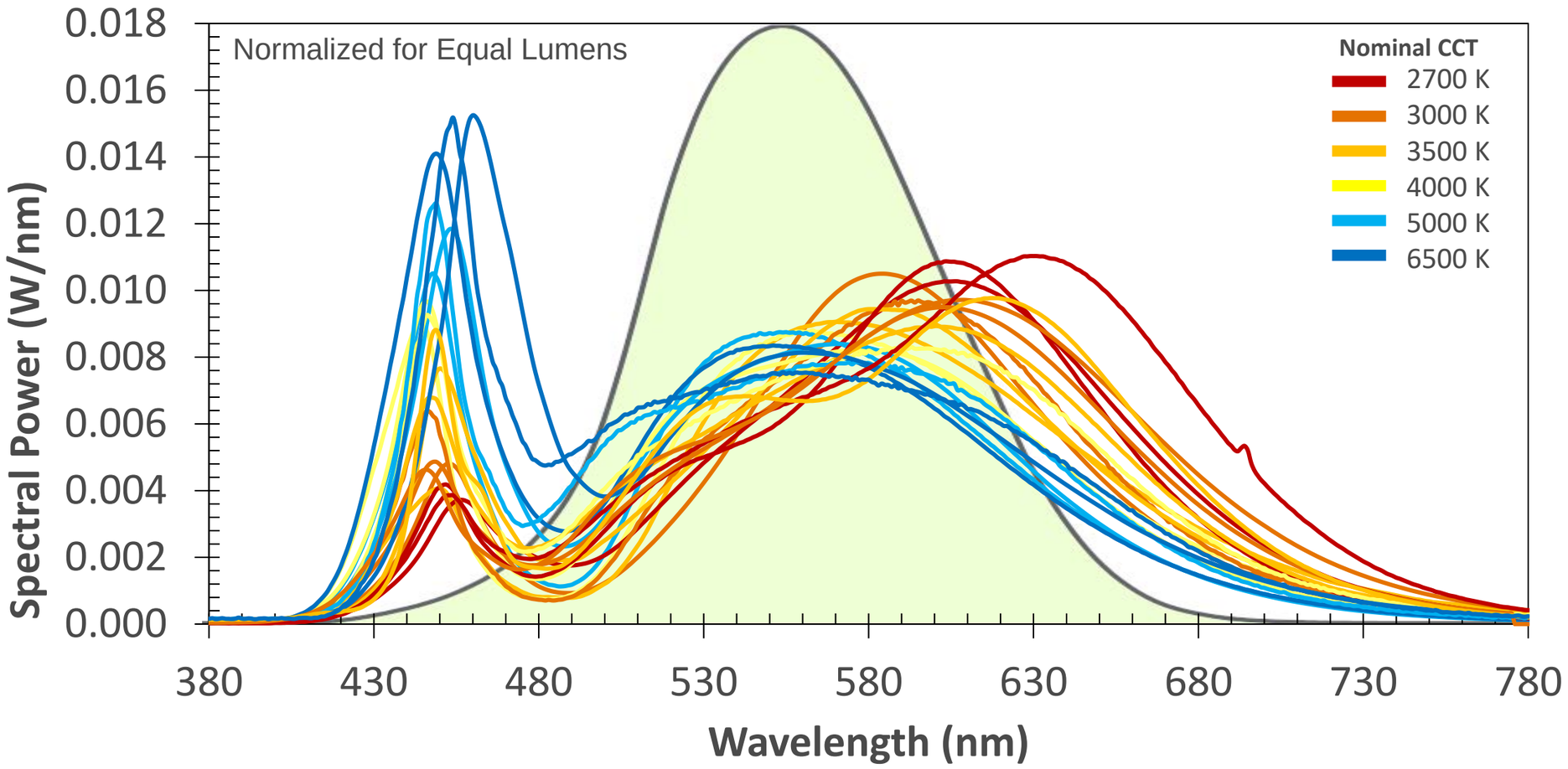

Red
Lime
Amber
Green
Cyan
Blue
Indigo

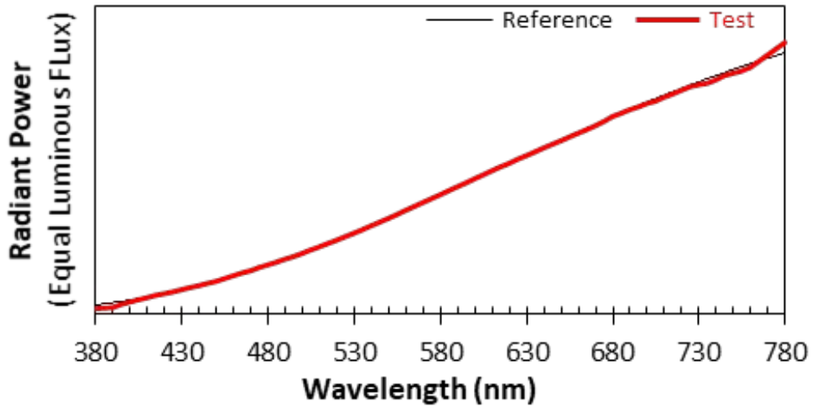

0.6
0.5
0.4
0.3
0.2
0.1
0.0
v'
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
u'

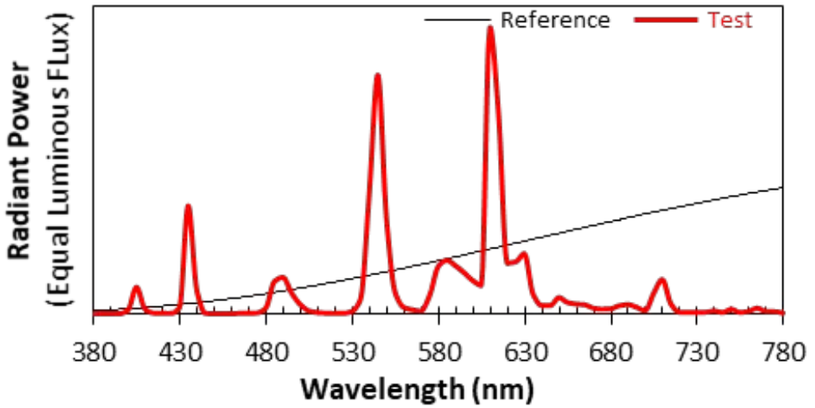

3.7
1.7
4.14
7.94

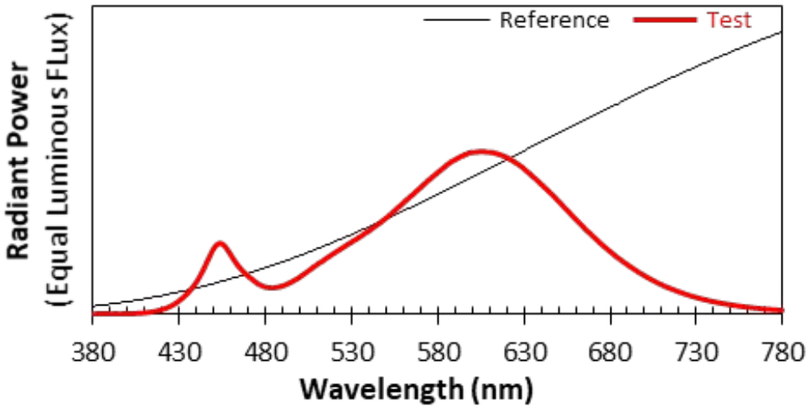

Equal luminous flux, equal chromaticity
R_f 68 – 94
R_g 79 – 120
$R_{cs,h1}$ -19% – 26%
R_t 88 – 96
CRI 43 – 95
R_9 -120 – 98
M/P 0.6 – 1.1
S/P 1.4 – 2.2
LER 286 – 352
Spectral Power (W/nm)
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
380
430
480
530
580
630
680
730
780
Wavelength (nm)

Status Quo: Given a CCT and minimum color fidelity, maximize lumens/watt.

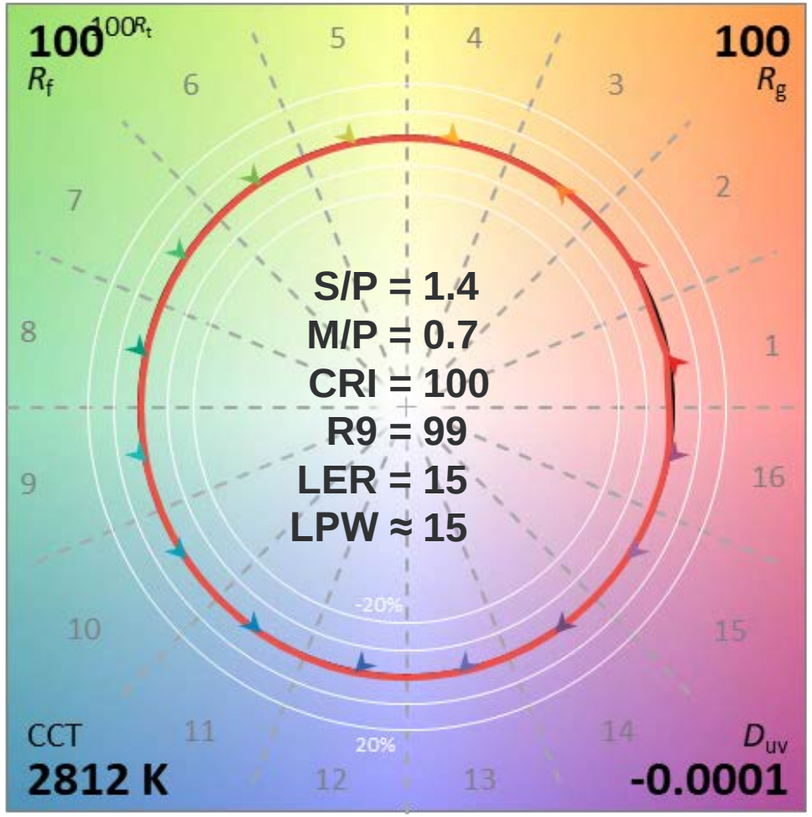




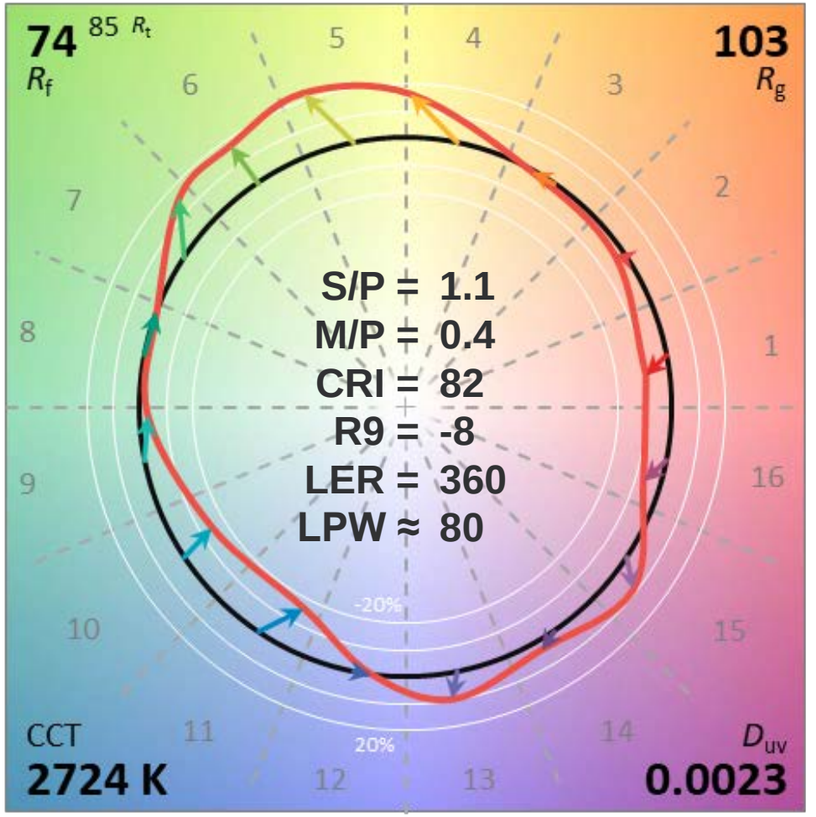




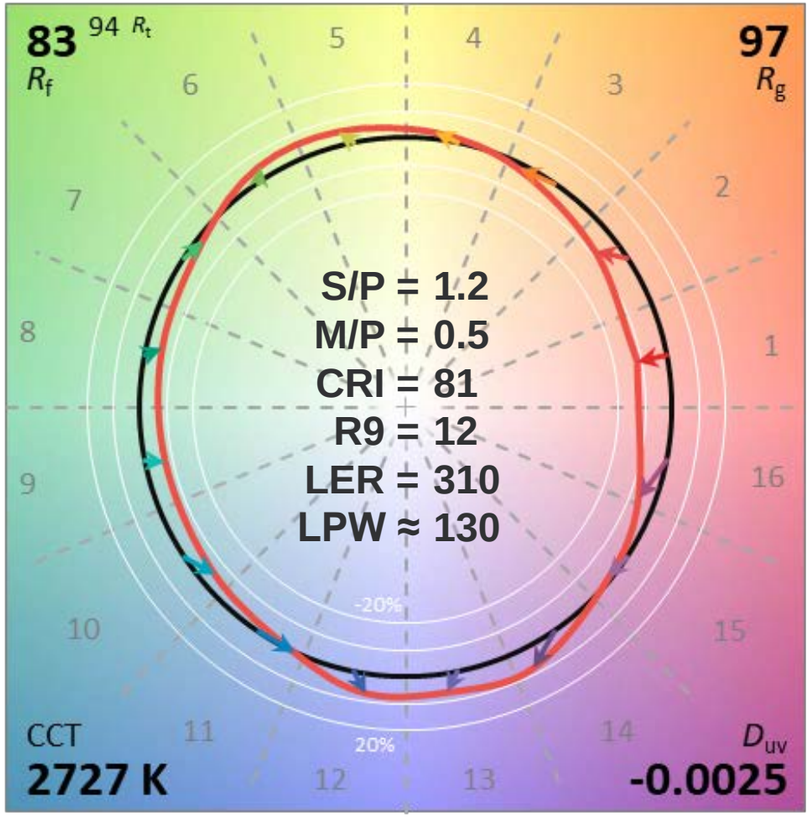
P1 V- F1



P3 V- F-



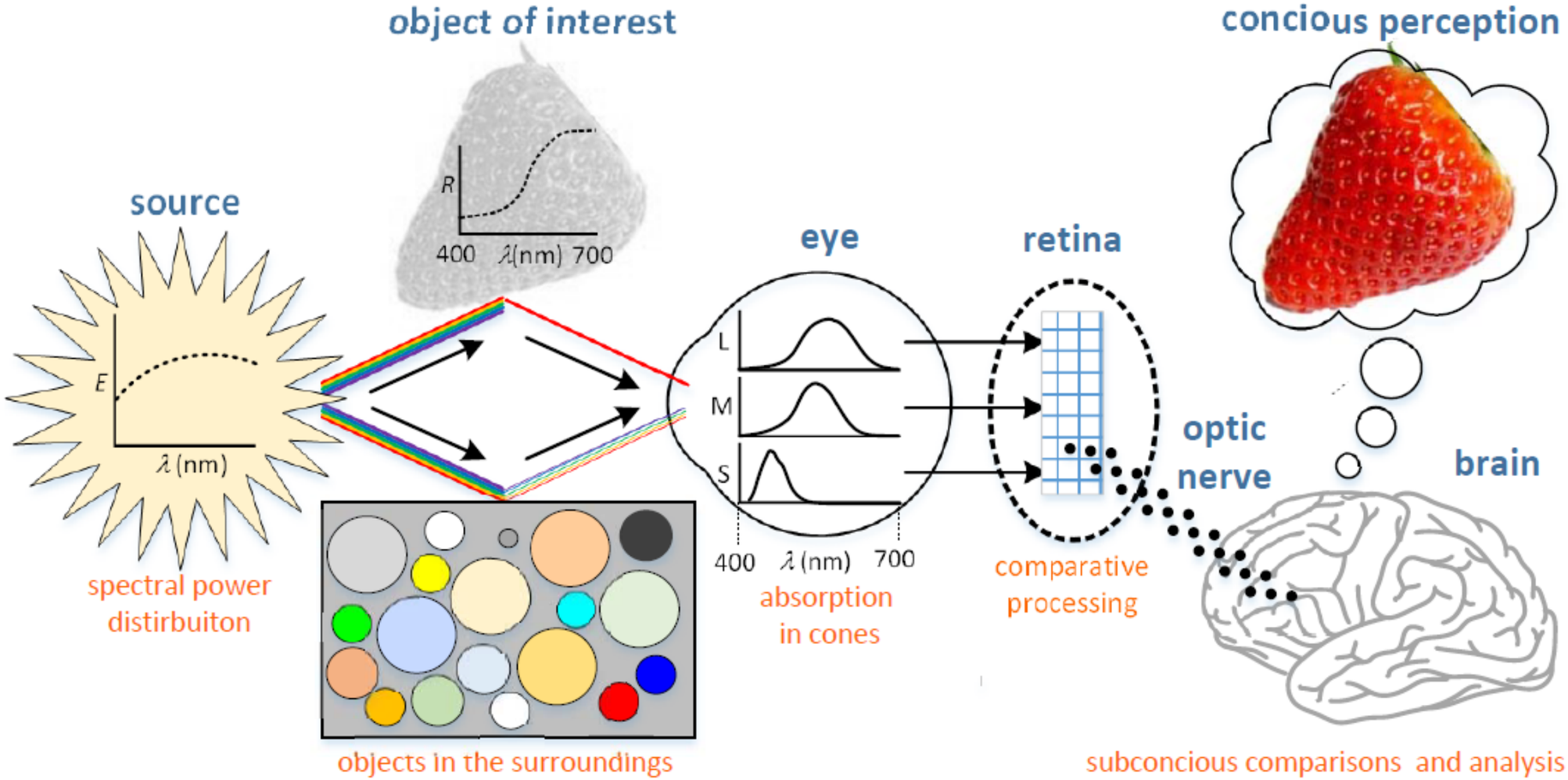
P3 V- F-



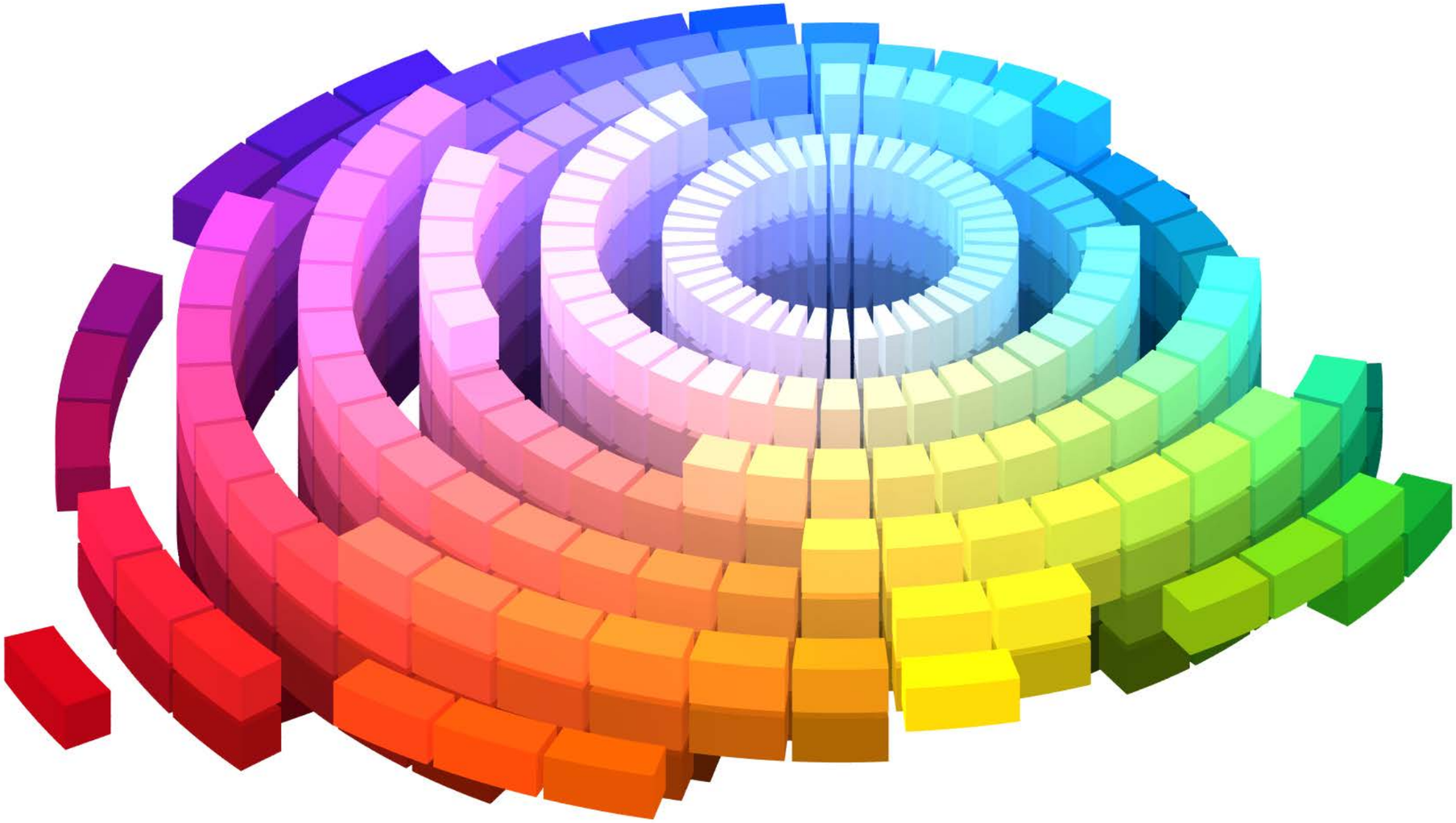
What will it take to change the status quo?

New metrics?
Induce demand / does anyone care?
Material R&D?
Patent barriers?
Cost?
Reevaluation of Tradeoffs?

How Vision Senses Surface Colors

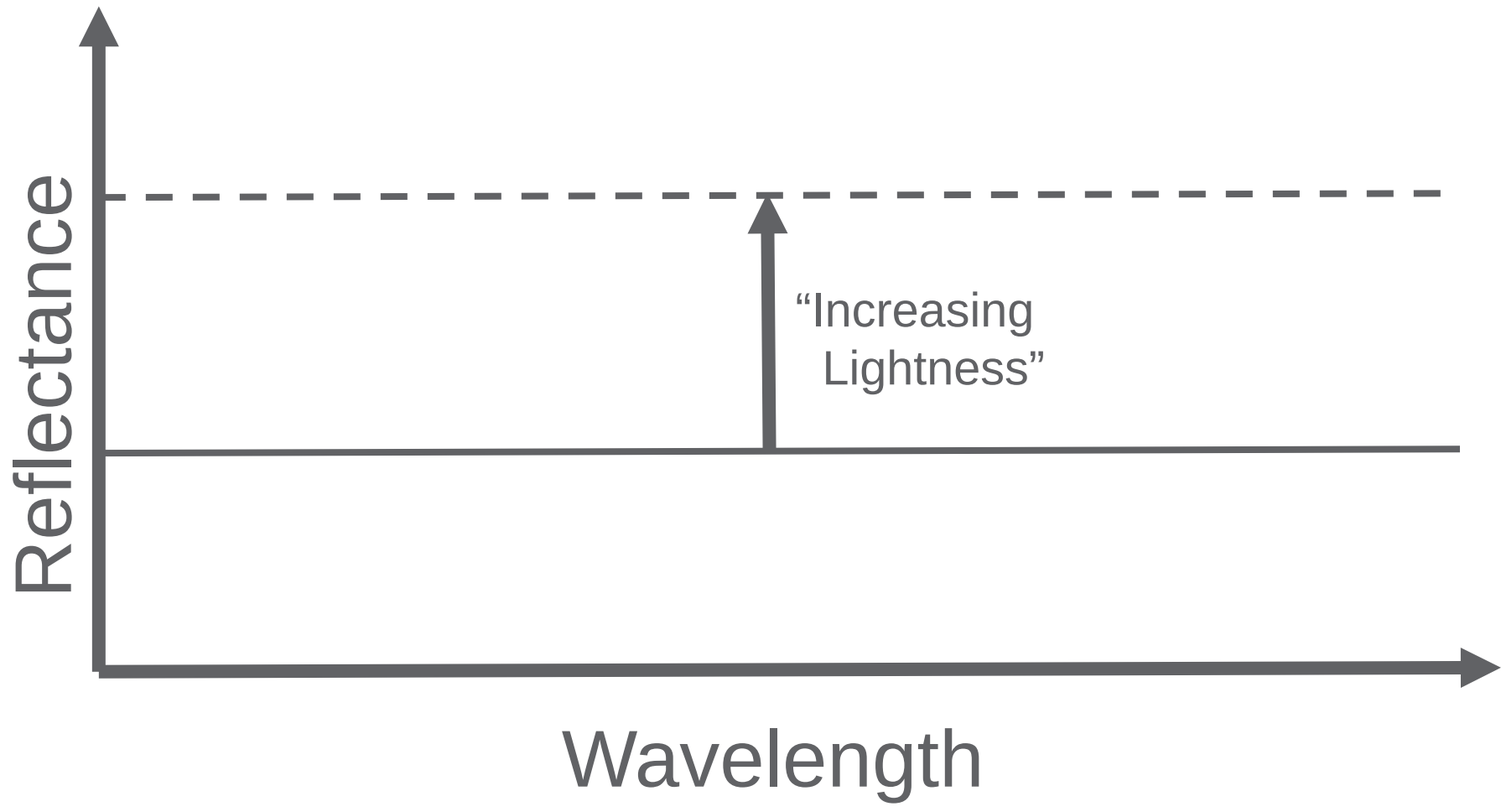


How Vision Senses Surface Colors

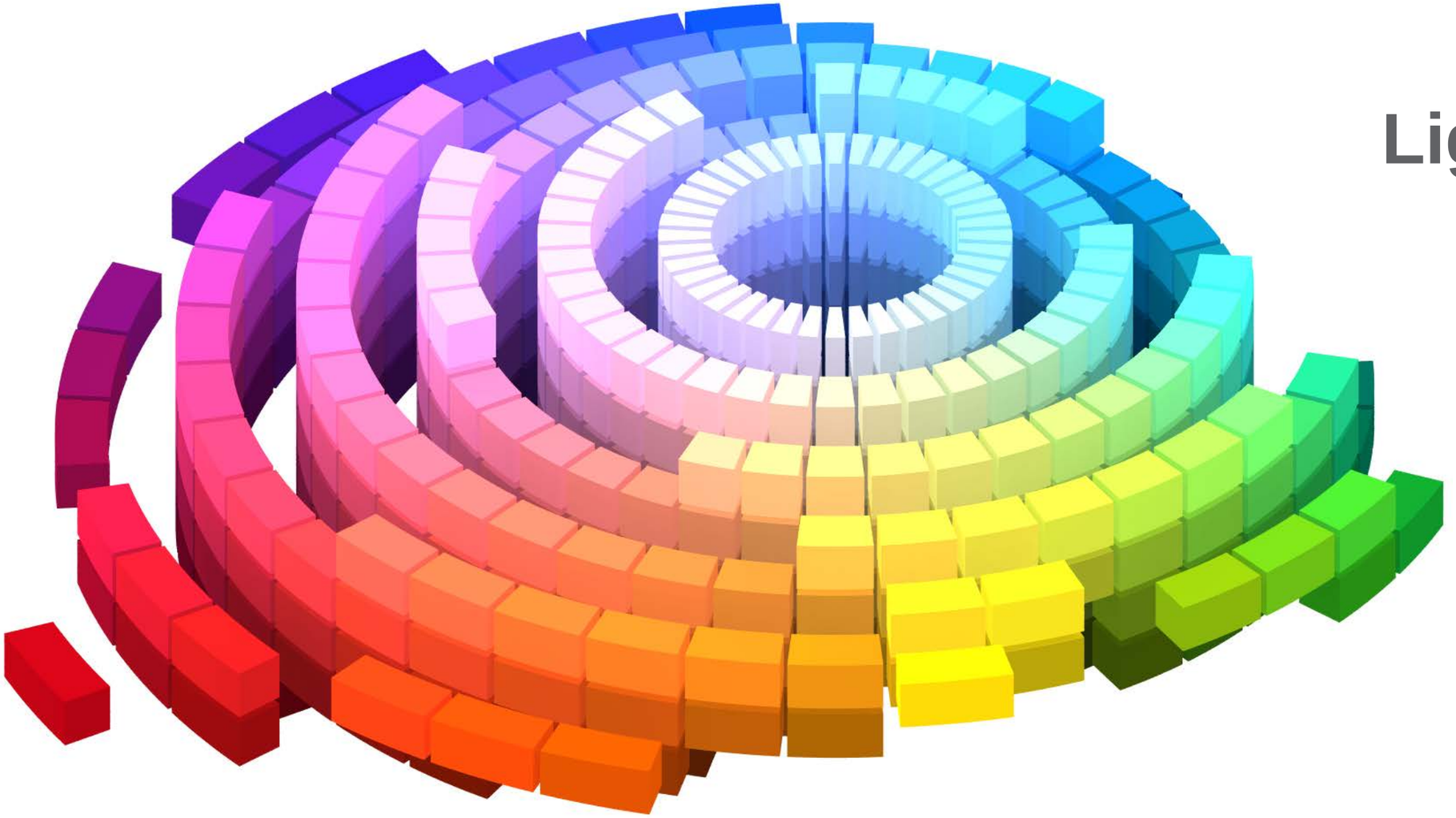


How Vision Senses Surface Colors

A Surface's Color Relates to its Spectral Reflectance Function



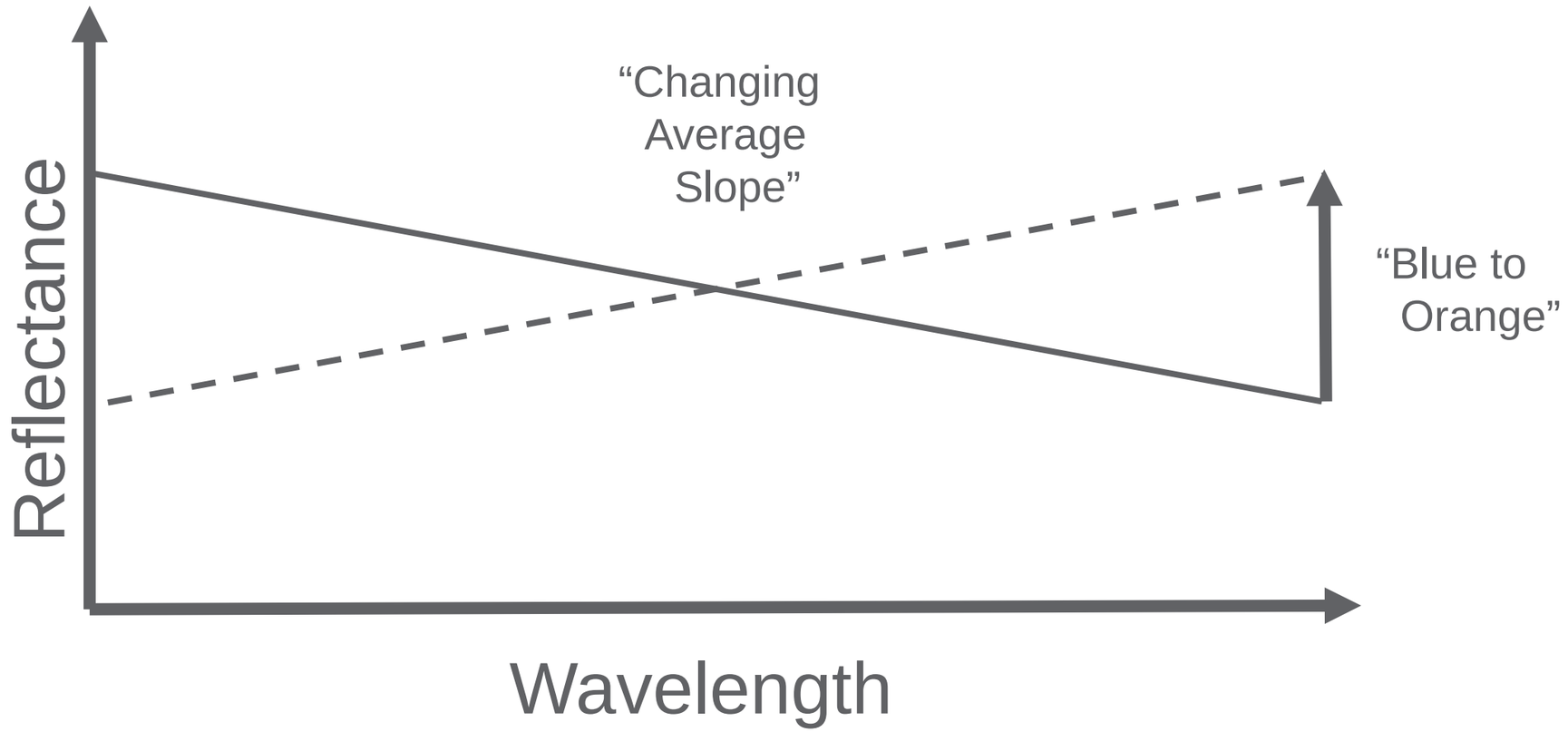
How Vision Senses Surface Colors

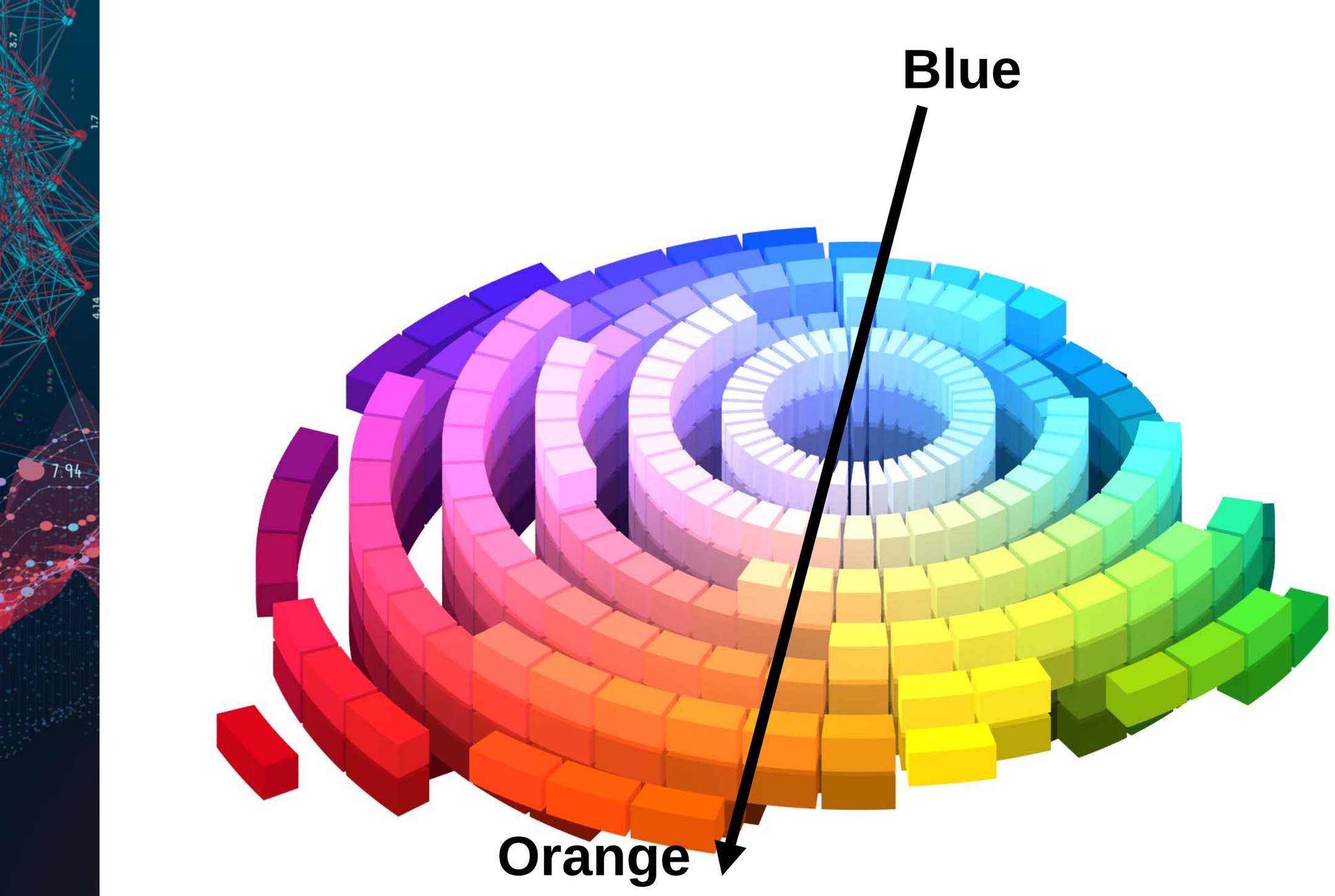


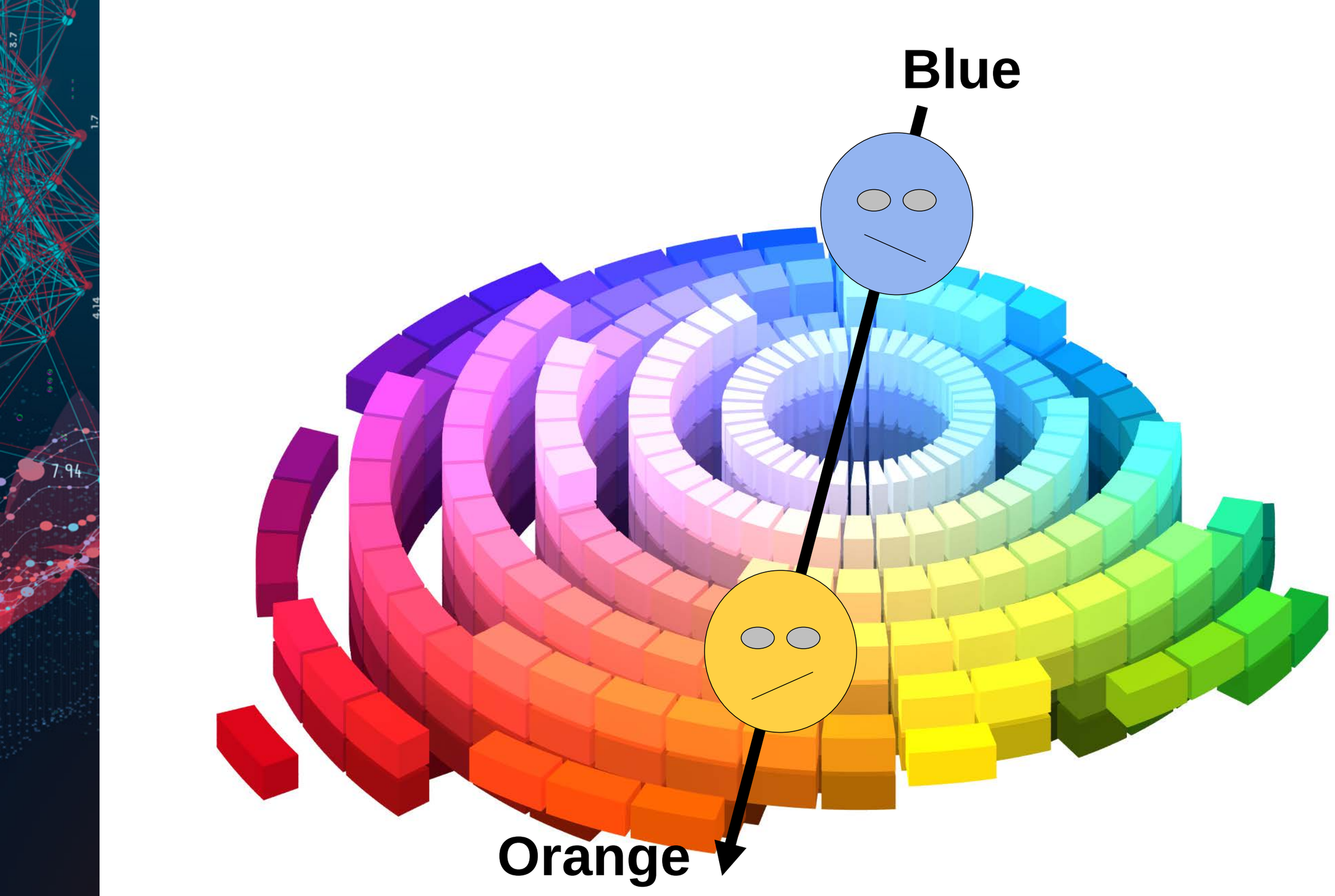
Lightness:

How Vision Senses Surface Colors

A Surface's Color Relates to its Spectral Reflectance Function

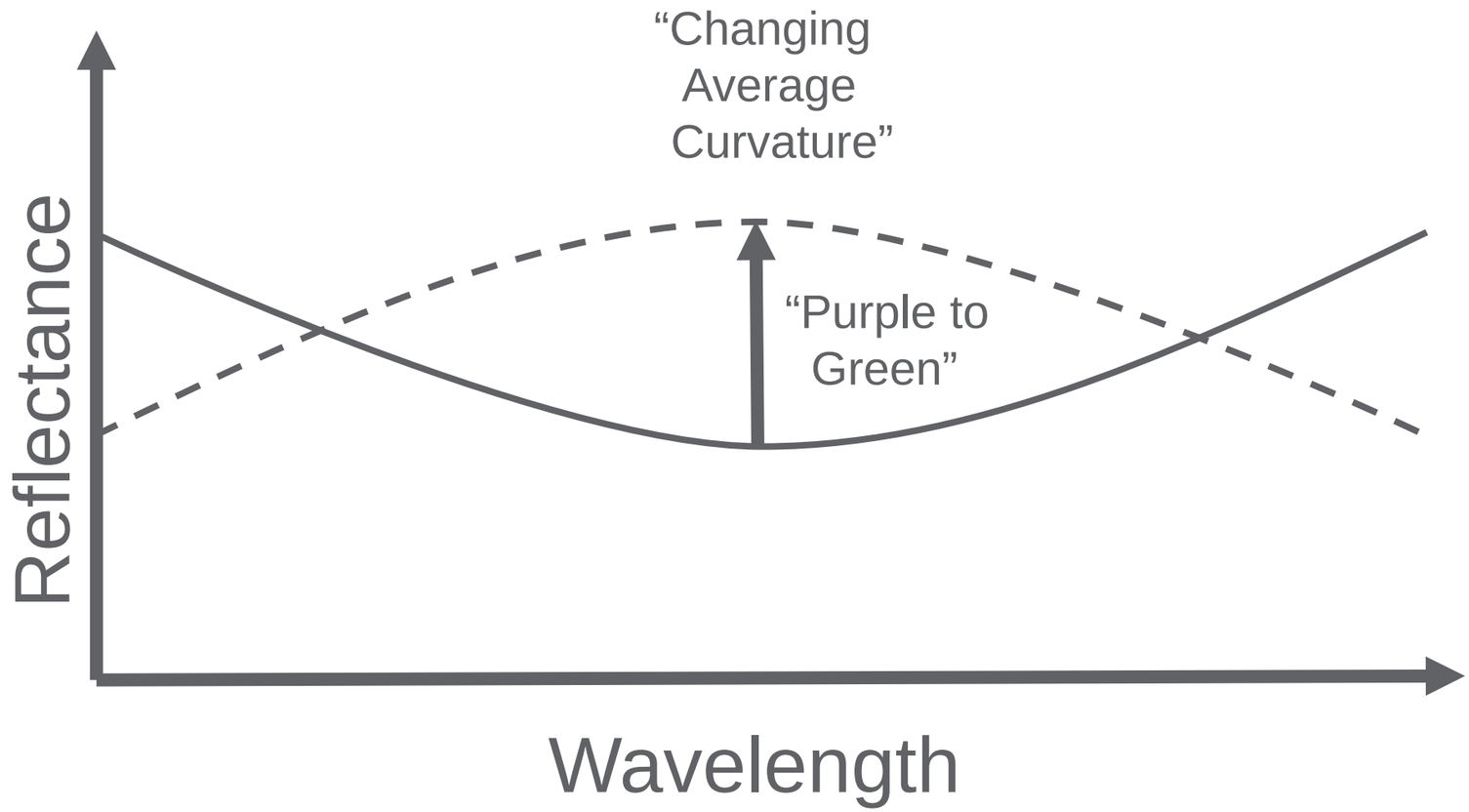


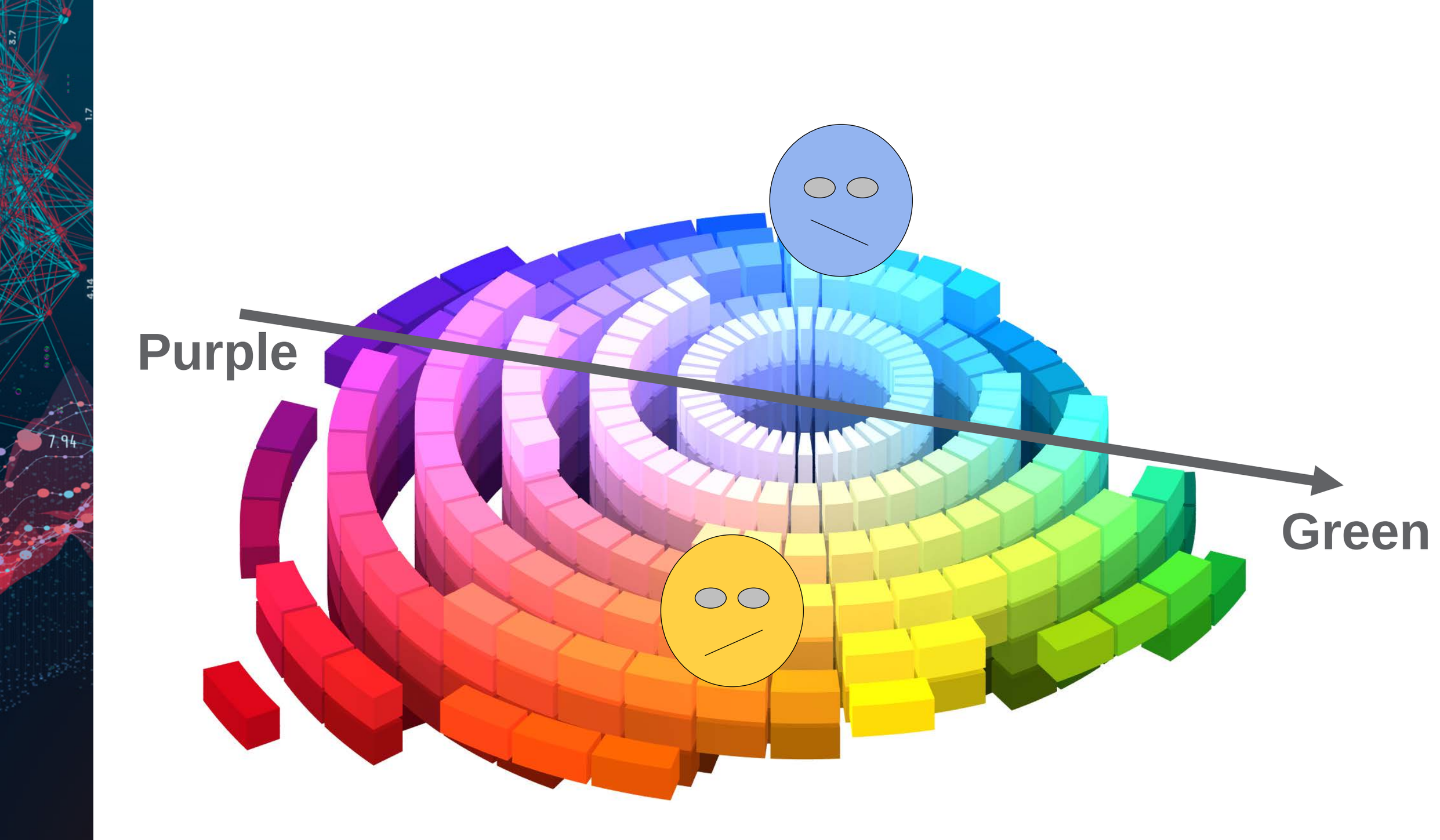

Blue
Orange

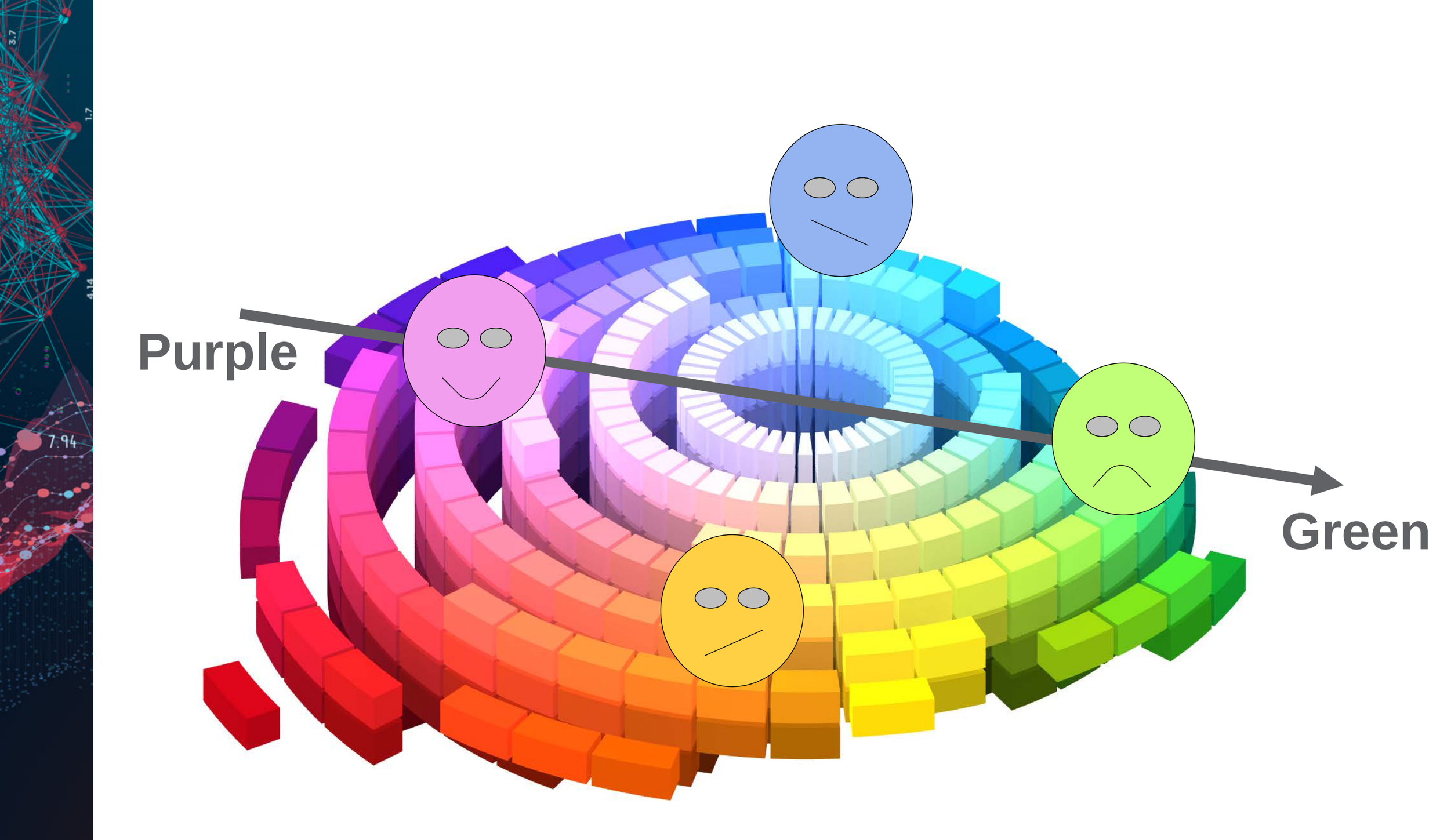

Blue
Orange

How Vision Senses Surface Colors

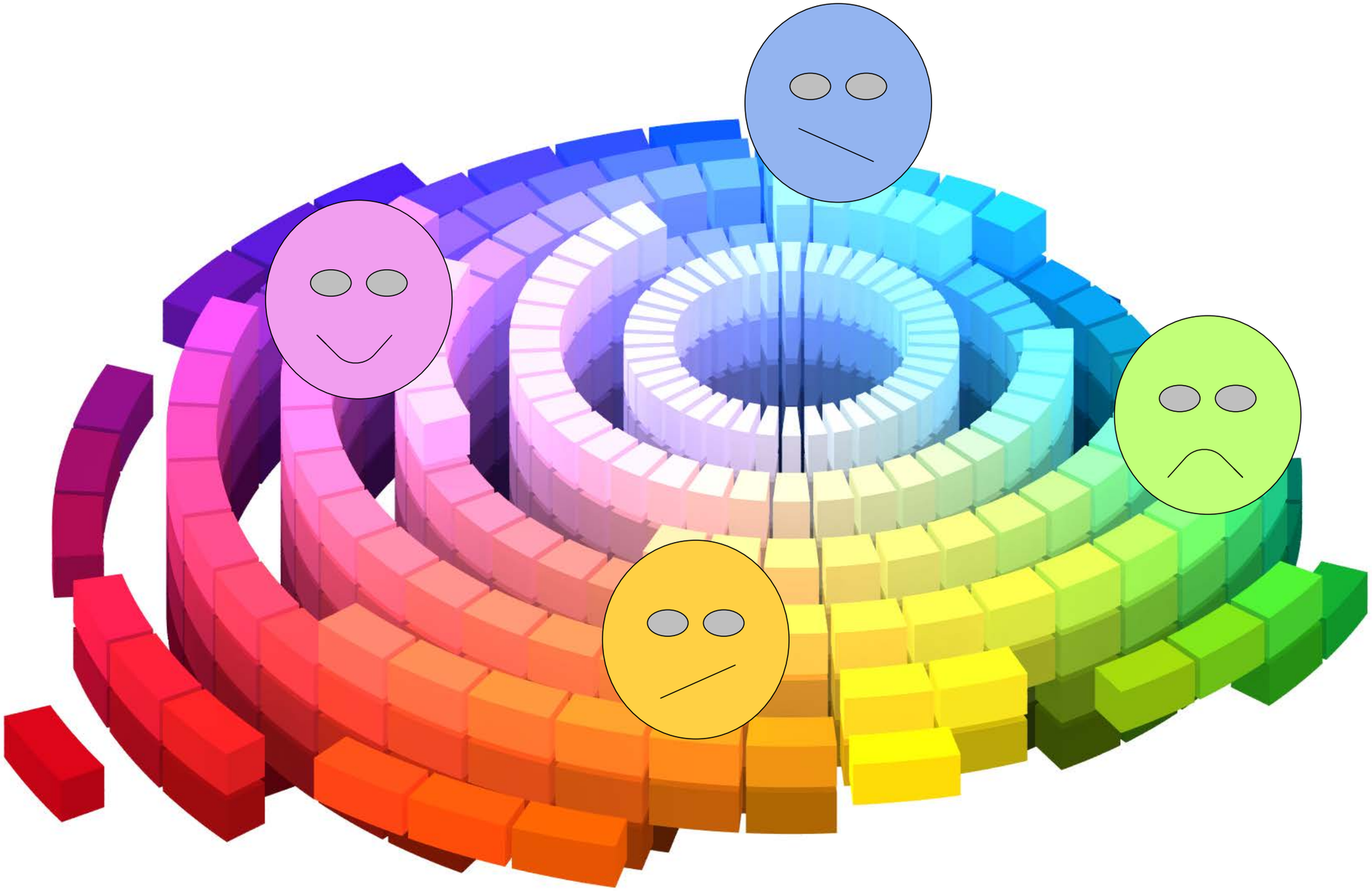
A Surface's Color Relates to its Spectral Reflectance Function



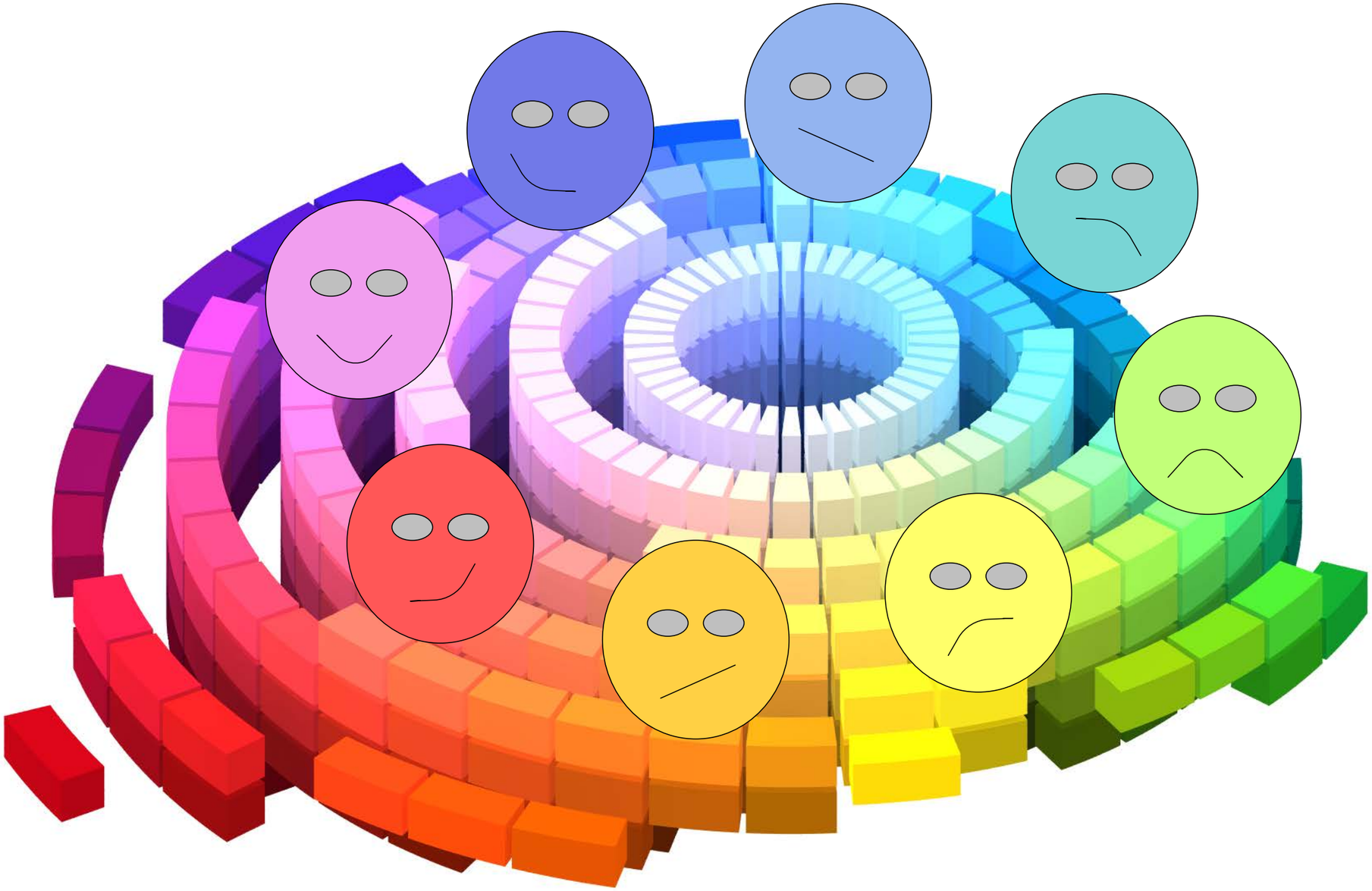

Purple
Green


Purple
Green

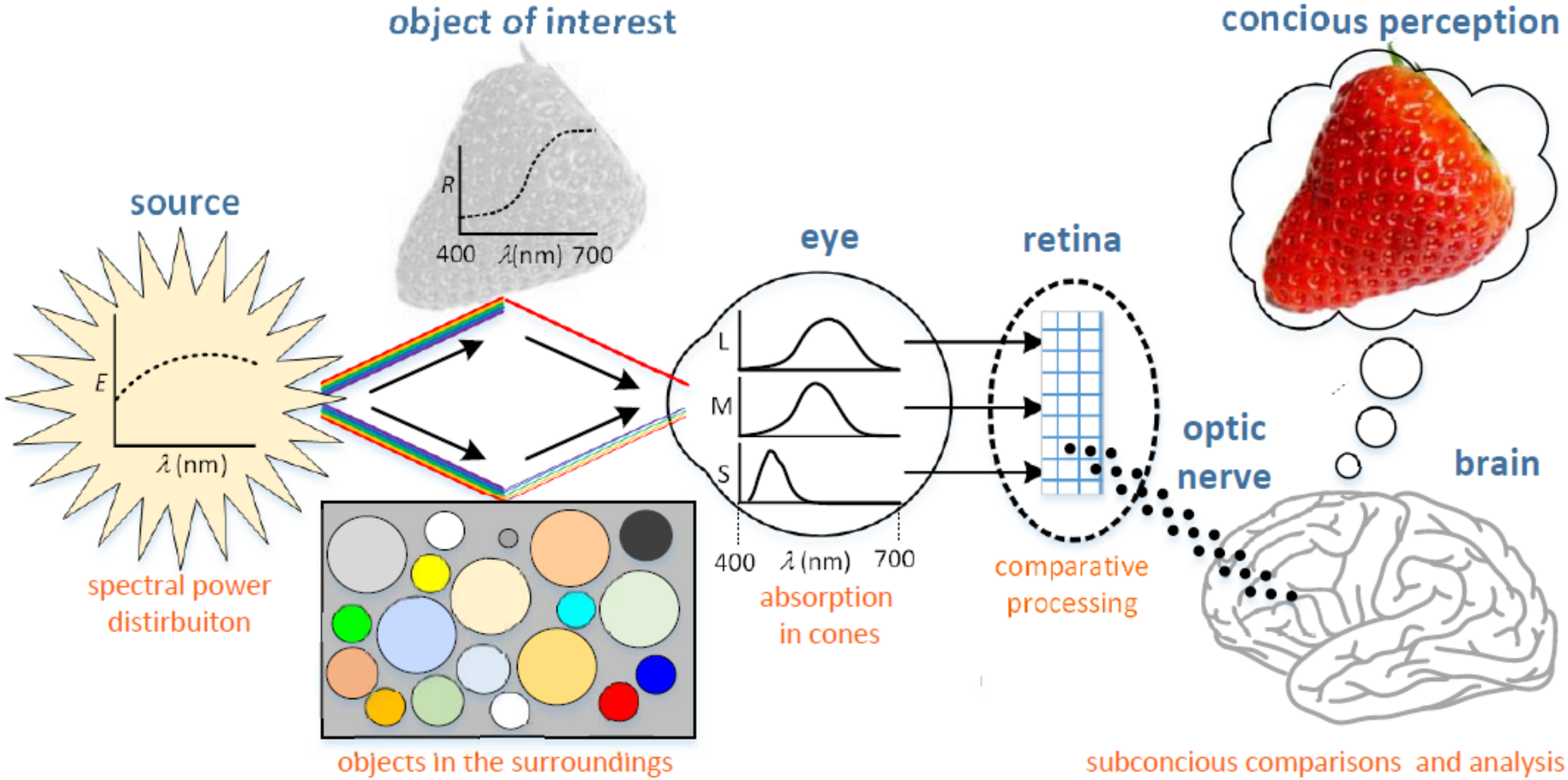

3.7
1.7
4.14
7.94



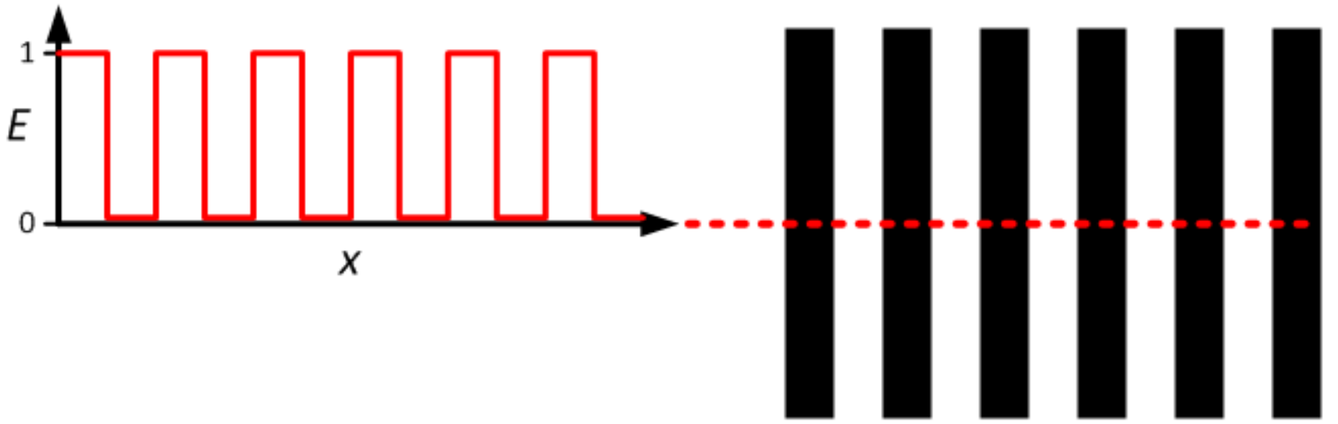

3.7
1.7
4.14
7.94

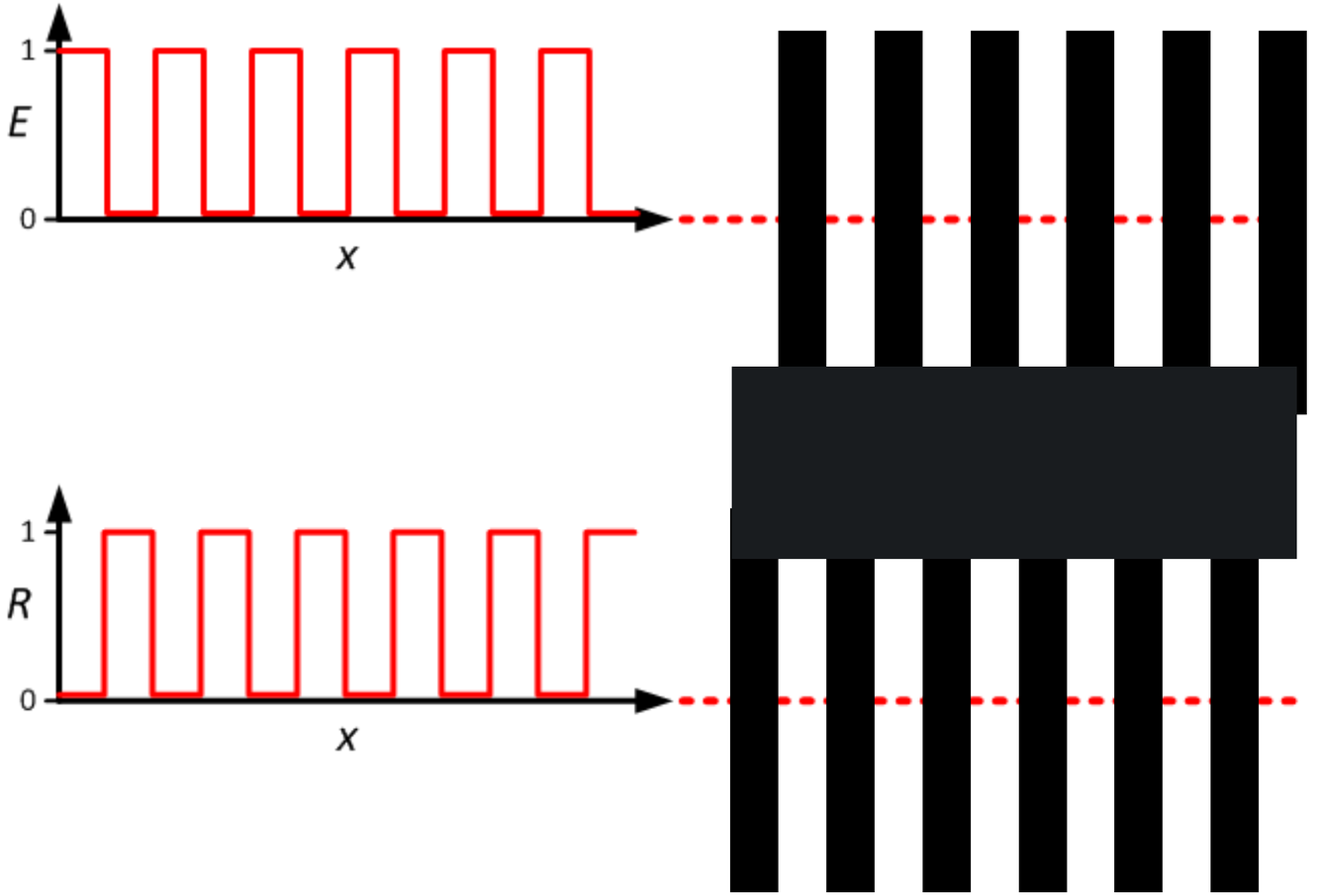


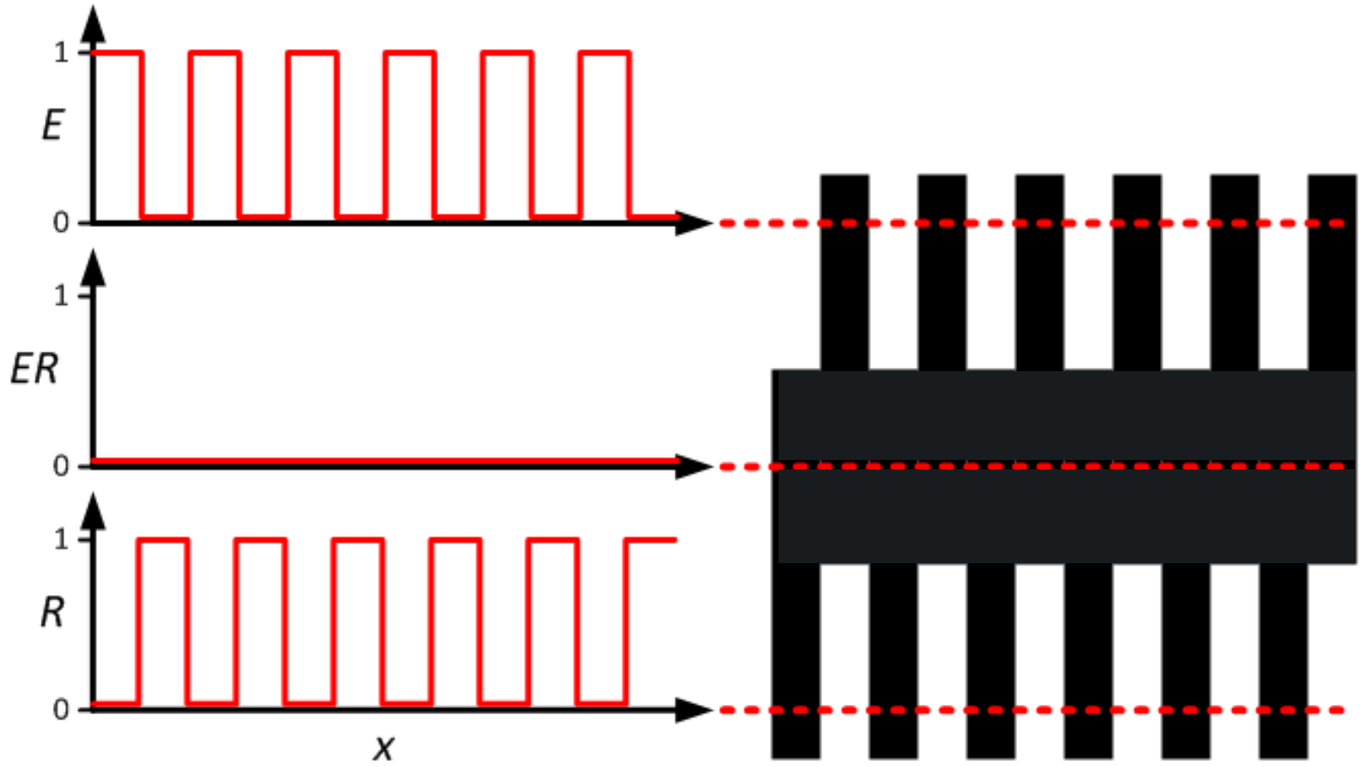
How Vision Senses Surface Colors

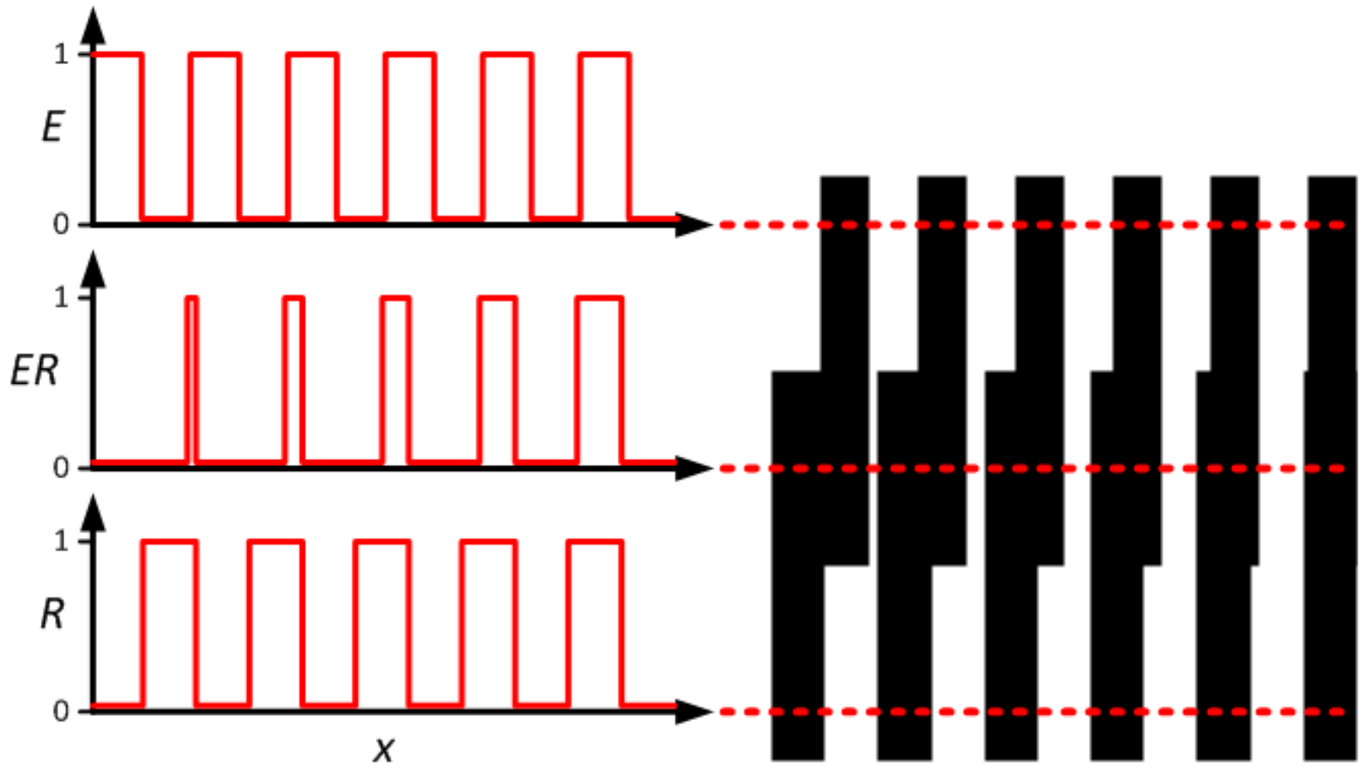


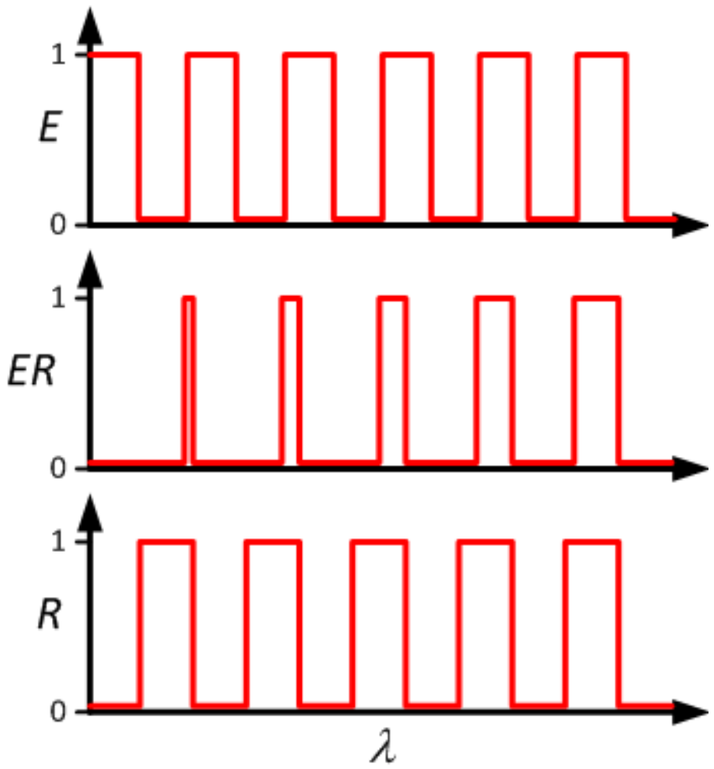

3.7
1.7
4.14
7.94


1
E
0
x


1
E
0
x
1
R
0
x


1
E
0
1
ER
0
1
R
0
x


1
E
0
1
ER
0
1
R
0
x



“white” light

orange reflection!

“gray” surface

Poor Rendering is Due to Spectral Interference !

FACTS ABOUT COLOR RENDERING AND SOME COMMON MISCONCEPTIONS

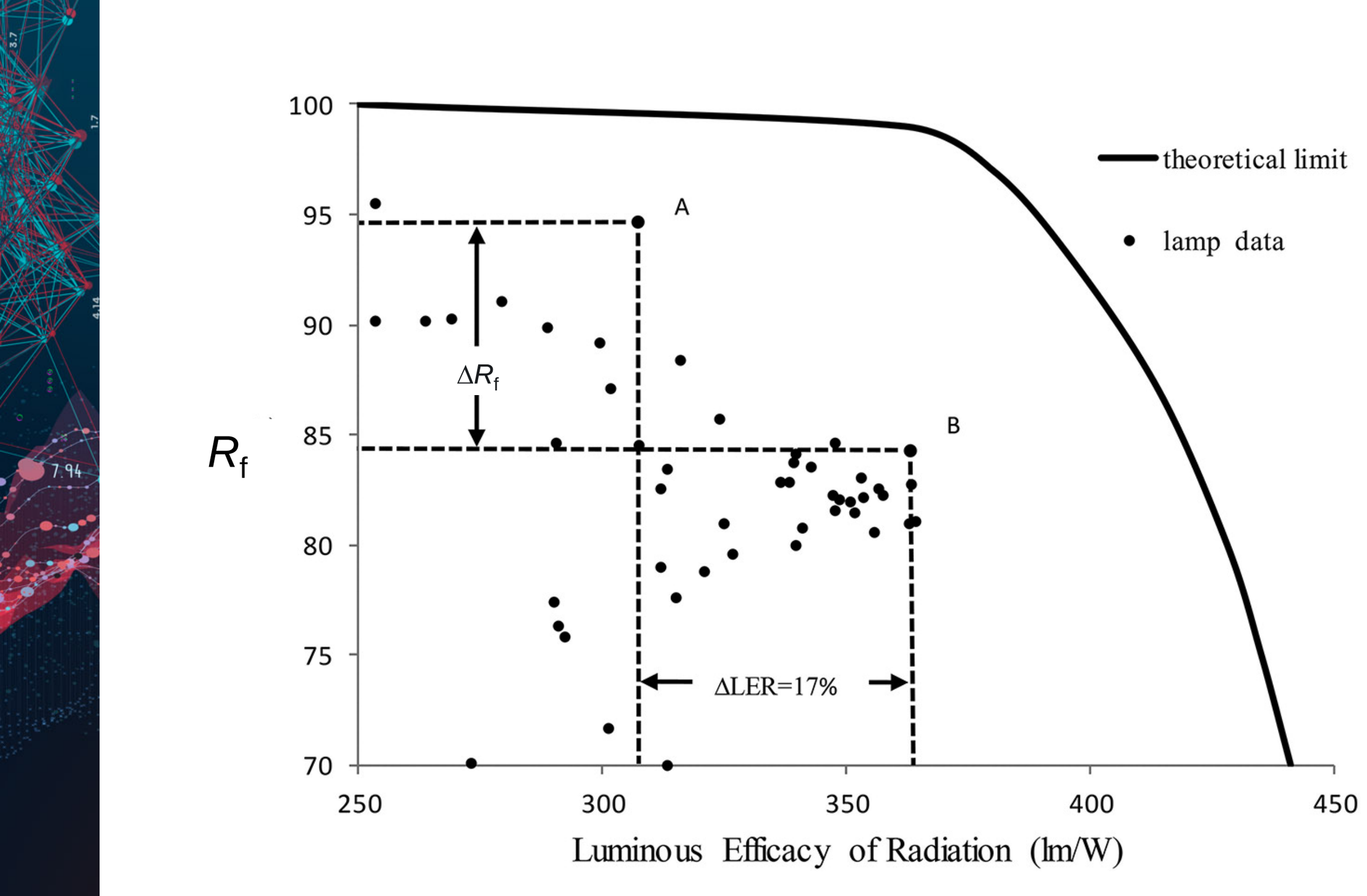
1. The IES/CIE Color Fidelity Index Is a number less than or equal to 100, but it is not a percentage.
2. If two objects look the same under daylight, they may not match under a poor color rendering source.
3. Lamps with the same color rendering score may have very different SPDs and cause different shifts.

FACTS ABOUT COLOR RENDERING AND SOME COMMON MISCONCEPTIONS

4. People cannot adapt to poor color rendering

5. Color rendering cannot be judged by looking directly at a light source.

6. Light source color rendering is a completely different property than light source color.


100
95
90
85
80
75
70
250
300
350
400
450
R_f
Luminous Efficacy of Radiation (lm/W)
theoretical limit
lamp data
A
B
ΔR_f
ΔLER=17%

Consider An Important Design Choice:

Design A
Design B

Most often, most designers select Design A
Yet usually, Design B is better for occupants

A look to the future:

Excellent Color Rendering (nearly) Everywhere

Requiring: Excellent Metrics for Color Rendering

ANSI/IES TM-30-18

What is it?

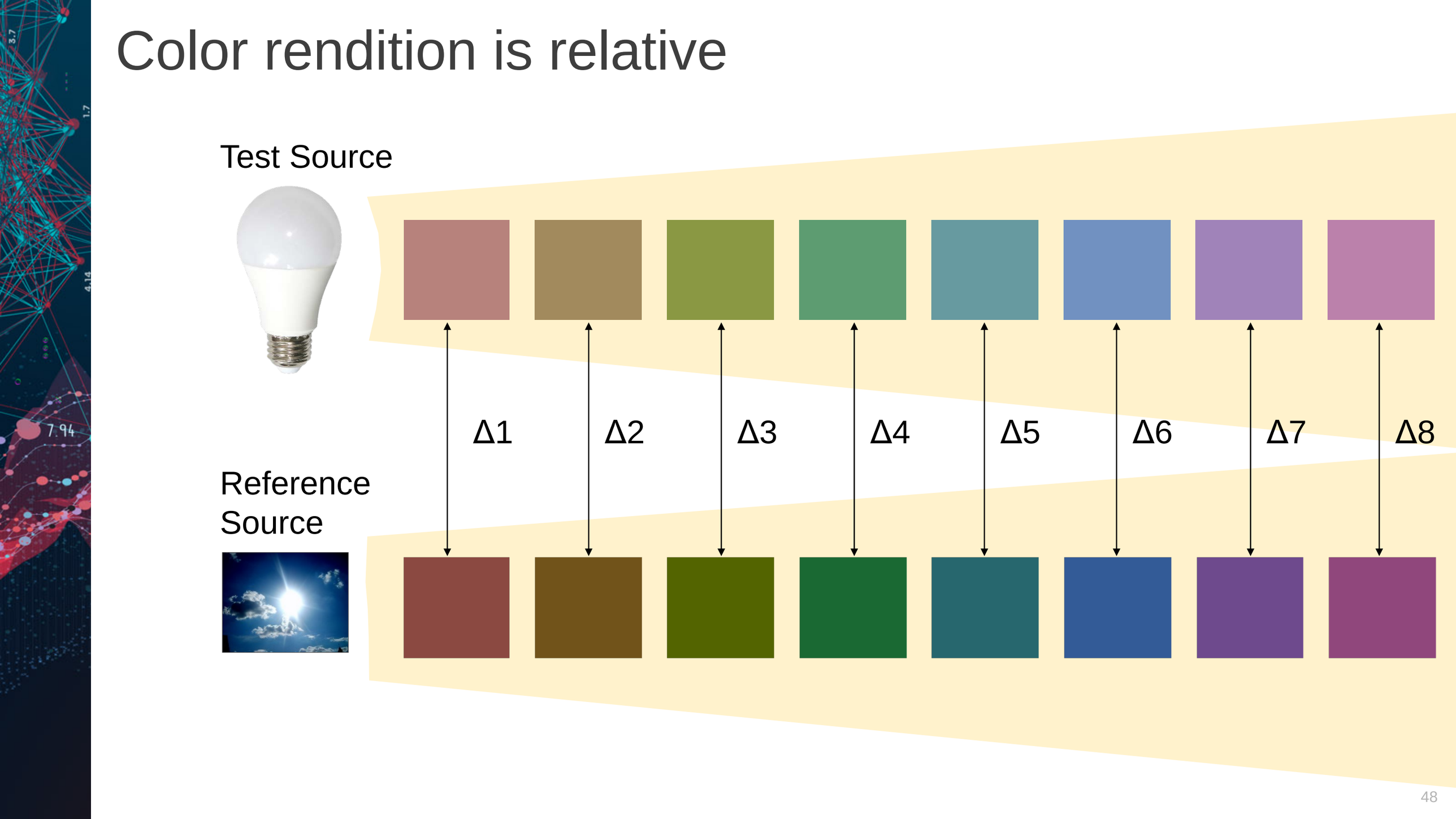
Review: color rendering, defined

"Effect of an illuminant on the color appearance of objects by conscious or subconscious **comparison** with their color appearance **under a reference illuminant."**

- International Commission on Illumination (CIE)

Color rendition is ***relative***

Color rendition is relative



Limitation of considering only color fidelity

Perfect Fidelity

Limitation of considering only color fidelity

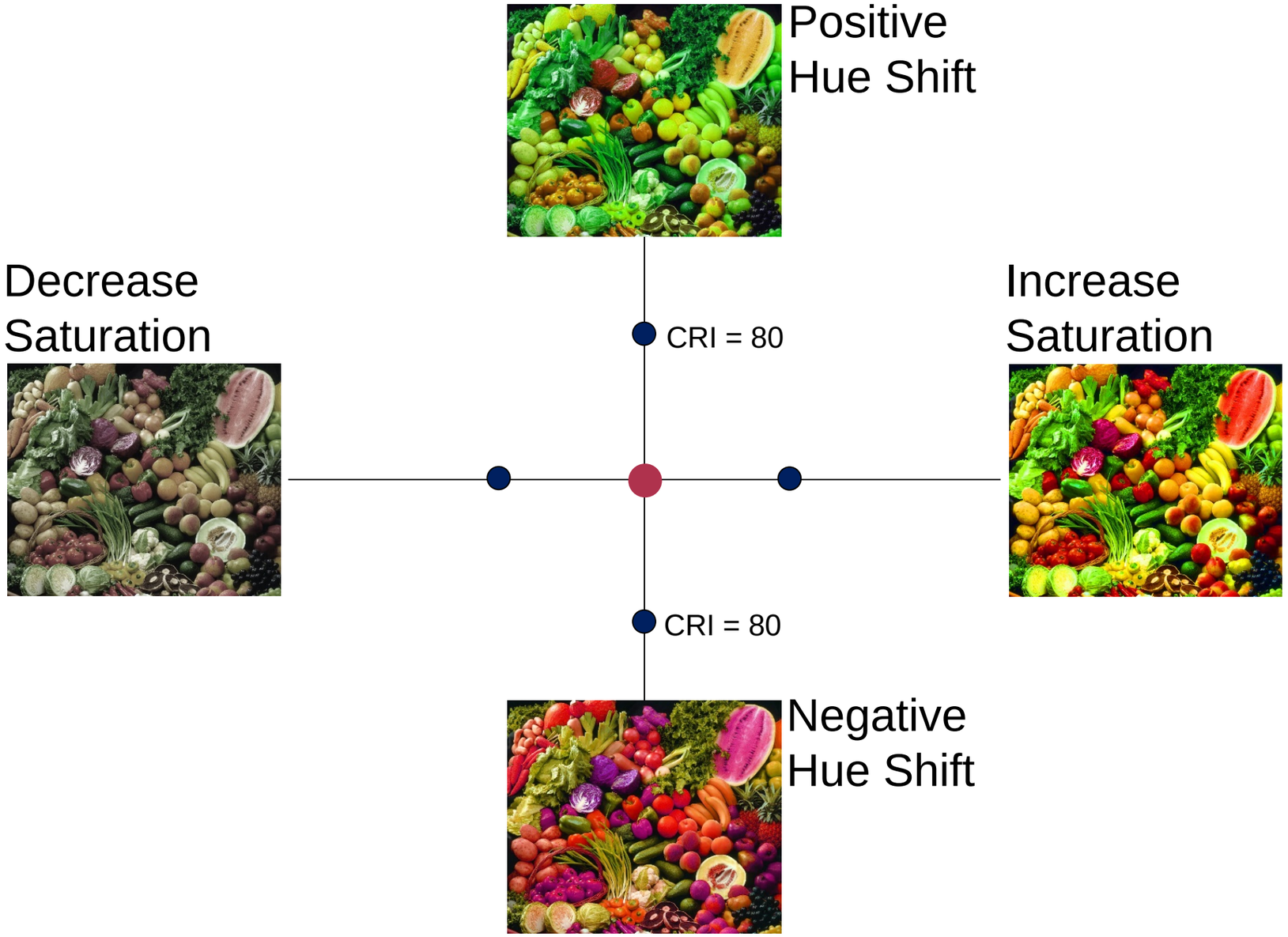
Decrease Saturation

CRI = 80

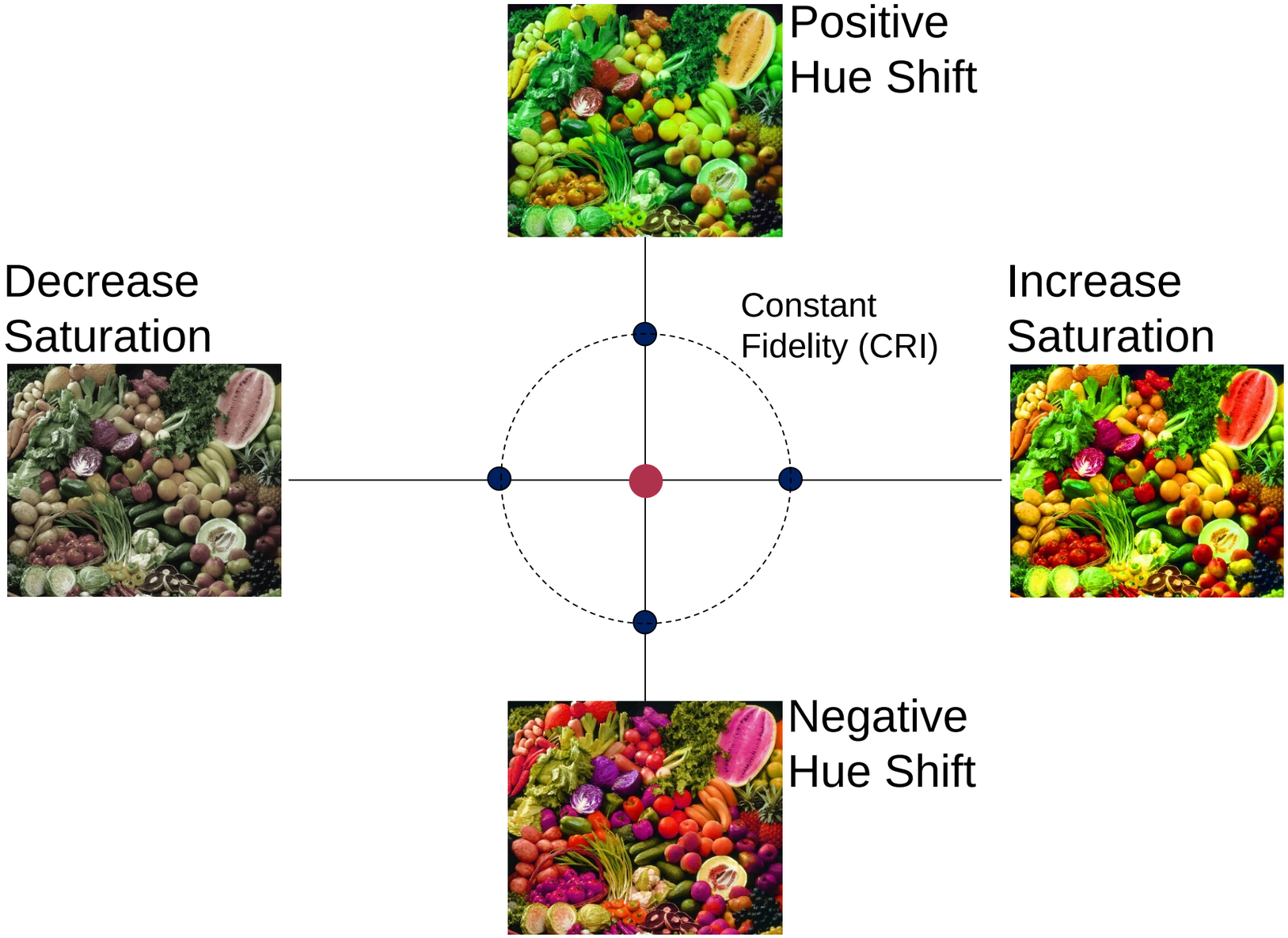
CRI = 80

Increase Saturation

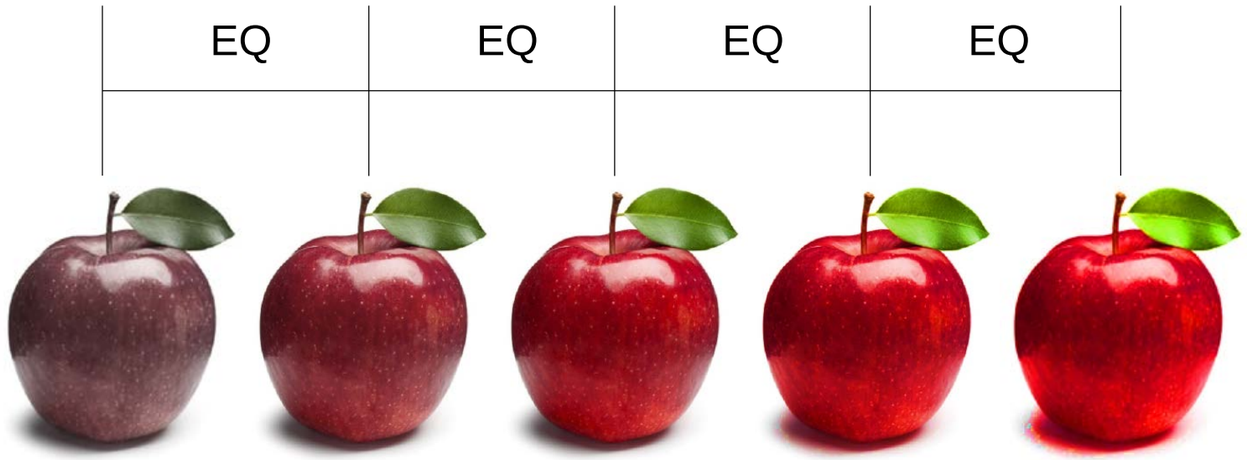
Limitation of considering only color fidelity



Limitation of considering only color fidelity



Limitation of considering only color fidelity



$R_{f,h1}$	$R_{f,h1}$	$R_{f,h1}$	$R_{f,h1}$	$R_{f,h1}$
60	80	100	80	60
$R_{cs,h1}$	$R_{cs,h1}$	$R_{cs,h1}$	$R_{cs,h1}$	$R_{cs,h1}$
-15%	-8%	0%	+8%	+15%

(Color appearances not accurate. For educational purposes only)

How many metrics are contained within TM-30?

How many metrics are contained within TM-30?

At least 149

(1) Average Color Fidelity, R_f

(1) Average Gamut Area, R_g

(16) Local Chroma Shift, $R_{cs,hj}$

(16) Local Hue Shift $R_{h1,hj}$

(16) Local Color Fidelity, $R_{f,hj}$

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

How many should be minimally considered?

How many should be minimally considered?

4

The main 4 metrics

e.g. “CRI”

Average Fidelity, R_f: indicates the **average** deviation from the source’s reference illuminant. It only indicates the **magnitude** of the difference, not the direction.

e.g. CQS Q_g GAI

Average Gamut Area, R_g: indicates the **average** increase or decrease in saturation relative to the source’s reference illuminant.

e.g. R_9

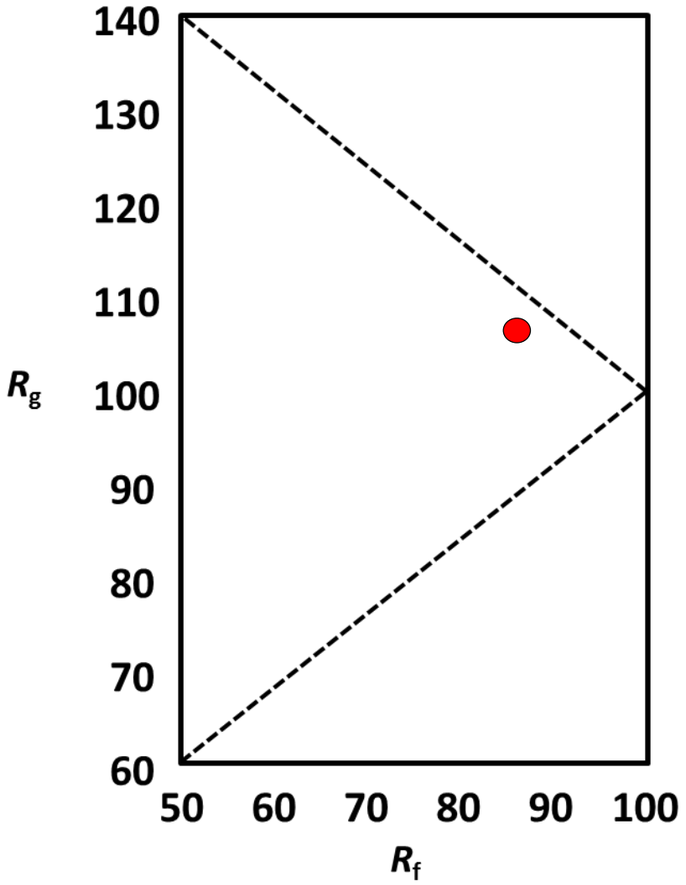
Local Color Fidelity Hue Bin 1 (Red), $R_{f,h1}$: indicates the **specific** deviation, relative to the source’s reference illuminant, for **red** hues.

e.g. *None*

Local Chroma Shift, $R_{cs,h1}$: indicates the **specific** increase or decrease in saturation, relative to the source’s reference illuminant, for **red** hues.

Metric Quizzzzzzzzzzz

TM-30 Metric Quiz



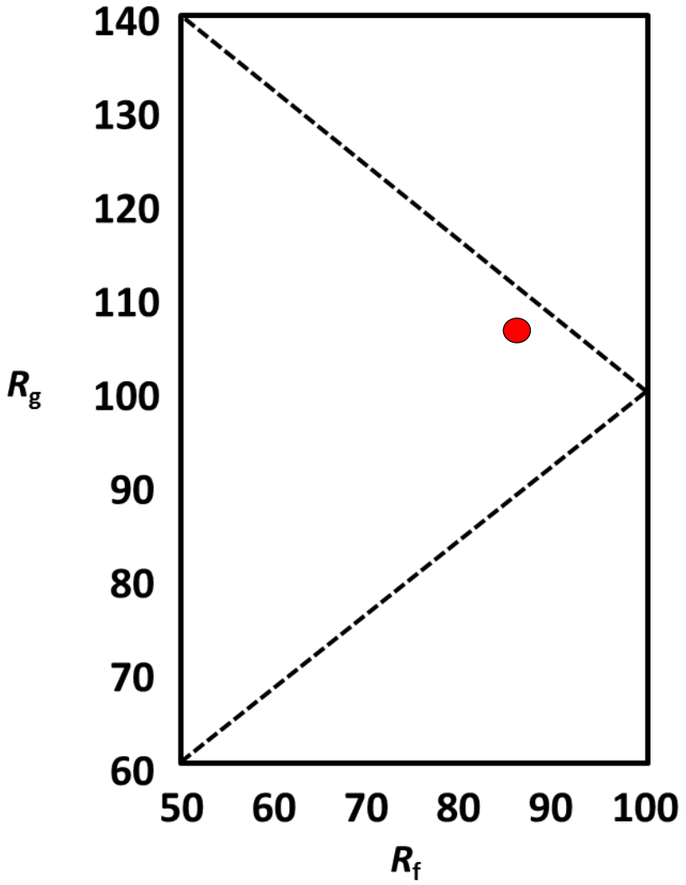
What can we say about this point?

R_f = 87, R_g = 109

R_f = 87 — This light source causes distortions relative to ref source (don't know direction of distortion)

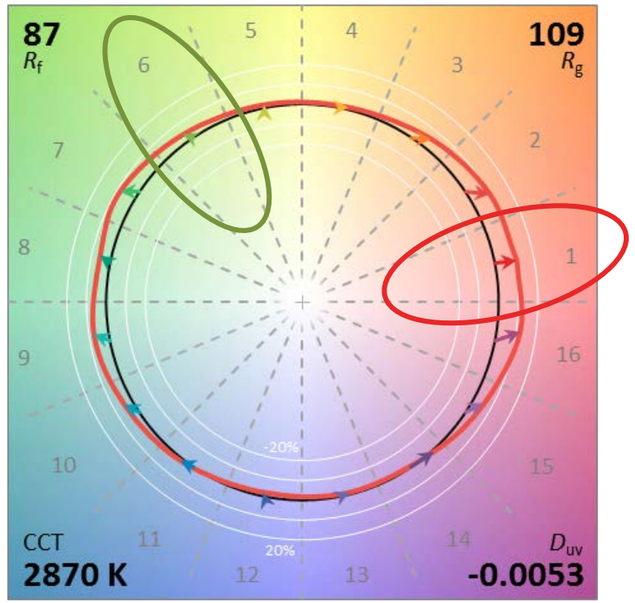
R_g = 109 — This light source, ON AVERAGE, increases the saturation of objects (relative to ref source). We don't know which hues are being enhanced.

TM-30 Metric Quiz



What can we say about this point?

R_f = 87, R_g = 109



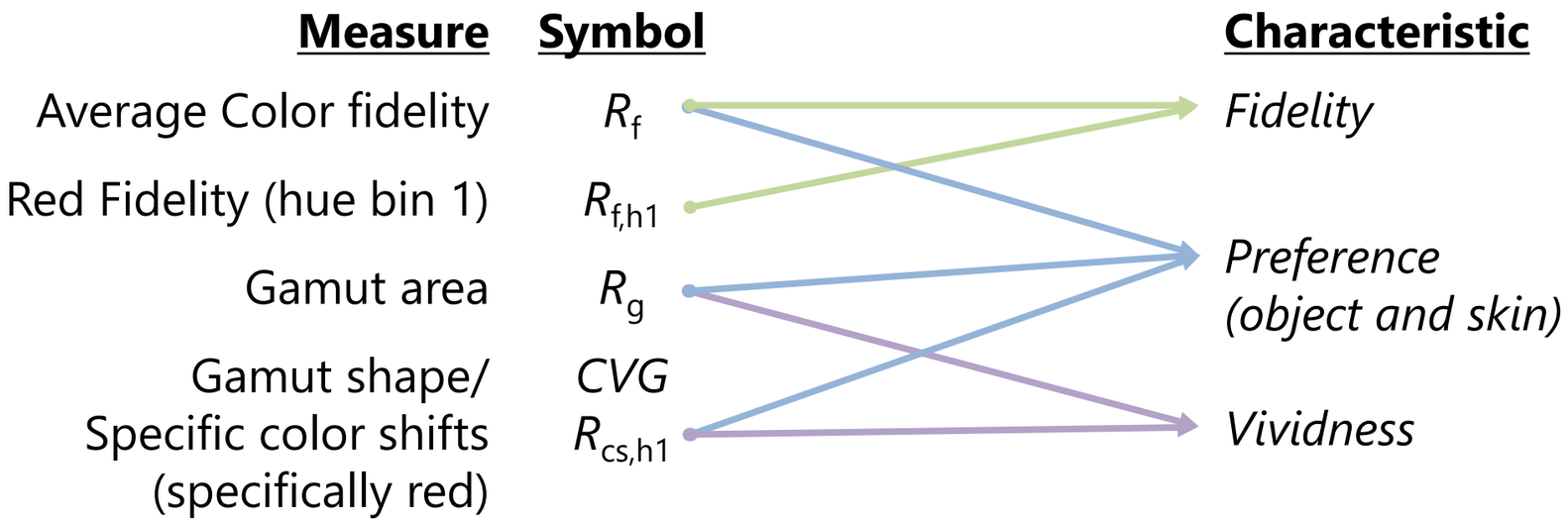
Relative to the ref source, this light source is:

- Increasing the average saturation of **RED** hues ($R_{cs,h1}$ = + 11%)
- *Slightly* increasing the saturation of green and **yellow-green** hues ($R_{cs,h6}$ = +4%)
- $R_{f,h1}$ < 100

ANNEX E

What is it?

IES TM-30 ANNEX E



IES TM-30 ANNEX E

Design Intent
The desired effect of color rendition on the illuminated environment.

Preference (P)	Vividness (V)	Fidelity (F)

IES TM-30 ANNEX E

Design Intent
The desired effect of color rendition on the illuminated environment.

Priority Level The balance between allowing tradeoffs and increasing the likelihood of meeting the design intent.	Preference (P)	Vividness (V)	Fidelity (F)
1			
2			
3			

Assumptions: 200-700 lux, polychromatic environment, single chromaticity

IES TM-30 ANNEX E

Design Intent
The desired effect of color rendition on the illuminated environment.

Priority Level The balance between allowing tradeoffs and increasing the likelihood of meeting the design intent.	Preference (P)	Vividness (V)	Fidelity (F)
1	P1: $R_f \geq 78$; $R_g \geq 95$; $-1\% \leq R_{cs,h1} \leq 15\%$		
2	P2: $R_f \geq 75$; $R_g \geq 95$; $-7\% \leq R_{cs,h1} \leq 15\%$		
3	P3: $R_f \geq 70$; $R_g \geq 88$; $-12\% \leq R_{cs,h1} \leq 18\%$		

Assumptions: 200-700 lux, polychromatic environment, single chromaticity

IES TM-30 ANNEX E

Design Intent
The desired effect of color rendition on the illuminated environment.

Priority Level The balance between allowing tradeoffs and increasing the likelihood of meeting the design intent.	Preference (P)	Vividness (V)	Fidelity (F)
1	P1: $R_f \geq 78$; $R_g \geq 95$; $-1\% \leq R_{cs,h1} \leq 15\%$	V1: $R_g \geq 118$; $R_{cs,h1} \geq 15\%$	
2	P2: $R_f \geq 75$; $R_g \geq 95$; $-7\% \leq R_{cs,h1} \leq 15\%$	V2: $R_g \geq 110$; $R_{cs,h1} \geq 6\%$	
3	P3: $R_f \geq 70$; $R_g \geq 88$; $-12\% \leq R_{cs,h1} \leq 18\%$	V3: $R_g \geq 100$; $R_{cs,h1} \geq 0\%$	

Assumptions: 200-700 lux, polychromatic environment, single chromaticity

IES TM-30 ANNEX E

Design Intent
The desired effect of color rendition on the illuminated environment.

Priority Level The balance between allowing tradeoffs and increasing the likelihood of meeting the design intent.	Preference (P)	Vividness (V)	Fidelity (F)
1	P1: $R_f \geq 78$; $R_g \geq 95$; $-1\% \leq R_{cs,h1} \leq 15\%$	V1: $R_g \geq 118$; $R_{cs,h1} \geq 15\%$	F1: $R_f \geq 95$
2	P2: $R_f \geq 75$; $R_g \geq 95$; $-7\% \leq R_{cs,h1} \leq 15\%$	V2: $R_g \geq 110$; $R_{cs,h1} \geq 6\%$	F2: $R_f \geq 90$; $R_{f,h1} \geq 90$
3	P3: $R_f \geq 70$; $R_g \geq 88$; $-12\% \leq R_{cs,h1} \leq 18\%$	V3: $R_g \geq 100$; $R_{cs,h1} \geq 0\%$	F3: $R_f \geq 85$; $R_{f,h1} \geq 85$

Assumptions: 200-700 lux, polychromatic environment, single chromaticity

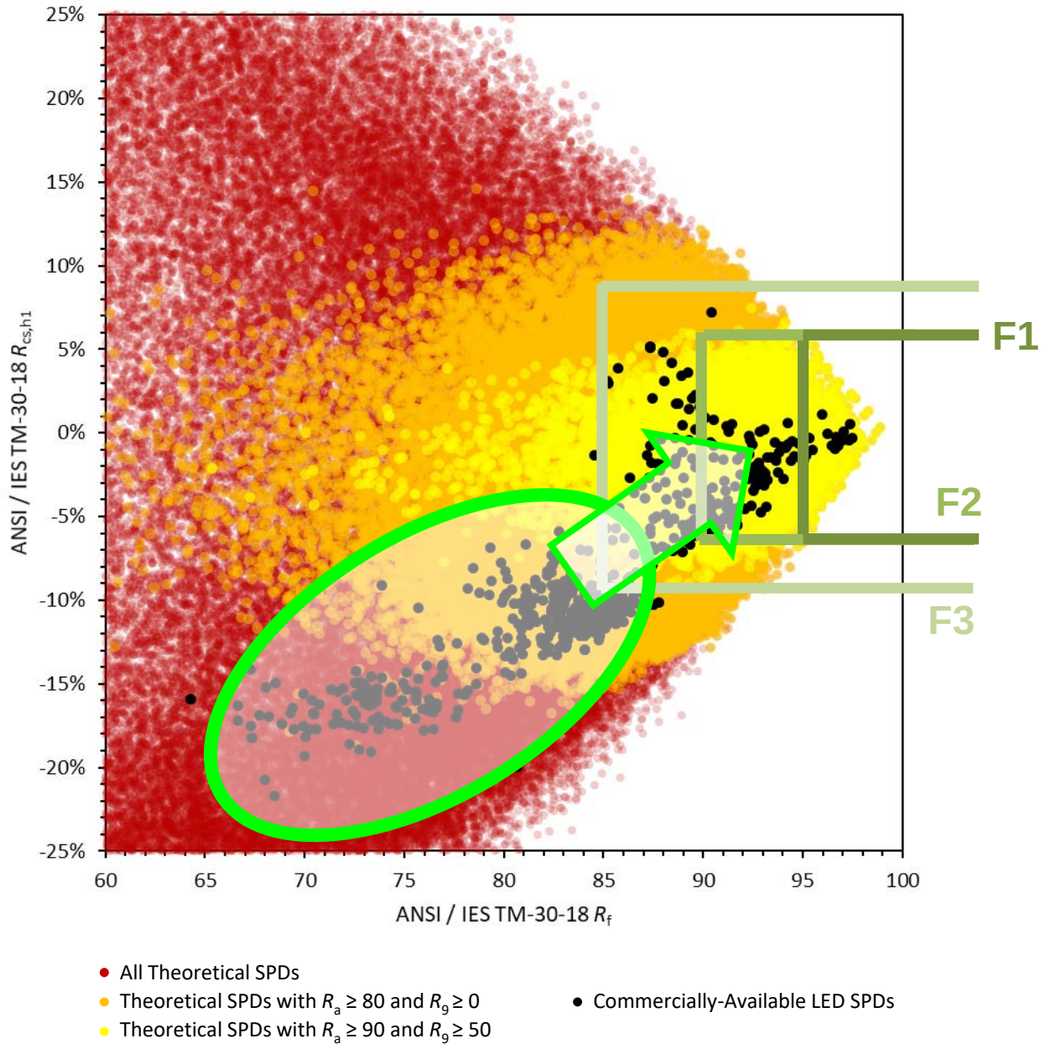
IES TM-30 ANNEX E

Important Notes

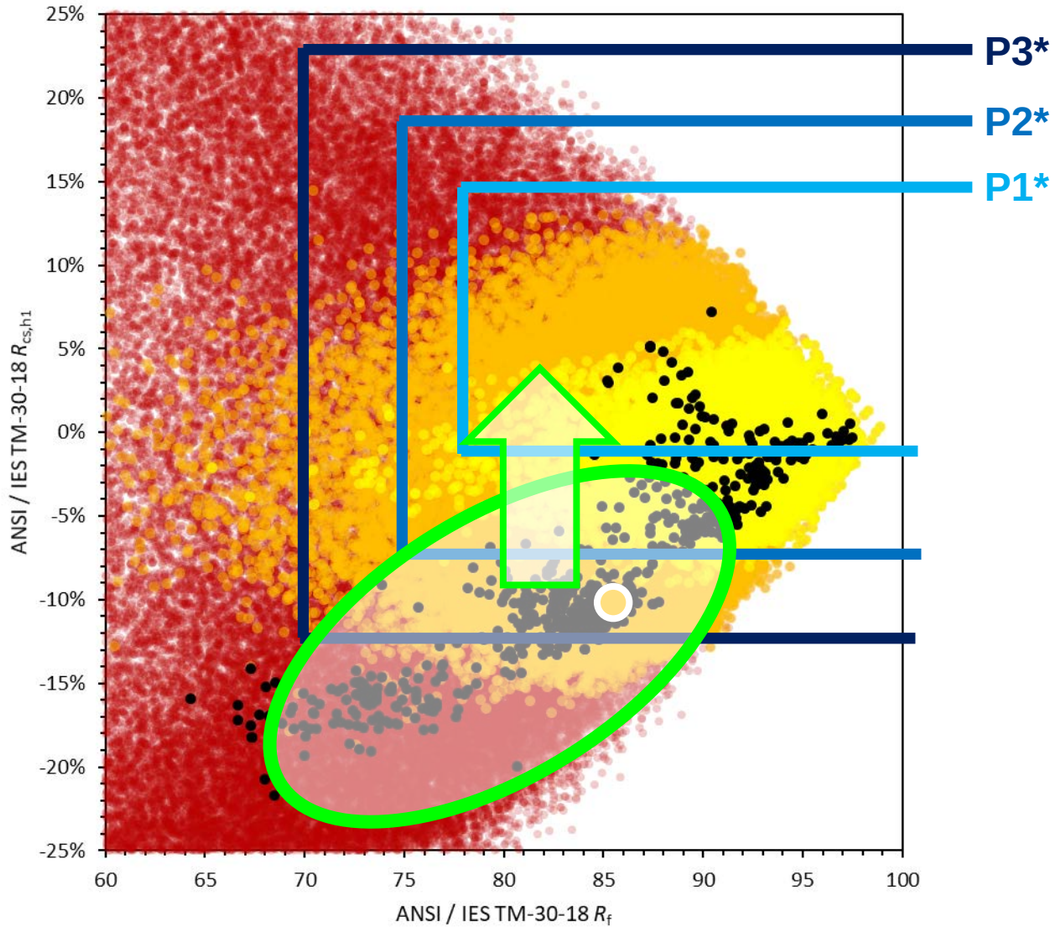
- The Assumptions are important!
  - 200 – 700 Lux
  - Polychromatic Environment
  - Single Chromaticity
- PVF categories ARE NOT INDEPENDENT.
  P1V1F1 is not possible
- ANNEX E does not specifically consider the rendition of skin tones

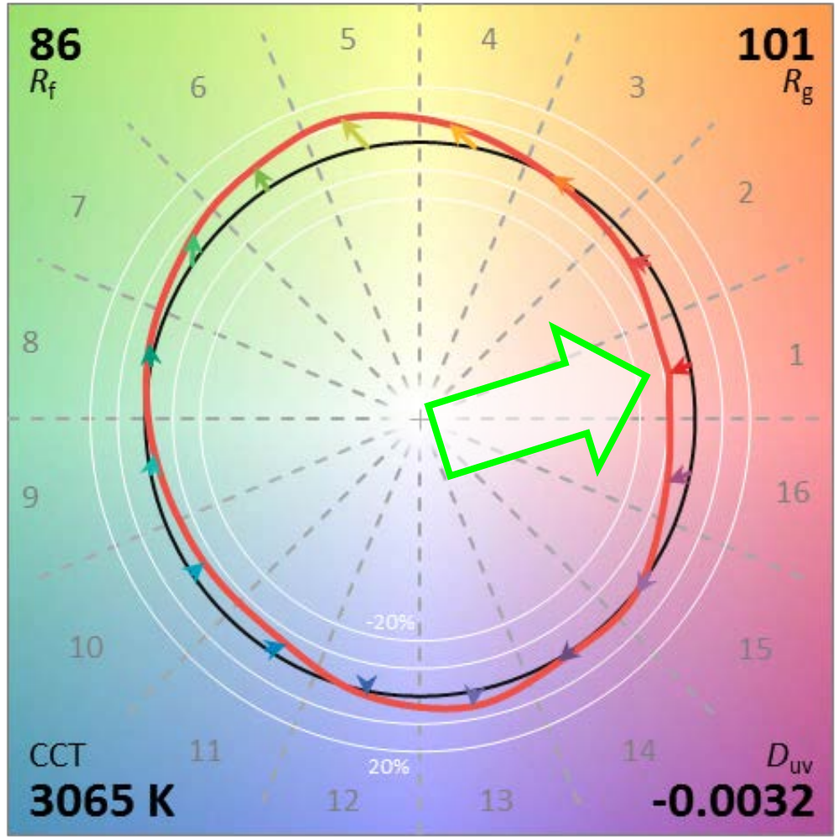
So What?

IES TM-30 ANNEX E: Color Fidelity



IES TM-30 ANNEX E: Color Preference





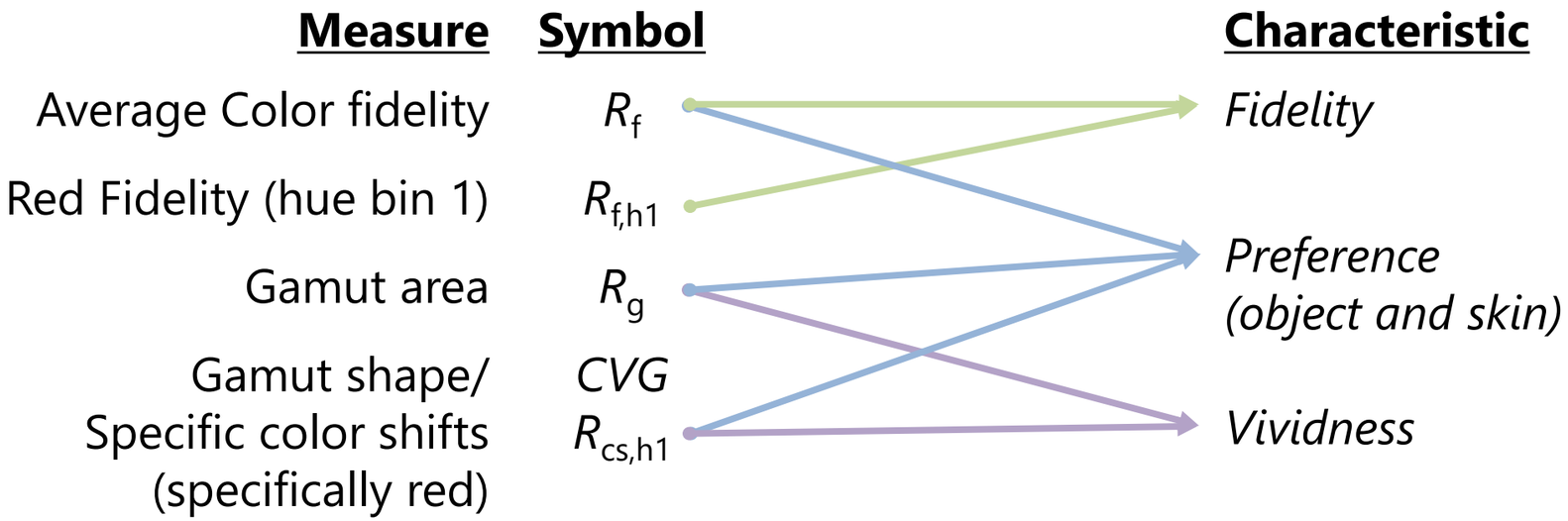
Summary, TM-30 and ANNEX E

- IES TM-30 is a unified system of objective measures that capture color difference
    - Specifically, TM-30 provides measures beyond average fidelity and average gamut area that provide information about hue-SPECIFIC color shifts
- IES TM-30 ANNEX E was developed to facilitate the ease of use of TM-30 and to help specifiers flex color rendition as a parameter in their designs
    - And, potentially, as a way for manufacturers to differentiate their products
- TM-30 helps illustrate the tradeoff between luminous efficacy and red rendition, and shows that many commercially available sources desaturate red colors
- TM-30 can be used in an optimization routine to produce sources with a spectrum that is more purposefully tuned to the intended application

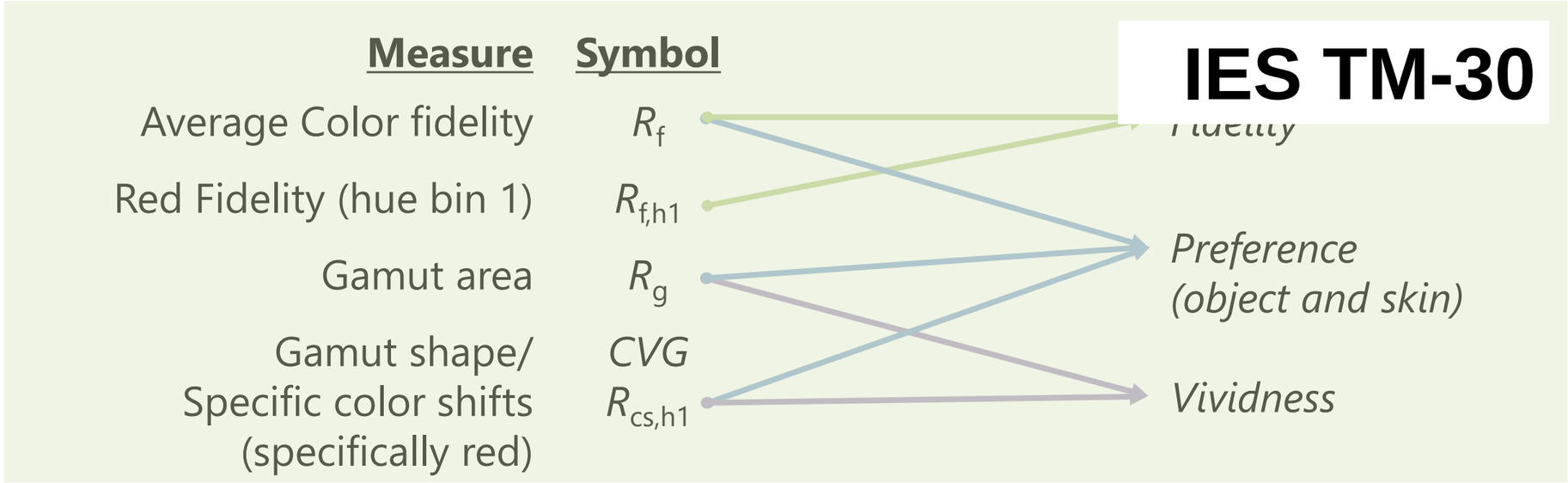
Metameric Uncertainty

https://www.astroml.org/book_figures/chapter3/fig_bivariate_gaussian.html

Metameric Uncertainty



Metameric Uncertainty



Light Source Error Score R_d → Color Discrimination

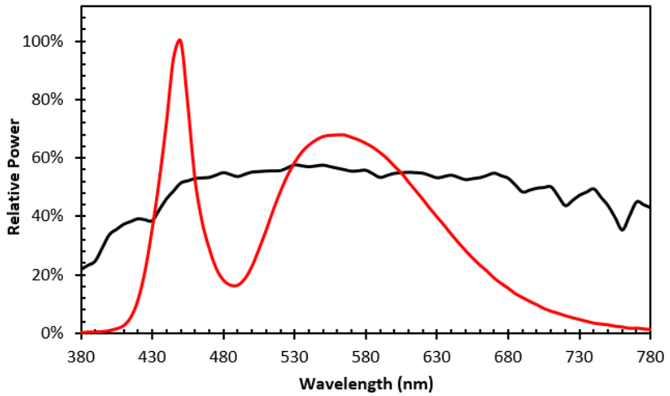
Metameric Uncertainty Index R_t → Metameric Mismatch

What is metamerism?

Metameric *Sources*

Sources that have different SPDs, but the same chromaticity.

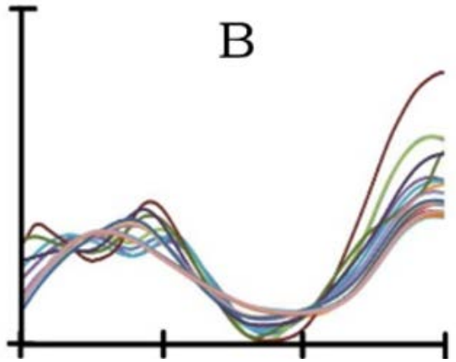
They have the same appearance when viewed directly.



Metameric *Objects*

Sources that have different “Practical Colors” (SPD*SRD), but the same chromaticity.

They have the same appearance when viewed directly.



Why is it so uncertain?

Who cares?

Metameric Mismatch

https://www.facebook.com/

https://twitter.com/starbucks

https://www.xrite.com/blog/two-essential-components-color-program

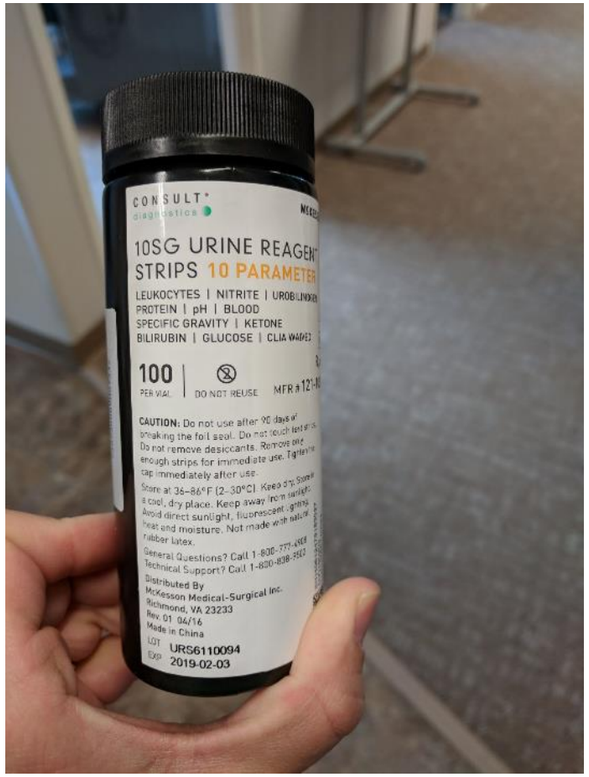
https://store.nike.com/us/en_us/product/air-force-1-high-essential-id/

https://www.socialbakers.com/statistics/twitter/profiles/detail/71026122-mcdonalds

https://apps.apple.com/us/app/t-mobile/id561625752

https://www.chick-fil-a.com/menu-items/coca-cola

Metameric Mismatch



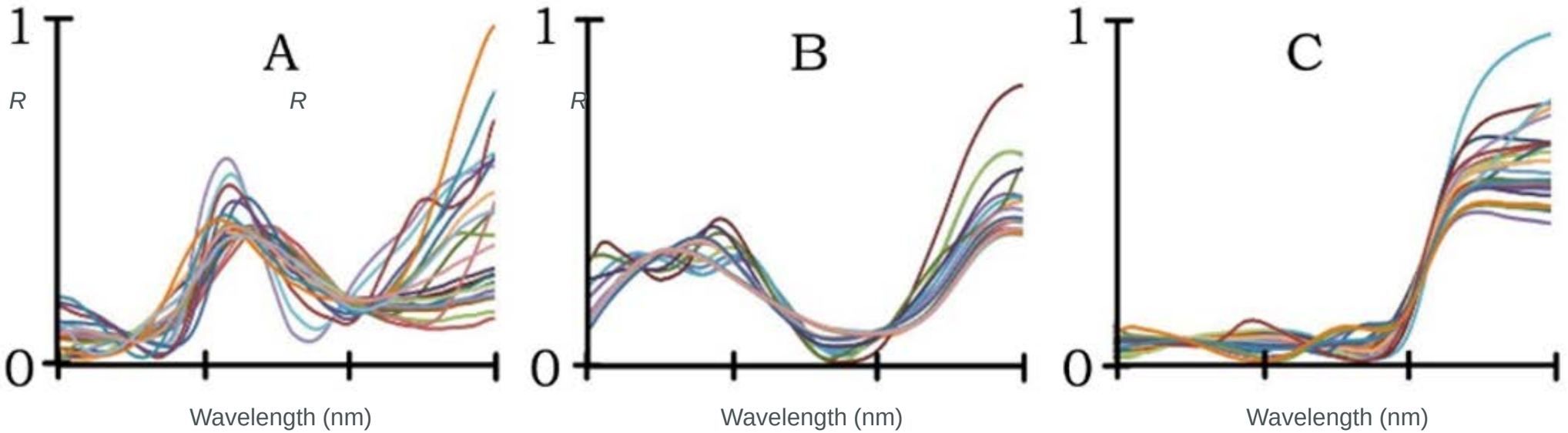
“The sensitivity of the strips on clinical urine specimens may vary depending upon several factors, such as the variability of color perception, specific gravity, pH value, and the lighting conditions when the strips are read visually.”

We want to know,

What is the likelihood that a light source will cause a mismatch between objects that were previously metameric (with respect to a given illuminant)

Metameric Uncertainty Index, R_t

SRDs that are metameric with respect to D50

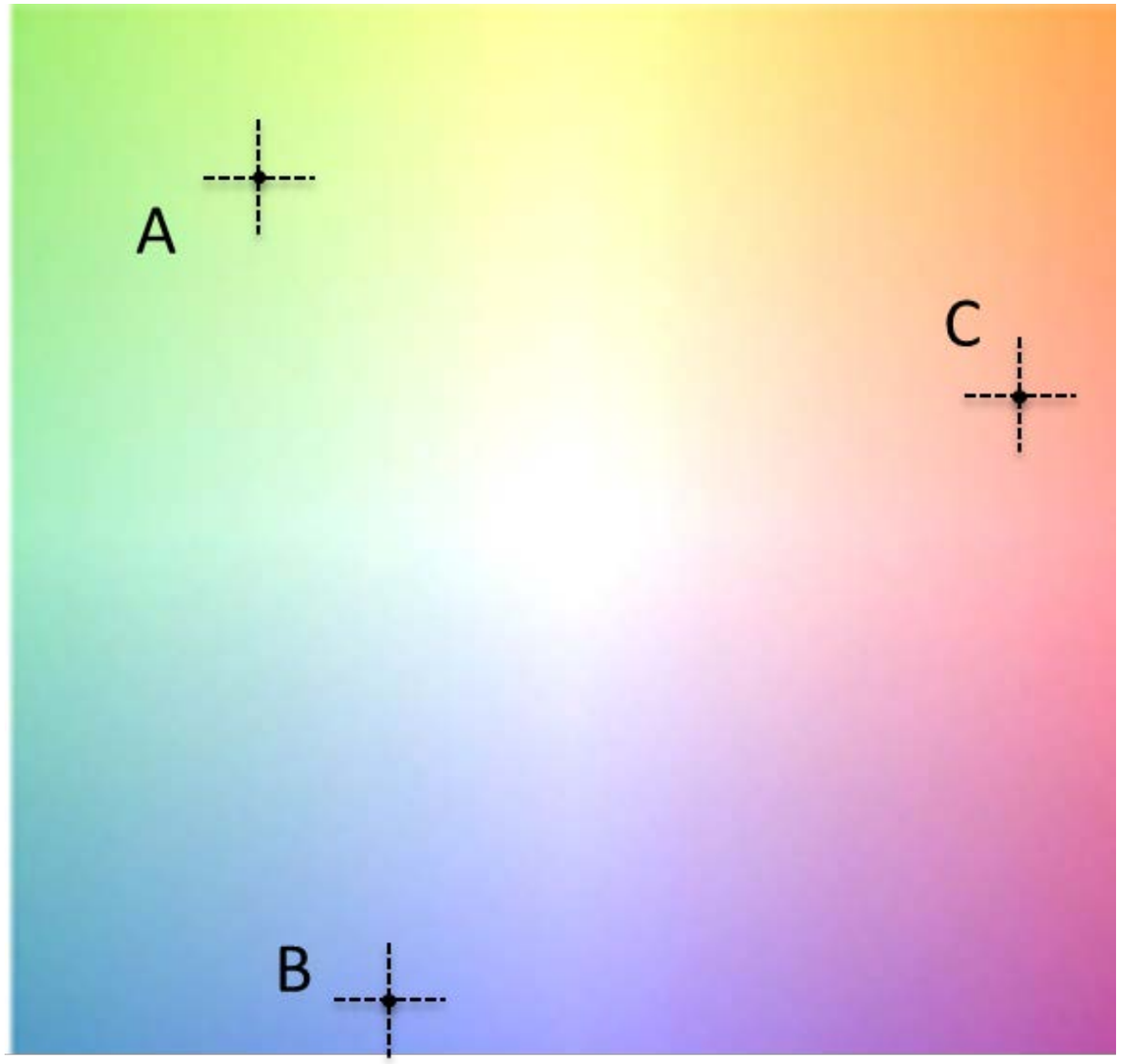


Matching ***green*** under 5000 K daylight

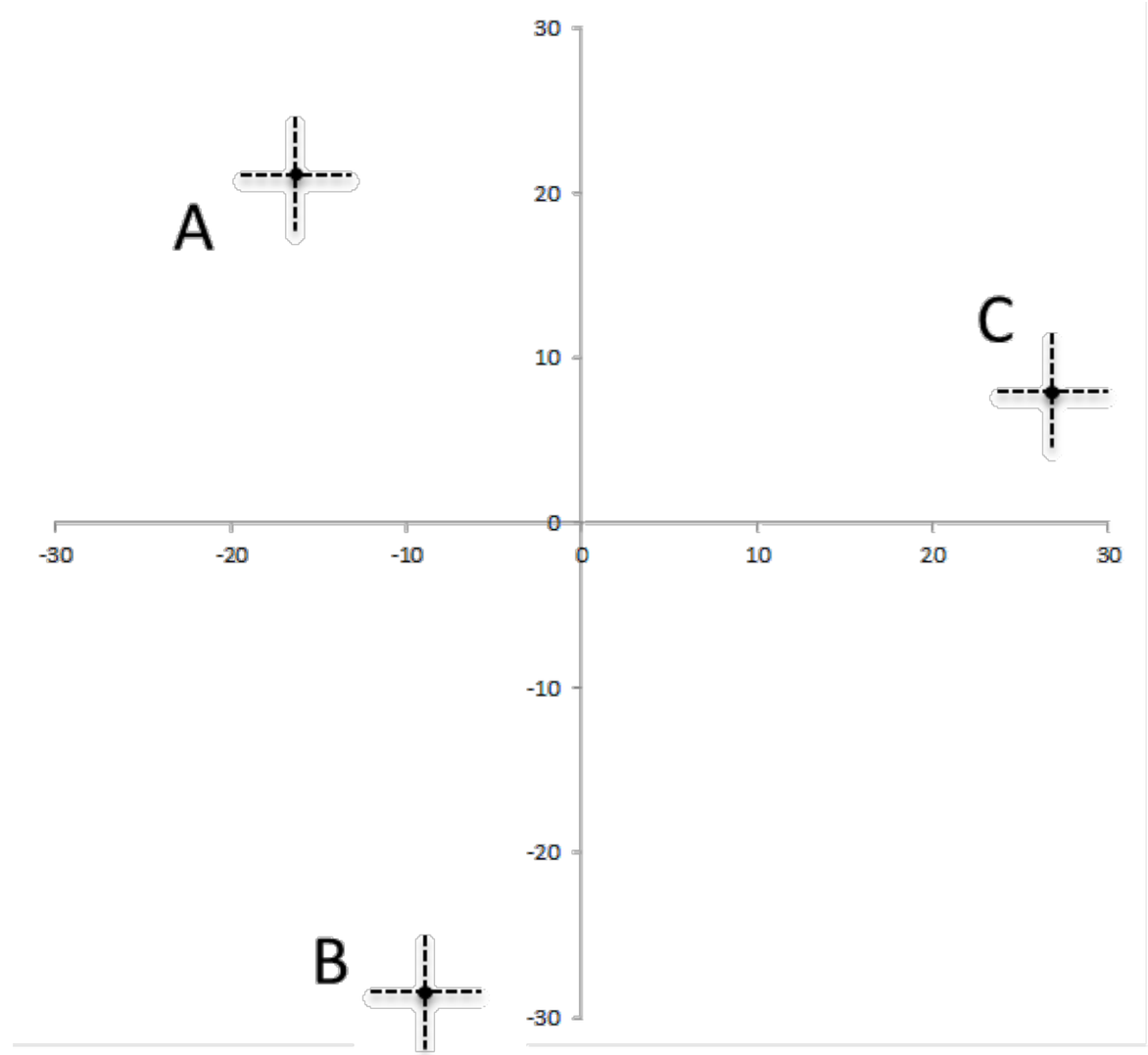
Matching ***blue*** under 5000 K daylight

Matching ***red*** under 5000 K daylight

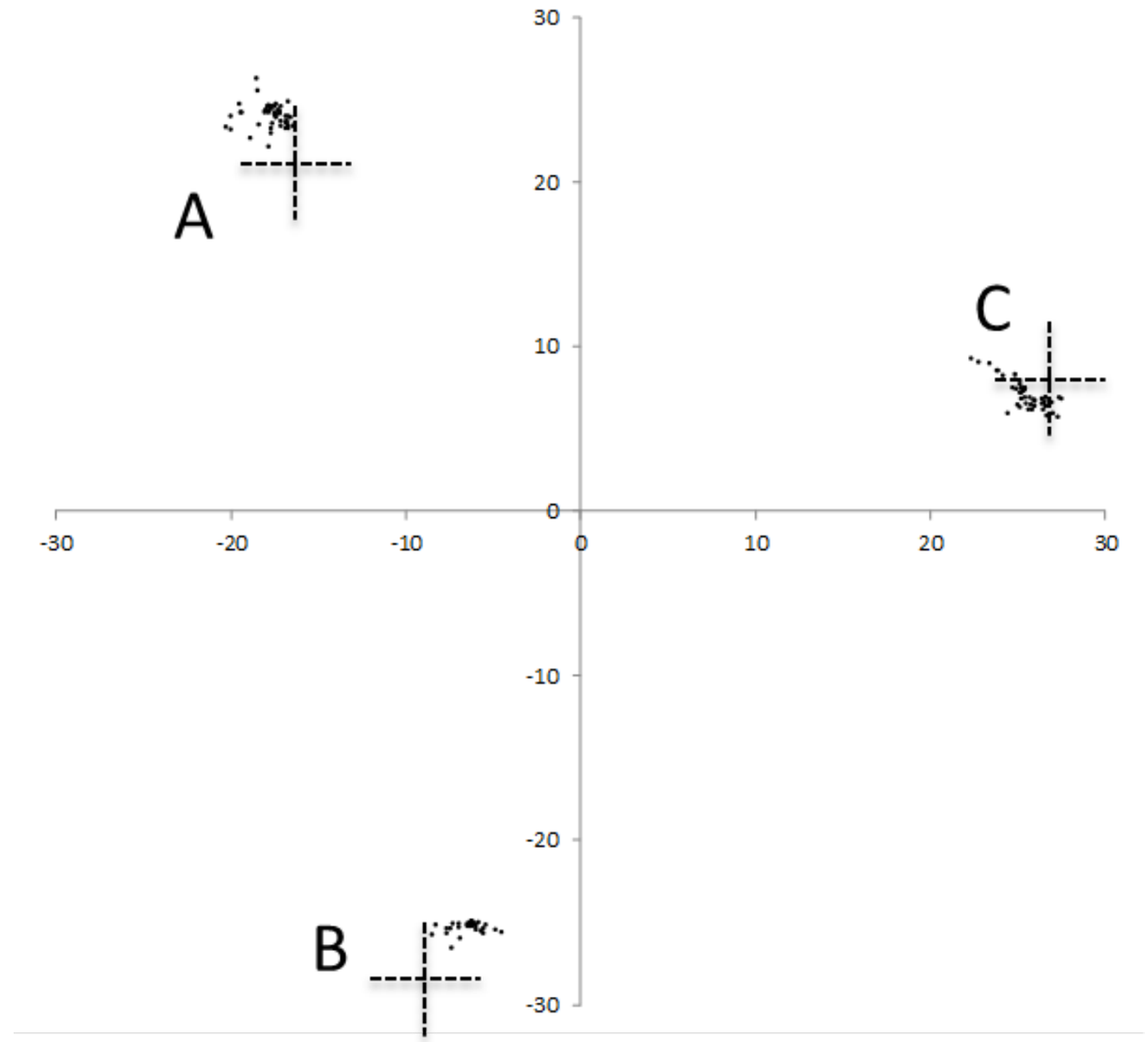
SRDs that are metameric with respect to D50



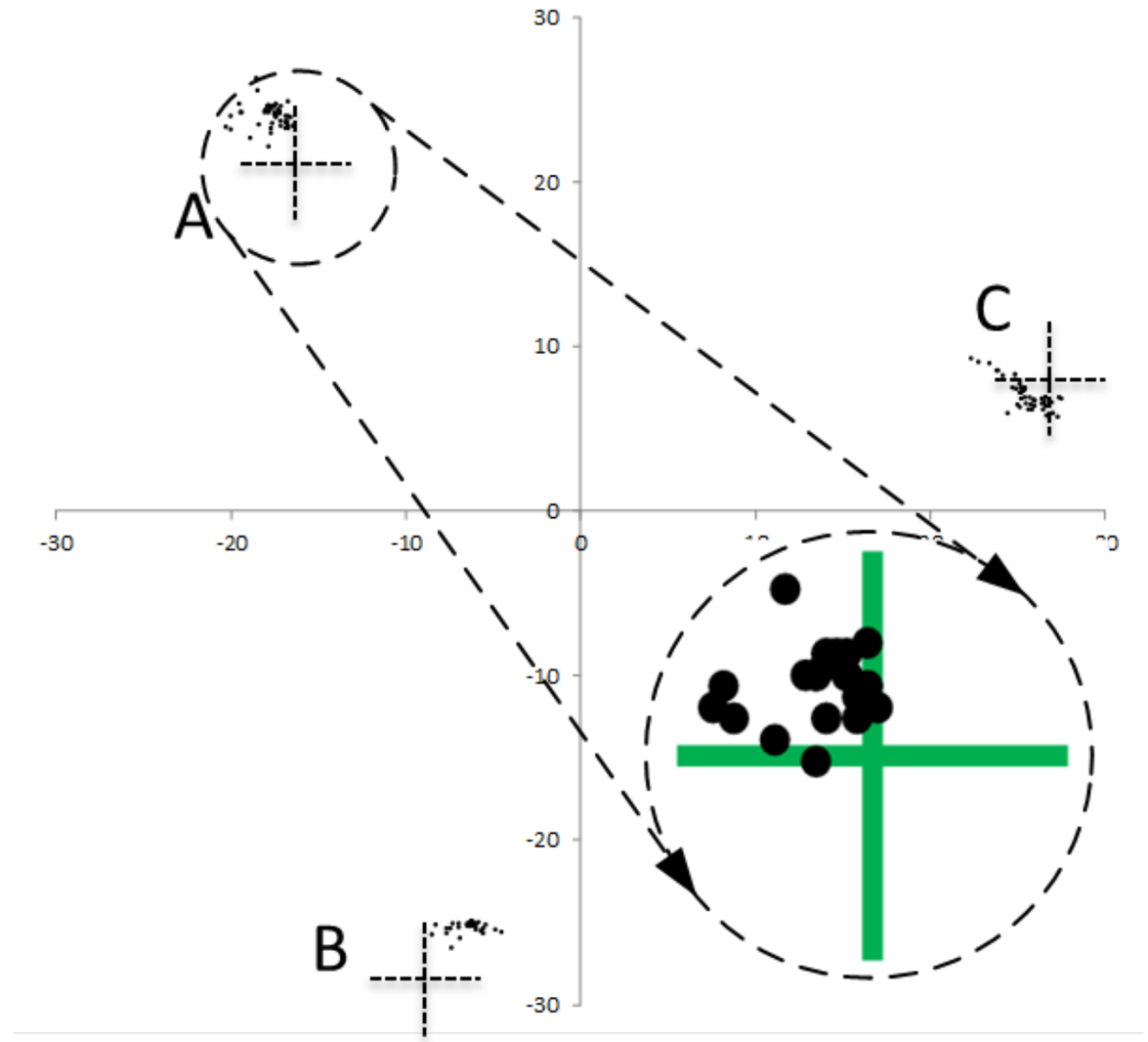
SRDs that are metameric with respect to D50



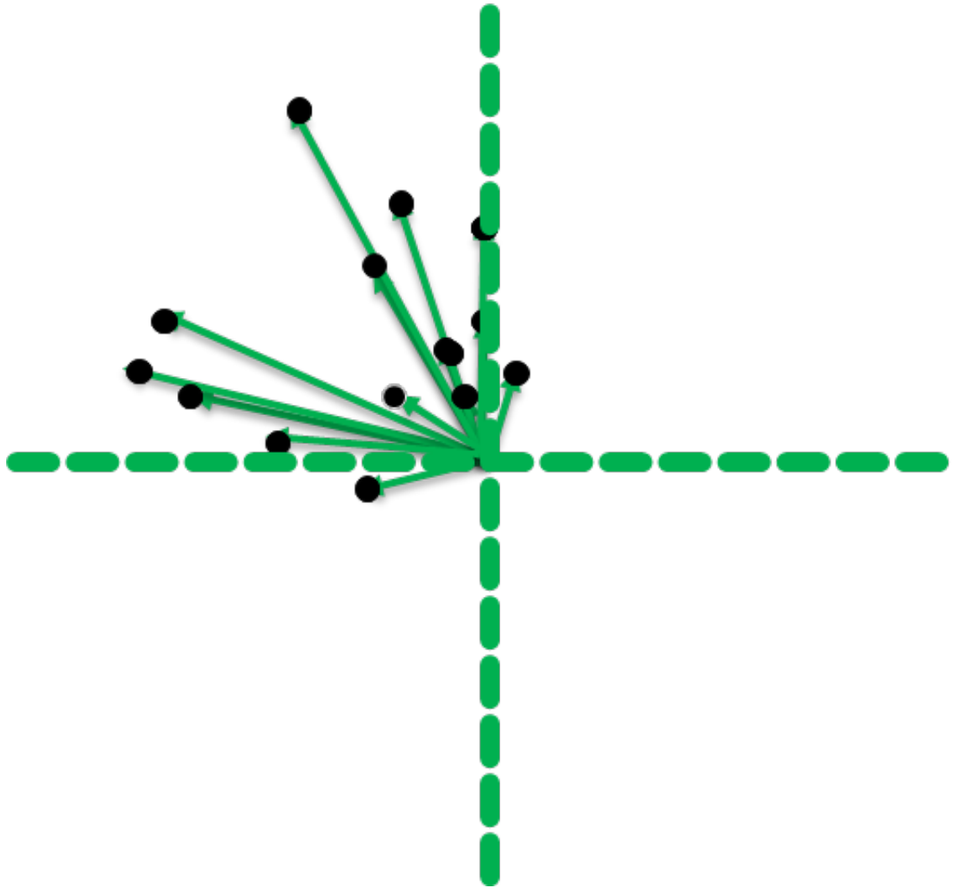
SRDs redistribute when the source is changed



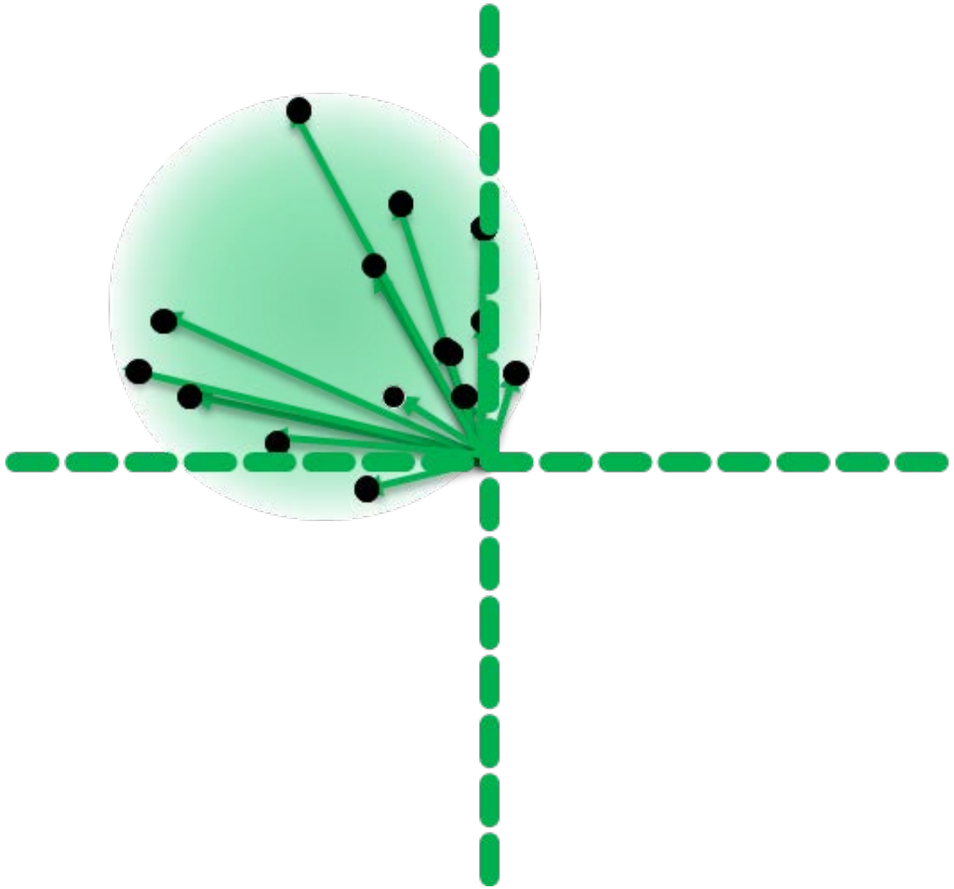
SRDs redistribute when the source is changed



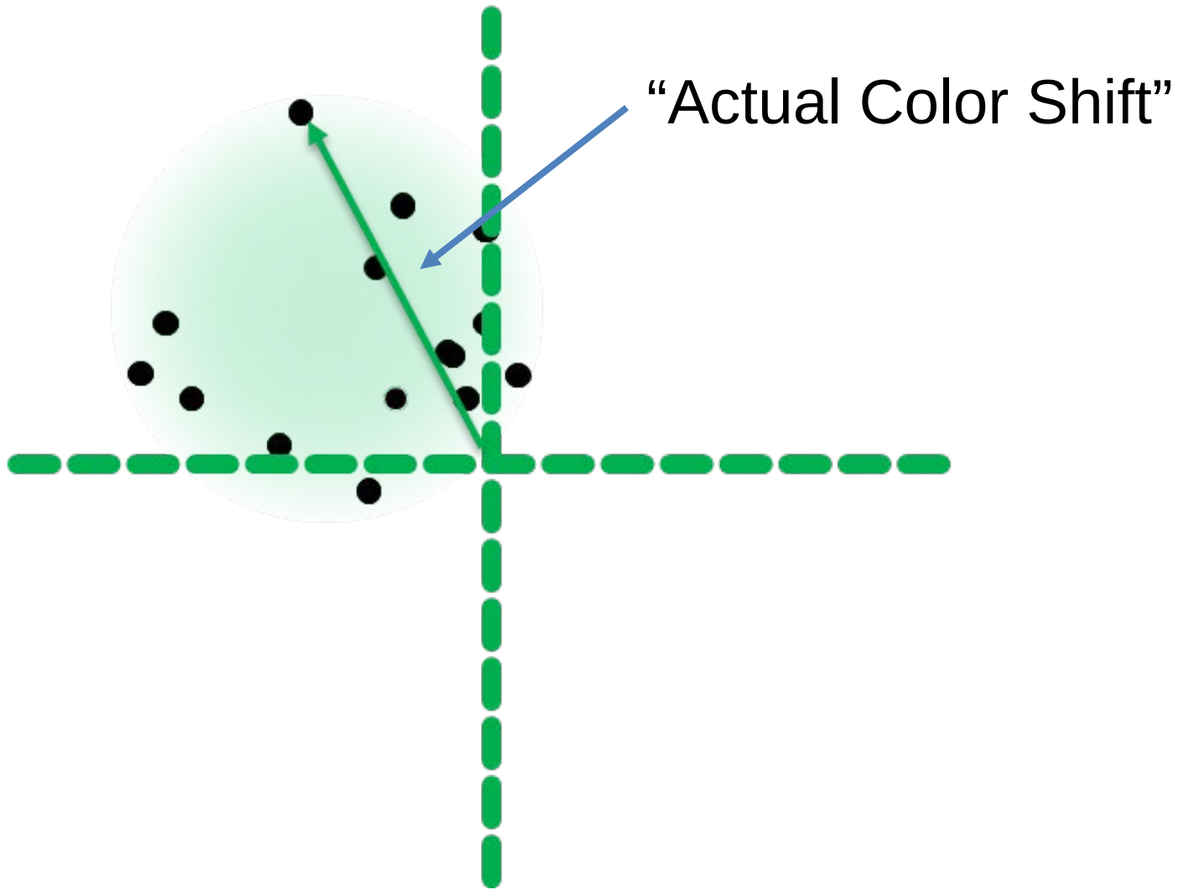
SRDs redistribute when the source is changed



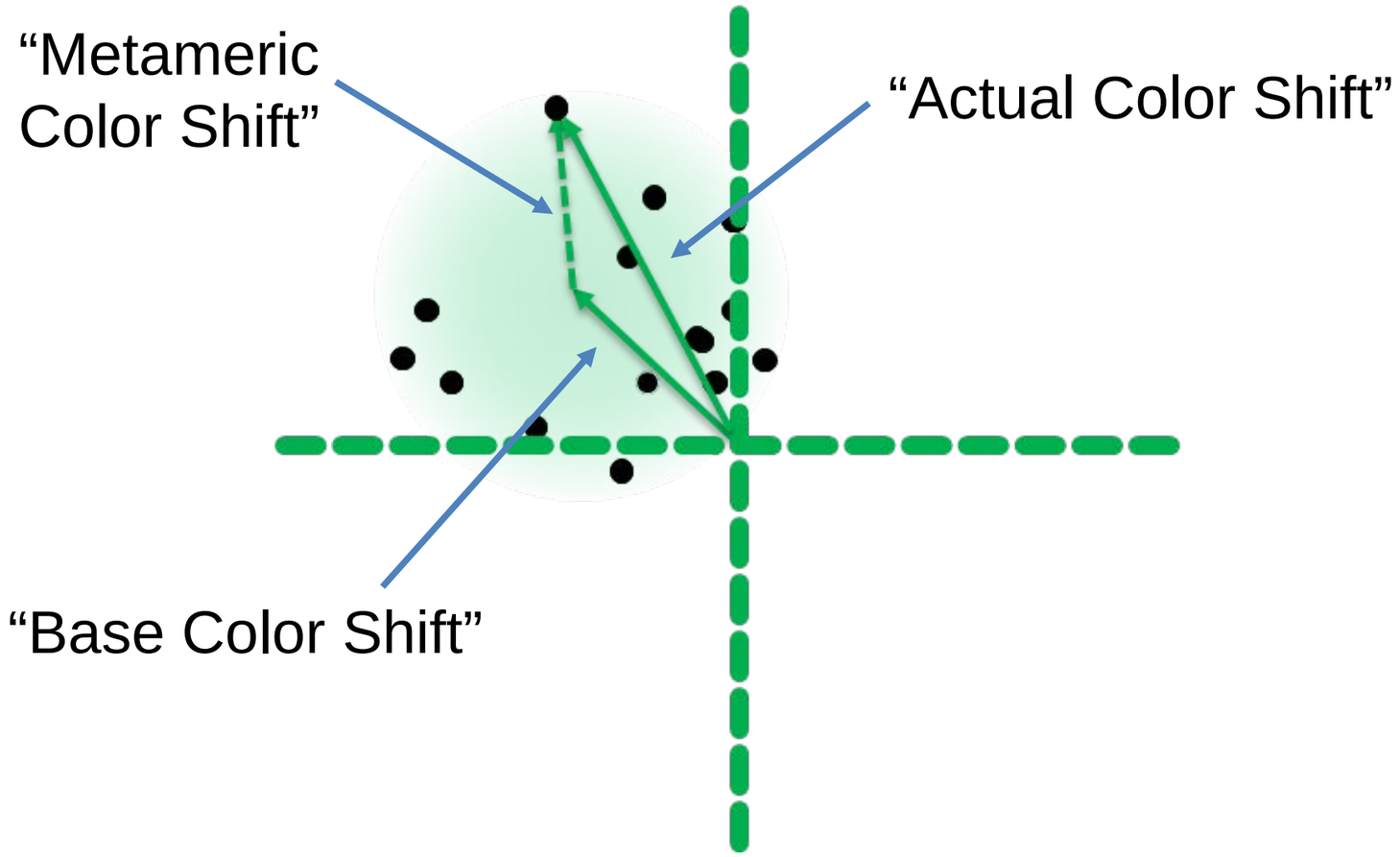
SRDs redistribute when the source is changed



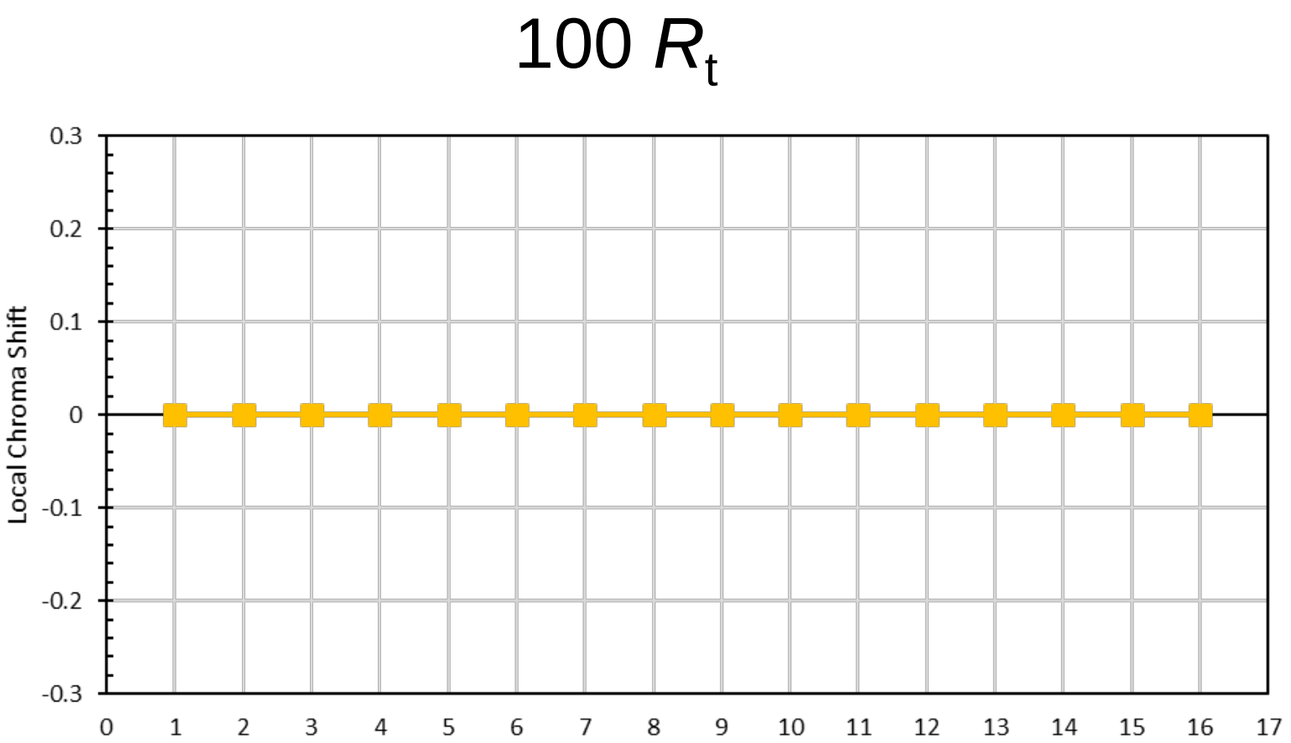
Actual color shift is dissected into two pieces

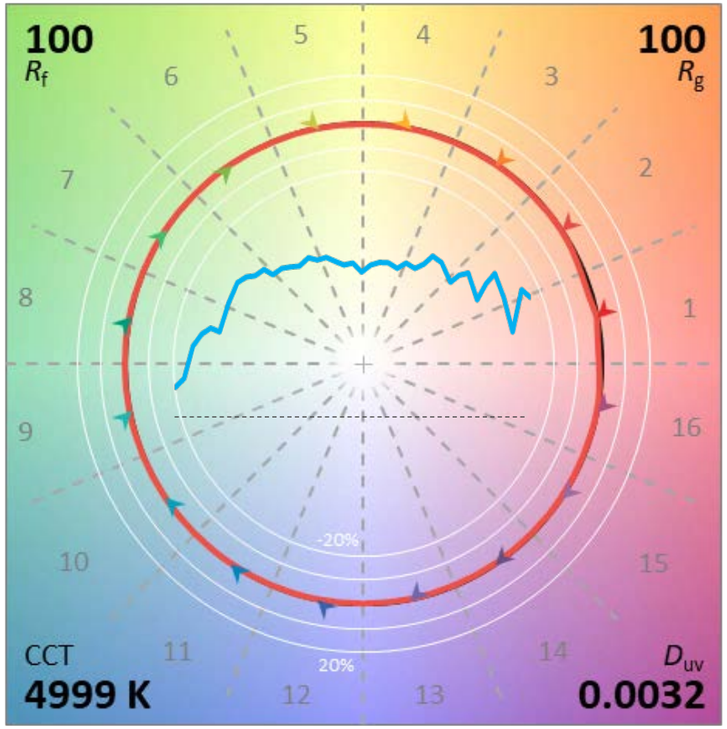


Actual color shift is dissected into two pieces



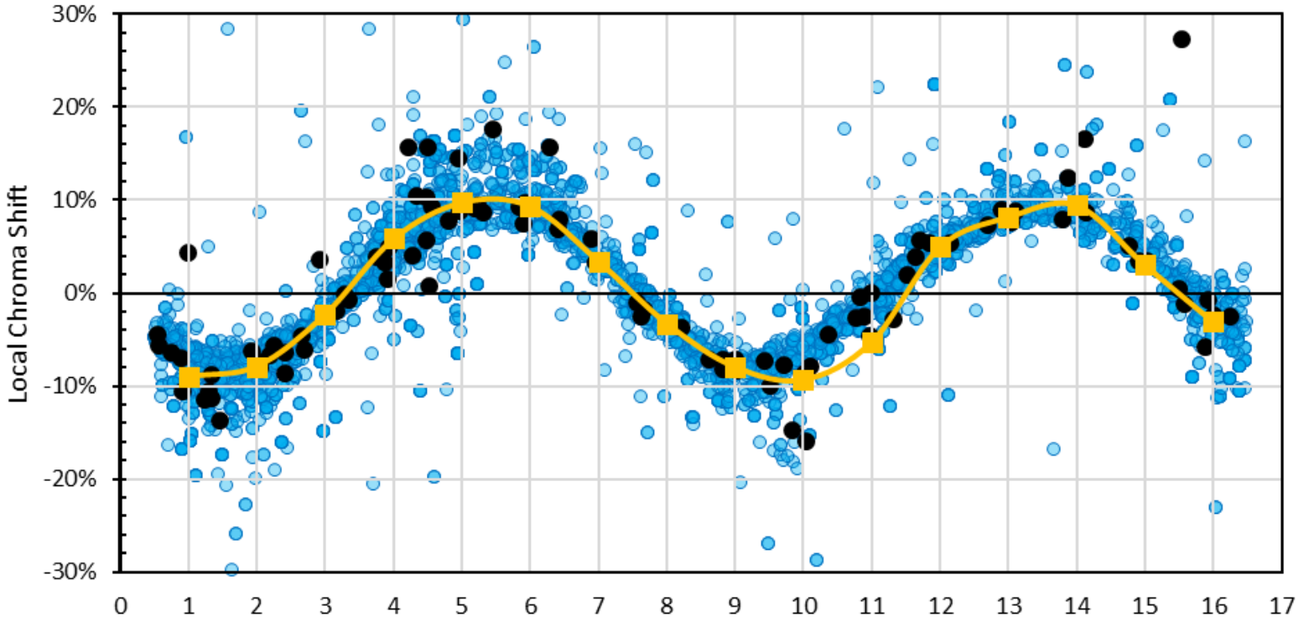
Metameric Uncertainty Index, Rt

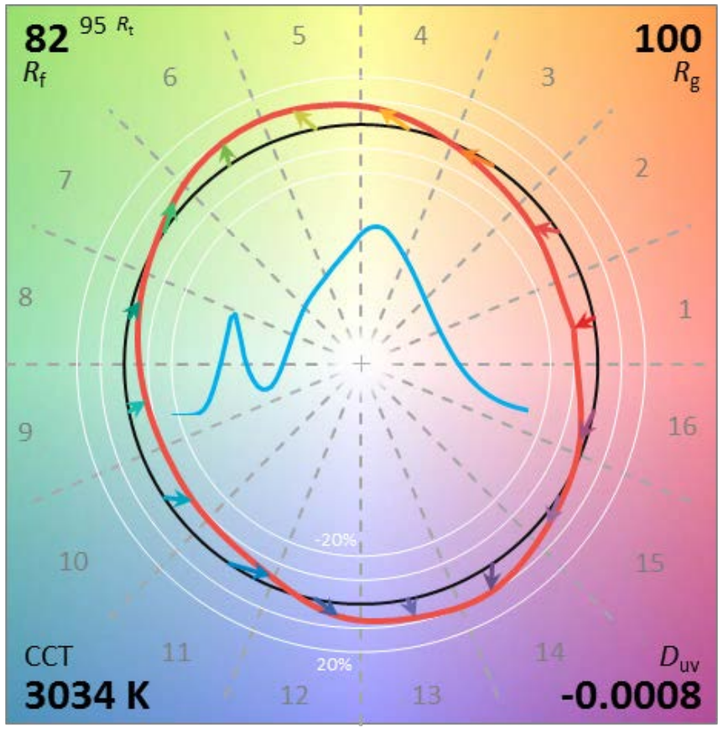




Metameric Uncertainty Index, Rt

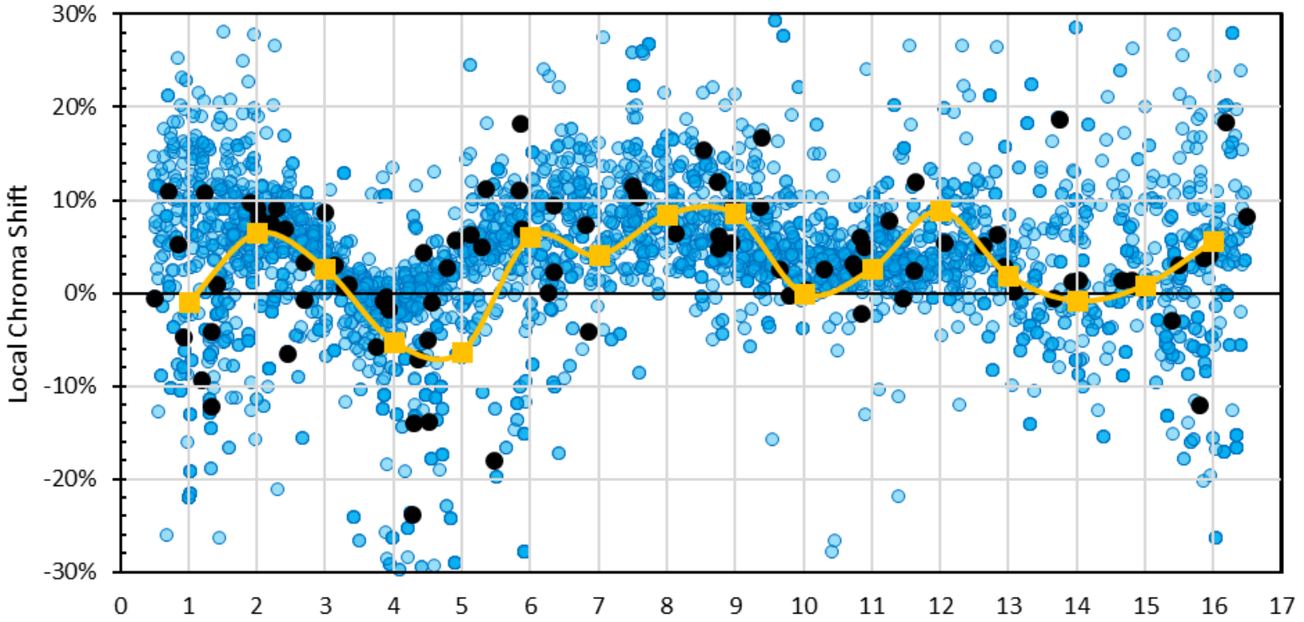
High R_t

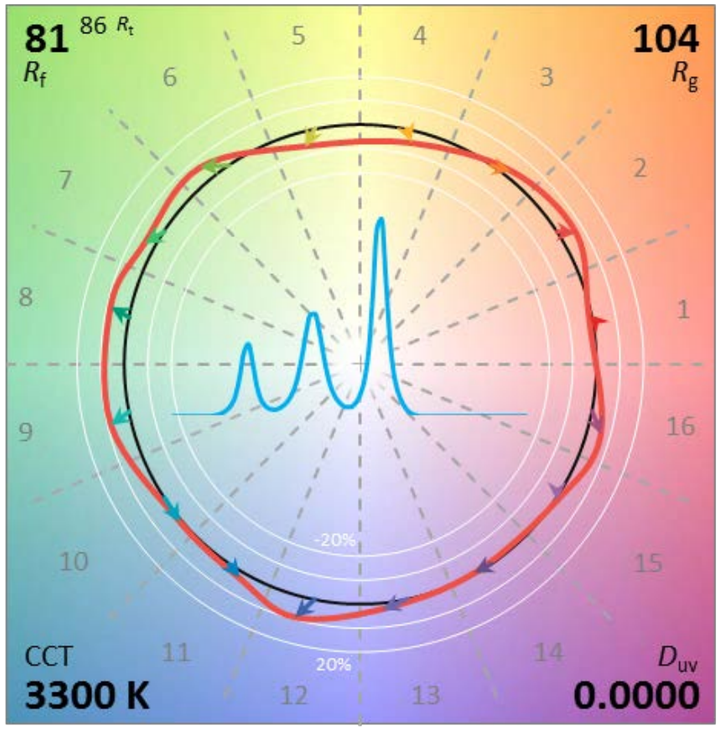




Metameric Uncertainty Index, Rt

Low R_t

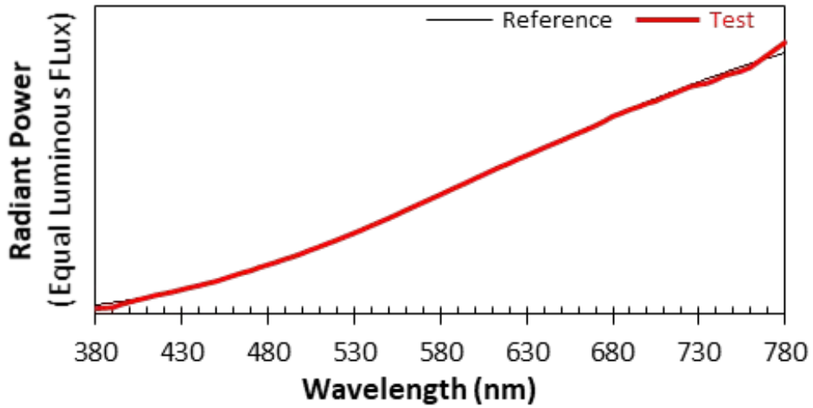


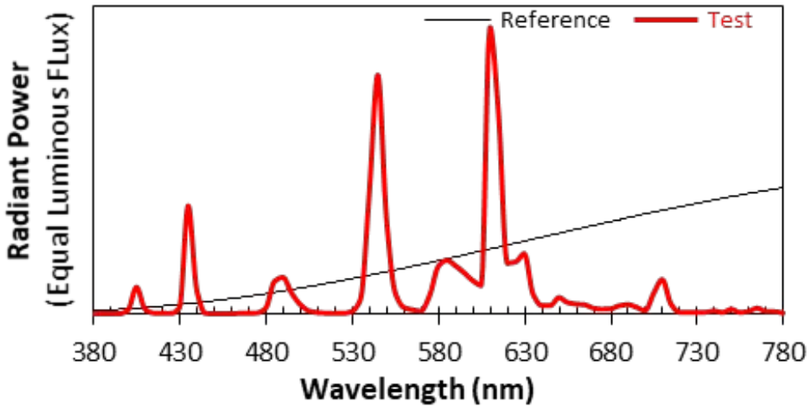


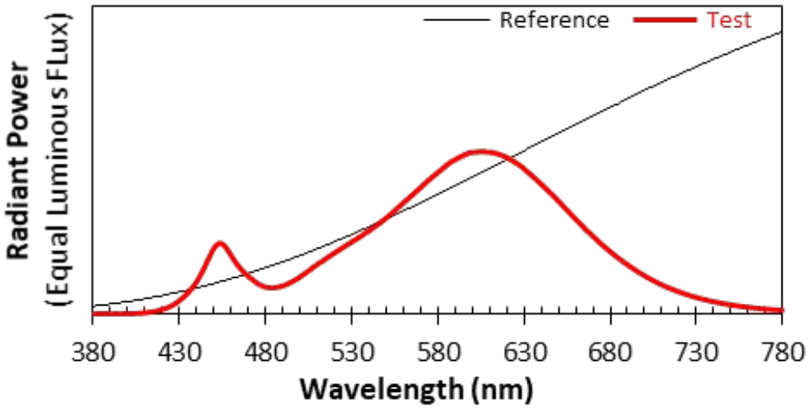
Summary, R_t

- Light source-induced color shifts divided into two components:
  - **base** color shift, following a regular pattern
  - **metameric** color shift, which is random
- These can be quantified using the 99 IES TM-30 samples and a vector field model for estimating base color shift
- Metameric color shift intensity is new useful information
- It can be converted into R_t, the Metameric Uncertainty Index
- This can be useful in situations where metamerism matters
- **Next steps for Rt include psychophysical experimentation. Does Rt actually measure what we think it does?**

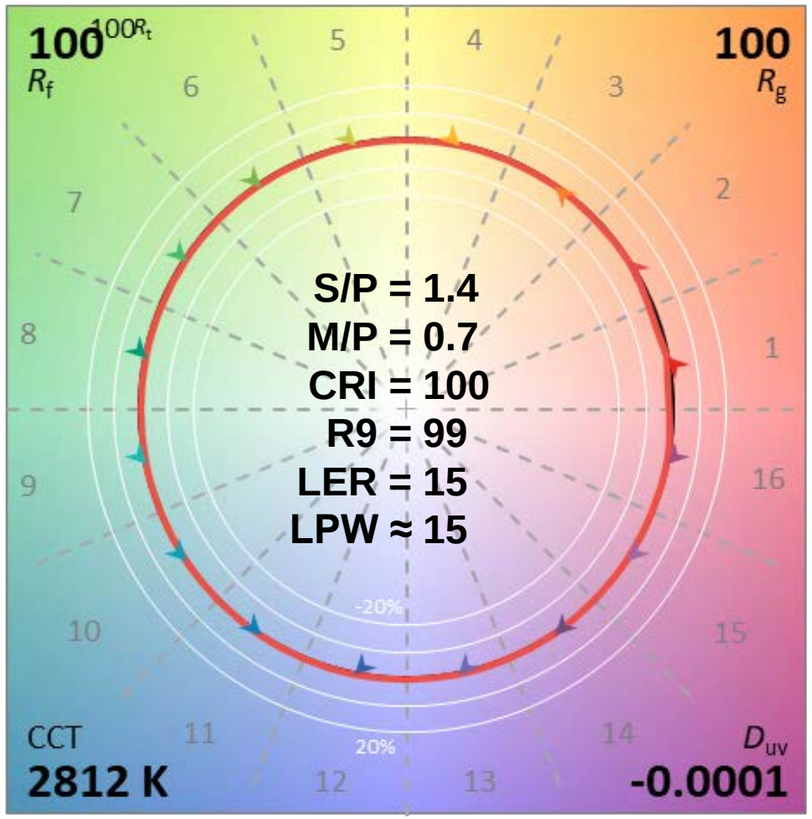
Great promise, few options:
Can advances in color science shift the market?



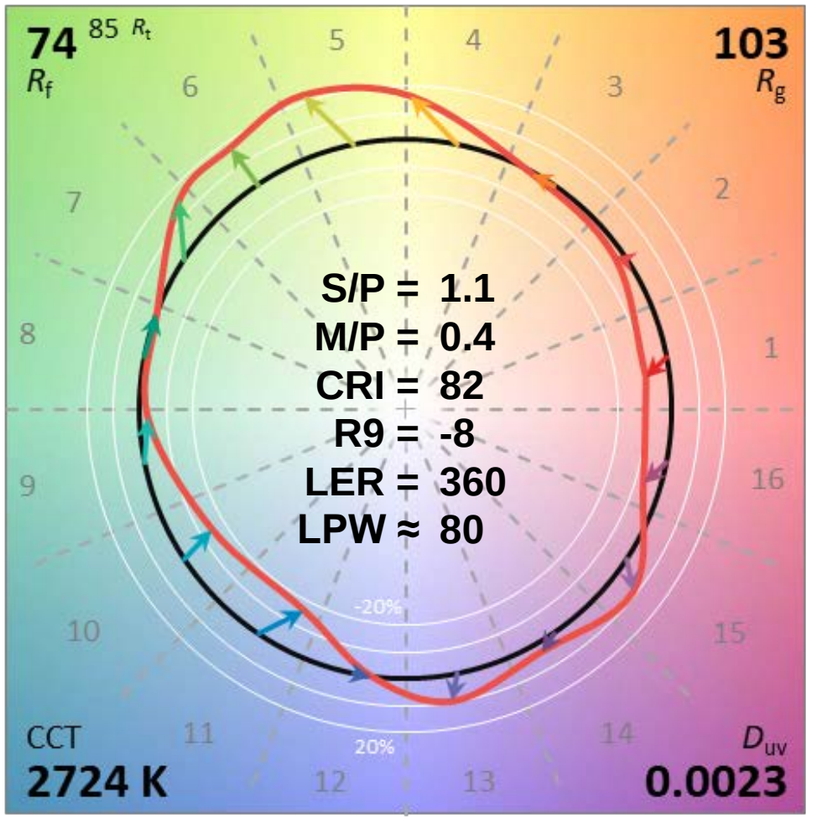




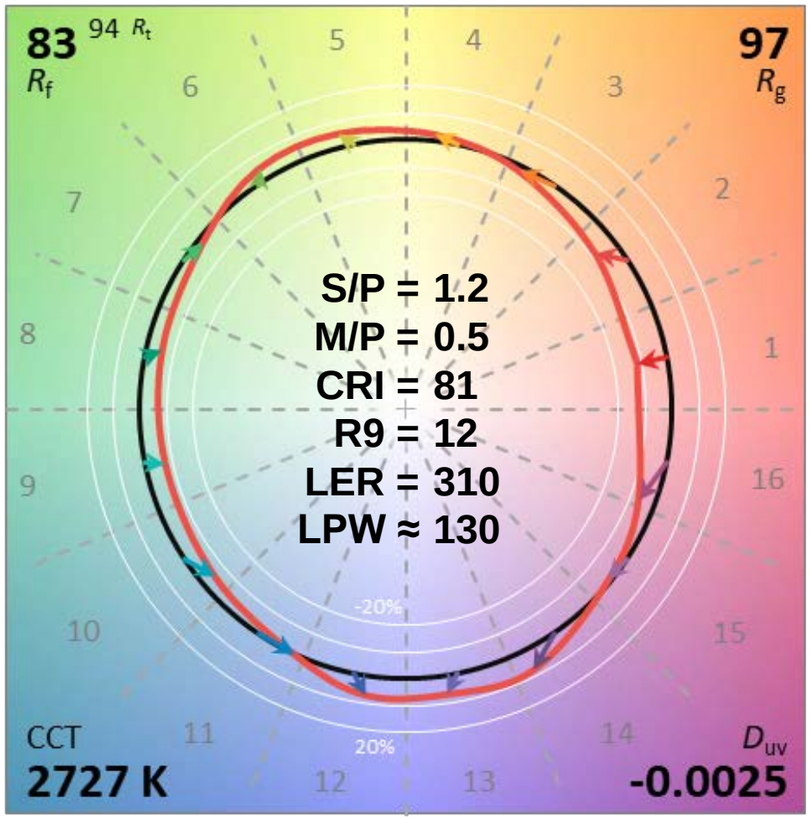
P1 V- F1

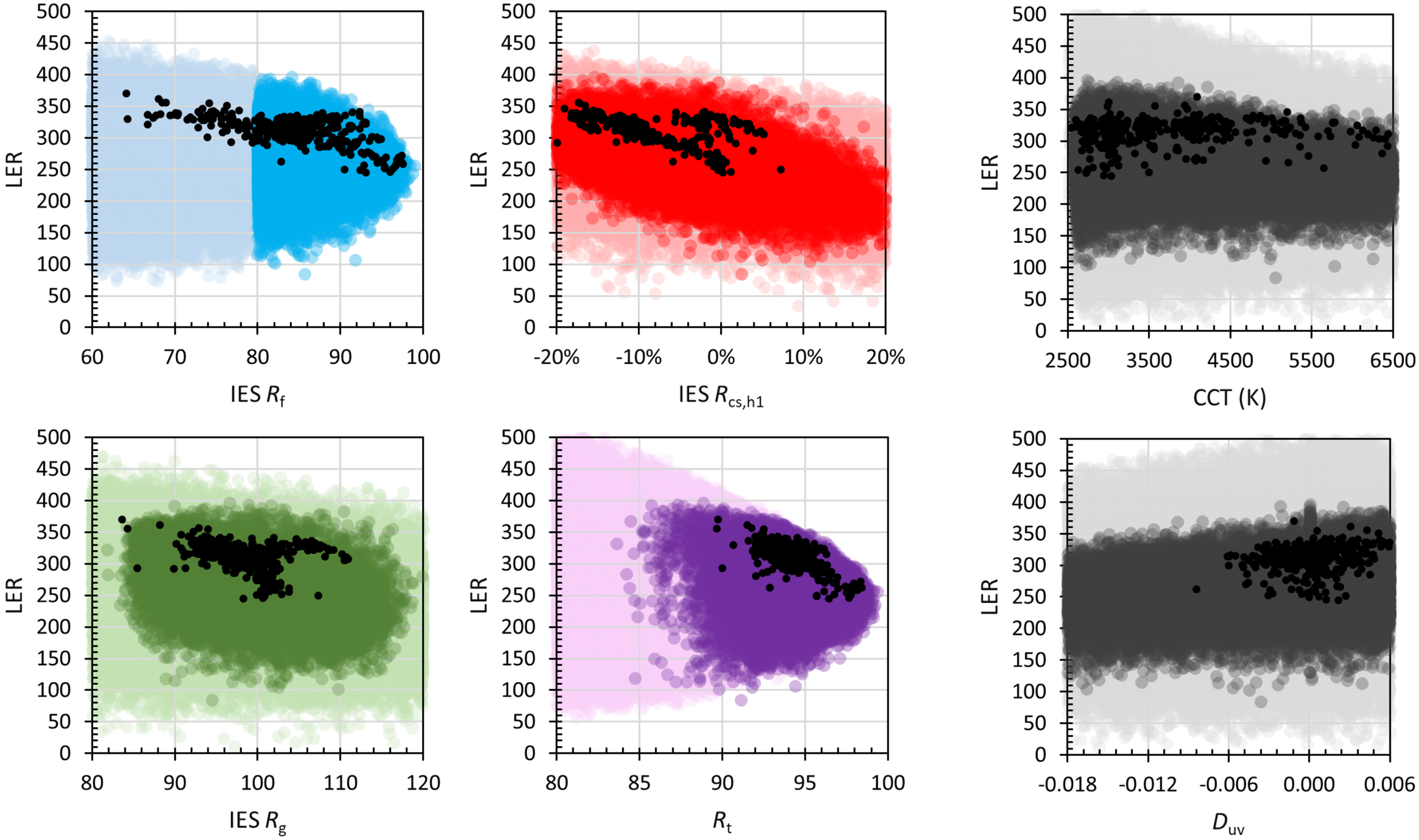


P3 V- F-

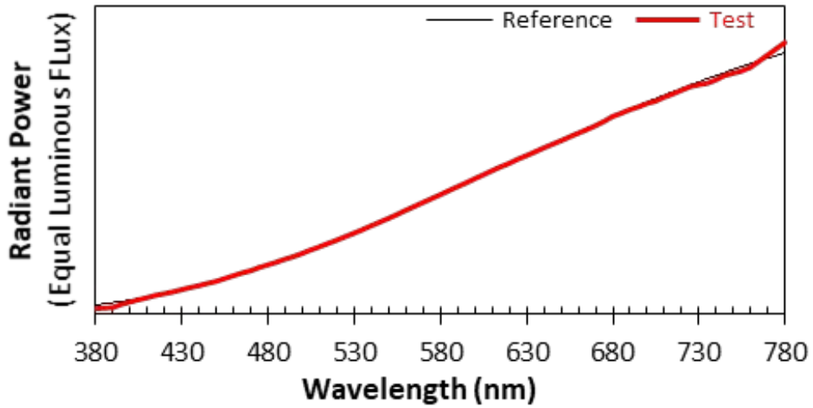


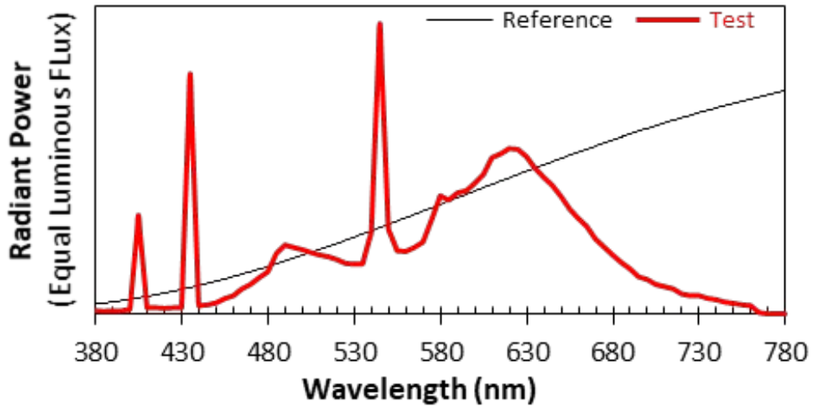
P3 V- F-

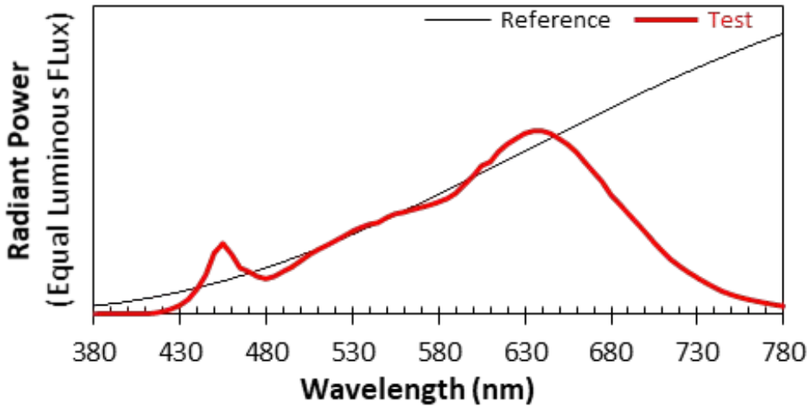




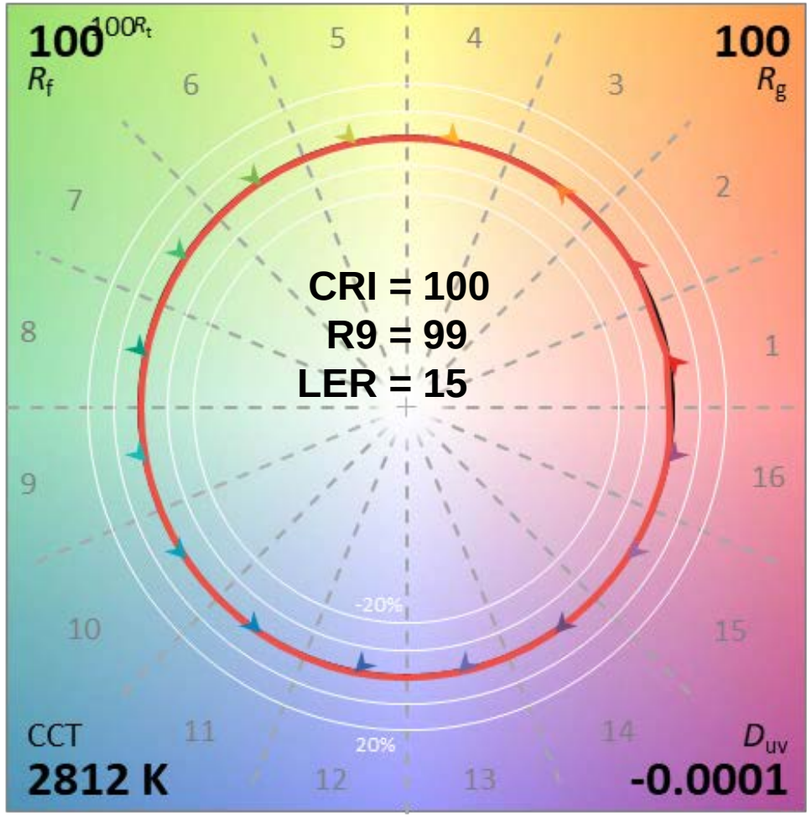
Royer M. Evaluating tradeoffs between energy efficiency and color rendition, OSA Continuum 2, 2308-2327 (2019)



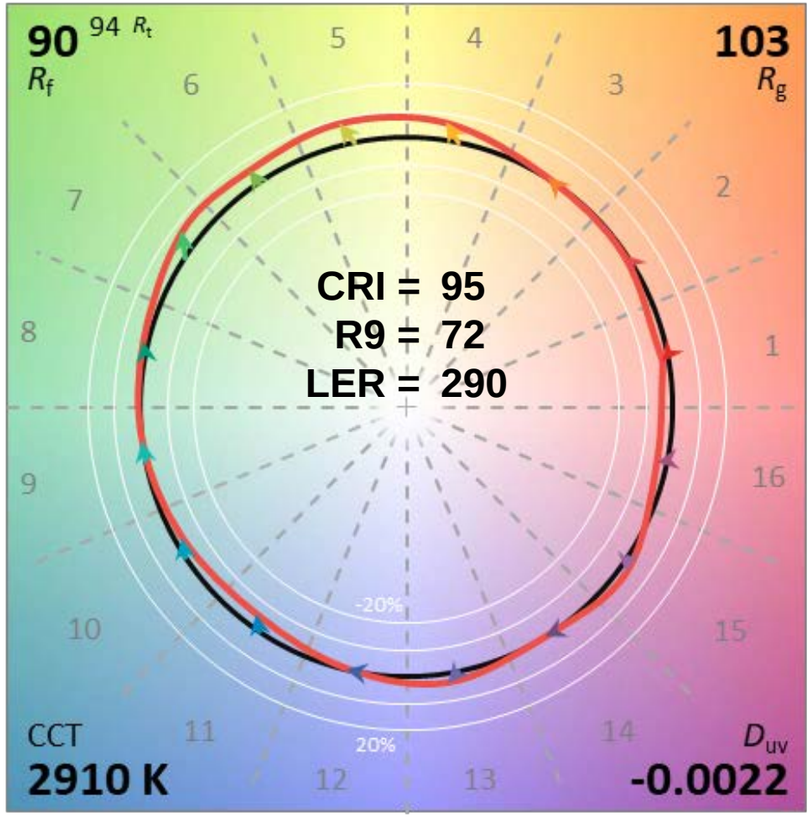




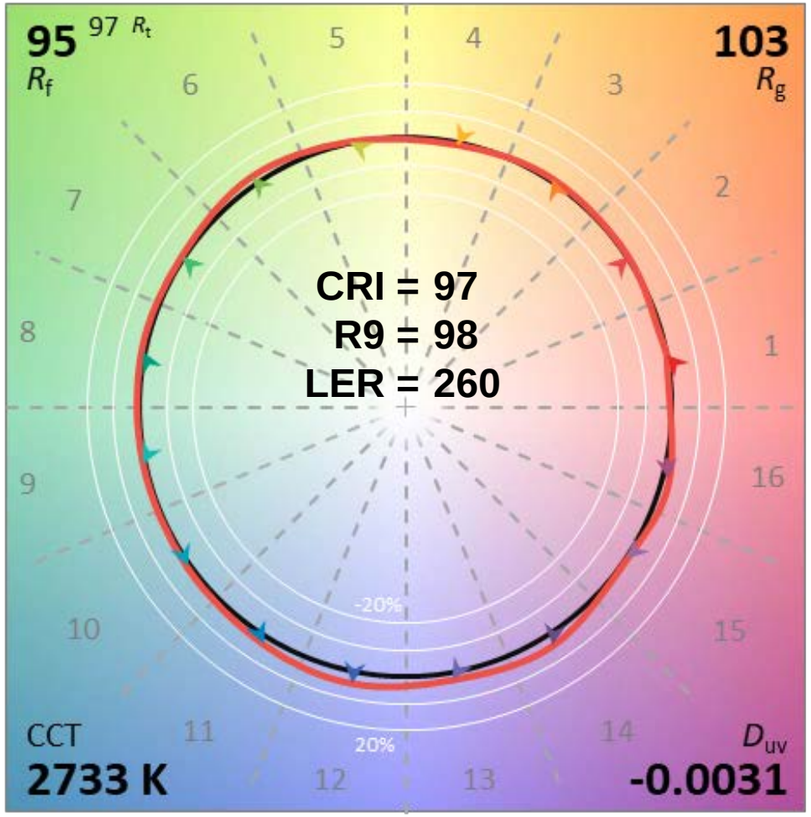
P1 V- F1

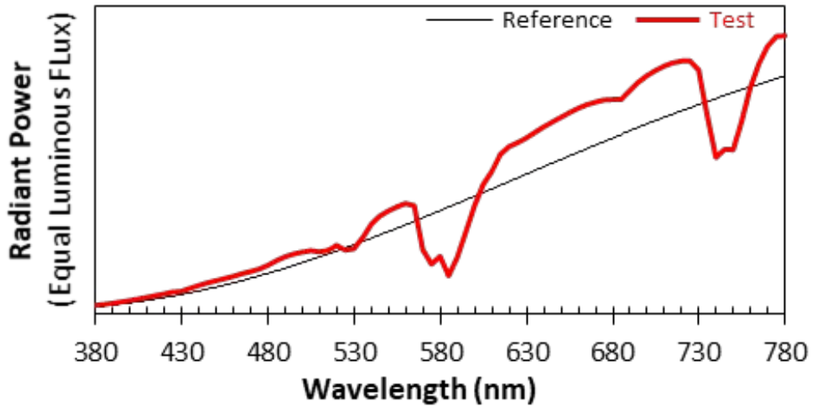


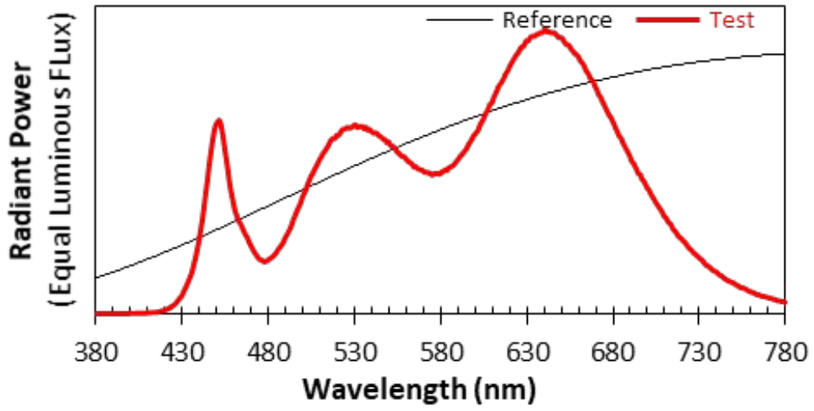
P2 V- F2

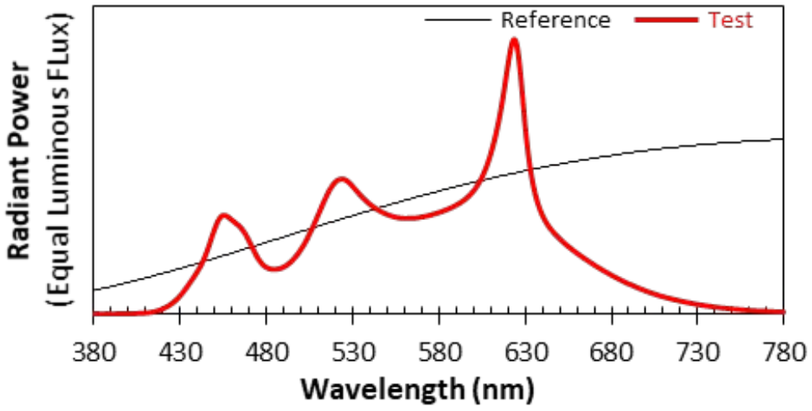


P1 V- F1

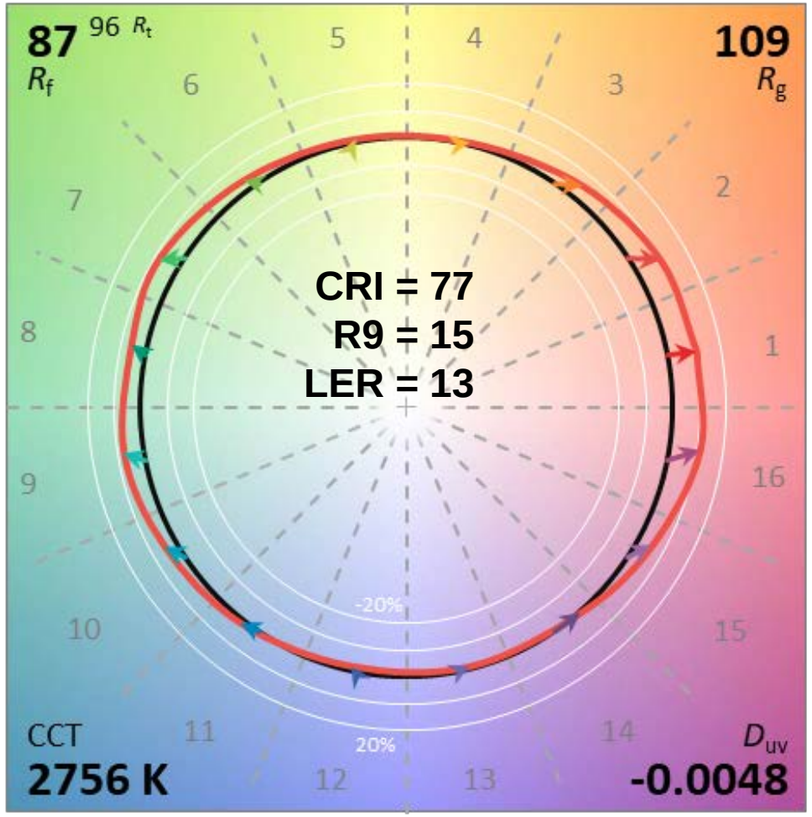




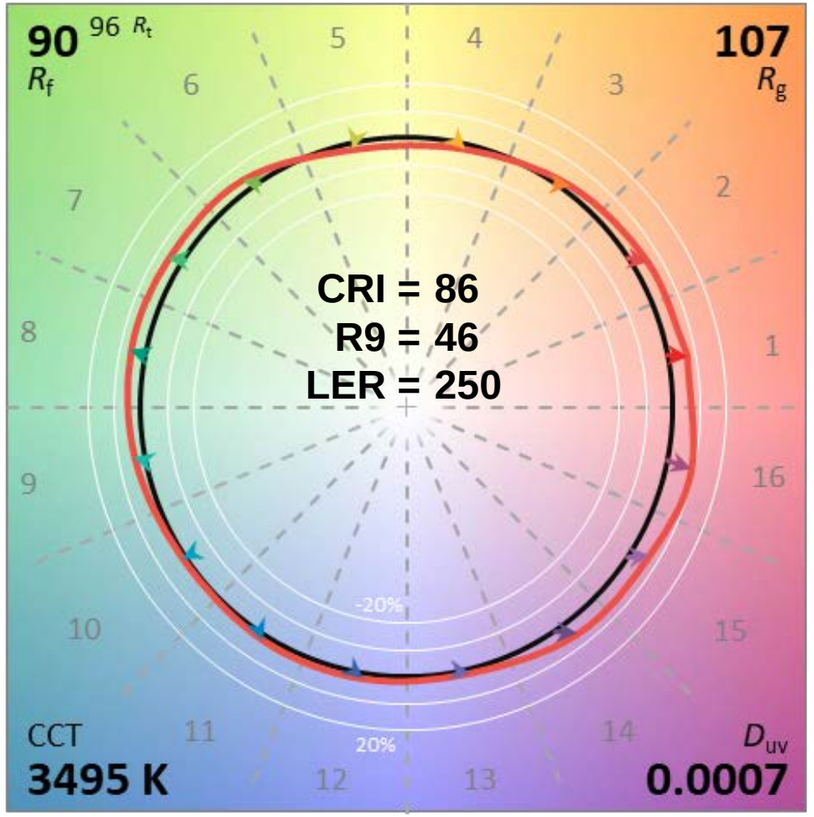




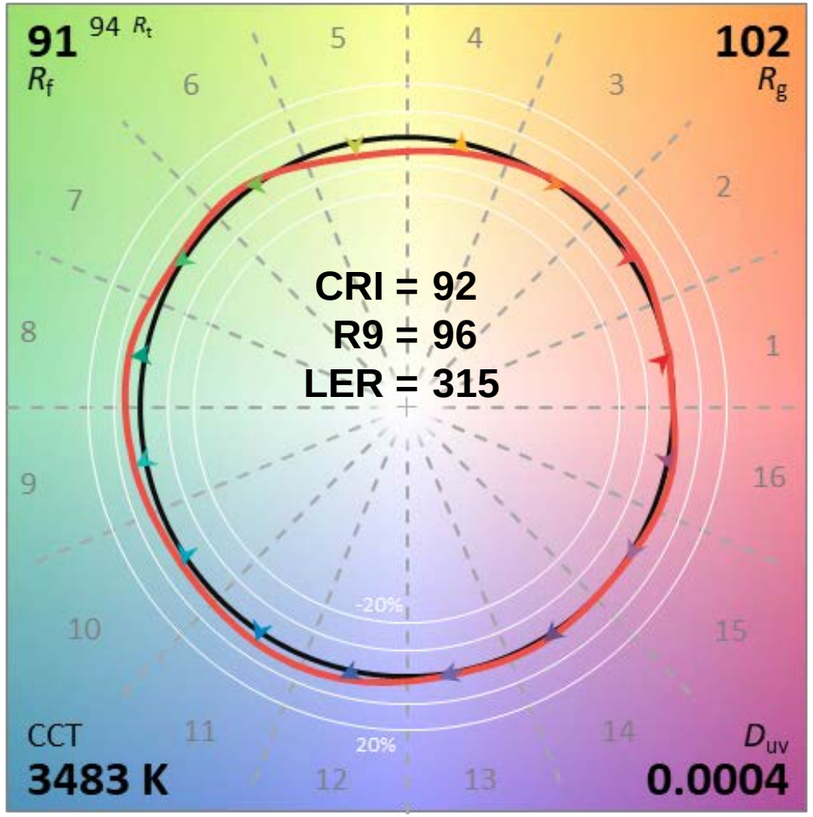
P1 V3 F-

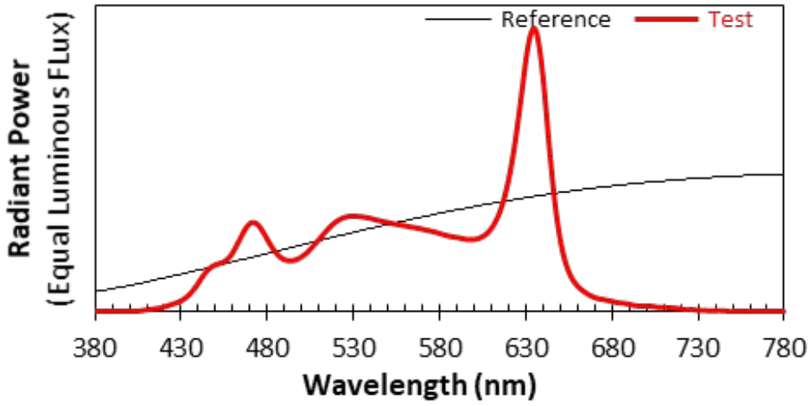


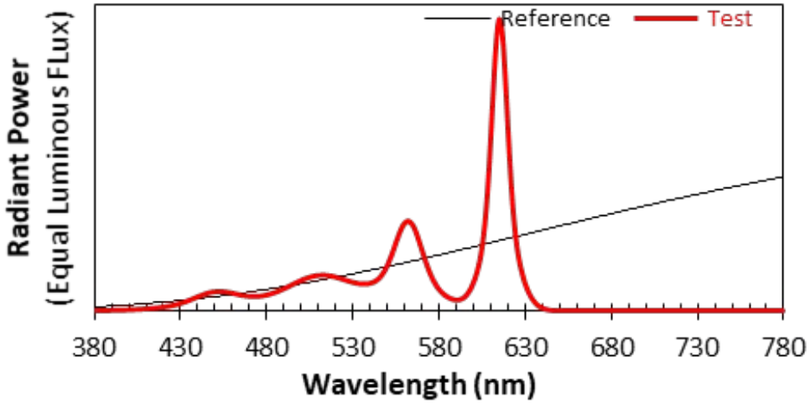
P1 V3 F3

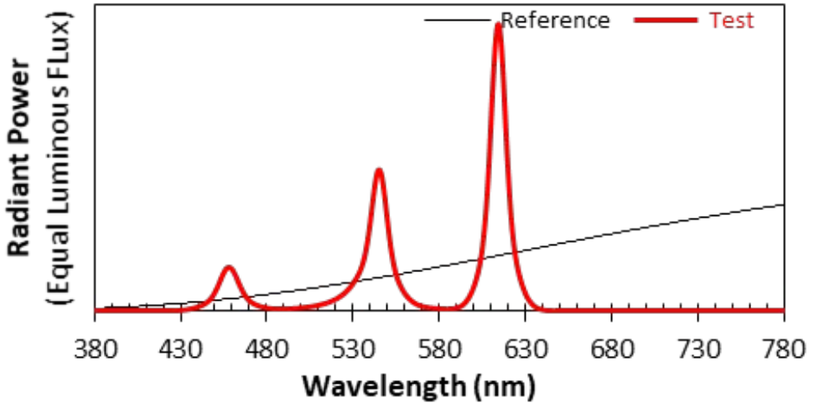


P1 V3 F2

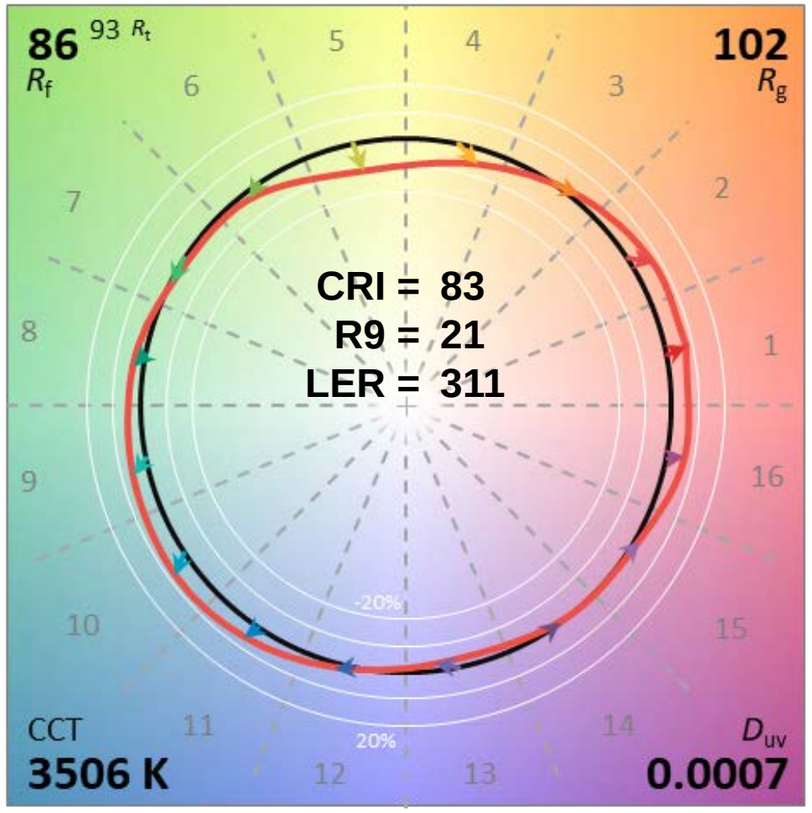




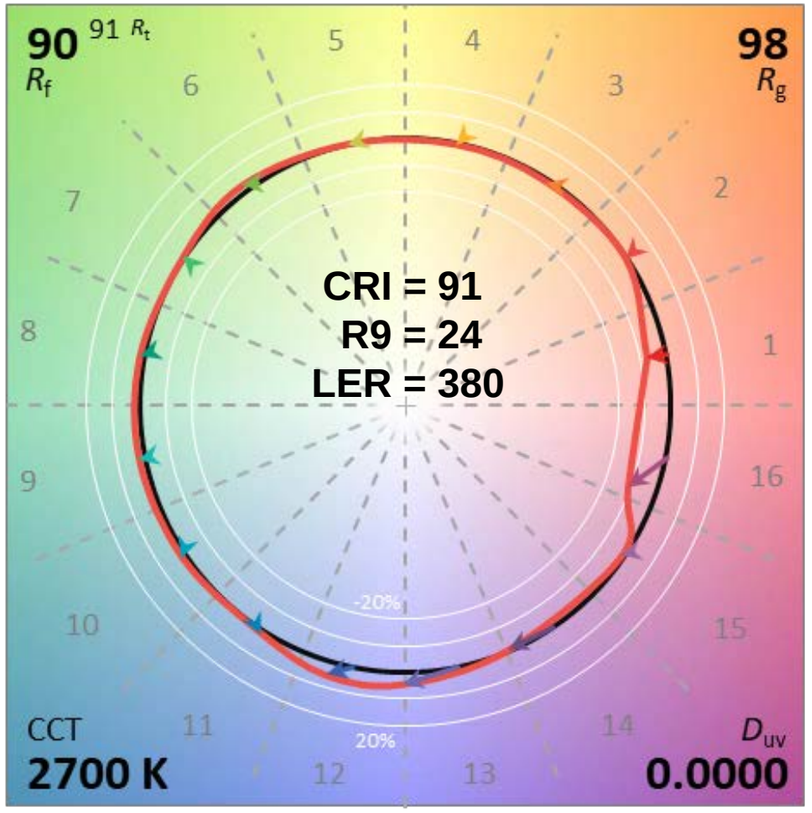




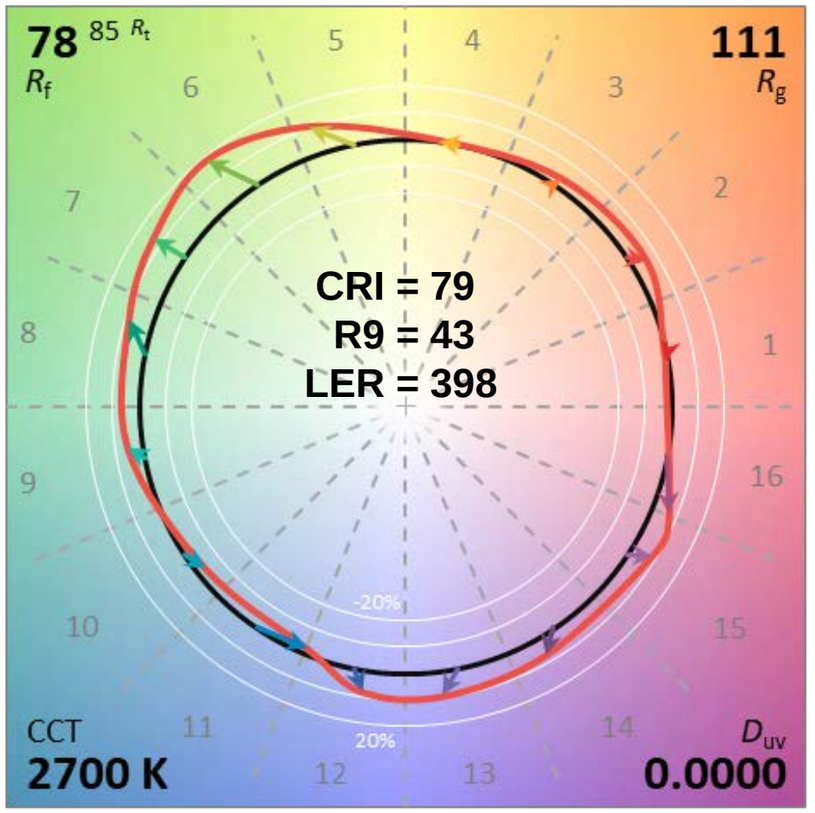
P1 V3 F3



P3 V- F3



P2 V- F-



Lightening Round:
What's Next In Color Science

- Updating Chromaticity
- Observer Variability
- Color Discrimination
- Color Rendition Variability
- Far Red
- Light Level Variation
- Tuning for Visually Impaired

Last Word

- What’s your vision for the future?
- What’s wrong with the status quo?