Advances in Characterizing Color Rendition of Light Sources

March 9, 2021

Webinar Sponsored by OSA Color Technical Group

OSA The Optical Society | 100 Since 1916

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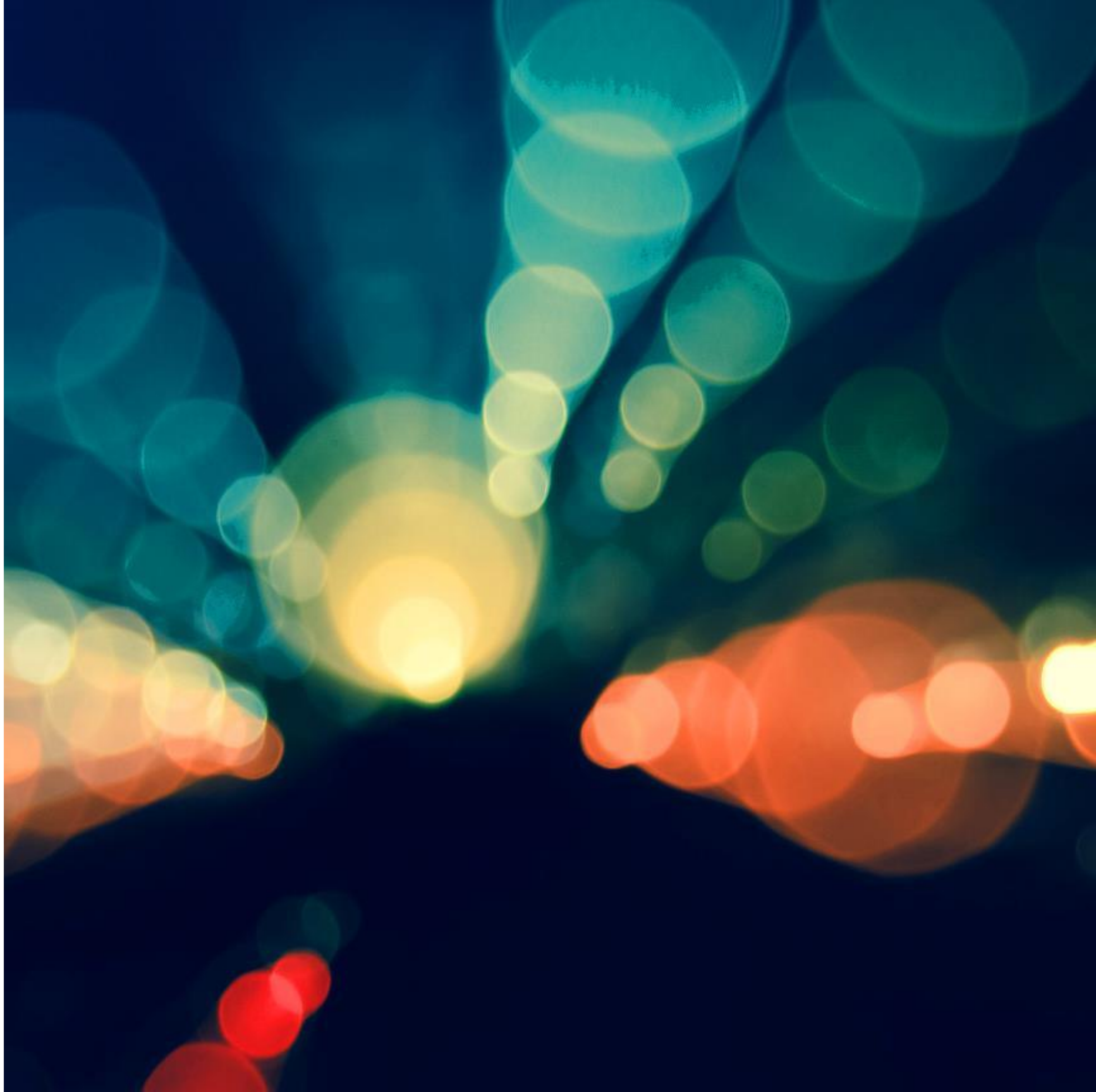
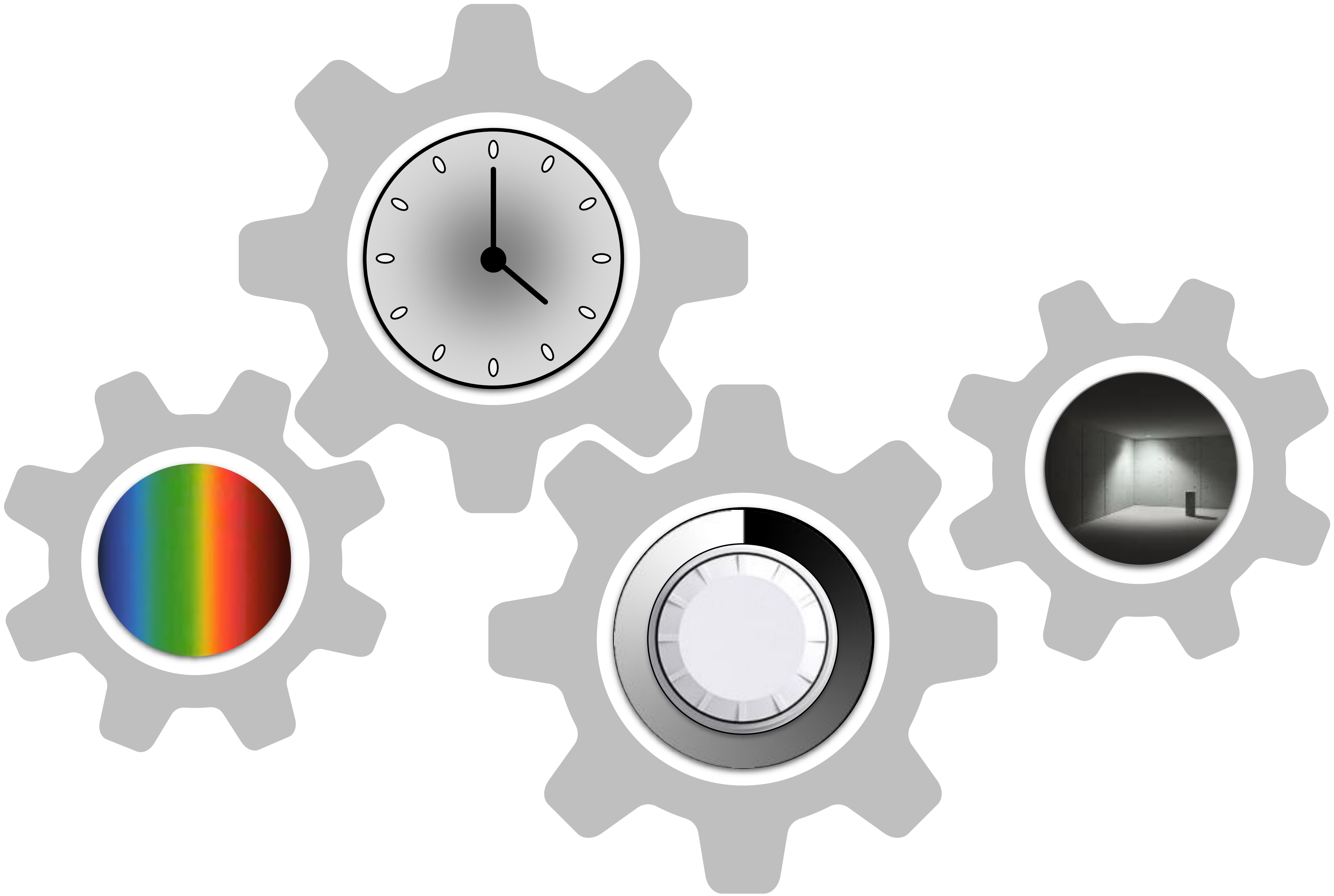


Color rendering is important because color gives us so much.

Lighting variables are time, intensity, spatial distribution, and spectrum.



Color rendition encompasses a collection of concepts that are all related to how light sources render color in objects.

Salient aspects of Color Rendition
- Fidelity
- Naturalness
- Preference
- Vividness
- Discrimination
- Memory
- Metamerism

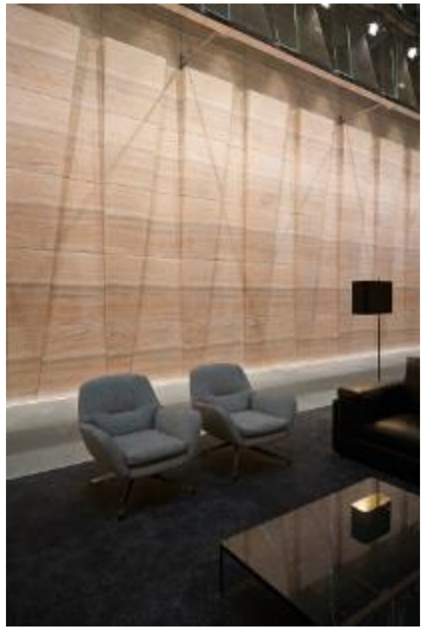
Understanding
Color Rendition is
knowing how to …

Venture Capital Office Building | Menlo Park, CA, USA
Lighting Design: Sean O’Connor Lighting Inc
Architecture: Paul Murdoch Architects
2014 IALD International Lighting Design Award of Excellence

… predict it.

… communicate it.

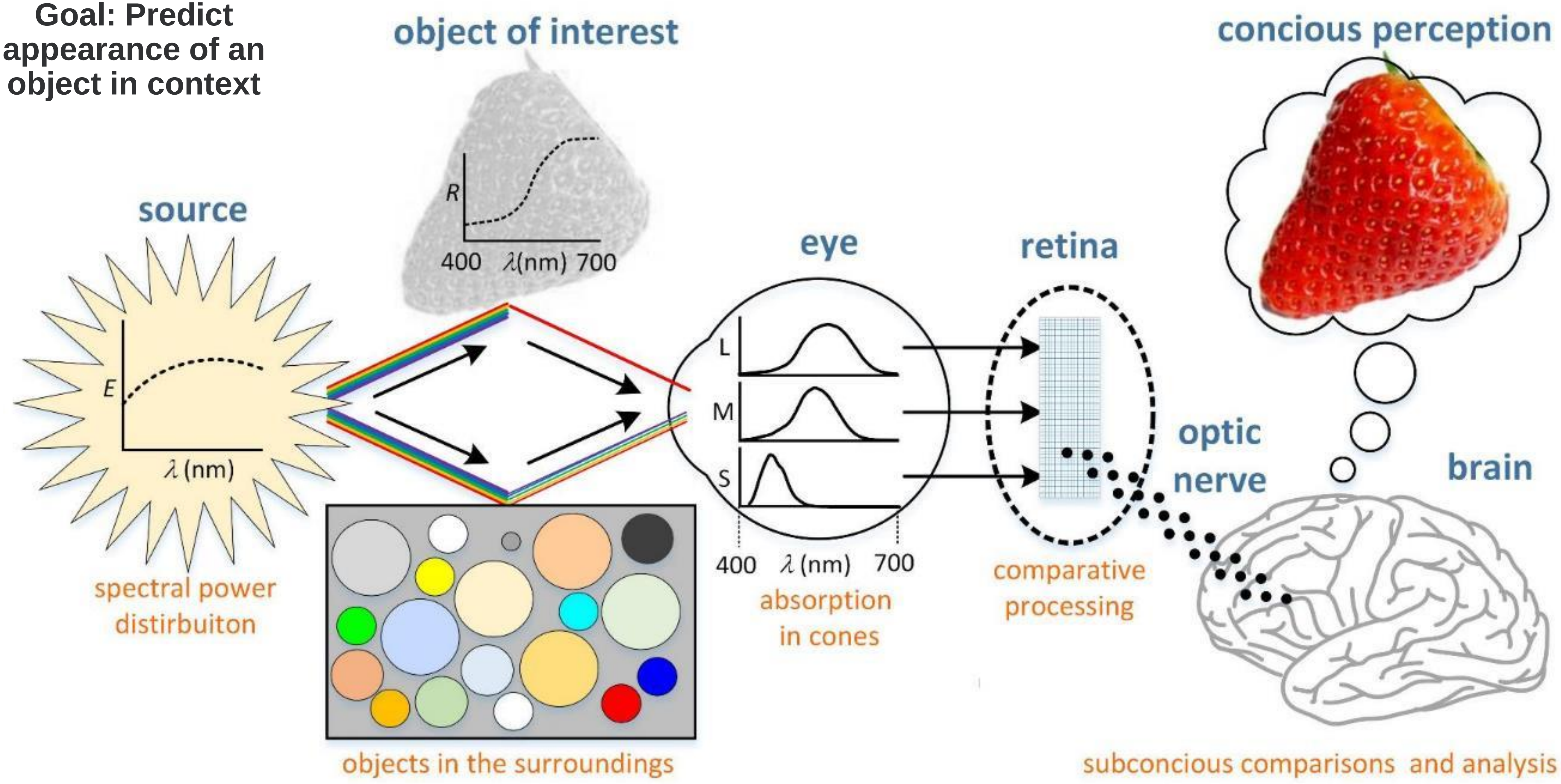
… realize it.



171 Collins Street | Melbourne, Australia
Lighting Design: Electrolight
Architecture: Bates Smart Architects
2014 IALD International Lighting Design Award of Merit

Color Appearance

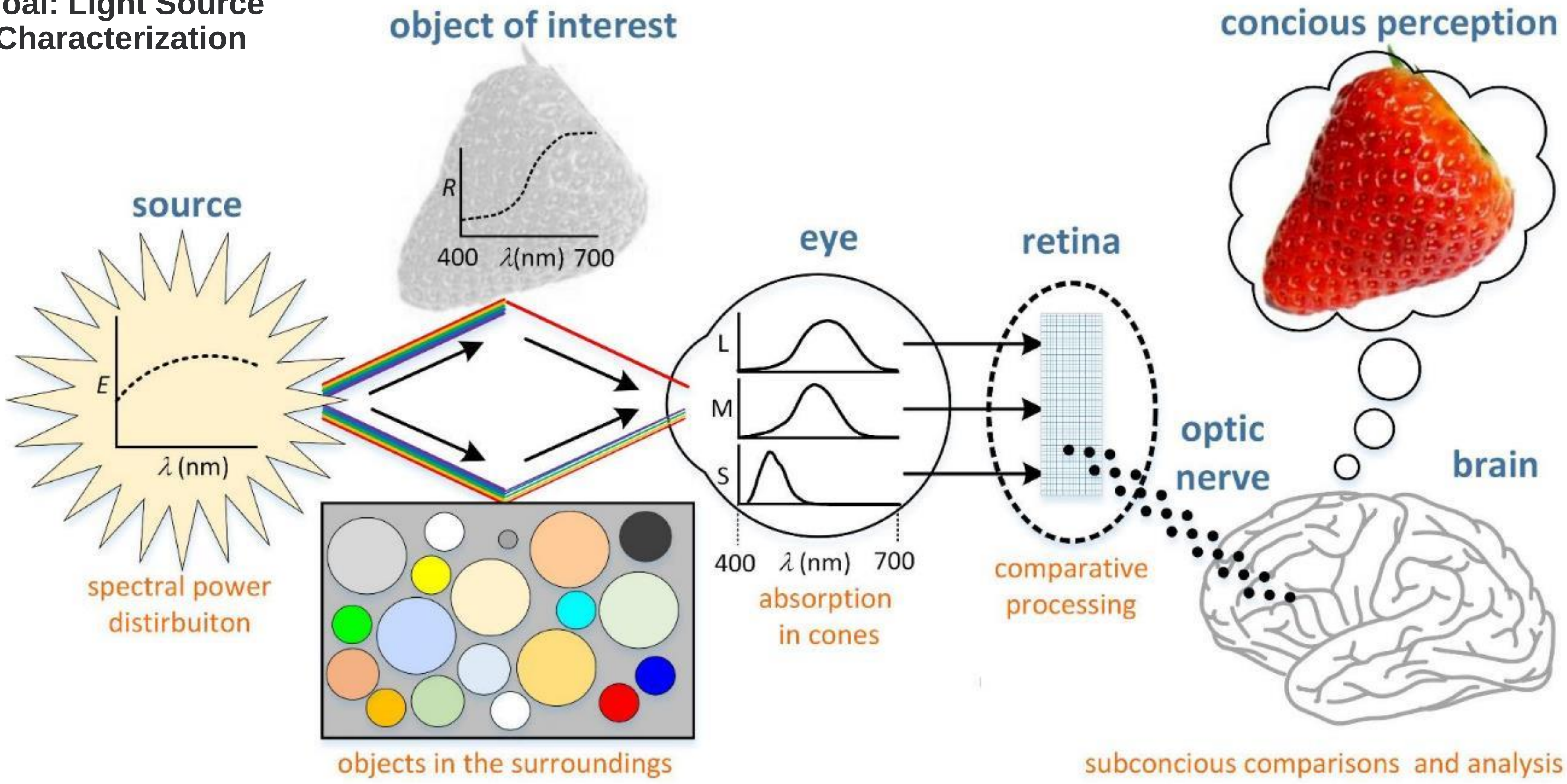
Goal: Predict appearance of an object in context



https://doi.org/10.1146/annurev-vision-091718-015018

Color Rendition

Goal: Light Source Characterization



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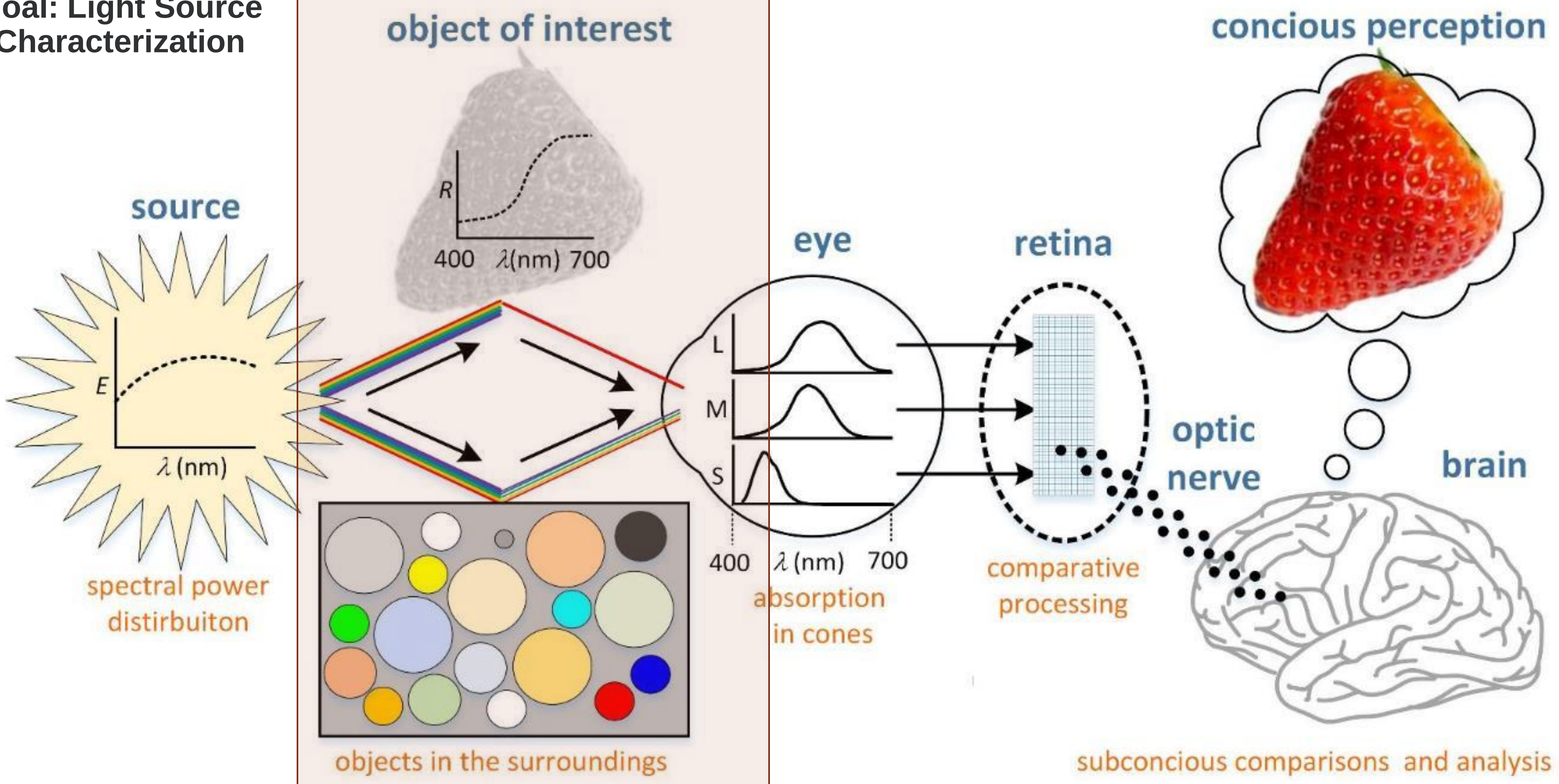
Color Rendition

Goal: Light Source Characterization

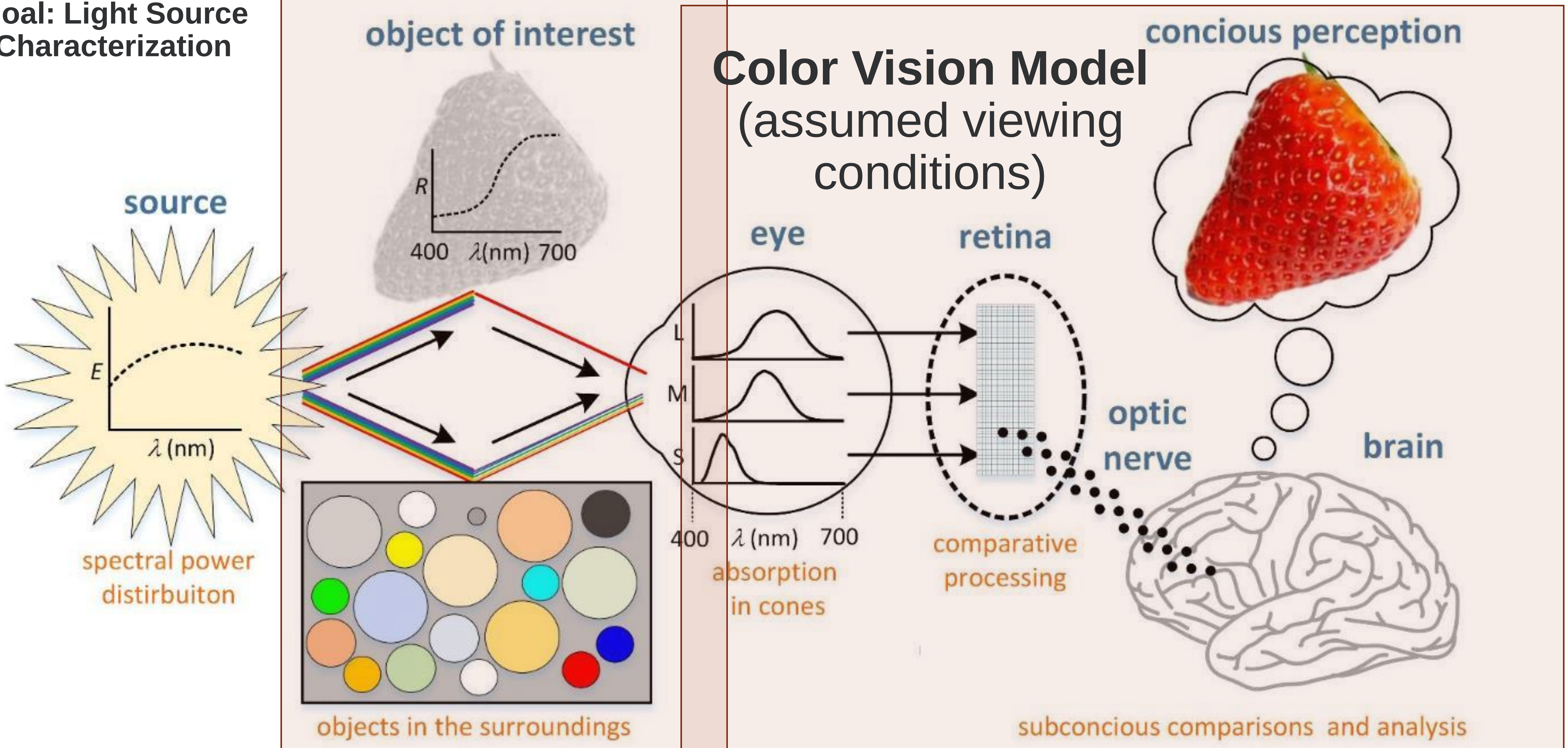


Sample Colors
(in isolation)

https://doi.org/10.1146/annurev-vision-091718-015018

Color Rendition

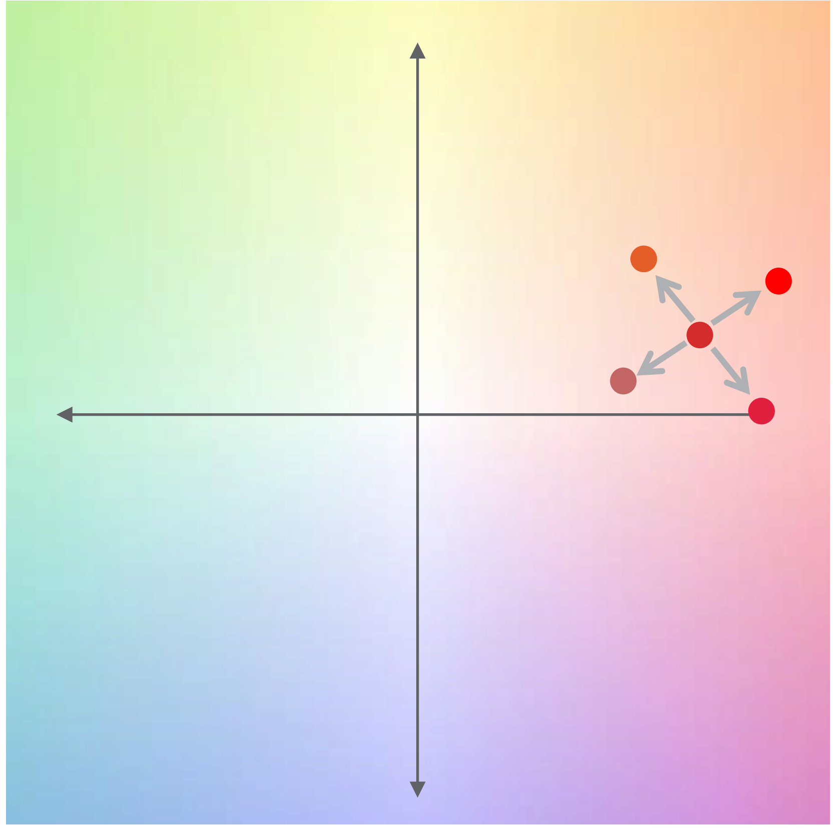
Goal: Light Source Characterization

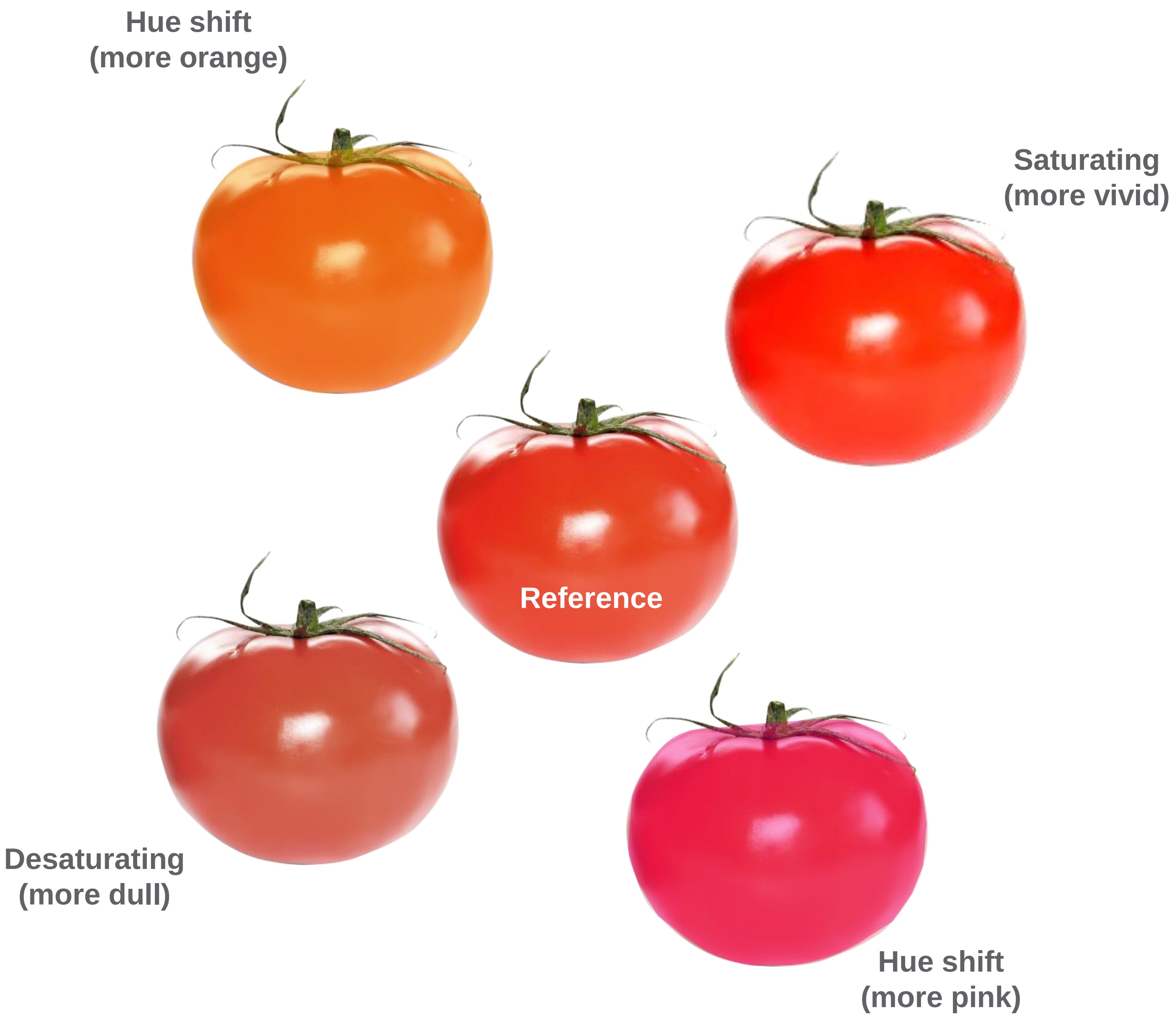


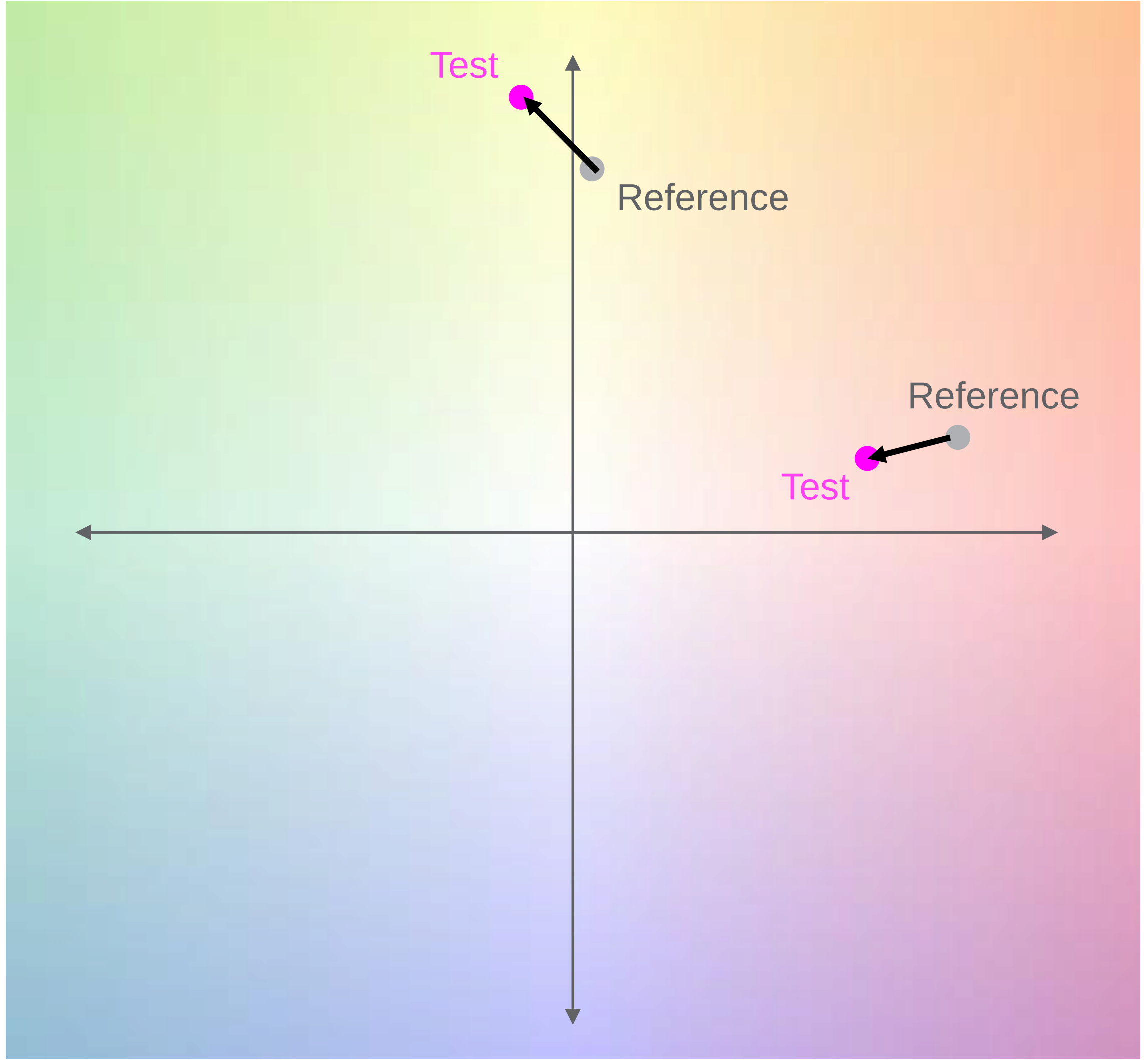
Color Vision Model
(assumed viewing conditions)

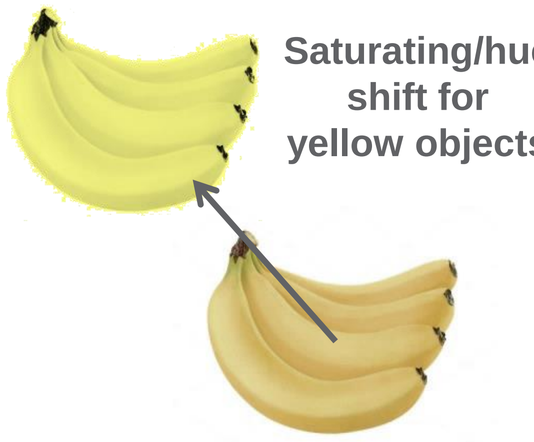
Sample Colors
(in isolation)

https://doi.org/10.1146/annurev-vision-091718-015018

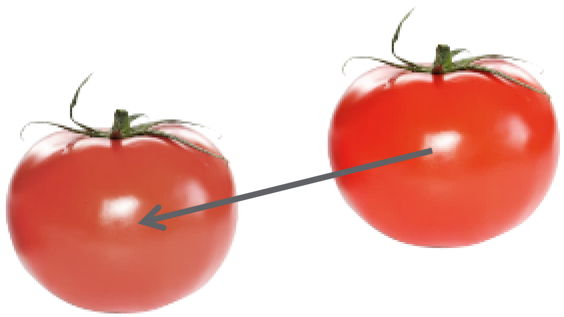



Hue shift
(more orange)
Saturating
(more vivid)
Reference
Desaturating
(more dull)
Hue shift
(more pink)

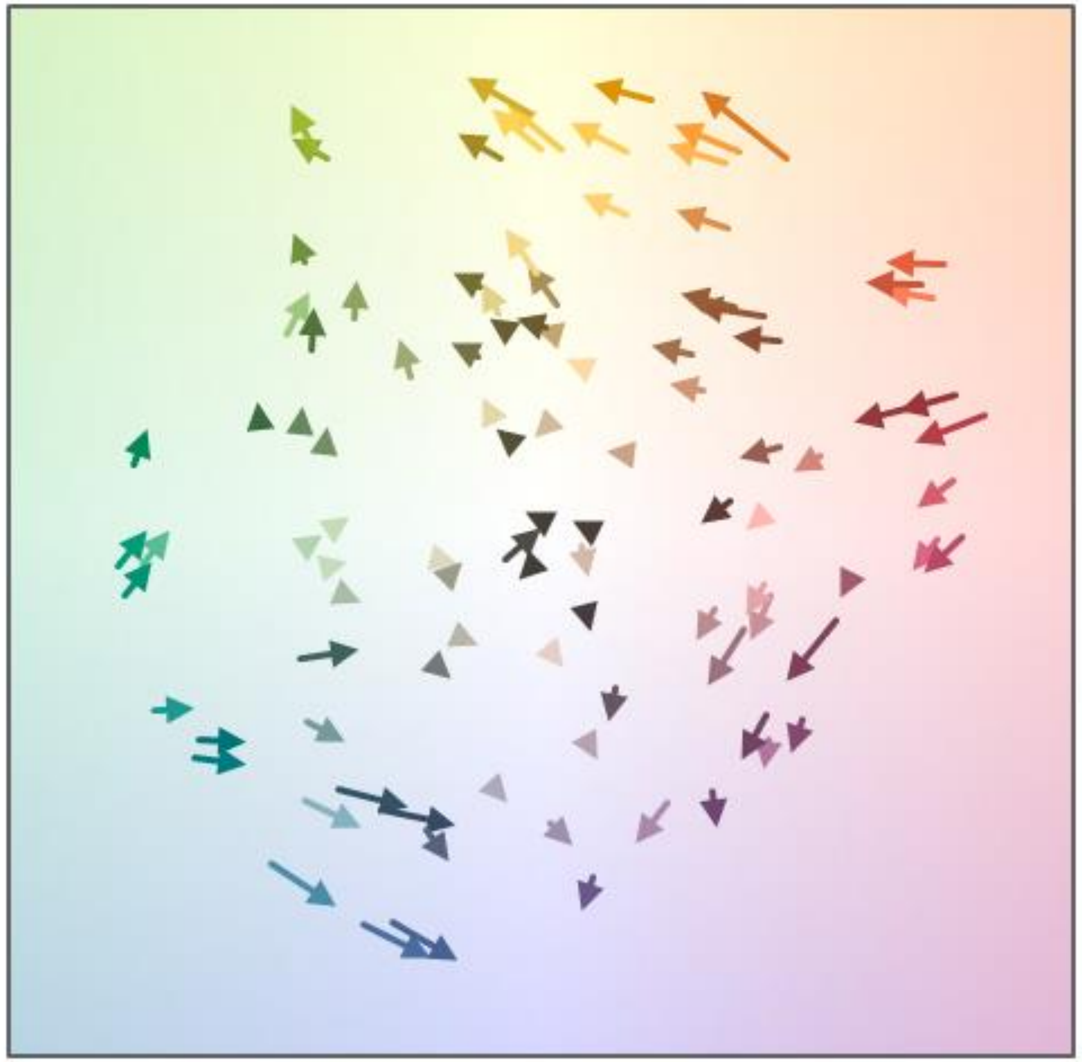




Saturating/hue shift for yellow objects



Desaturating for red objects



Challenge: Summarize complex information about colors shifts for the purpose of light source characterization and specification.

IES TM-30-15
ANSI/IES TM-30-18
Annex E/F
ANSI/IES TM-30-20

Solution 1:
Updated models of color & color vision

TM-30 Calculation Framework

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

Solution 2:
Provide more information

Global Average Values
Fidelity Index (R_f)
Gamut Index (R_g)
Metameric Uncertainty Index (R_t)
Proposed Addition

Graphical Representations
Color Vector Graphic (CVG)

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

Gamut Shape

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

June 2018 webinar covering calculation details:
https://www.ies.org/standards-webinars/tm-30-in-2018-and-beyond-guidance-for-improving-color-quality/

Fidelity Index

R_f

~60 to 100

IES R_f = CIE R_f

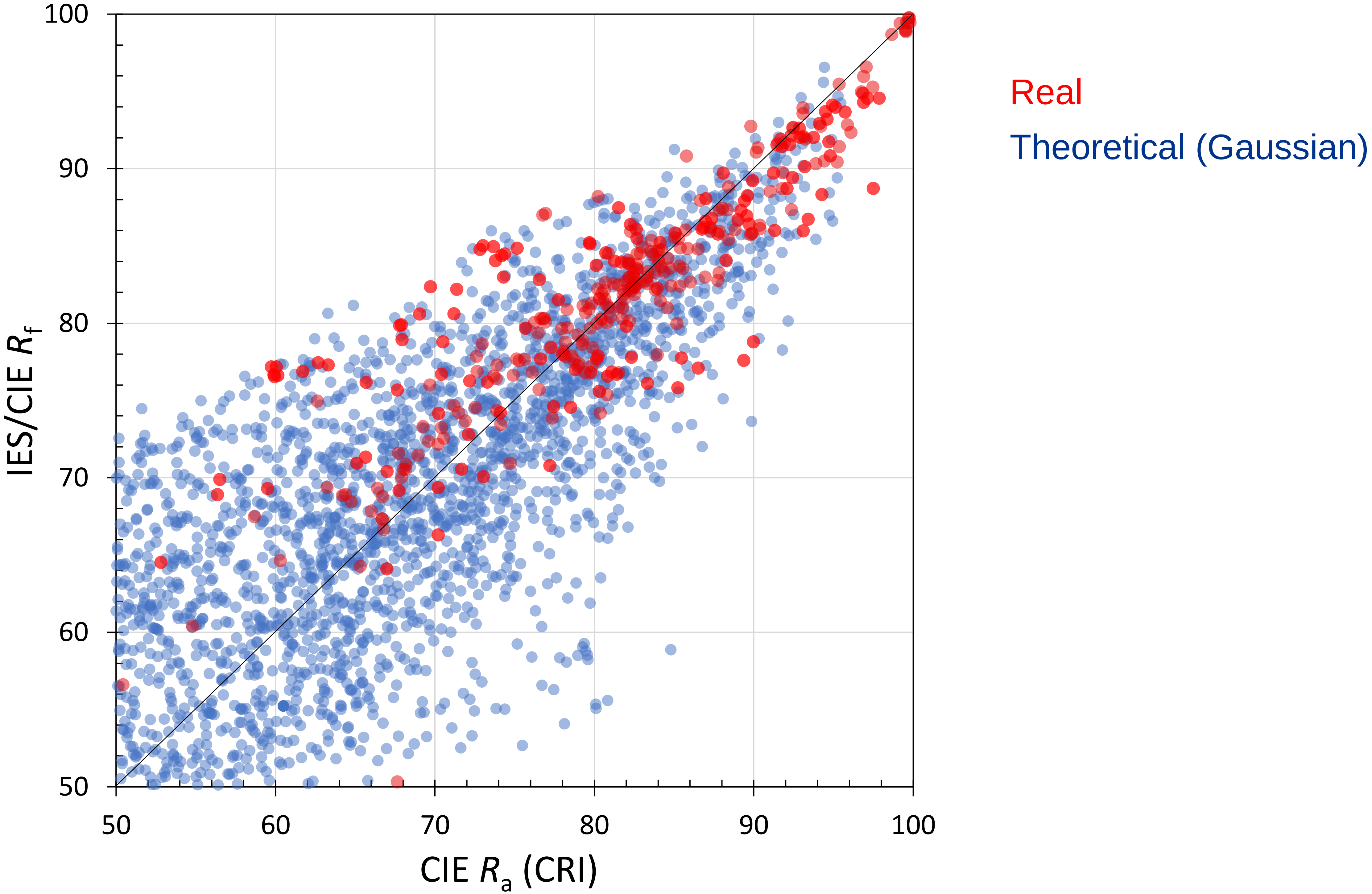
Equal R_f

Similar Past Measures

1965	CIE 13 (CRI) R_a
1974	CIE 13.2 (CRI) R_a
1974	Absolute Color Rendering
1985	Rb
1985	R'13
1990	Categorical Color Rendering
1995	CIE 13.3 (CRI) R_a
1999	R96a
2005	CQS Q_f
2006	Visual Color Rendering
2009	CR100
2010	Rank Order Color Rendering Index
2011	CRI-CAM02UCS
2012	CRI2012 (nCRI)

Illustrations Only. Not actual lighting conditions

Conceptual equivalents don't perform the same.

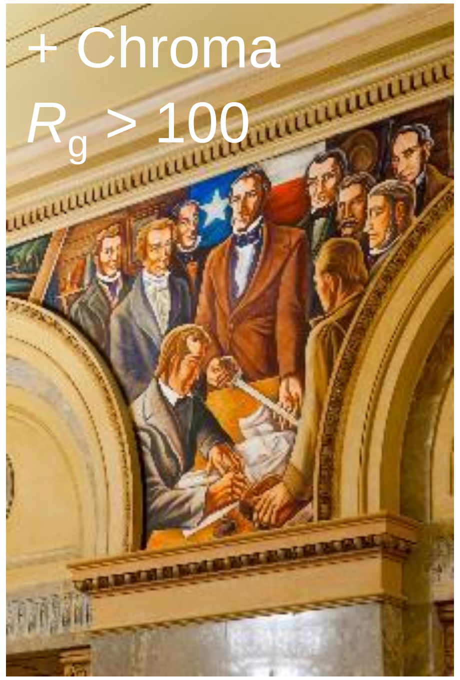


Gamut Index

R_g

~80 to 120

Original image courtesy of Randy Burkett Lighting Design



Similar Past Measures

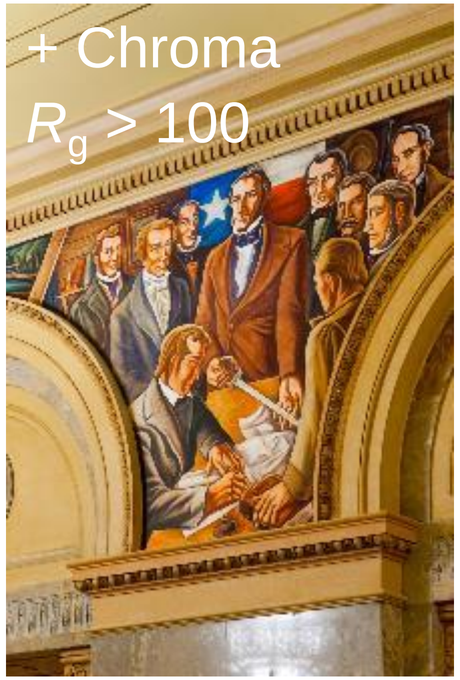
1972	Color Discrimination Index
1984	Color Rendering Capacity
1993	Feelings of Contrast Index
1997	Cone Surface Area
2005	CQS Q_g
2008	Gamut Area Index

Illustrations Only. Not actual lighting conditions

Gamut Index

R_g

~80 to 120



Equal R_g

Similar Past Measures

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2005	CQS Q_g
2008	Gamut Area Index

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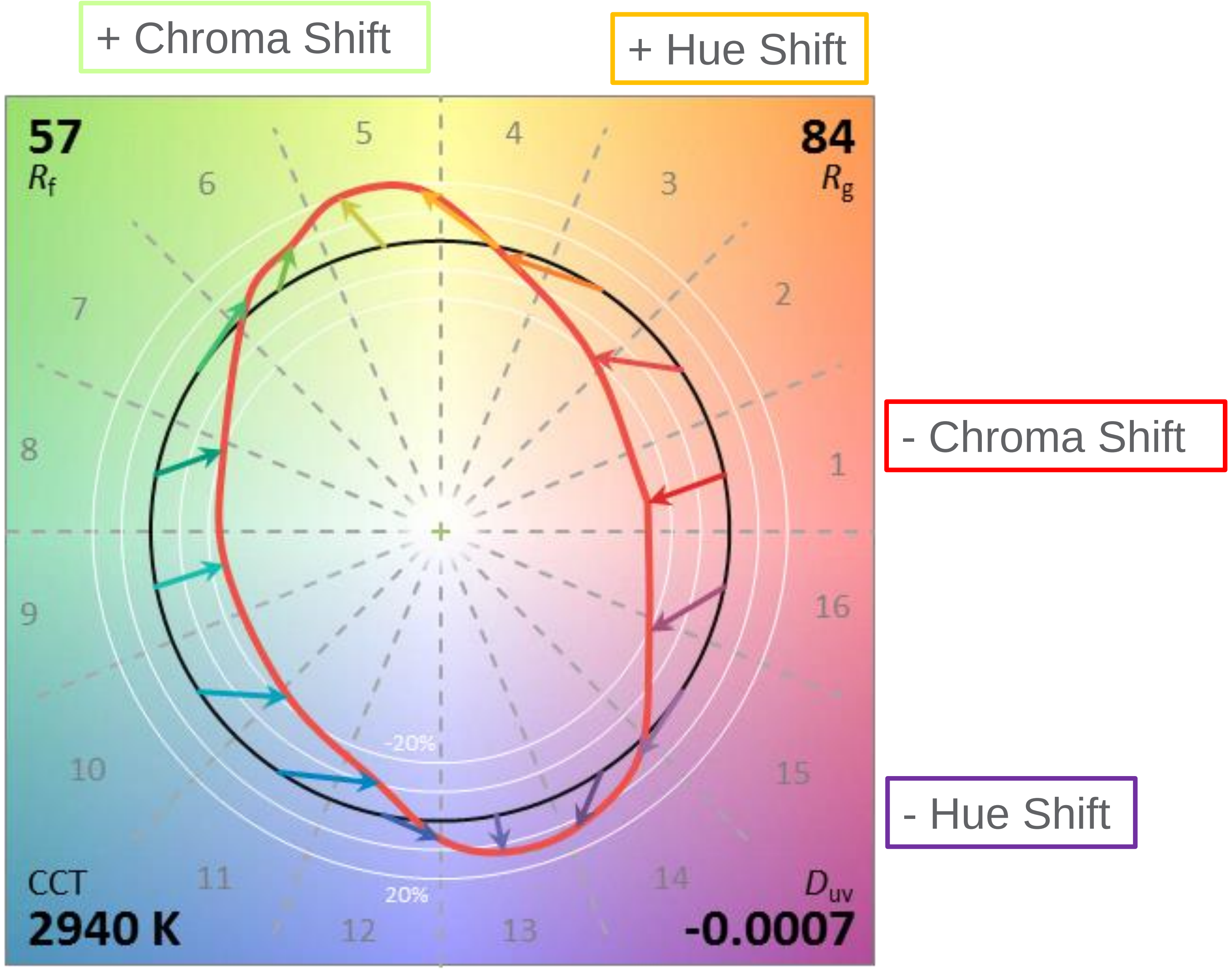
Color Vector Graphic

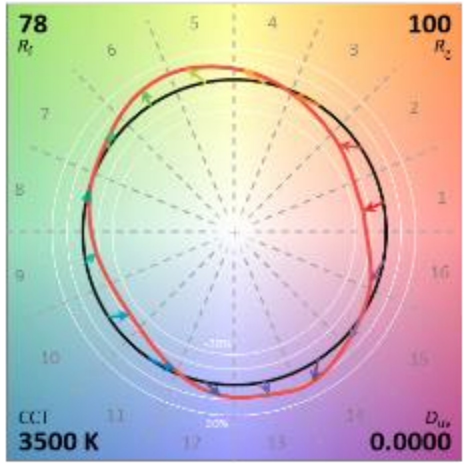
CVG

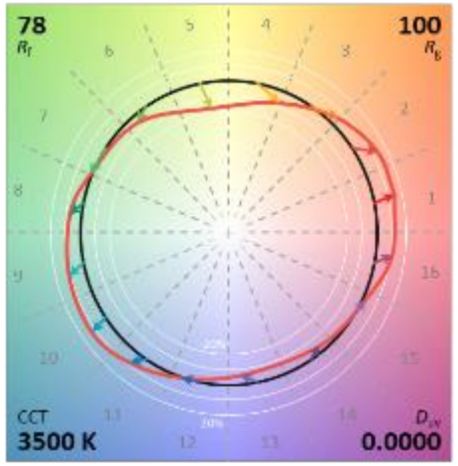


Similar Past Concepts

1988	Color Rendering Vectors
2005	CQS

Gamut Shape





R_g = 100

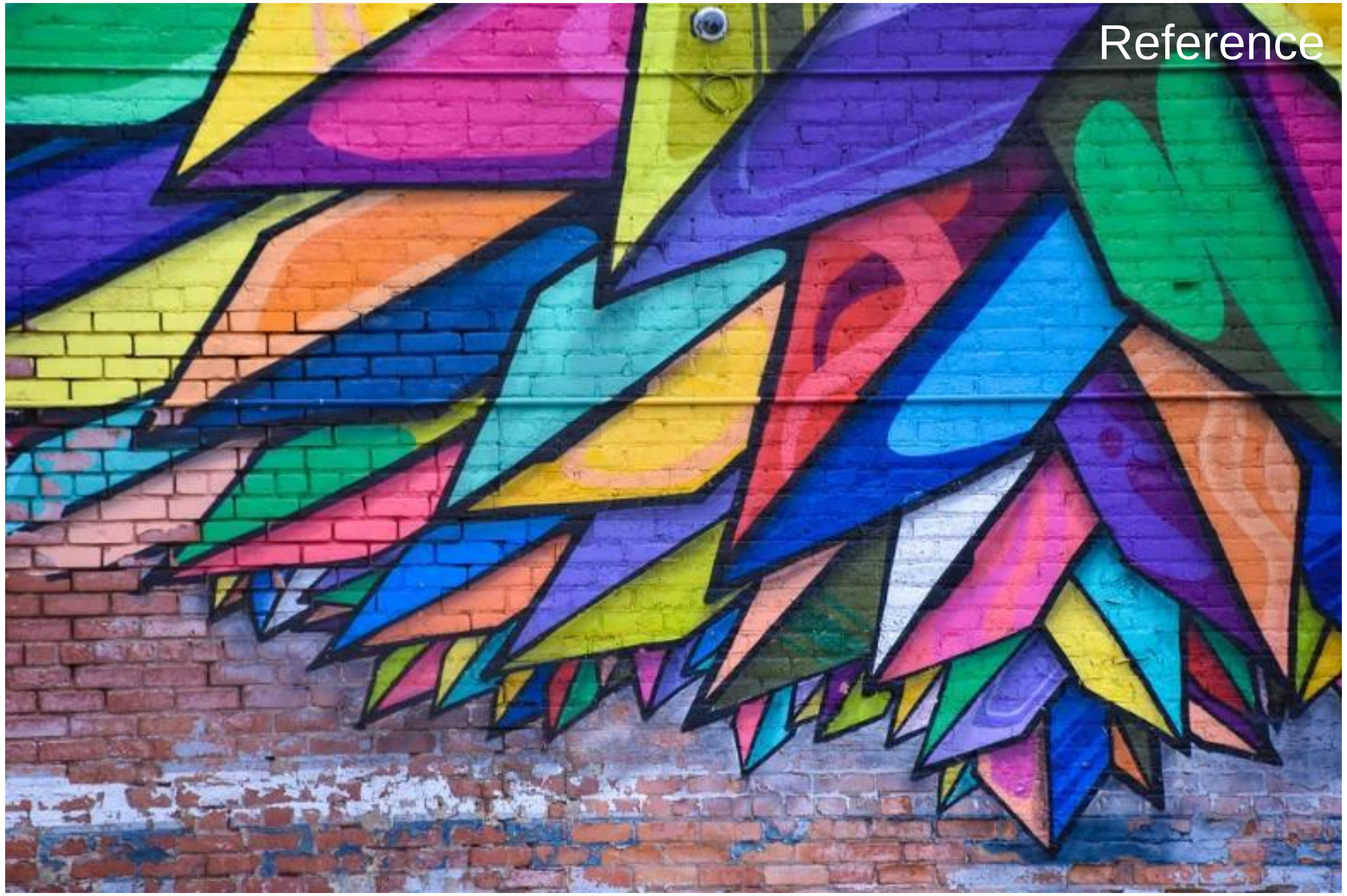
R_f = 78

Similar Past Concepts

1988	Color Rendering Vectors
2005	CQS

Illustrations Only. Not actual lighting conditions

Gamut Shape



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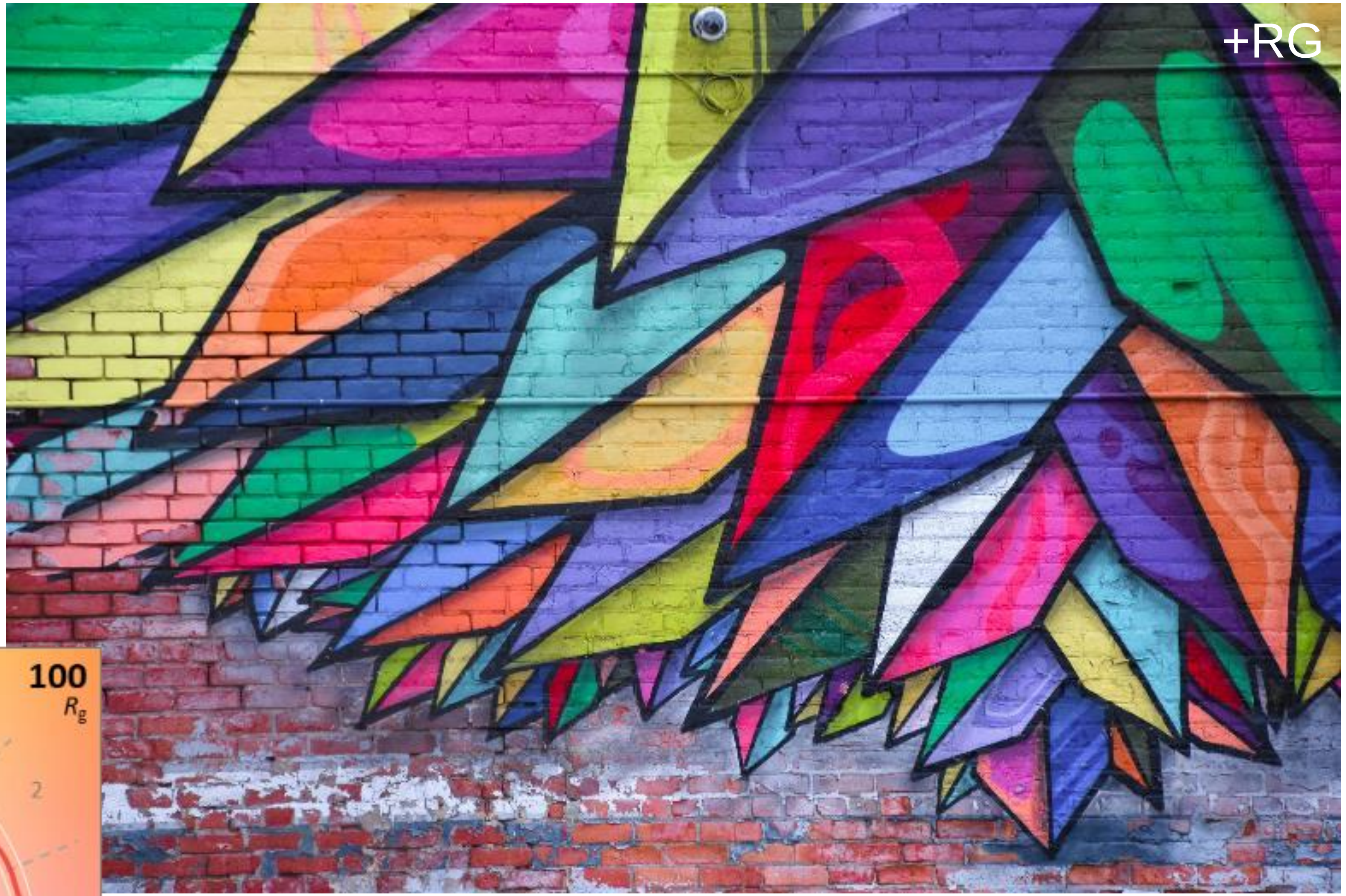
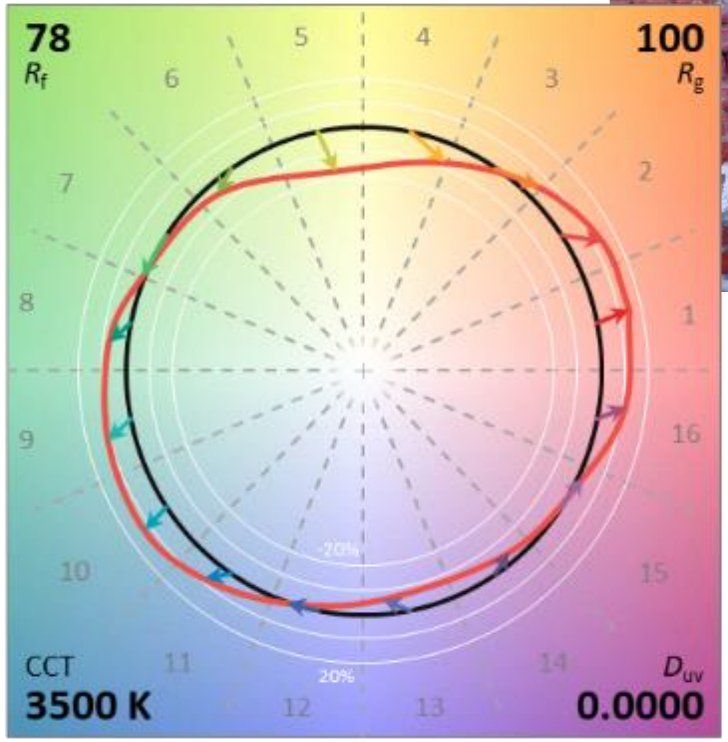
Illustrations Only. Not actual lighting conditions

Gamut Shape





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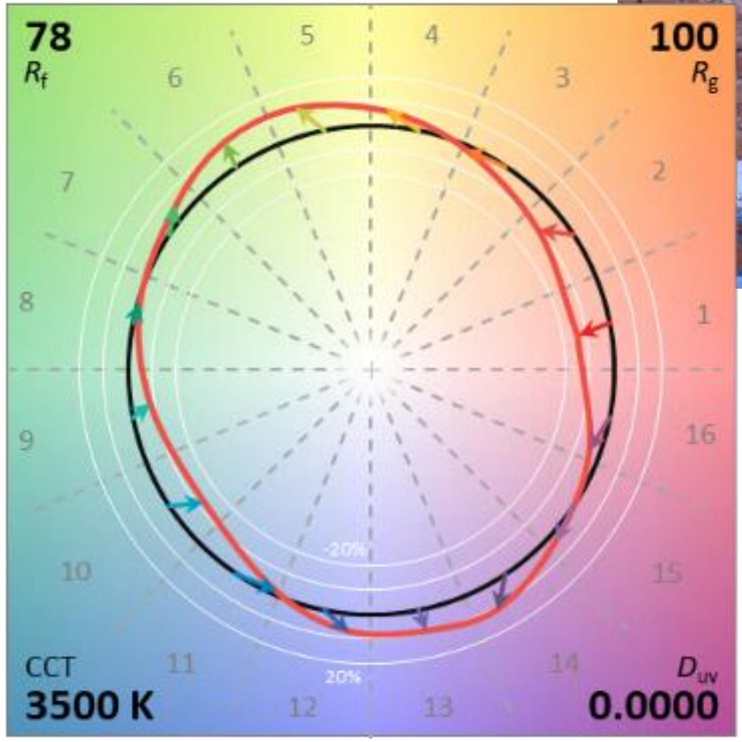
Illustrations Only. Not actual lighting conditions

Gamut Shape



Similar Past Concepts

1988	Color Rendering Vectors
2005	CQS

Illustrations Only. Not actual lighting conditions

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Local Chroma Shift

$R_{cs,hj}$

j = 1 to 16

~-25% to 25%

Similar Past Concepts

1986 Pointer's Index

Illustrations Only. Not actual lighting conditions

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Local Hue Shift

$R_{hs,hj}$

j = 1 to 16

~-0.25 to 0.25

Similar Past Concepts

1986 Pointer's Index

Illustrations Only. Not actual lighting conditions

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Local Color Fidelity

$R_{f,hj}$

j = 1 to 16

~60 to 100

Equal $R_{f,h1}$

Similar Past Concepts

1974	CIE 13 R_i
2005	CQS

Illustrations Only. Not actual lighting conditions

To have a preference is to like something more than something else.

In lighting, color preference refers to the preferred rendition of object colors. It is a property we attribute to light sources.

Buck GB. 1950. Color preference studies with fluorescent lamps. Illuminating Engineering. 45:165-167.

There is a well-developed body of knowledge with some robust findings.

- Narendran and Deng 2002
- Jost-Boissard and others 2009
- Smet and others 2010
- Islam and others 2013
- Jost-Boissard and others 2014
- Wei and others 2014
- Wei and others 2014a
- Ohno and others 2015
- Teunissen and others 2016
- Wei and Houser 2016
- Royer and others 2017
- Zhang and others 2017
- Kawashima and Ohno 2017
- Royer and others 2018
- Esposito and Houser 2019
- Royer and others 2020

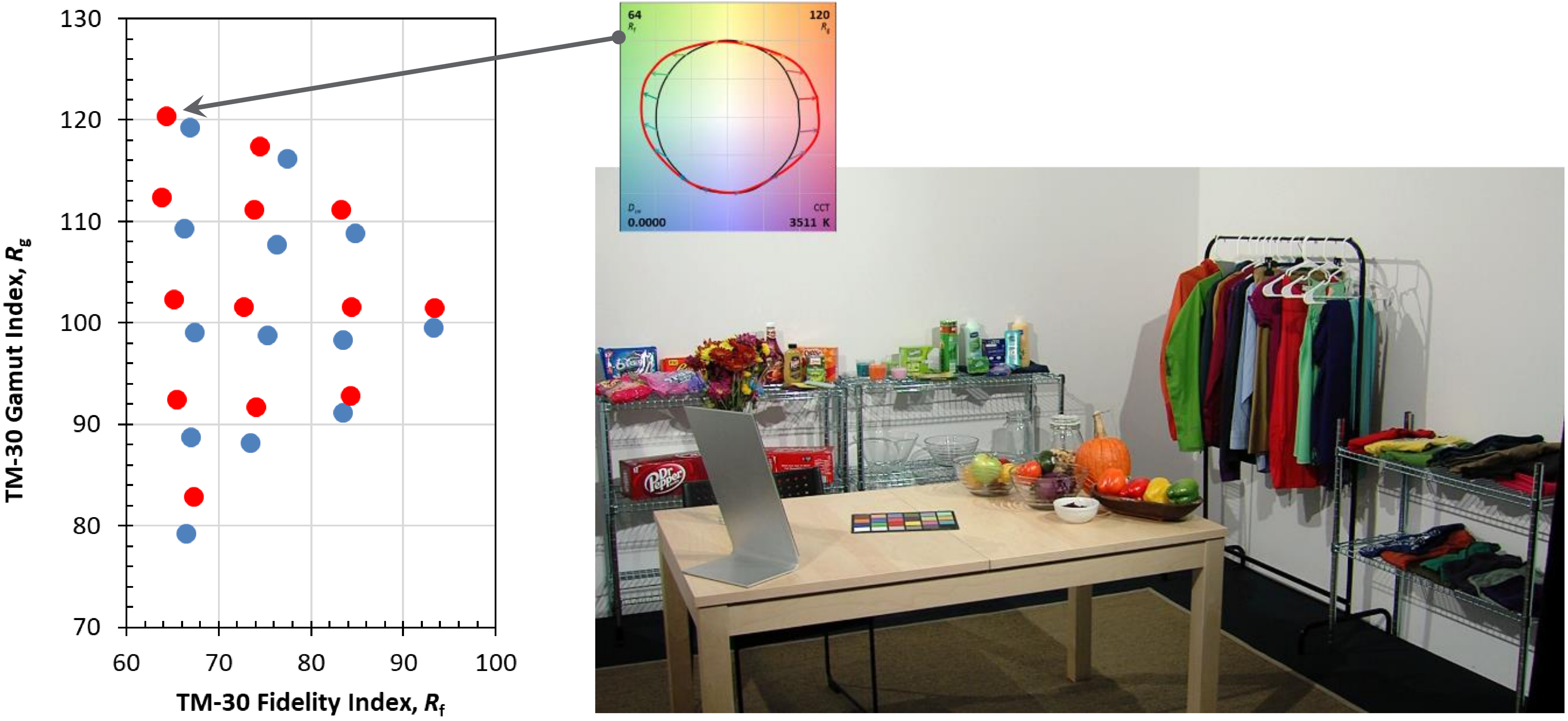
These studies have found
preference for an increase in saturation.

There is a well-developed body of knowledge with some robust findings.

- Narendran and Deng 2002
- **Jost-Boissard and others 2009**
- Smet and others 2010
- Islam and others 2013
- Jost-Boissard and others 2014
- **Wei and others 2014** ← Example 4
- Wei and others 2014a
- **Ohno and others 2015**
- Teunissen and others 2016
- **Wei and Houser 2016**
- **Royer and others 2017** ← Example 1
- **Zhang and others 2017**
- **Kawashima and Ohno 2017**
- **Royer and others 2018**
- **Esposito and Houser 2019** ← Example 2
- **Royer and others 2020** ← Example 3

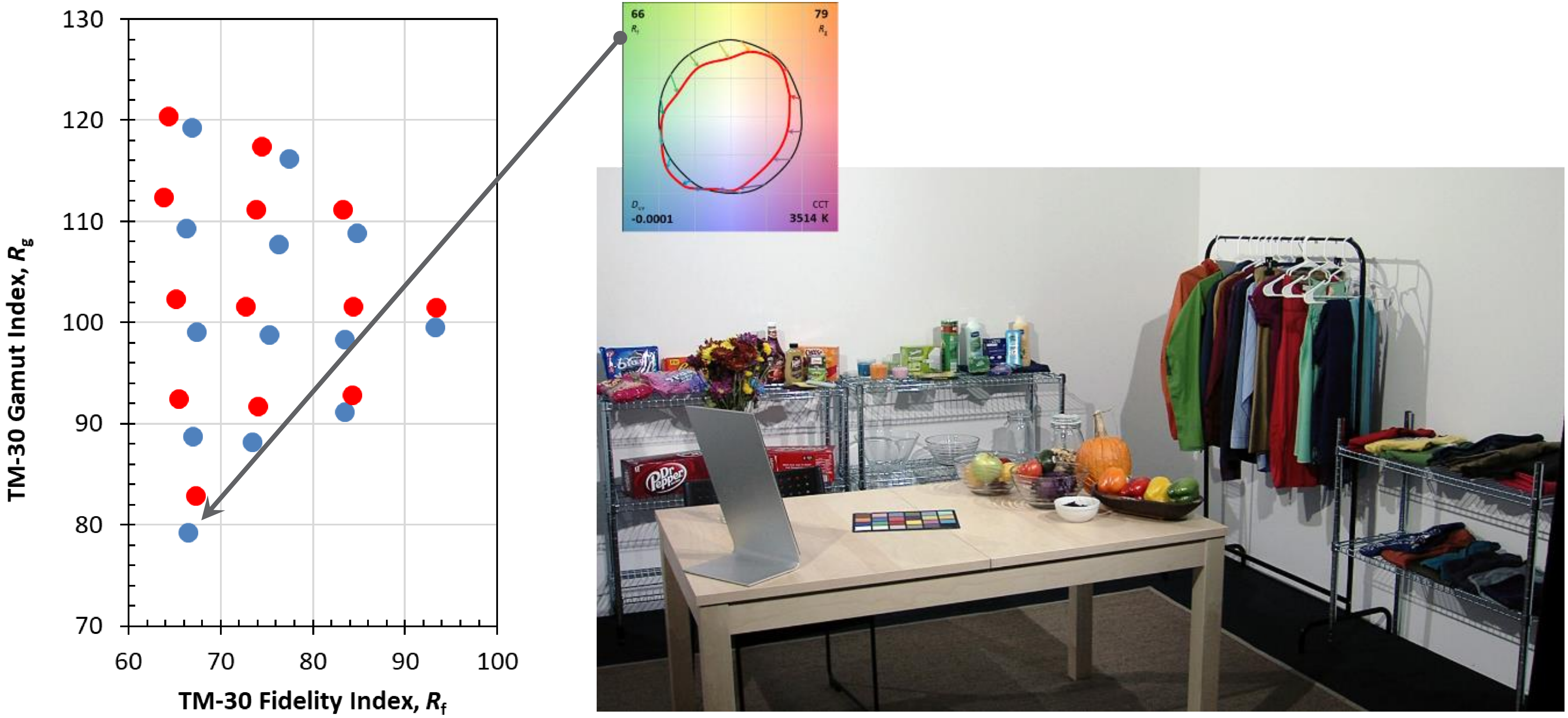
Some suggest the importance of the rendering of ***red*** and ***red-orange hues***.

Example 1. Experimental Conditions



Royer MP, Wilkerson A, Wei M, Houser KW, Davis RG. 2017. Human perceptions of color rendition vary with average fidelity, average gamut, and gamut shape. Lighting Res. Technol. 49(8):966-991. http://dx.doi.org/10.1177/1477153516663615

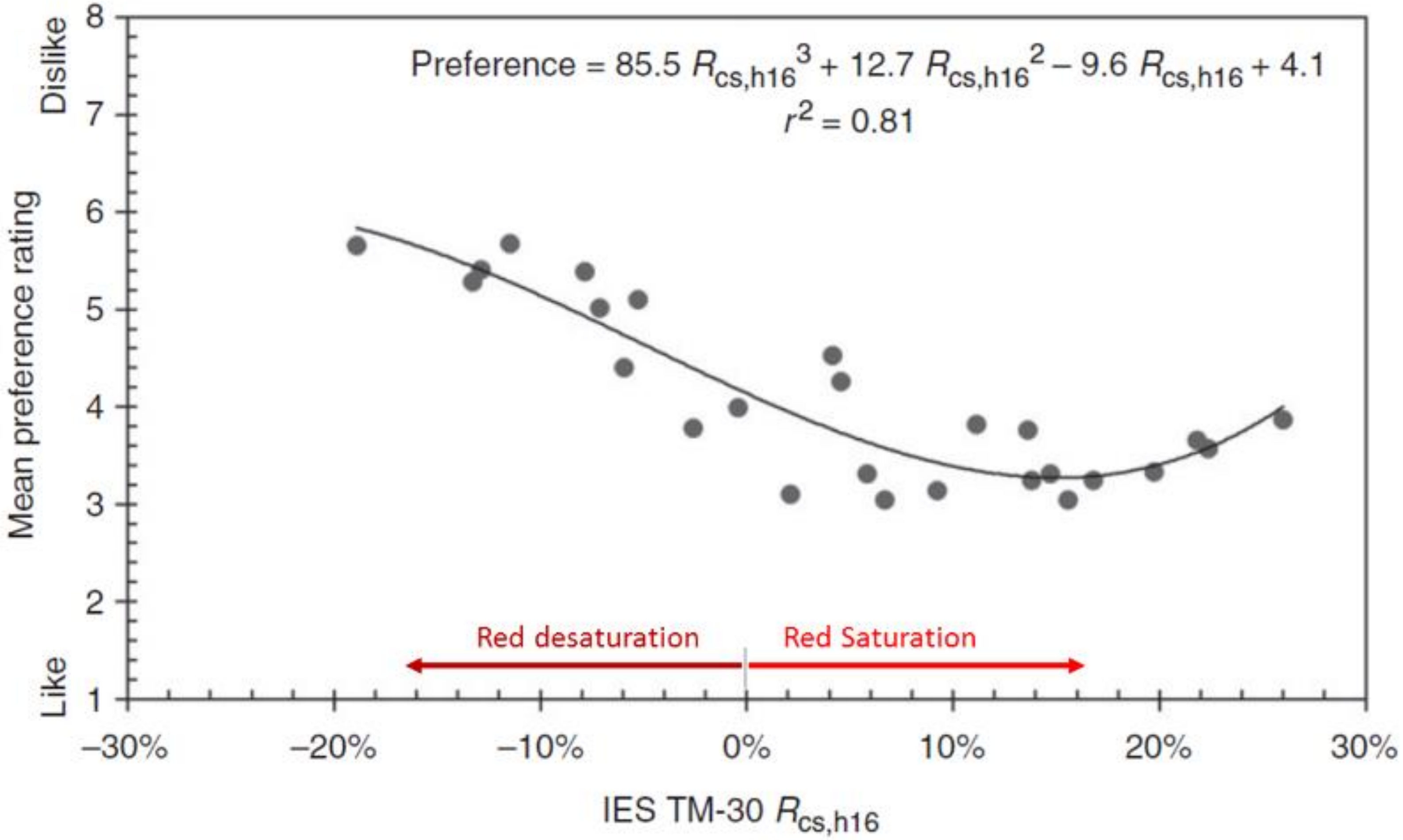
Example 1. Experimental Conditions



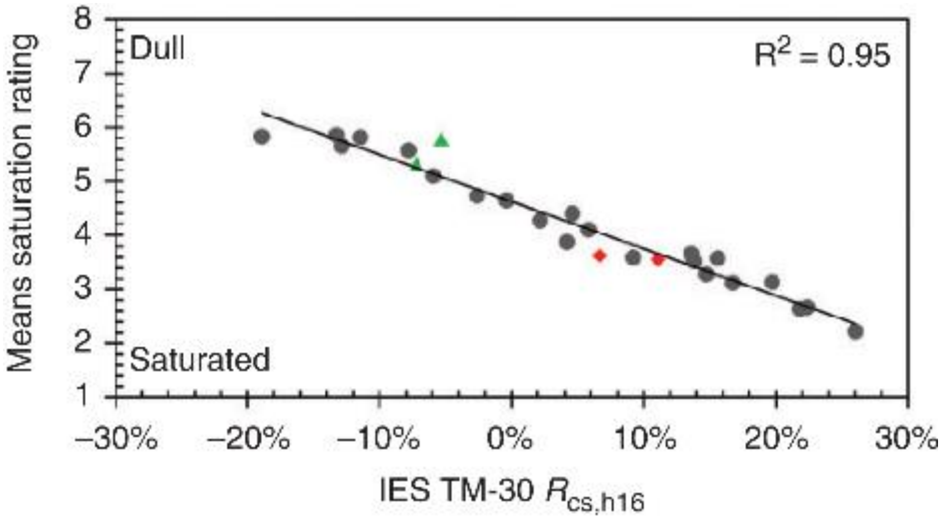
Royer MP, Wilkerson A, Wei M, Houser KW, Davis RG. 2017. Human perceptions of color rendition vary with average fidelity, average gamut, and gamut shape. Lighting Res. Technol. 49(8):966-991. http://dx.doi.org/10.1177/1477153516663615

Example 1. Sample Results

Preference ratings increased with red saturation, up to a point.



$R_{cs,h16}$ (red) highly correlated with perception of saturation



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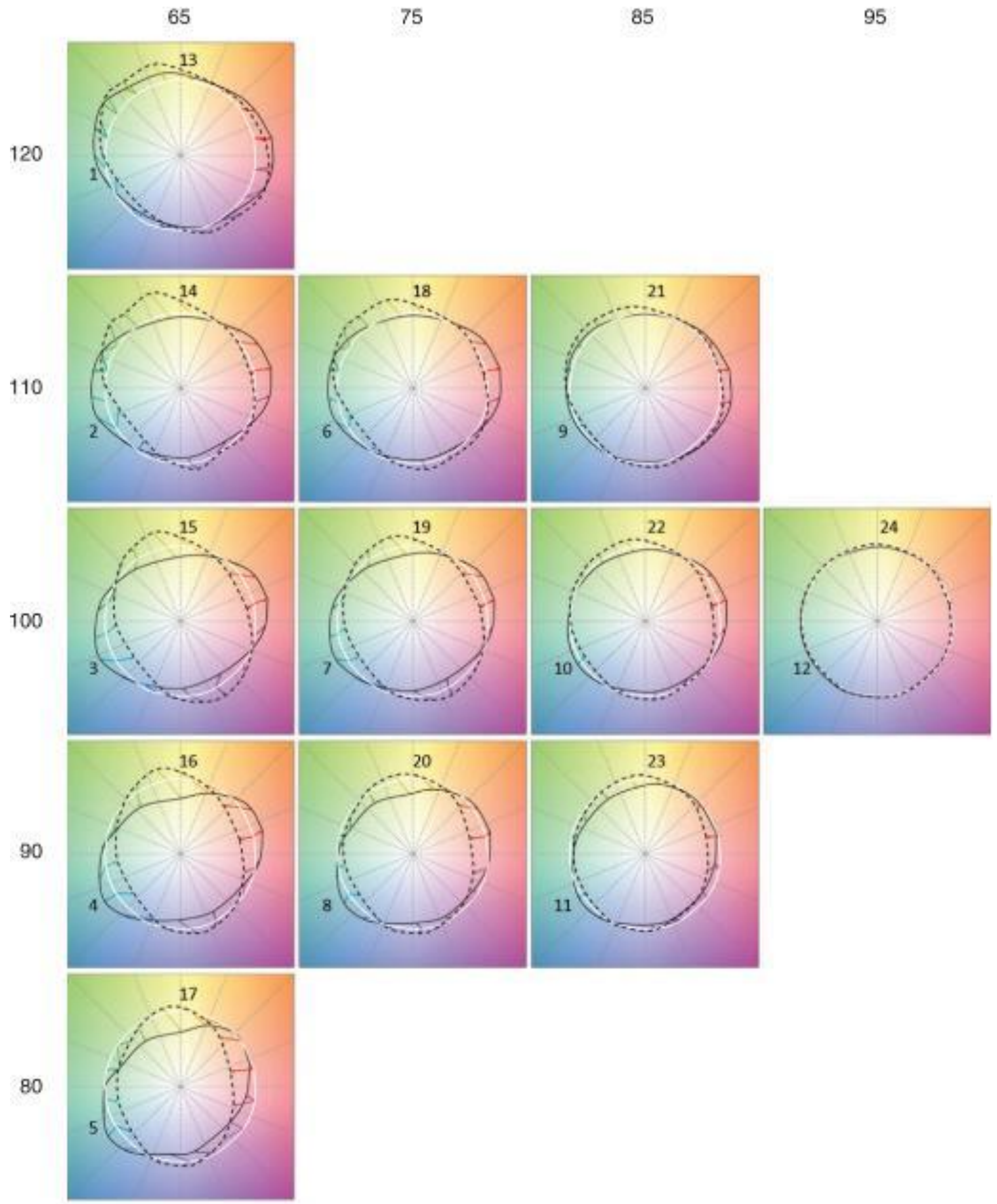
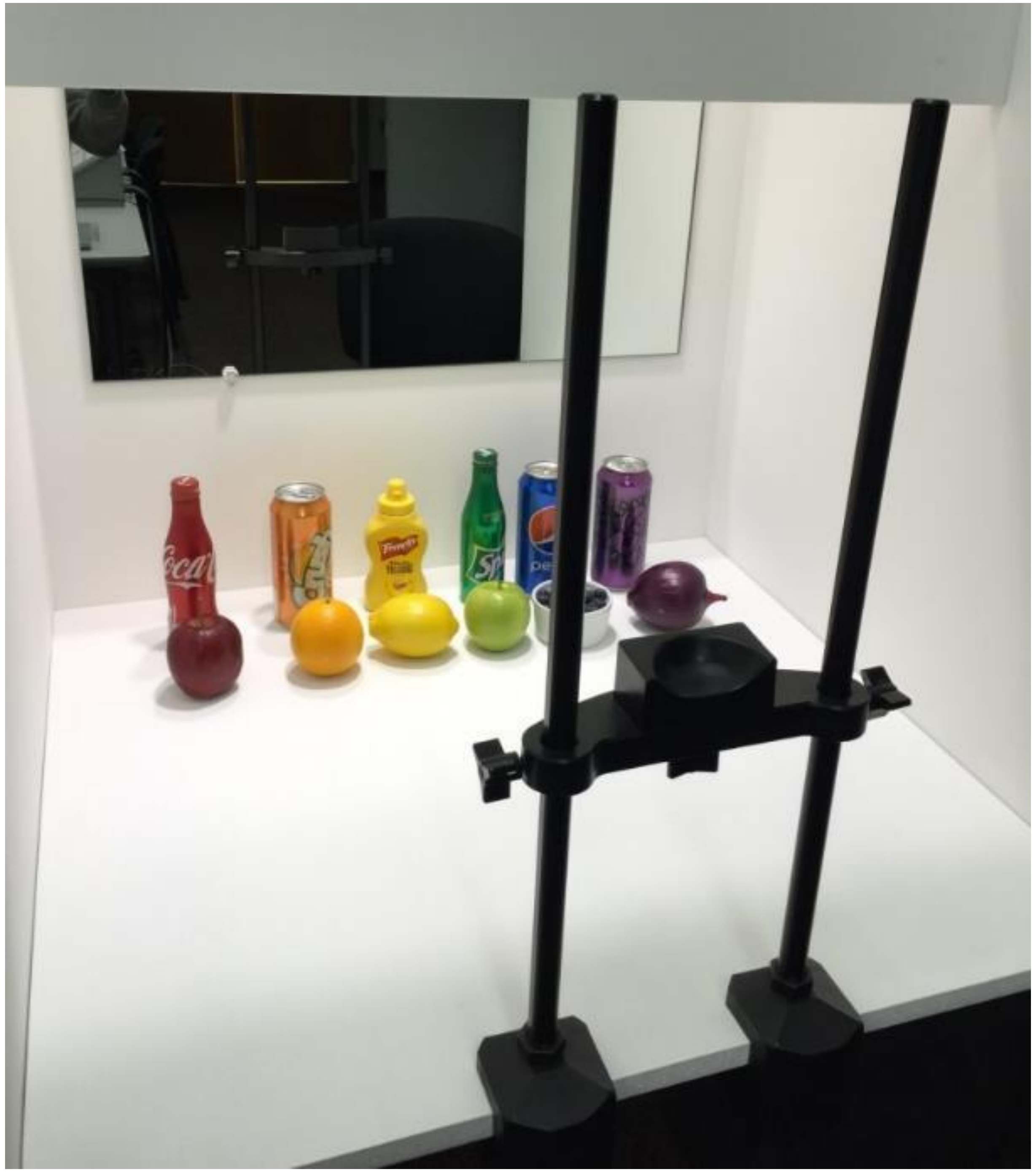
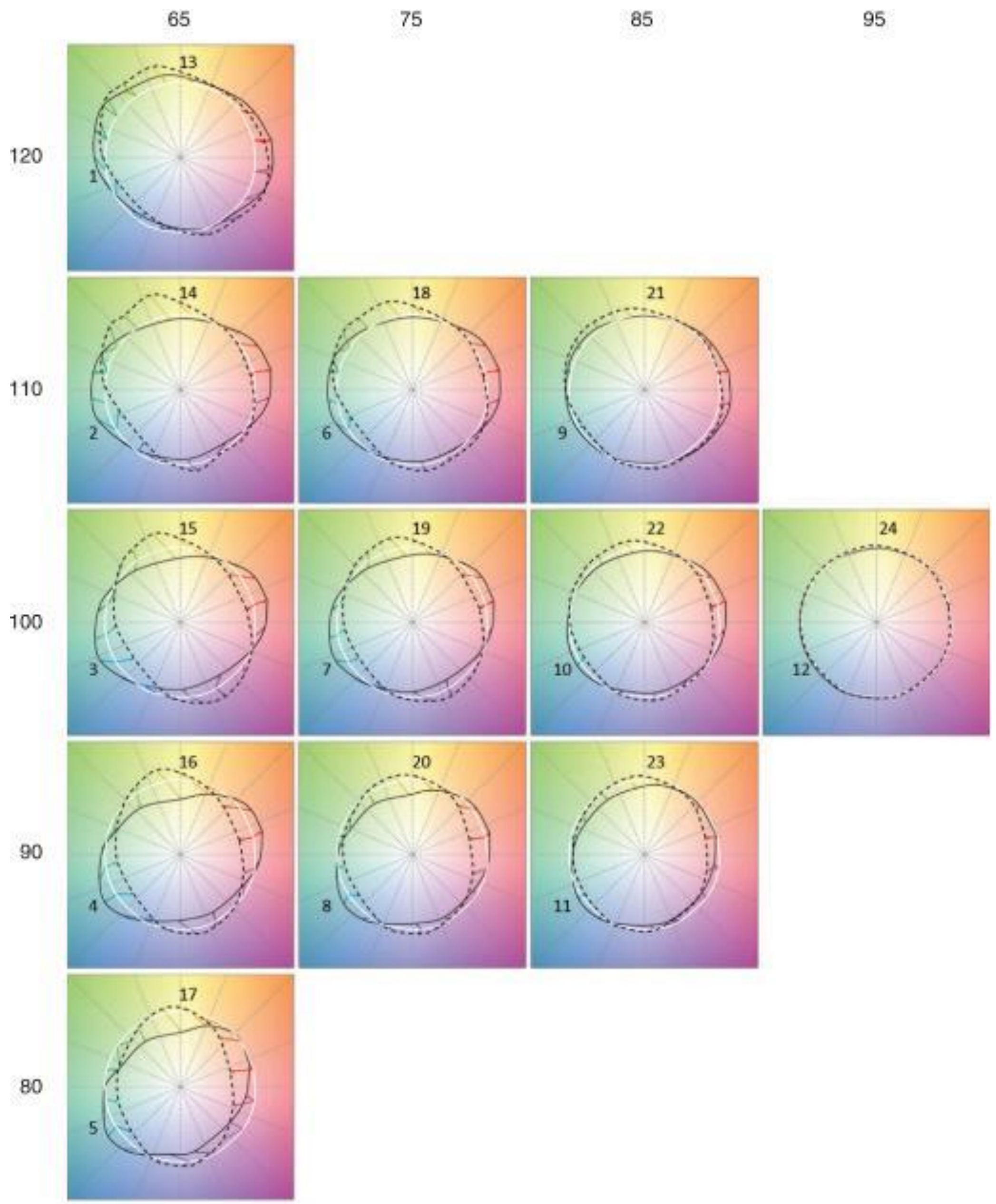
Example 2. Experimental Conditions

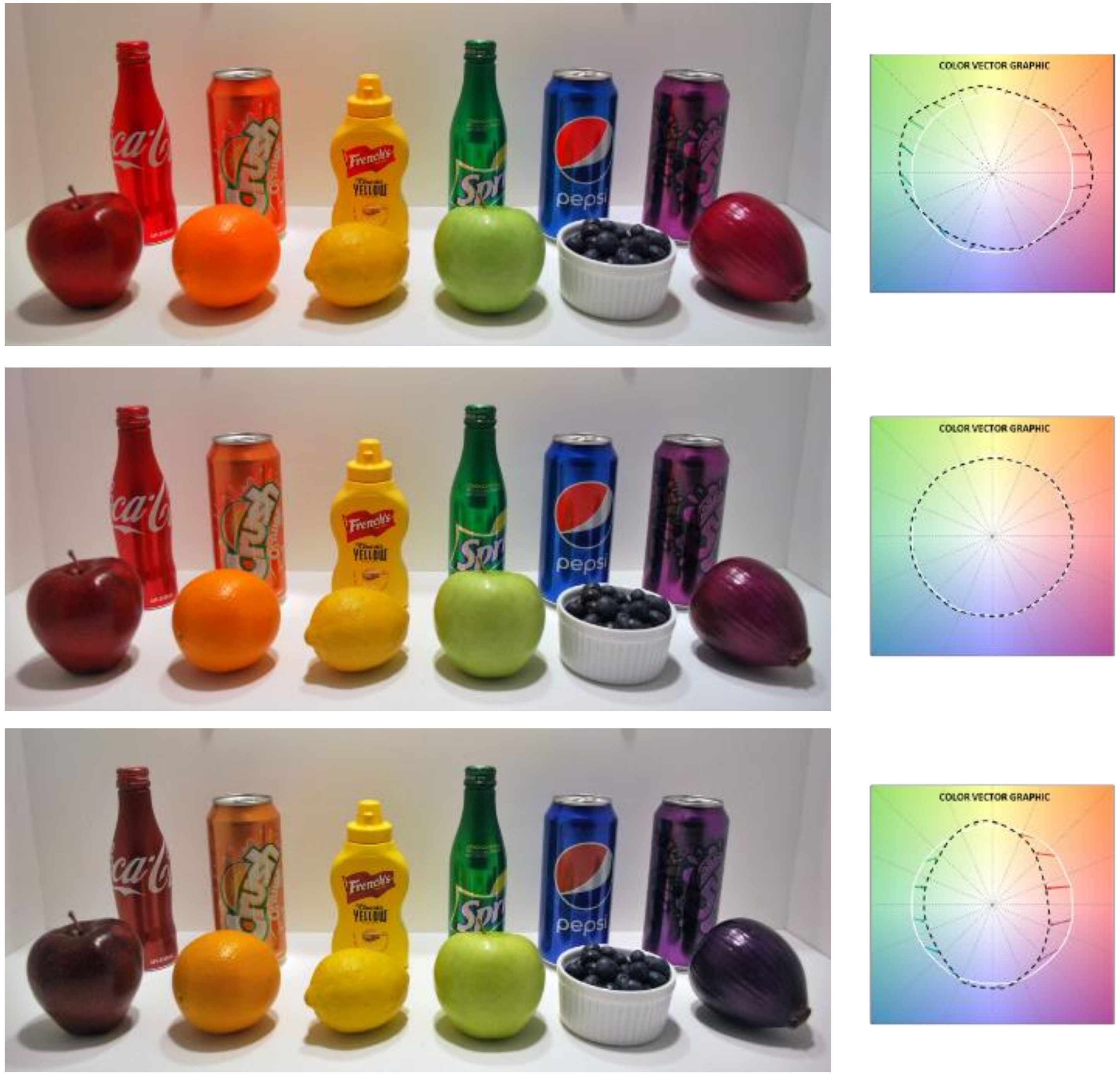




Esposito T, Houser KW. 2019. Models of colour quality over a wide range of spectral power distributions. Lighting Res Technol. 51(3):331-352. https://doi.org/10.1177/1477153518765953

Example 2. Experimental Conditions

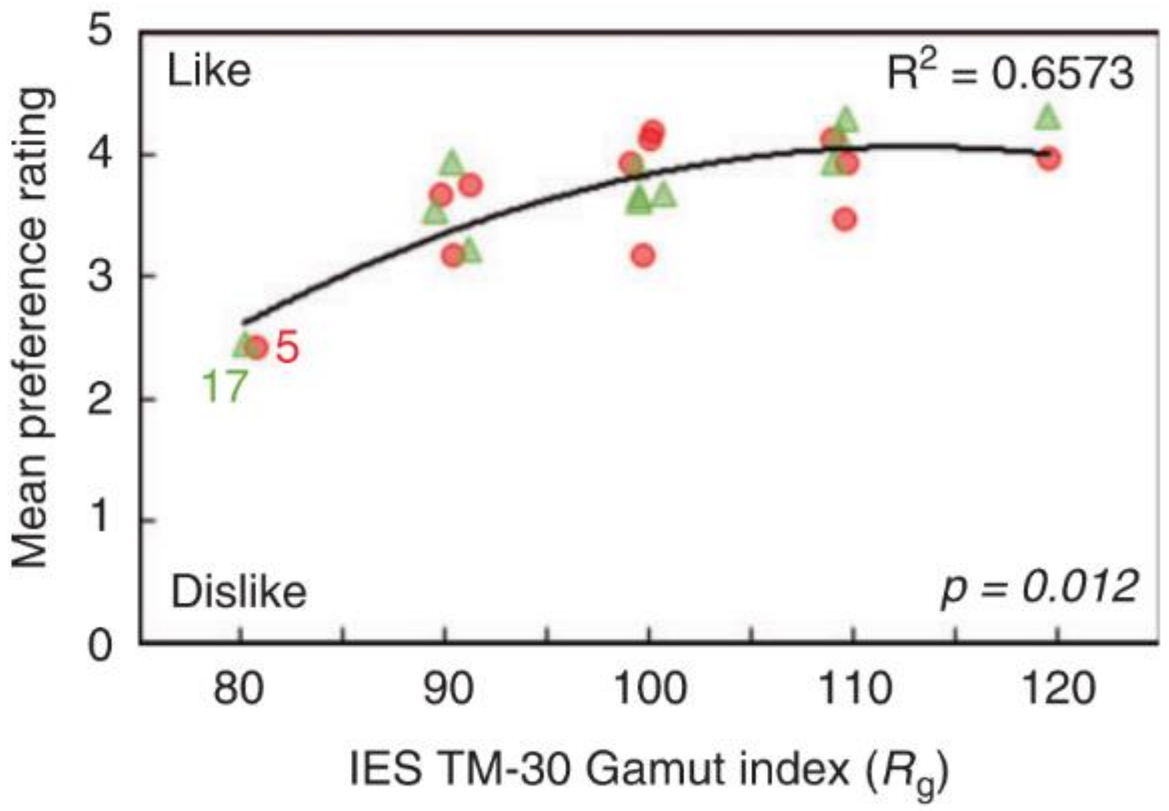




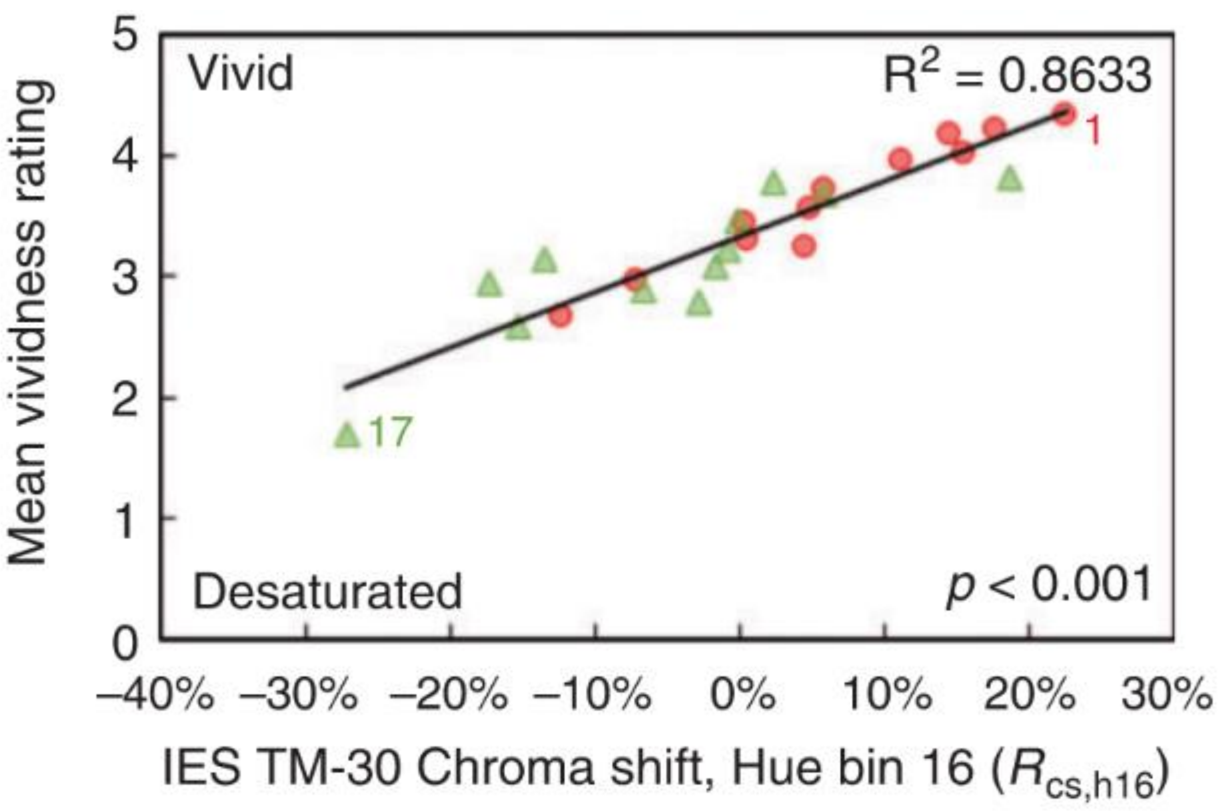
Esposito T, Houser KW. 2019. Models of colour quality over a wide range of spectral power distributions. Lighting Res Technol. 51(3):331-352. https://doi.org/10.1177/1477153518765953

Example 2. Sample Results

Preference was correlated with increase in gamut, with a plateau.

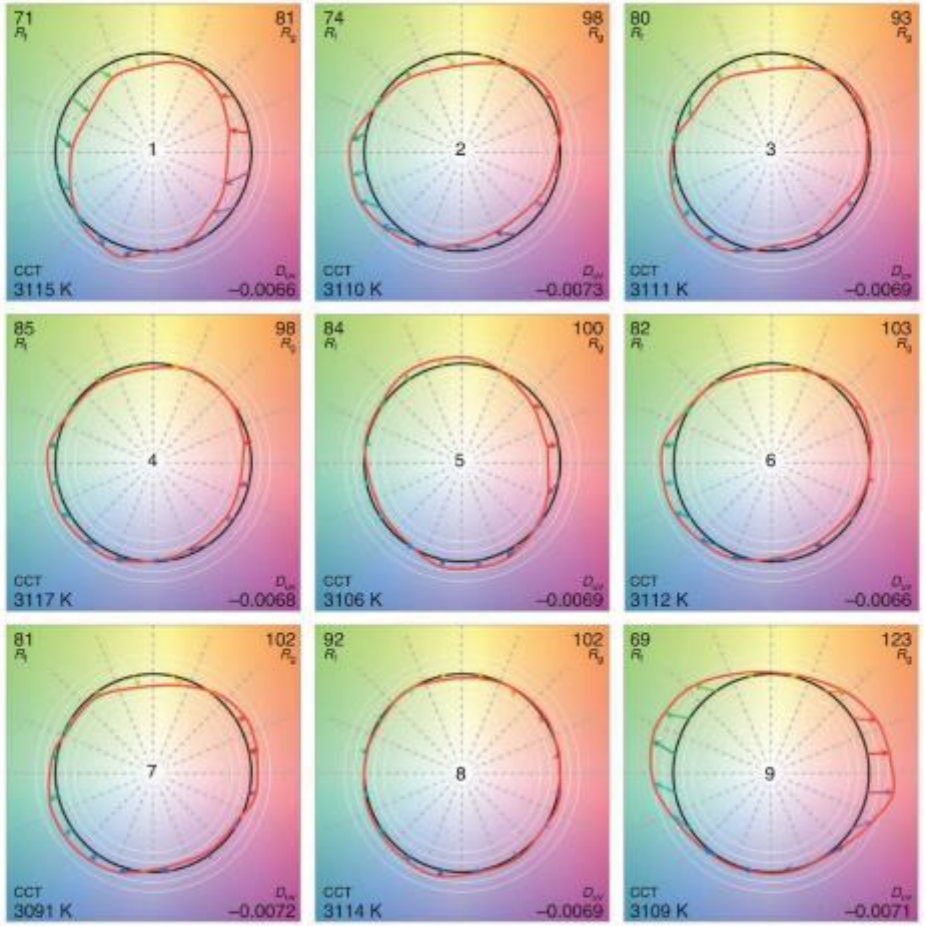


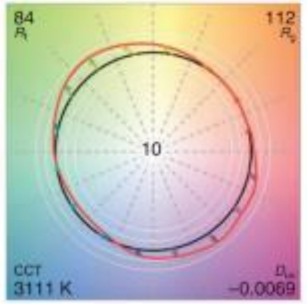
Perceived vividness was highly correlated with red saturation.



Esposito T, Houser KW. 2019. Models of colour quality over a wide range of spectral power distributions. Lighting Res Technol. 51(3):331-352. https://doi.org/10.1177/1477153518765953

Example 3. Experimental Conditions



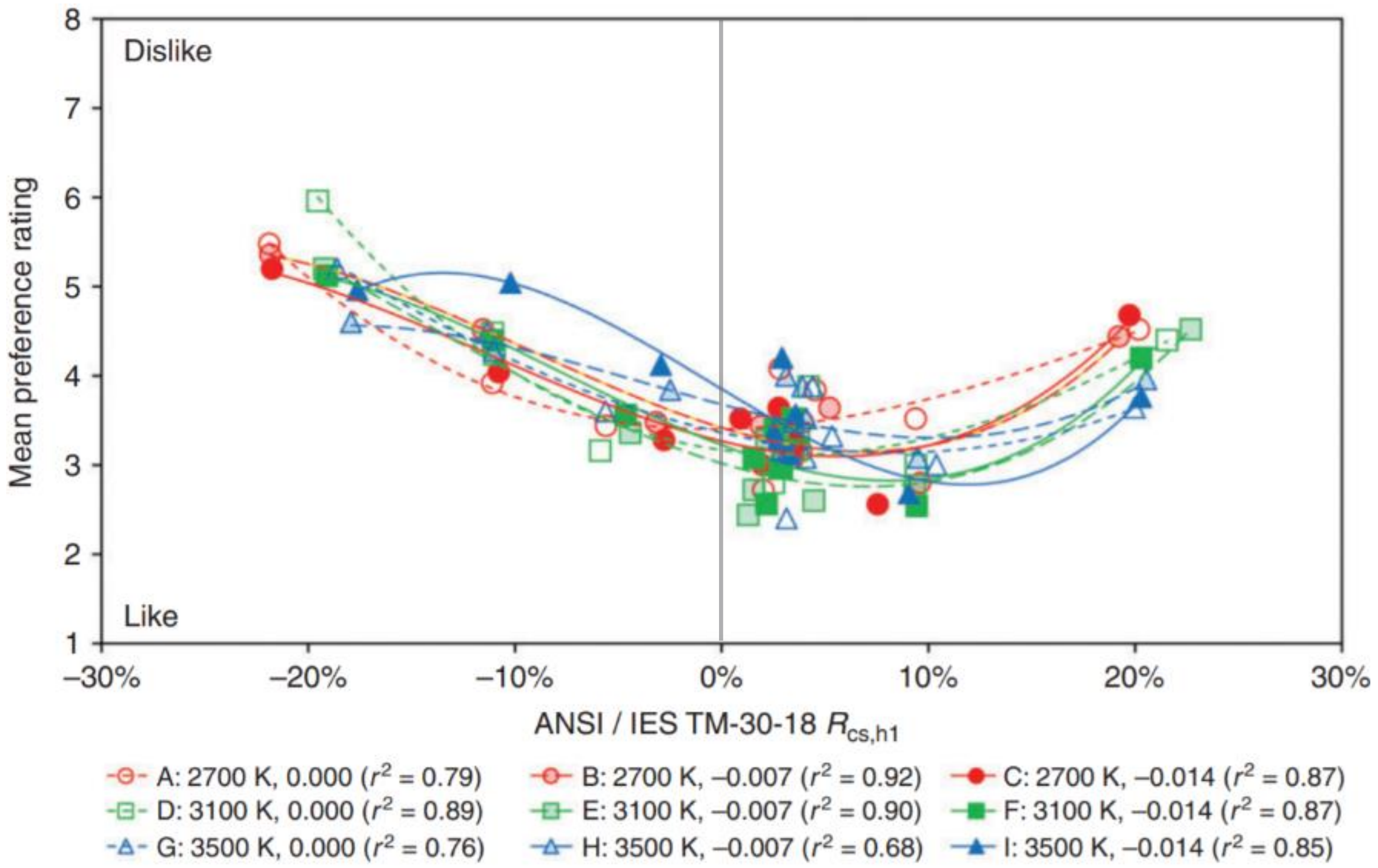


Experiment included 90 SPDs. The 10 represented here are at CCT ≈ 3100 K, Duv ≈ -0.007

Royer M. Wei M, Wilkerson A, Safranak S. 2020. Experimental validation of color rendition specification criteria based on ANSI/IES TM-30-18. Lighting Res Technol. 52(3):323-349. https://doi.org/10.1177/1477153519857625

Example 3. Sample Results

Preference was correlated with positive red saturation (to a point), with similar trends at various (CCT, Duv) combinations.



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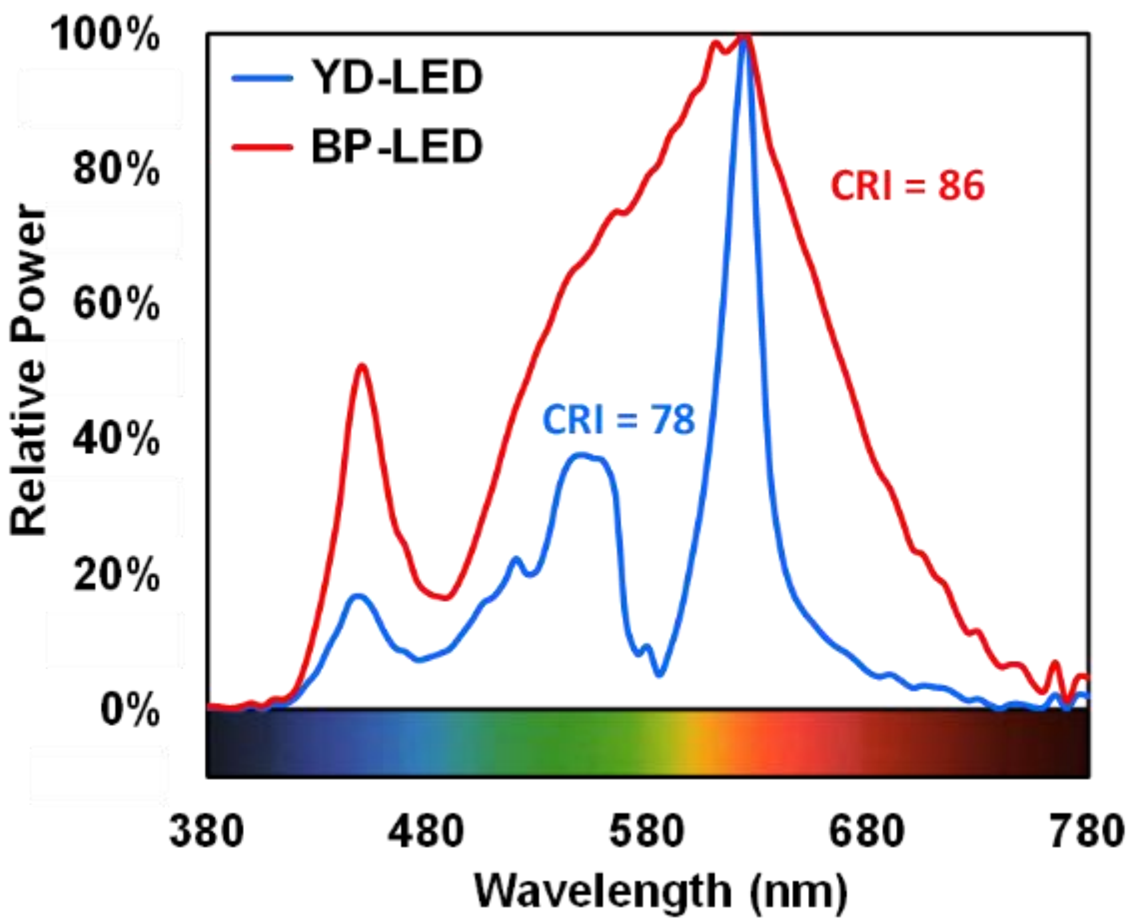
https://doi.org/10.1177/1477153519857625

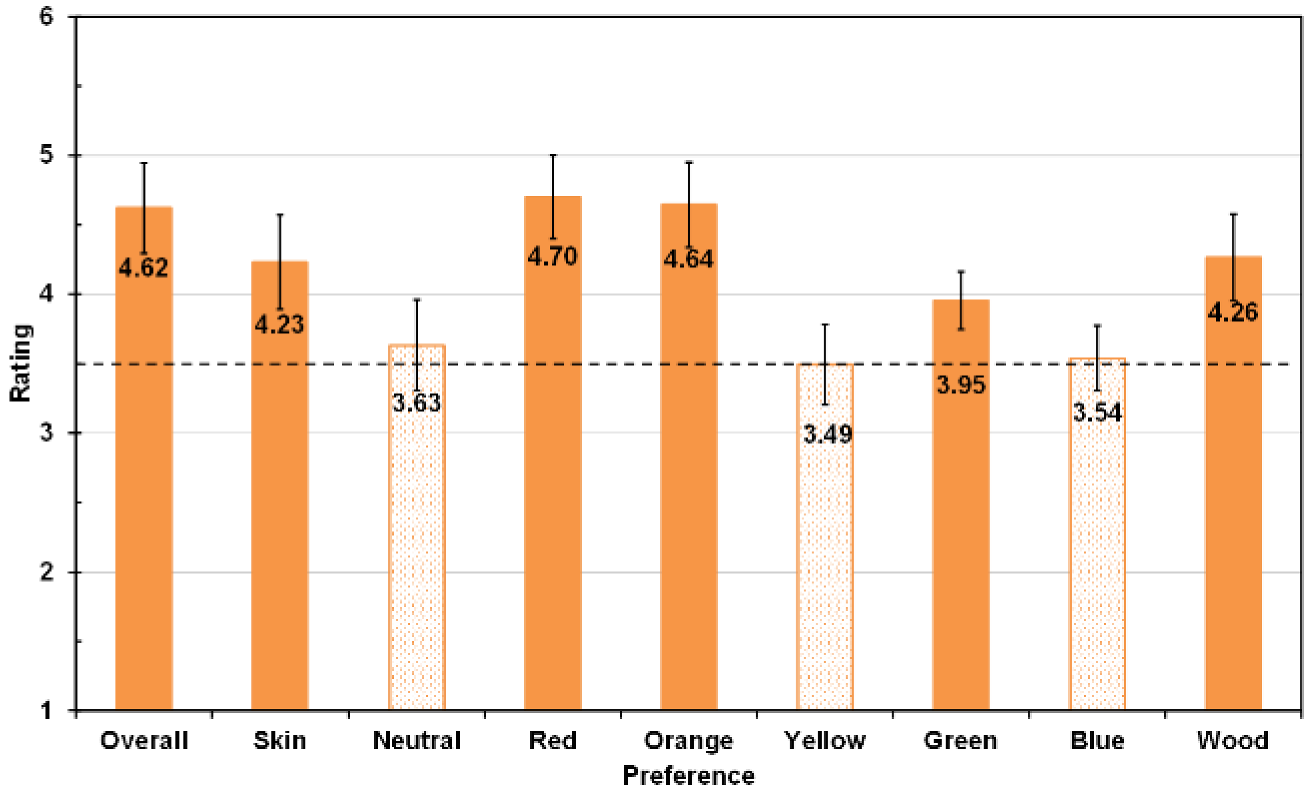
Example 4. Experimental Conditions

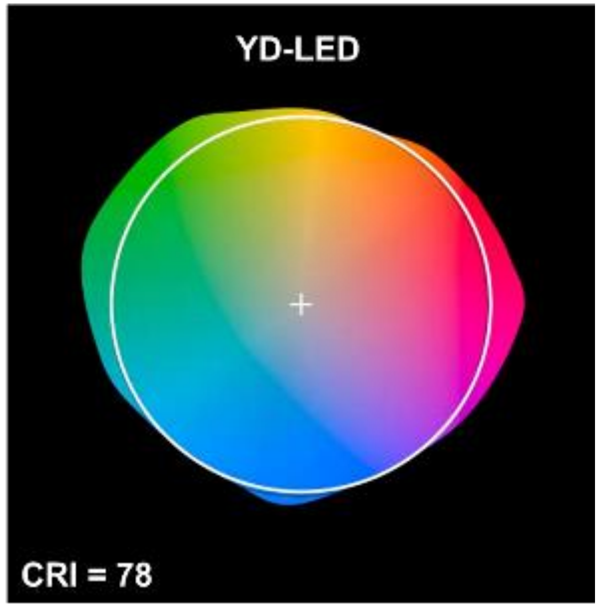


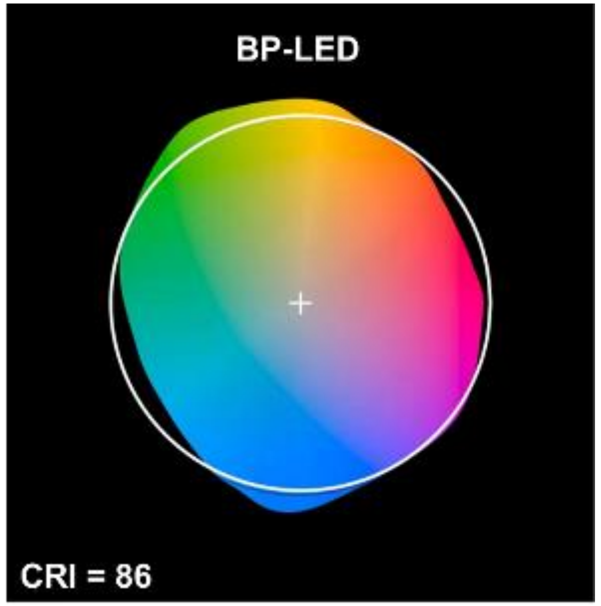
Wei M, Houser KW, Allen GR, Beers WW. 2014. Color preference under LEDs with diminished yellow emission. LEUKOS. 10(3):119-131. https://doi.org/10.1080/15502724.2013.865212

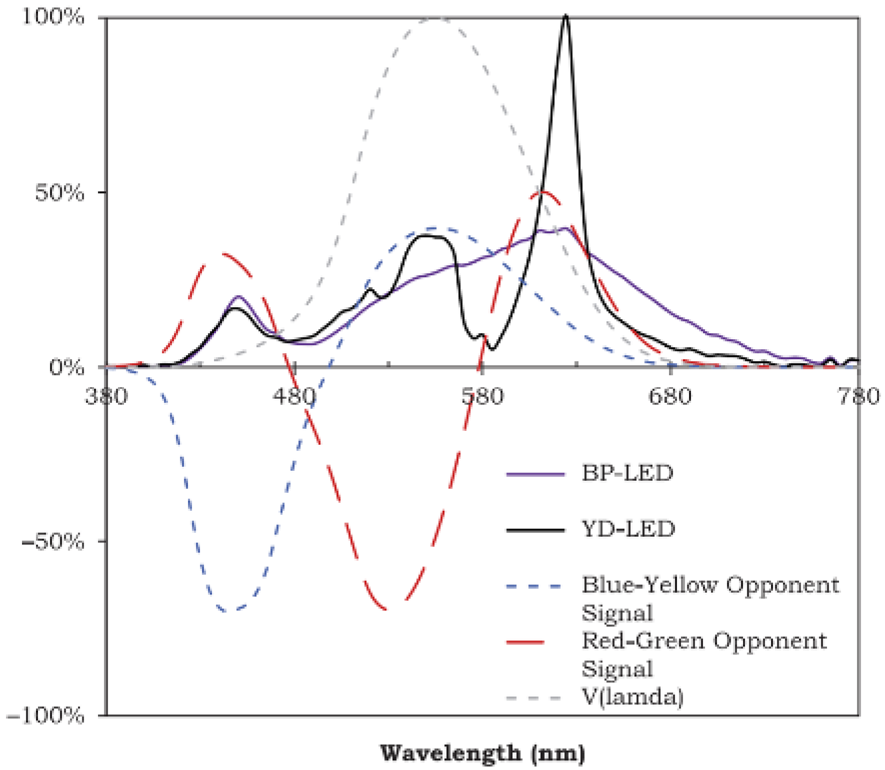
Example 4. Sample Results

YD-LED was preferred.









YD-LED to BP-LED opponent channel signals at equal brightness:

R/G = 1.22

B/Y = 1.01

Wei M, Houser KW, Allen GR, Beers WW. 2014. Color preference under LEDs with diminished yellow emission. LEUKOS. 10(3):119-131. https://doi.org/10.1080/15502724.2013.865212

CRI: 80 is good. Higher is “better.”

CRI: 80 is good. Higher is "better."

TM-30: What are you trying to accomplish?

Annex E
Annex F
(2019)

<u>Primary Factors</u>

1. Objects/scene being illuminated
2. Desired appearance effect
3. Illuminance level
4. Balance with competing needs

<u>Secondary Factors</u>

1. Culture
2. Age
3. Hue stability
4. Uncertainty tolerance
5. Viewing condition

What combination of measures and values will meet the goals?

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			

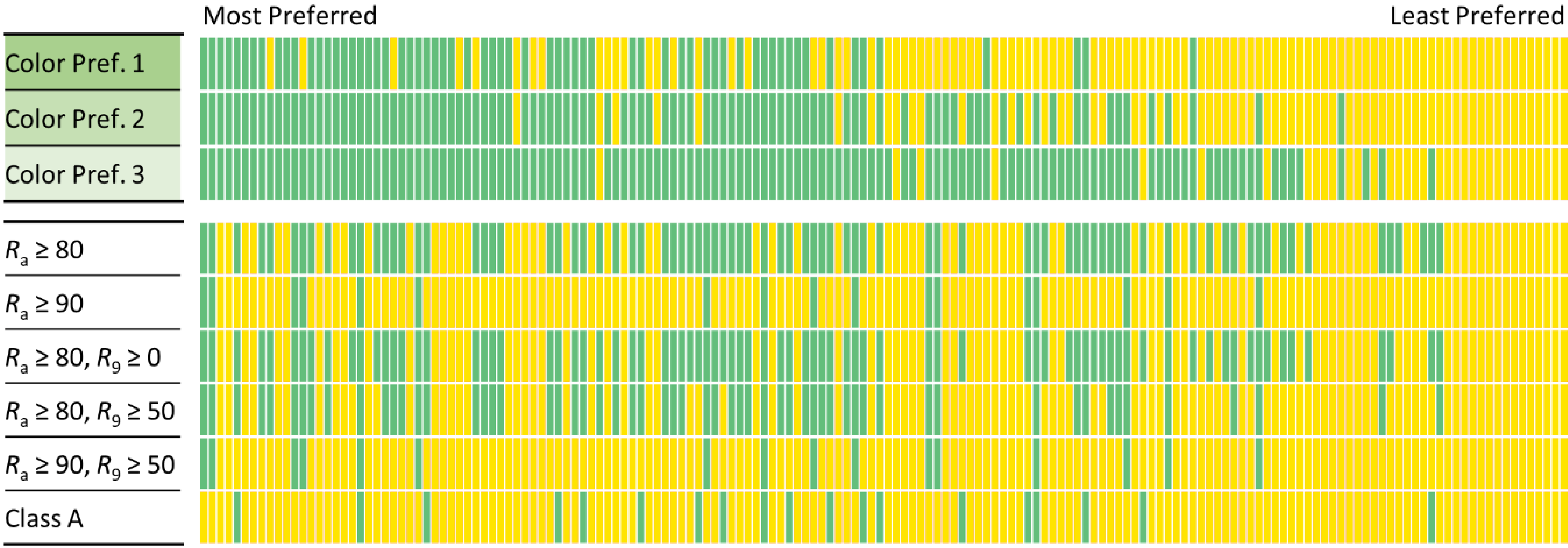
Assumptions: 200-700 lux, polychromatic environment, single chromaticity

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

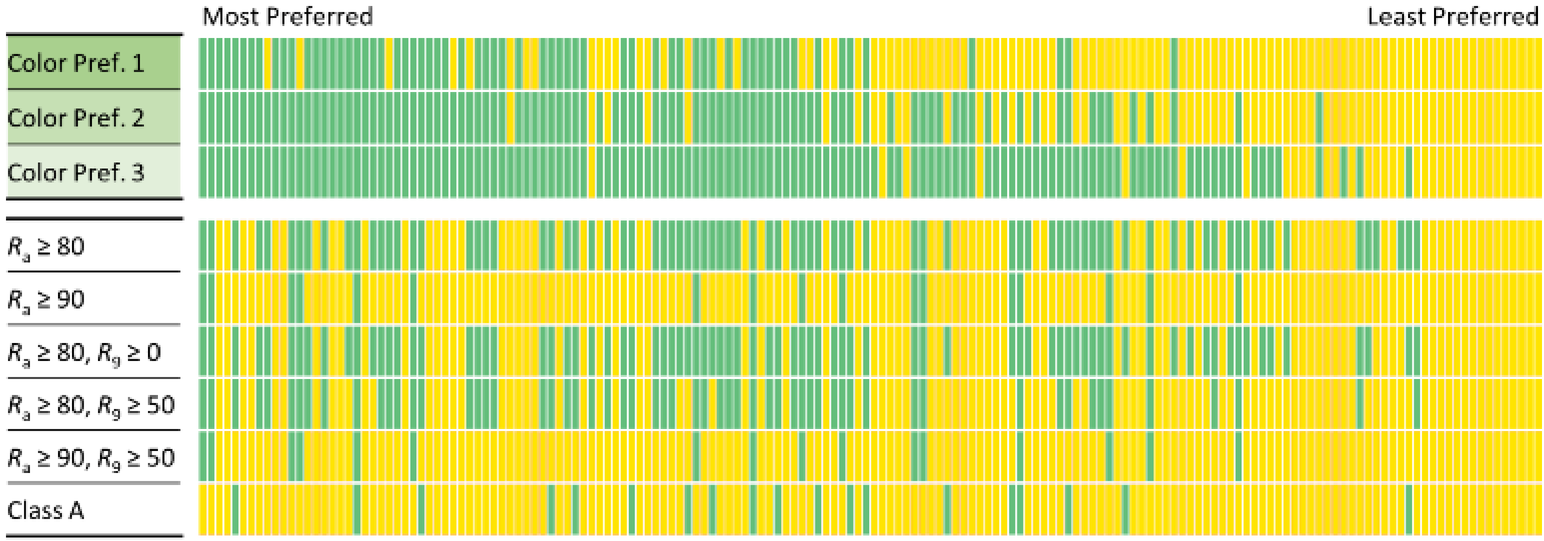
Priority Level The balance between allowing tradeoffs and increasing the likelihood of meeting the design intent.		Preference (P)		Vividness (V)	Fidelity (F)
	1	P1	$R_f \geq 78$ $R_g \geq 95$ $-1\% \leq R_{cs,h1} \leq 15\%$		
	2	P2	$R_f \geq 75$ $R_g \geq 92$ $-7\% \leq R_{cs,h1} \leq 19\%$		
	3	P3	$R_f \geq 70$ $R_g \geq 89$ $-12\% \leq R_{cs,h1} \leq 23\%$		

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

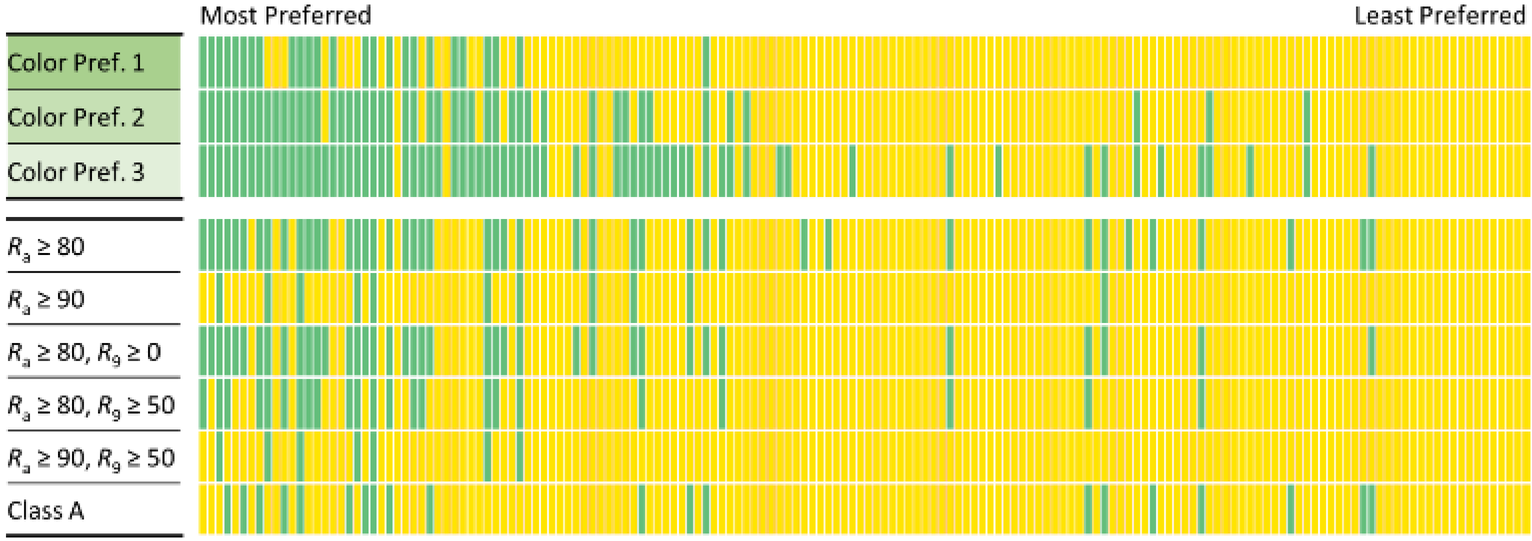
Royer and others 2017, 2018, 2020



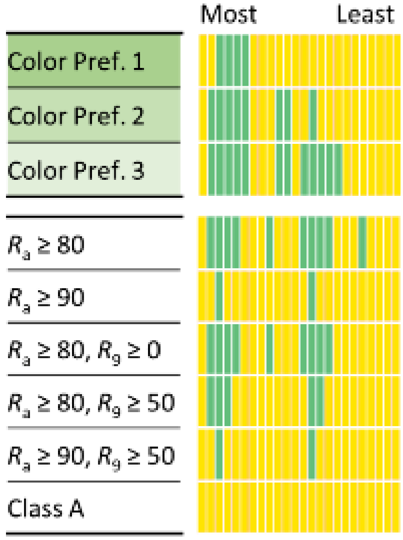
Royer and others 2017, 2018, 2020

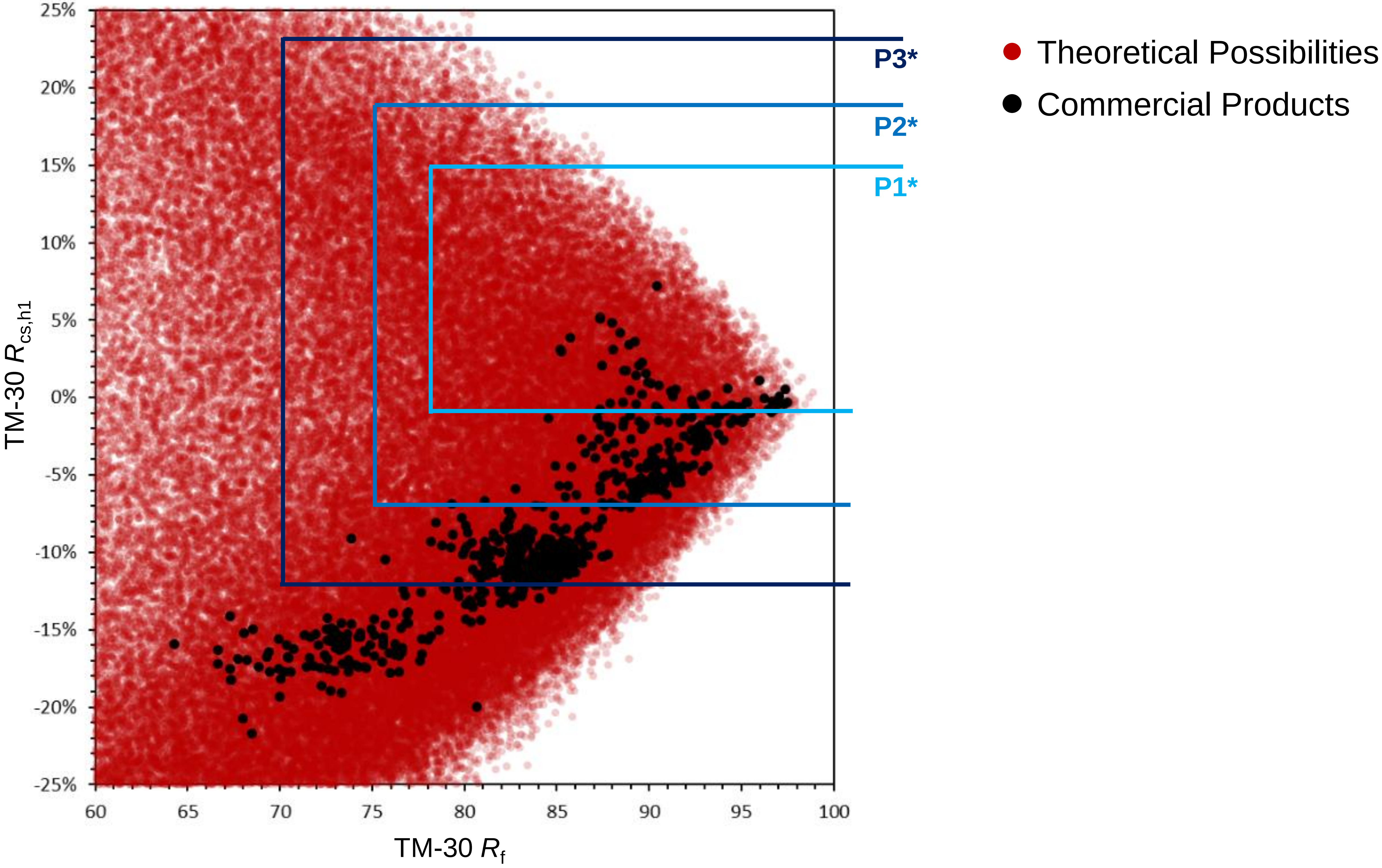


Zhang and others 2017



Esposito and Houser 2019



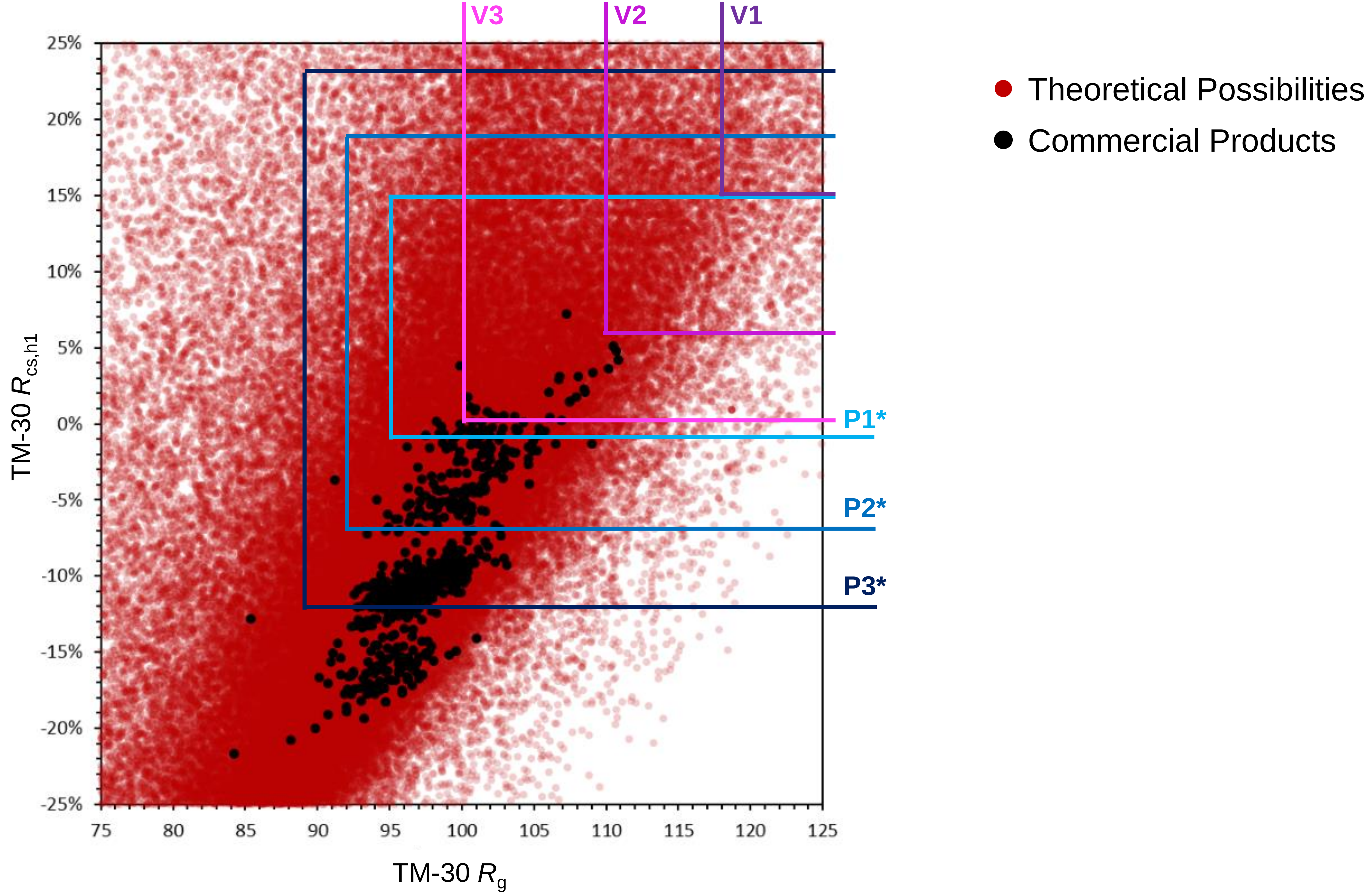


Theoretical Possibilities
Commercial Products
P3*
P2*
P1*
25%
20%
15%
10%
5%
0%
-5%
-10%
-15%
-20%
-25%
TM-30 $R_{cs,h1}$
60
65
70
75
80
85
90
95
100
TM-30 R_f

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	$R_f \geq 75$ $R_g \geq 92$ $-7\% \leq R_{cs,h1} \leq 19\%$	V2	$R_g \geq 110$ $R_{cs,h1} \geq 6\%$	
	3	P3	$R_f \geq 70$ $R_g \geq 89$ $-12\% \leq R_{cs,h1} \leq 23\%$	V3	$R_g \geq 100$ $R_{cs,h1} \geq 0\%$	

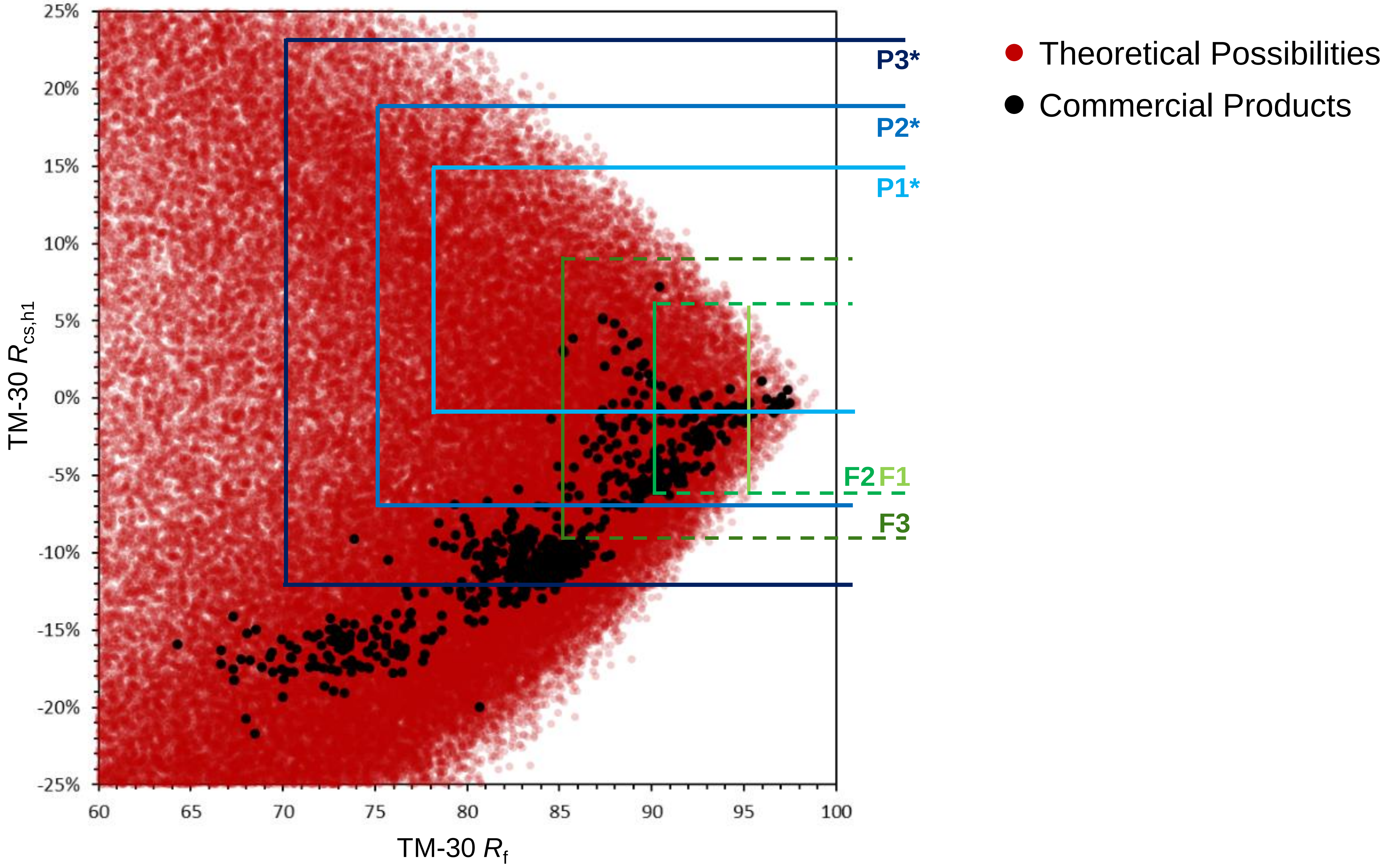
Assumptions: 200-700 lux, polychromatic environment, single chromaticity


V3
V2
V1
25%
20%
15%
10%
5%
0%
-5%
-10%
-15%
-20%
-25%
TM-30 $R_{cs,h1}$
75
80
85
90
95
100
105
110
115
120
125
TM-30 R_g
P1*
P2*
P3*
Theoretical Possibilities
Commercial Products

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	$R_f \geq 75$ $R_g \geq 92$ $-7\% \leq R_{cs,h1} \leq 19\%$	V2	$R_g \geq 110$ $R_{cs,h1} \geq 6\%$	F2	$R_f \geq 90$ $R_{f,h1} \geq 90$
3	P3	$R_f \geq 70$ $R_g \geq 89$ $-12\% \leq R_{cs,h1} \leq 23\%$	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



TM-30 $R_{cs,h1}$
25%
20%
15%
10%
5%
0%
-5%
-10%
-15%
-20%
-25%
60
65
70
75
80
85
90
95
100
TM-30 R_f
P3*
P2*
P1*
F2
F1
F3
Theoretical Possibilities
Commercial Products

$R_f \geq 80$

$97 \leq$ IES $R_g \leq 110$

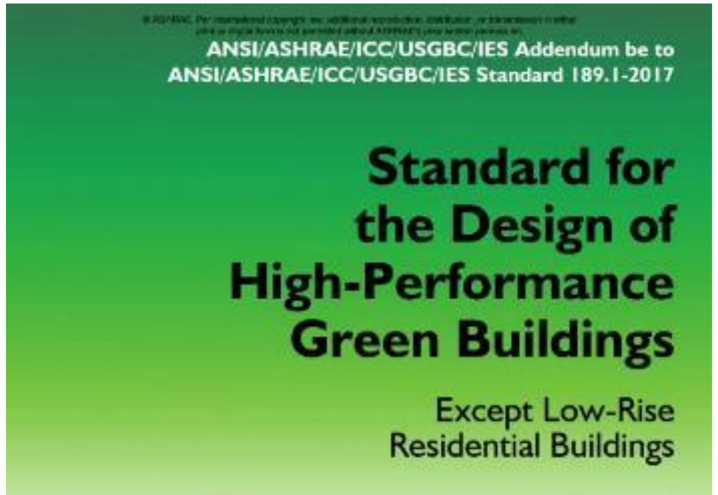
IES $R_{f,h1} \geq 78$

$-9\% \leq$ IES $R_{cs,h1} \leq +9\%$

P1* P2* (Circulation)

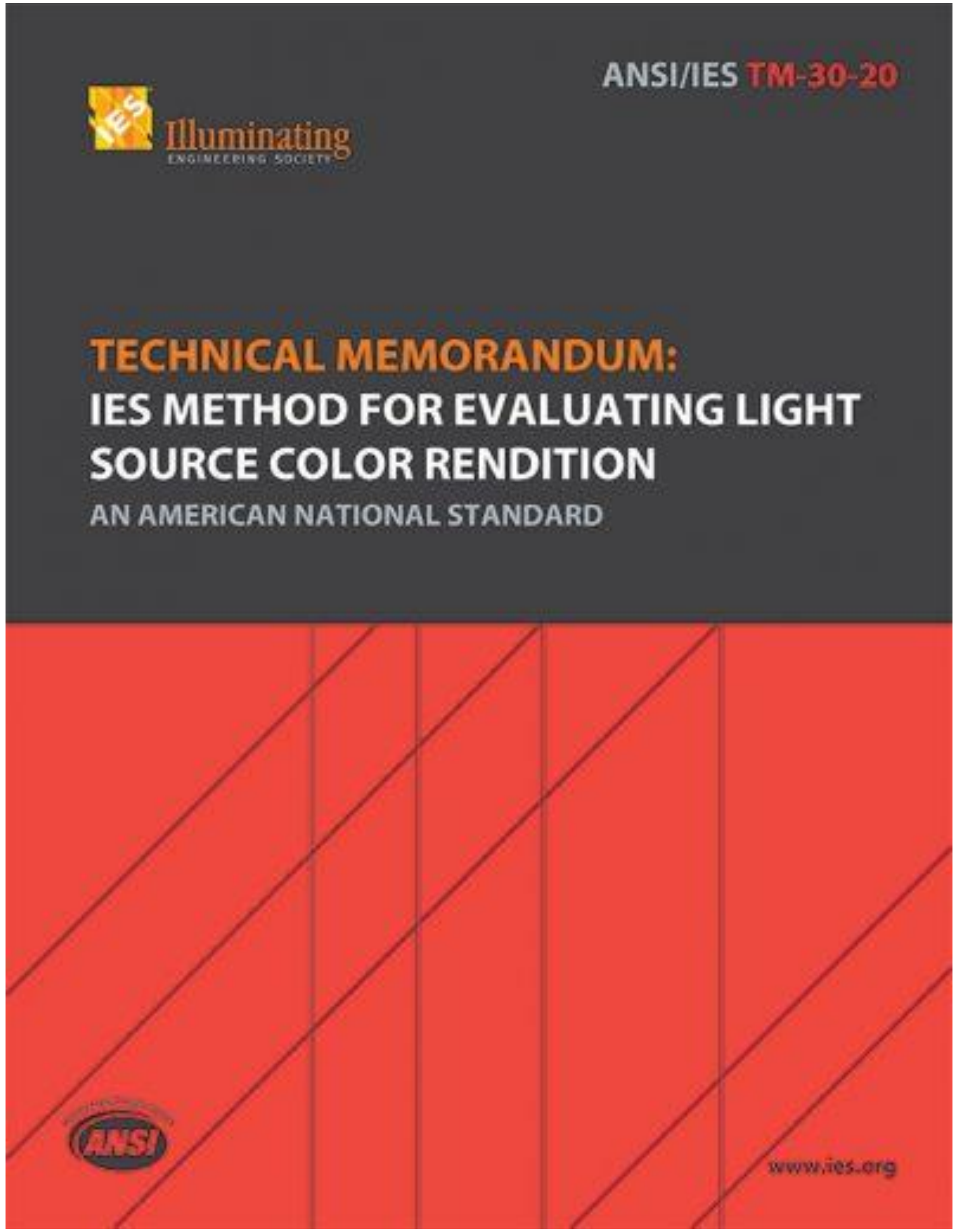
Technical Requirements V5.1

P3 Custom (Outdoor)



P2 F3

*Higher R_g value. (Pre Annex E)



Free Download:

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Coming Summer 2021:

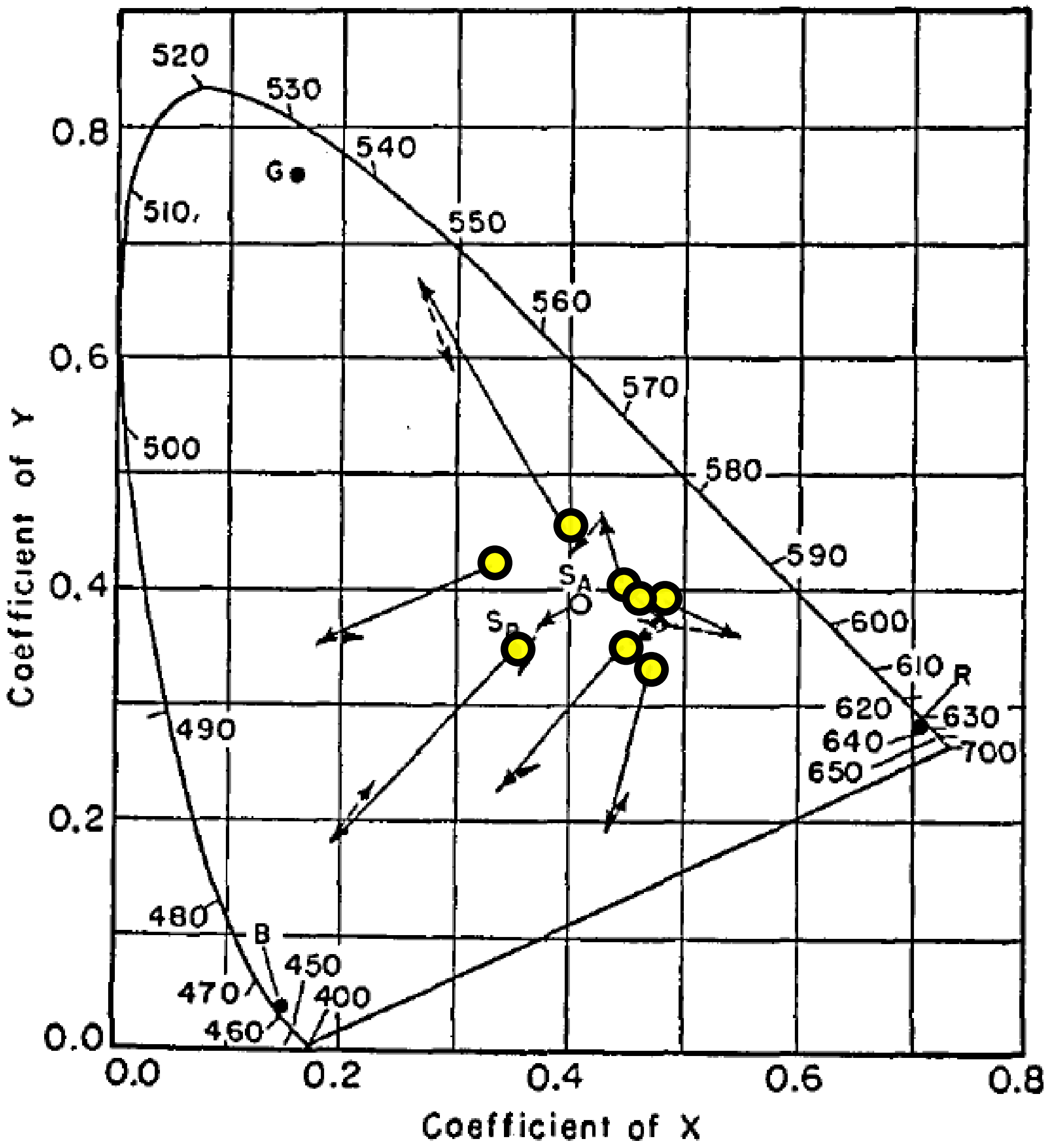
Web based calculation application

Emerging color rendition work that may one day be standardized.

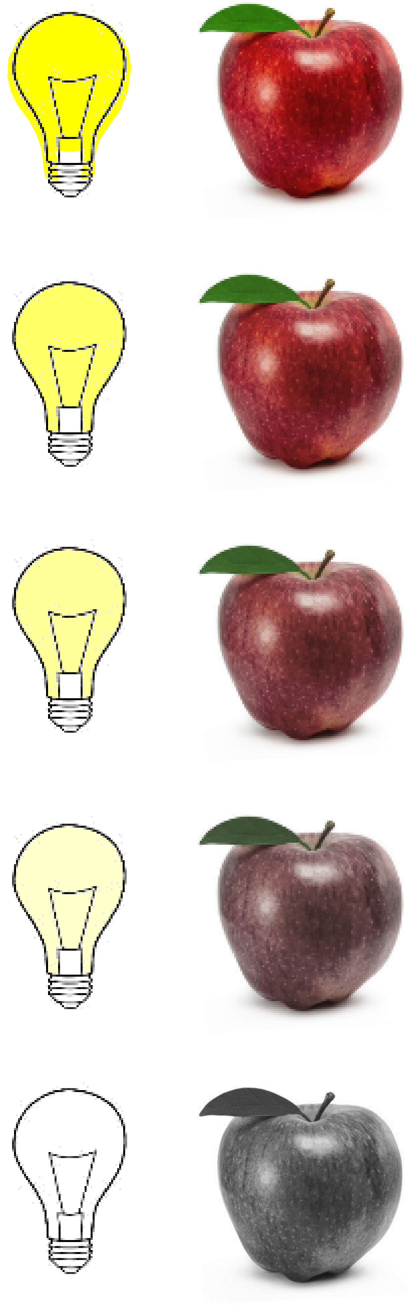
- Light level
- Color discrimination
- Metamerism
- Adaptation


x·rite ColorChecker® Color Rendition Chart

Hunt was the first to systematically document that colors appear duller under low light



Hunt RWG. 1950. The effects of daylight and tungsten light-adaptation on color perception. J. Opt. Soc. Am. 40(6):362-371.



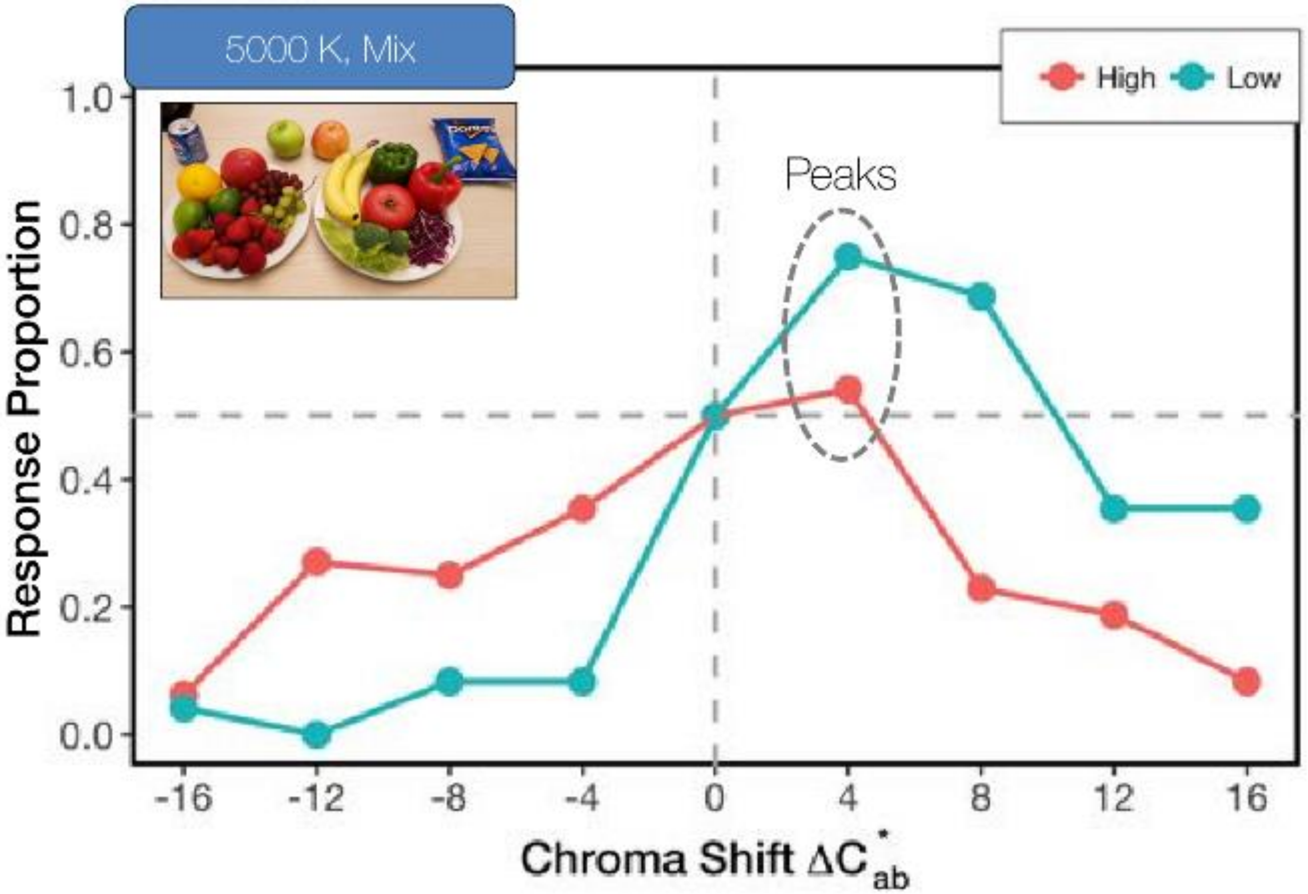
Kawashima and Ohno verified the Hunt Effect using everyday objects and naturalistic viewing.

Independent variables

- Visual Scene (shown)
- Illuminance (100, 1000 lx)
- CCT (3000, 5000 K)

Example results

- Mixed scene, 5000 K, 100 and 1000 lx
- Kawashima and Ohno concluded that the Hunt Effect is active at typical indoor lighting conditions.



Kawashima Y. Ohno Y. 2017. Vision Experiment on Verification of Hunt Effect for Lighting. Biennial Joint Meeting of CIE/USA and CNC/CIE. Washington (DC): NIST.

Bao and Wei found that TM-30 measures can be related to preferred color appearance of a piece of artwork from 20 to 15,000 lux

Fig 1. Photograph of the artwork taken at the observer's viewing position in Experiment 1, with the SRD measurement locations labelled.

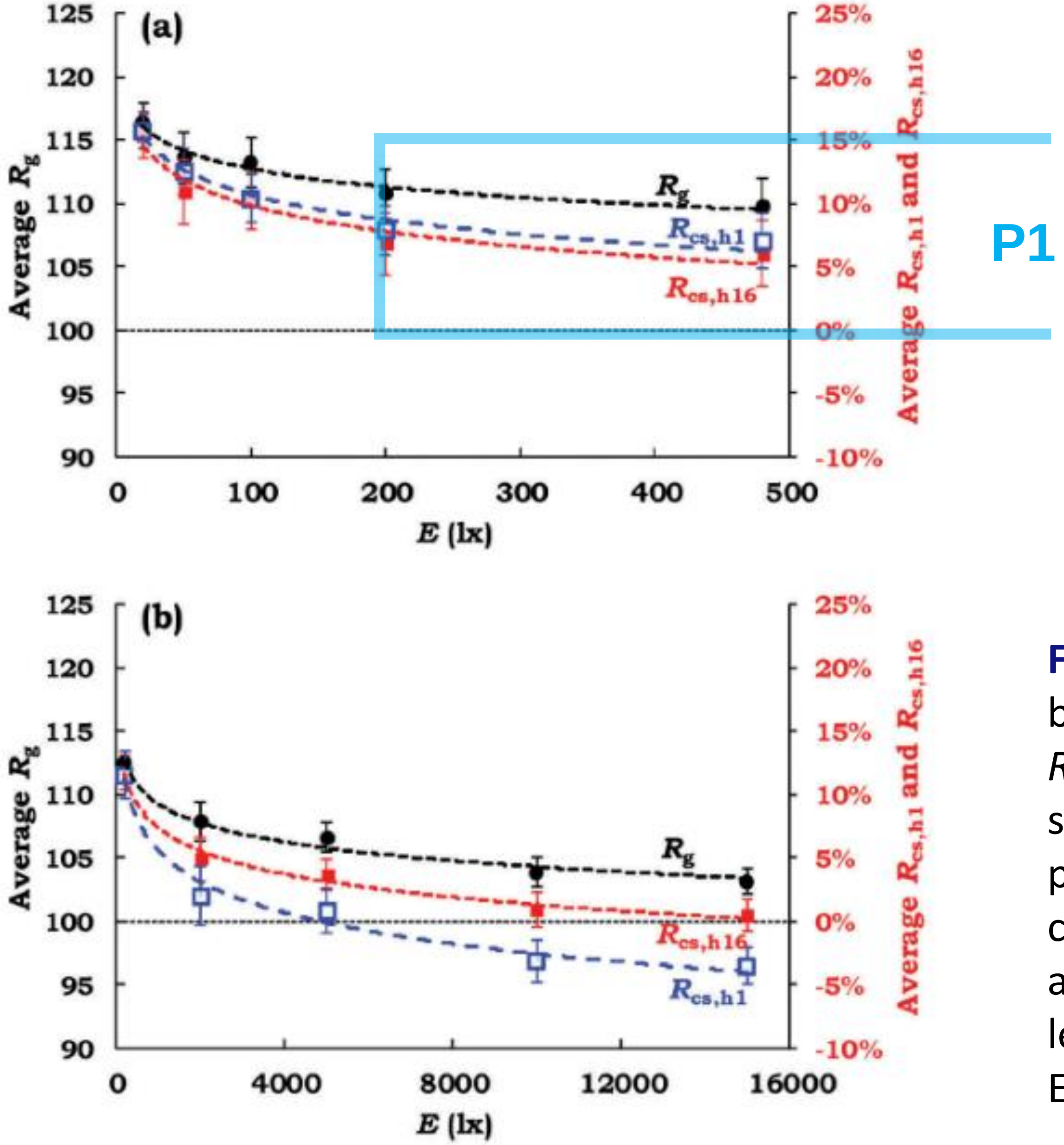
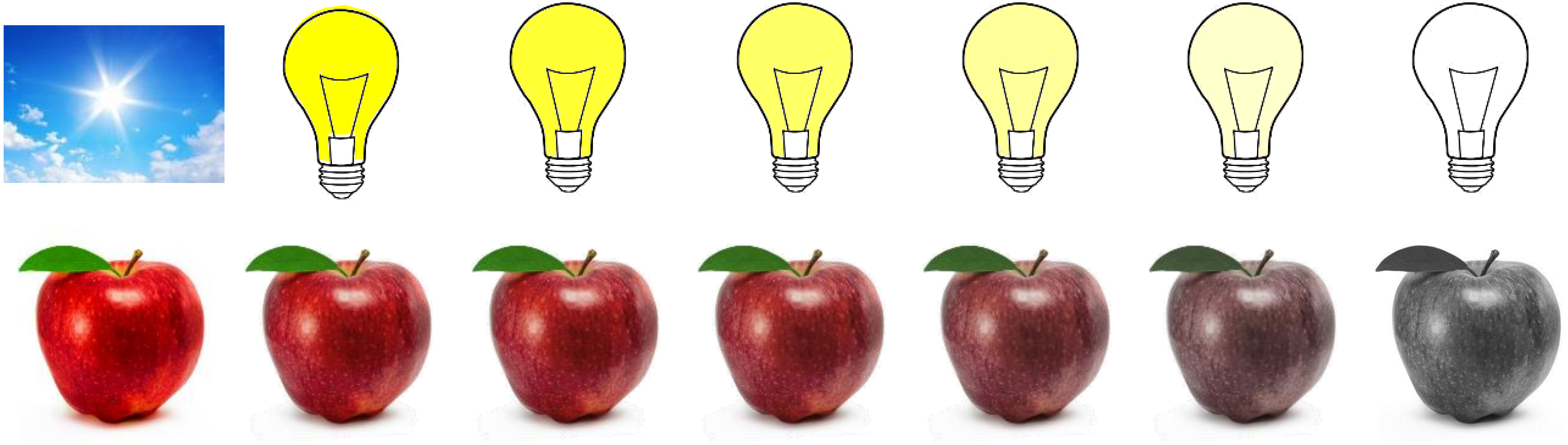


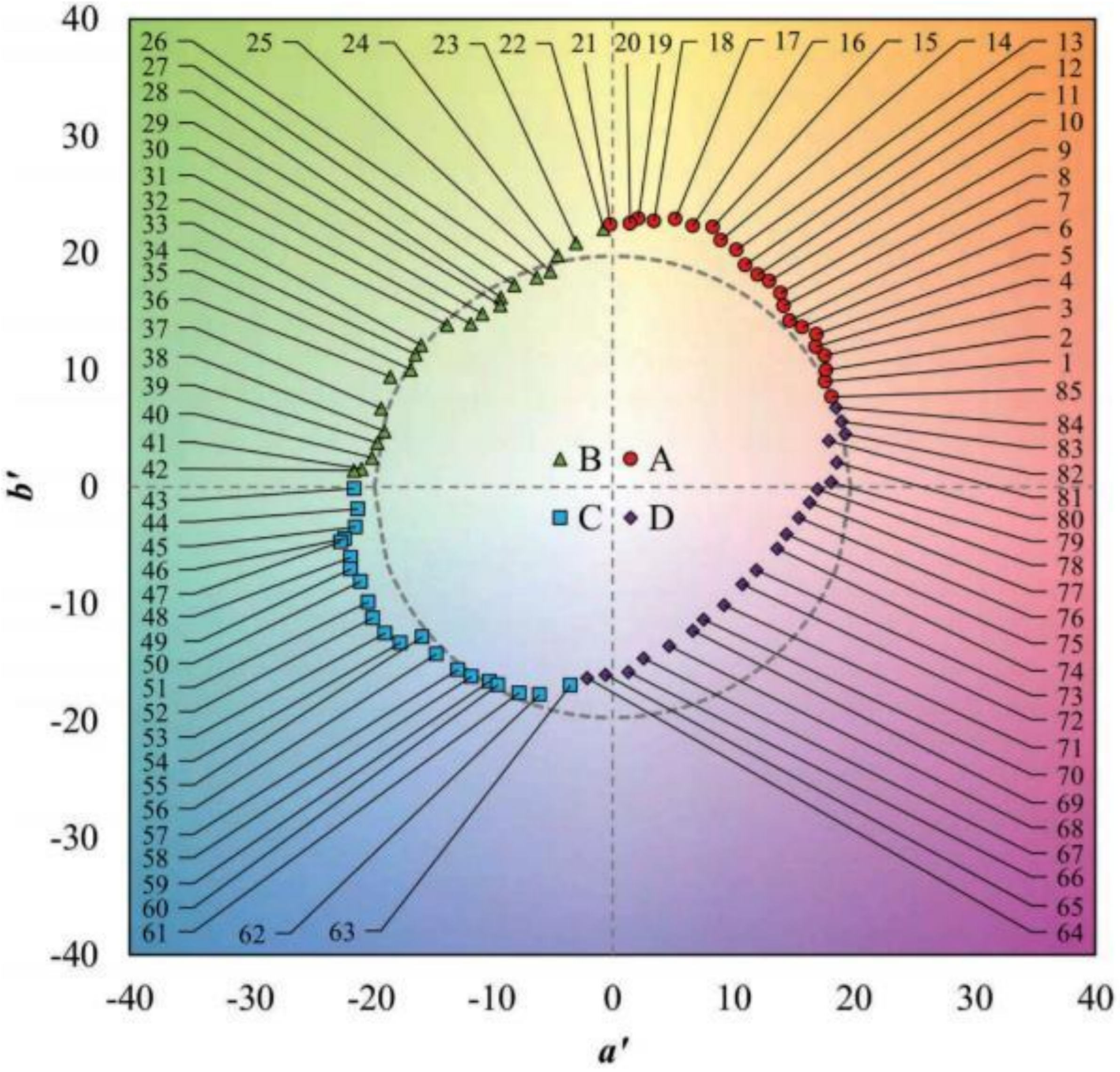
Fig 11. Relationship between the average *R*g, *R*cs,h1, and *R*cs,h16 of the stimuli that were selected to produce the most preferred color appearance of the artwork and illuminance levels. (a) Experiment 1; (b) Experiment 2.

Bao W, Wei M. 2021. Change in gamut size for producing preferred color appearance from 20 to 15000 lx. LEUKOS. 17(1):21-42. https://doi.org/10.1080/15502724.2019.1587621

The Hunt Effect is present in typical working and living environments and is especially pronounced under low light.

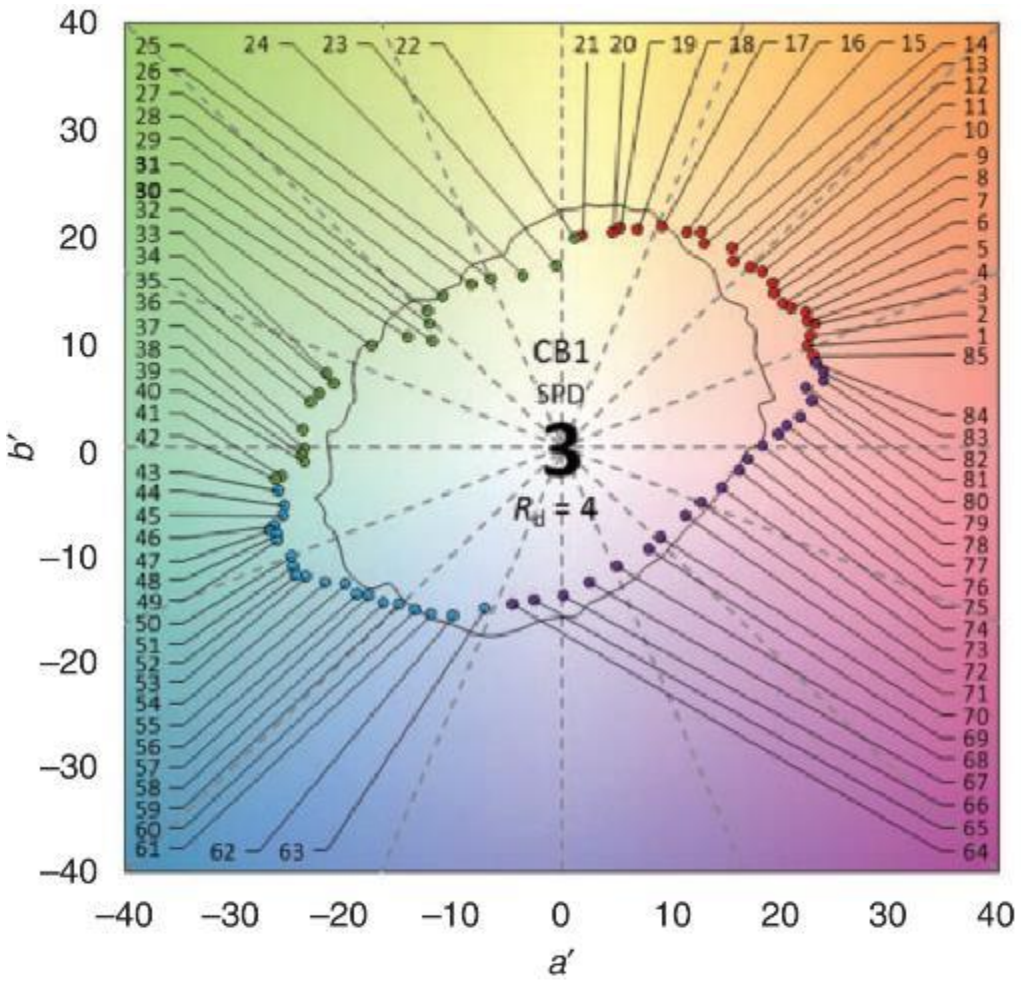


Color discrimination can be conceptualized as light-source-induced hue transpositions (shown here using FM-100 Hue Test).

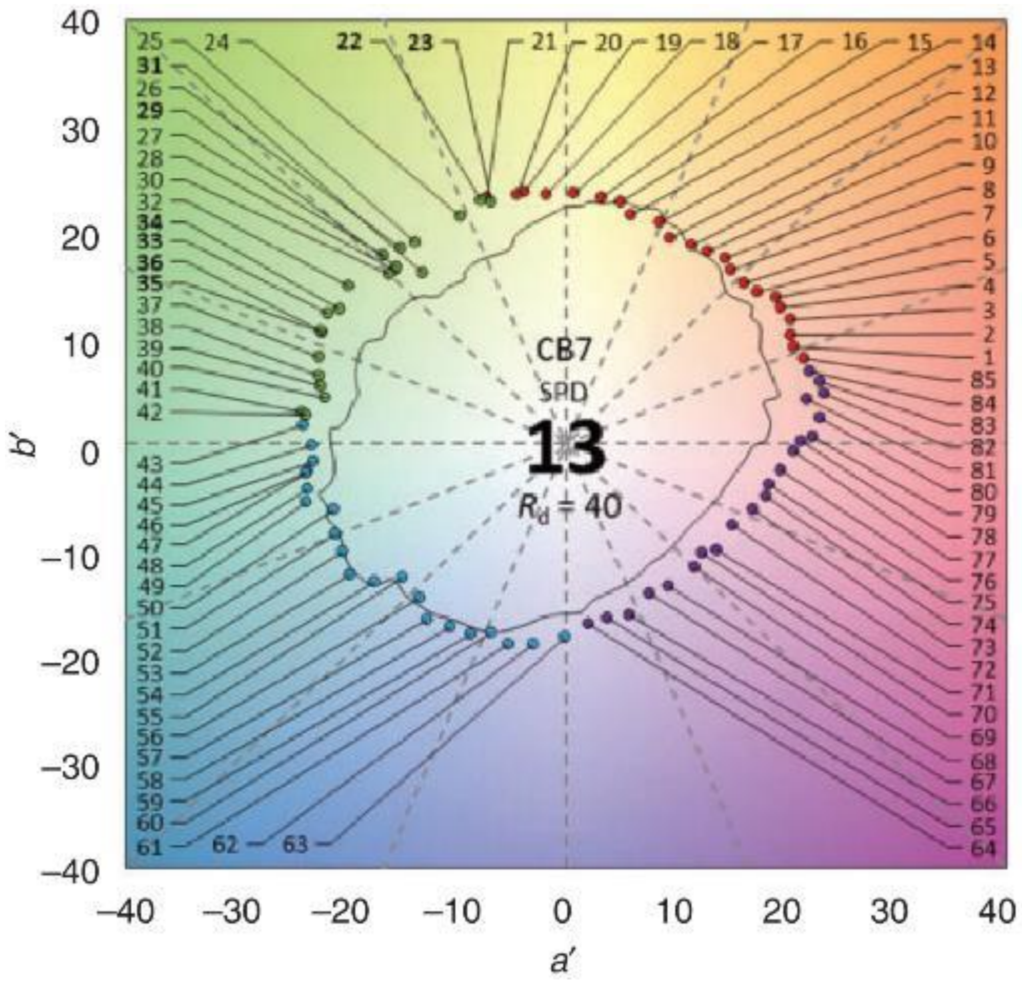


Esposito T. 2019. An Adjusted Error Score Calculation for the Farnsworth Munsell 100 Hue Test. LEUKOS, 15(2-3):195-202. https://doi.org/10.1080/15502724.2018.1514265

Color discrimination is not related to measures associated with gamut area!



R_f = 65
R_g = 100



R_f = 65
R_g = 120

Two caps transposed
R_d = 4
(Interpretation: “Average Color Discrimination”)

Eight caps transposed
R_d = 40
(Interpretation: “Poor Color Discrimination”)

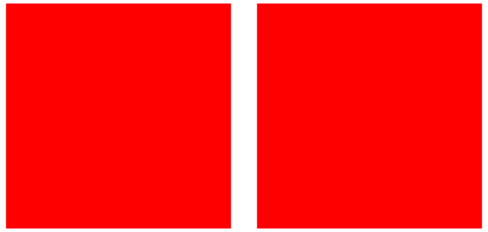
Esposito T, Houser K. 2019. A new measure of color discrimination for LEDs and other light sources. Lighting Res. Technol. 51:5-23. https://doi.org/10.1177/1477153517729200

Metameric Uncertainty Index, R_t

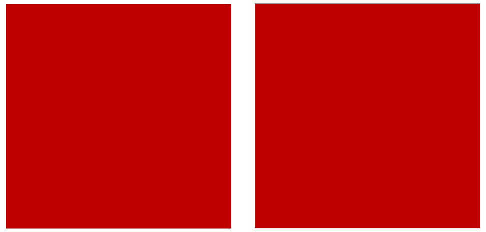
More information: https://www.tandfonline.com/doi/abs/10.1080/15502724.2018.1554369

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

Reference



Light Source 1



$R_f = 80$

$R_t = 95$

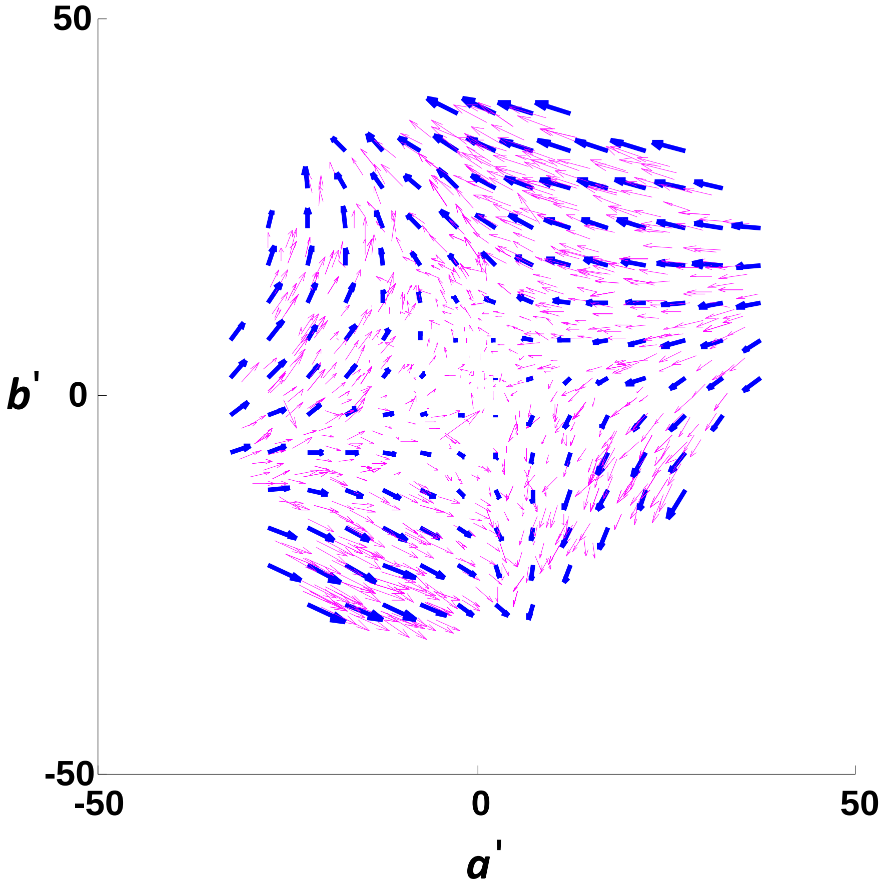
Light Source 2

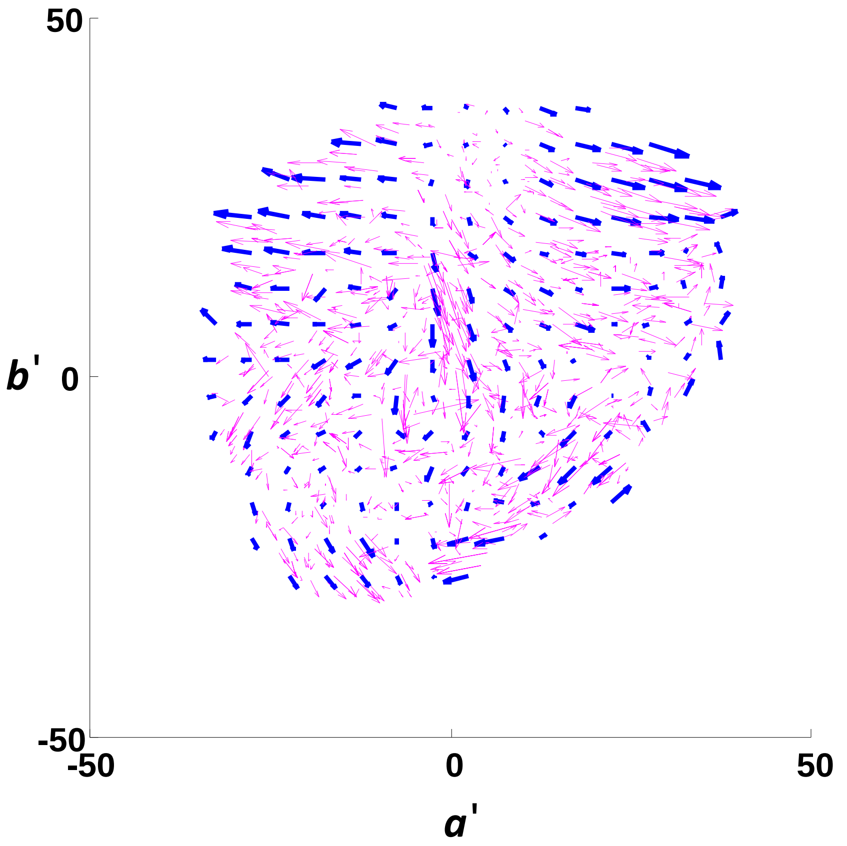
$R_f = 80$

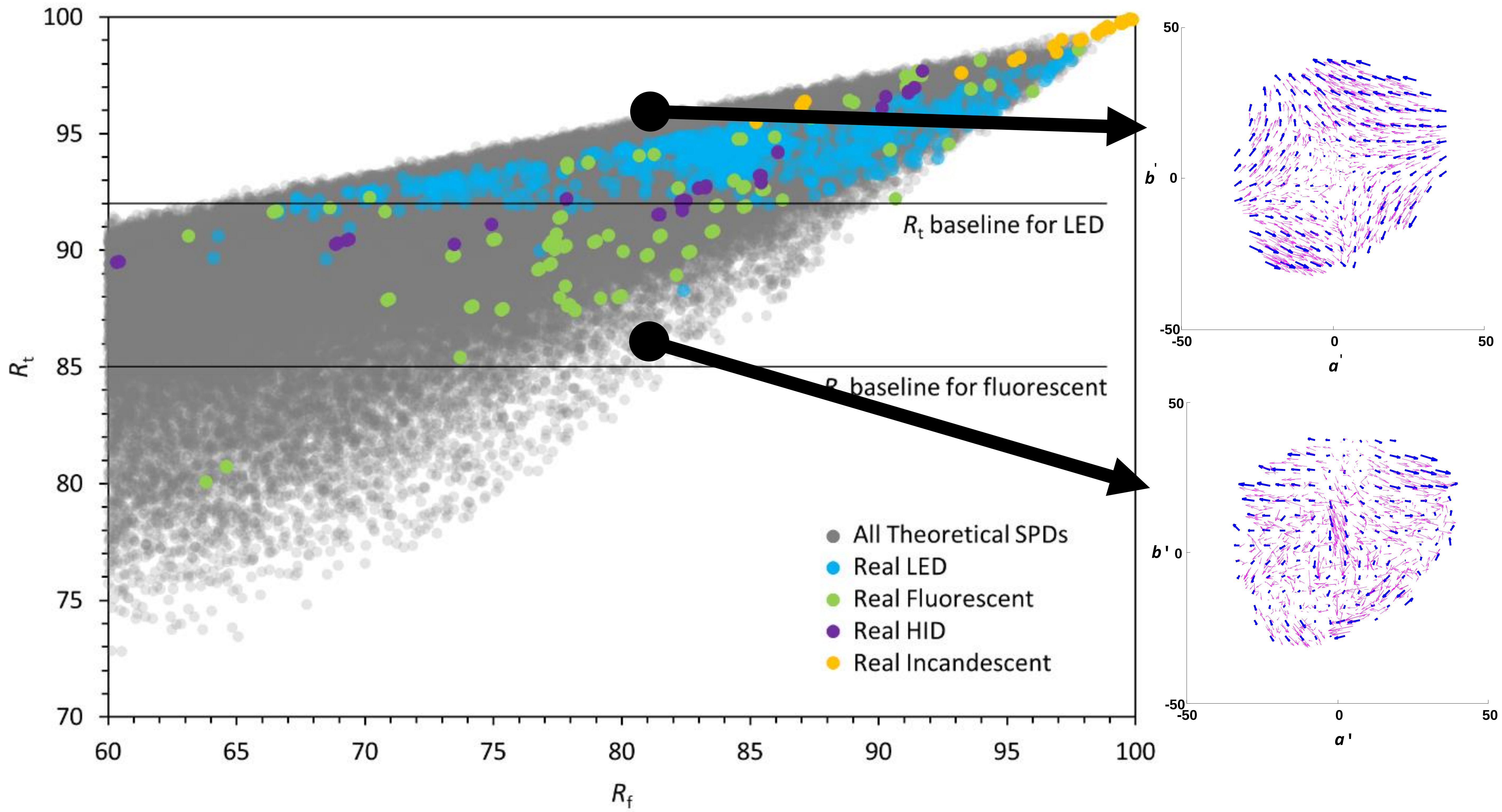
$R_t = 87$

Color Shifts Predicted by Vector Field Model (Least Squares Fit)

Actual Color Shifts

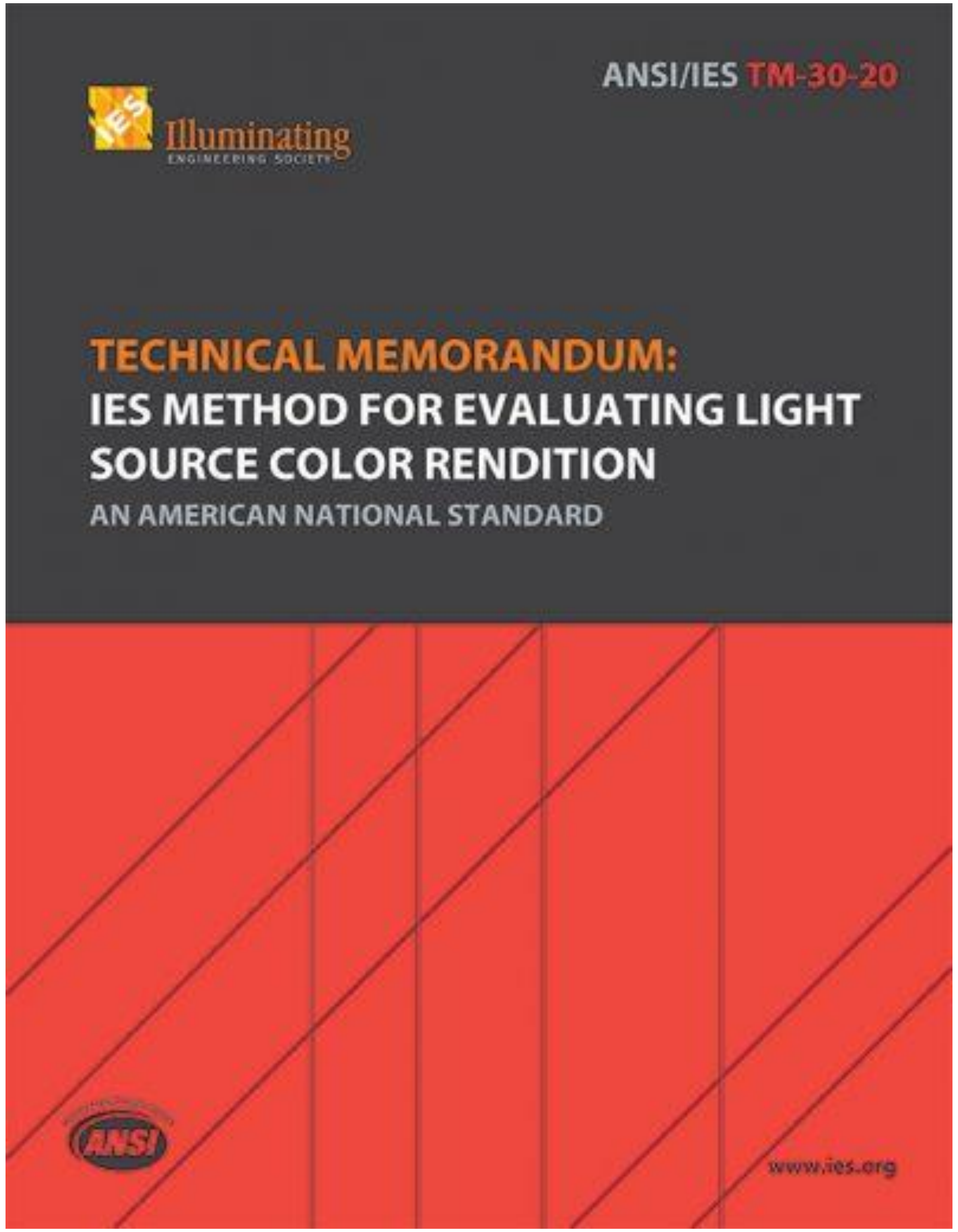






100
95
90
85
80
75
70
60
65
70
75
80
85
90
95
100
R_t
R_f
R_t baseline for LED
R_t baseline for fluorescent
All Theoretical SPDs
Real LED
Real Fluorescent
Real HID
Real Incandescent
50
0
-50
-50
0
50
b'
a'
50
0
-50
-50
0
50
b'
a'

Mixed Conditions



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