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

Illuminating ENGINEERING SOCIETY

Understanding and Applying TM-30-15

DOE+IES Webinar | September 15, 2015

Michael Royer
Pacific Northwest National Laboratory

Kevin Houser
Penn State University

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

Today's Topics

1. TM-30-15: How It Came To Be
2. Overview of the TM-30-15 Method
3. TM-30-15 R_f Vs. CIE R_a

   [Questions]

4. Excel Tool Demonstration
5. TM-30-15 Adoption Considerations
   I. Manufacturers
   II. Specifiers
   III. Researchers
   IV. Programs

   [Questions]

Part 1:
TM-30-15: How It Came To Be

Limitations of Existing Metric

\+ Acknowledgement of Need for Alternative

\+ Research and Scientific Advancement

\+ Consensus Process

TM-30-15: IES Method for Evaluating Light Source Color Rendition

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)
No lower limit for scores	→	0 to 100 scale (fidelity)

“Original”

Image courtesy of Randy Burkett Lighting Design

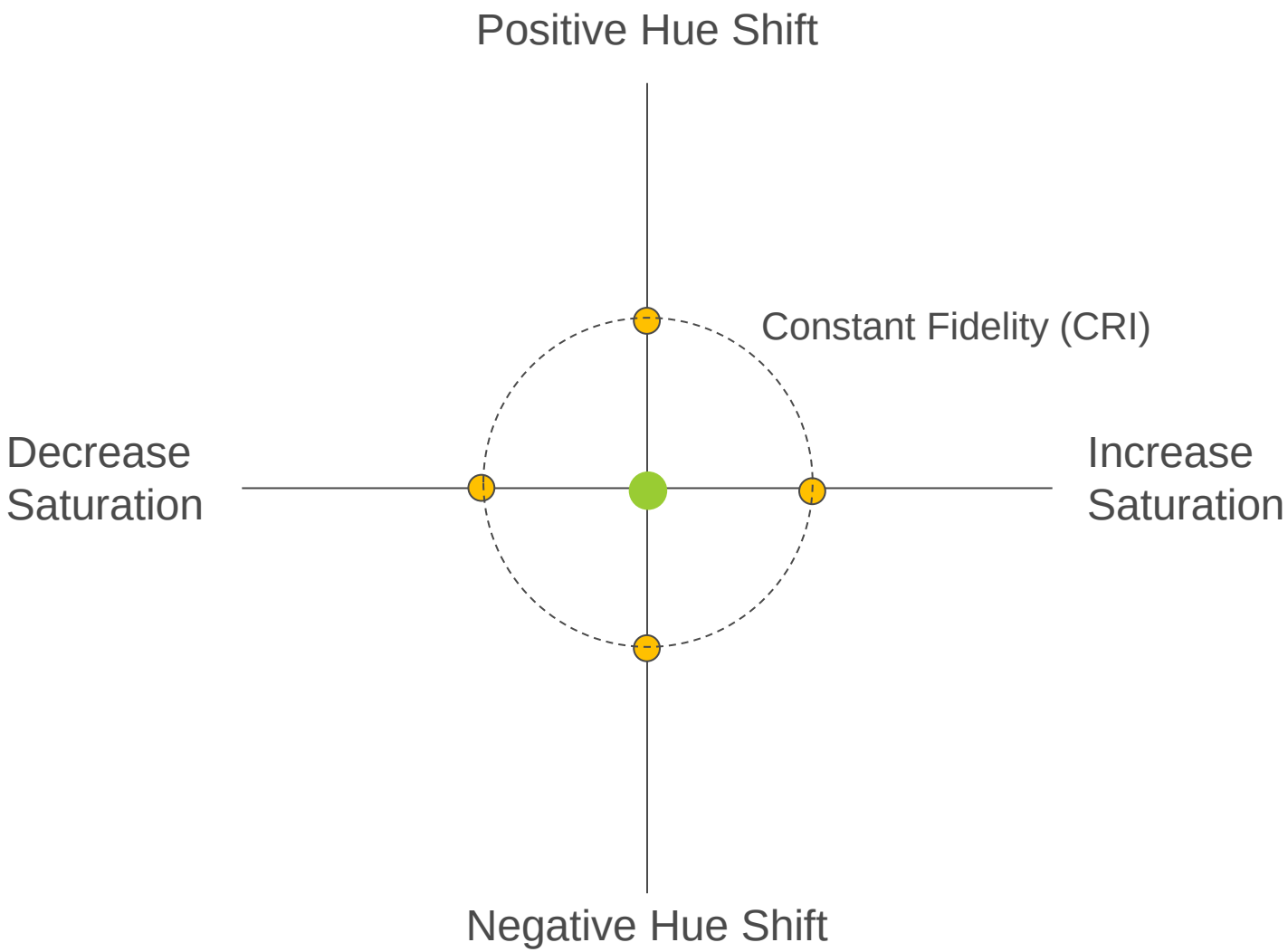
“CRI = 80” Desaturated

Image courtesy of Randy Burkett Lighting Design

“CRI = 80” Saturated

Image courtesy of Randy Burkett Lighting Design

Limitations of Considering Only Fidelity



Limitations of Considering Only Fidelity

One metric is not enough!

How many metrics are needed?

Attributes of Color Rendition include:

- Color Fidelity
- Color Discrimination
- Color Preference

} Tend to be related to saturation, which can be quantified with gamut

Sidebar, for Further Reading:

The more than 25 indices of color rendition that appear in the scientific literature tend to cluster into two categories, those based on comparison to a reference illuminant (i.e., to quantify fidelity), and those related to gamut area (i.e., to quantify increase or decrease in saturation).*

* Houser KW, Wei M, David A, Krames MR, Shen XS. Review of Measures for Light-Source Color Rendition and Considerations for a Two-Measure System for Characterizing Color Rendition. Optics Express. 2013; 21(8);10393-10411. http://dx.doi.org/10.1364/OE.21.010393

Limitations of Existing Metric

\+ **Acknowledgement of Need for Alternative**

\+ Research and Scientific Advancement

\+ Consensus Process

TM-30-15: IES Method for Evaluating Light Source Color Rendition

Timeline of Color Rendering Metric *Committees*

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

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

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

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

"This committee was not successful in its purposes mainly due to the disagreement between those who advocated including the advances of science and those who recommended that industry did not want change."[1]

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

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

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

Timeline of Color Rendering Metric Committees

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

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

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

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

Limitations of Existing Metric

\+ Acknowledgement of Need for Alternative

\+ **Research and Scientific Advancement**

\+ Consensus Process

TM-30-15: IES Method for Evaluating Light Source Color Rendition

Contributing Ideas (Not Exhaustive)

- **Two-metric concept**
  Indices to complement CRI include Judd's Flattery Index [1967]; Thornton's Color Preference Index [1974]; Guo and Houser's analysis showed complementarity of reference and gamut based indices [2004]; Lighting Research Center proposed "Class A" employing CRI and GAI [2008]; NIST proposed CQS employing Qa and Qg [2010]; Houser and colleagues provided analysis, rationale, and discussed considerations for a two-metric system [2013].
- **Graphic to display hue and saturation changes**
  van der Burgt and van Kemenade's Color Rendering Vectors [1988]; NIST CQS [2010]
- **CAM02-UCS**
  University of Leeds (CRI-CAM02UCS) [2011]
- **Wavelength uniformity of samples**
  University of British Columbia, University of Pannonia, University of Leeds (CRI2012) [2013]

Limitations of Existing Metric

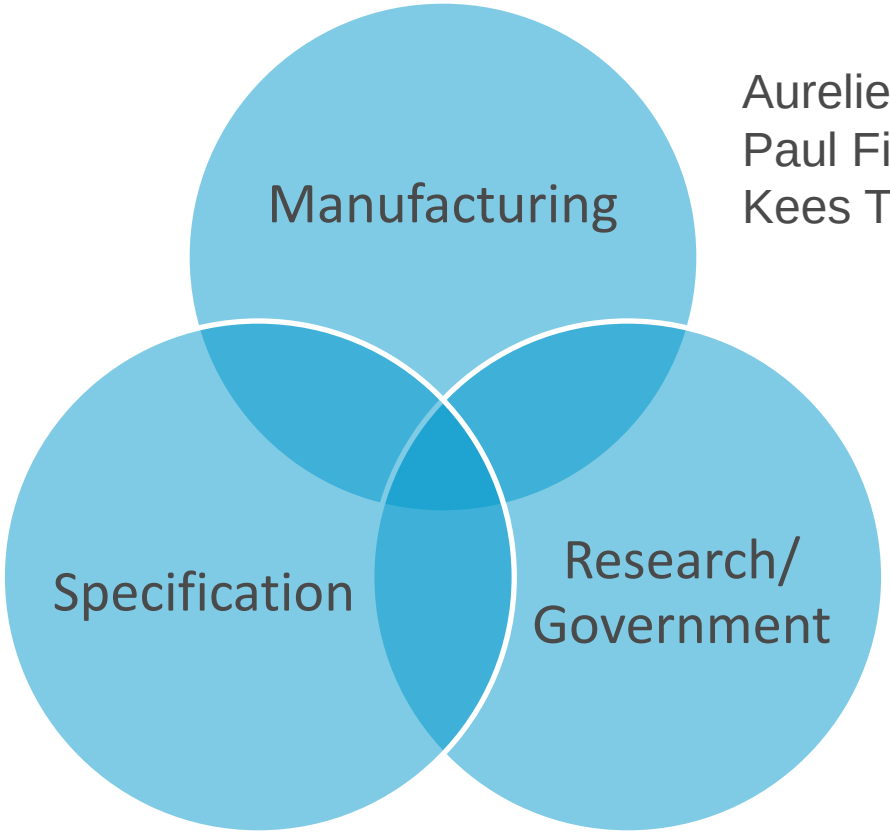
\+ Acknowledgement of Need for Alternative

\+ Research and Scientific Advancement

\+ **Consensus Process**

TM-30-15: IES Method for Evaluating Light Source Color Rendition

Voting Members of Color Metrics Task Force

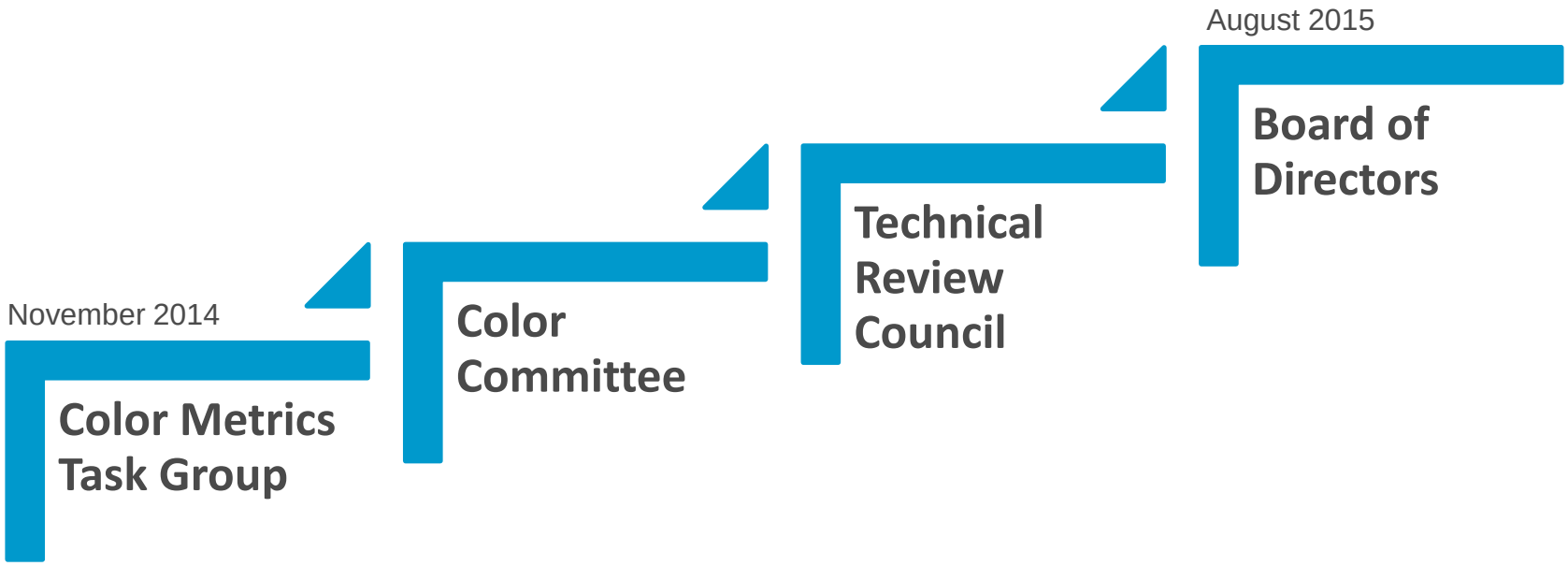


Aurelien David (Soraa)
Paul Fini (Cree)
Kees Teunissen (Philips)

Kevin Houser (Penn State)
Yoshi Ohno (NIST)
Michael Royer (PNNL/DOE)

Randy Burkett (RBLDI)

IES Balloting Process



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

Metrics/Measures

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

Criteria

≥ 80
≥ 0
2700 K – 5000 K
≤ 0.007

Standards

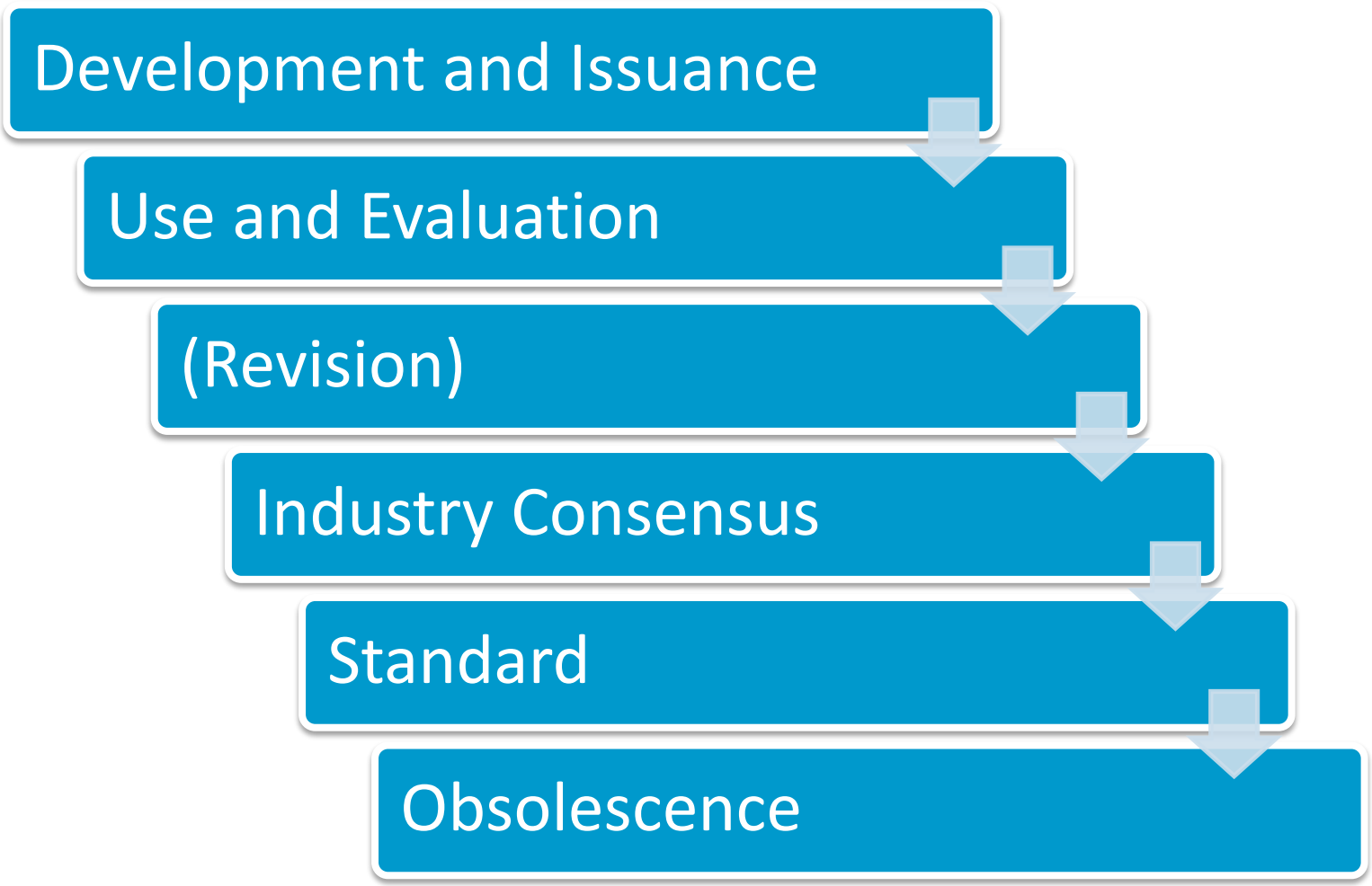
ANSI C78.377
ANSI/IES RP-1-12
ISO 8995-1 (CIE S 008)

Design Guidance

IES DG-1

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

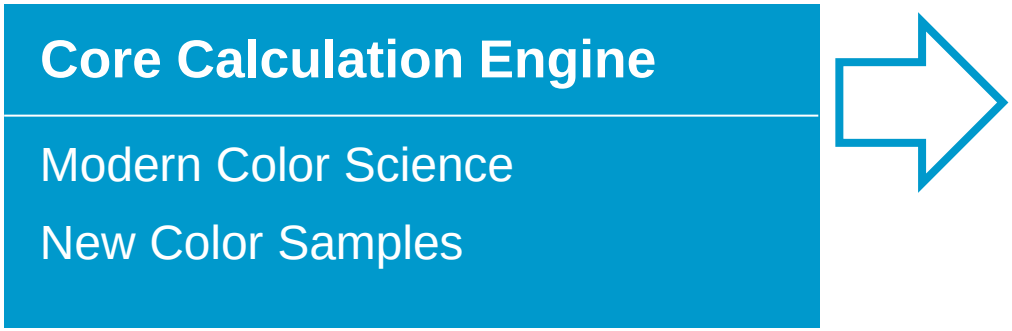
Metric Development



Part 2:
Overview of the TM-30-15 Method

Kevin Houser

IES Method for Color Rendition



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 ($R_{f\#}$)

Chroma Shift by Hue ($R_{c\#}$)

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

IES Method for Color Rendition

Color Fidelity

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

Fidelity Index (R_f)
(0-100)

Color Gamut

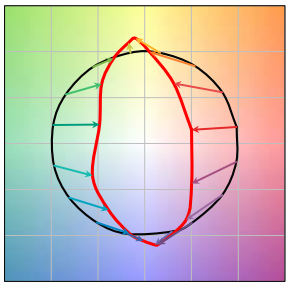
The average level of saturation relative to familiar (reference) illuminants.

Gamut Index (R_g)
~60-140 when $R_f > 60$

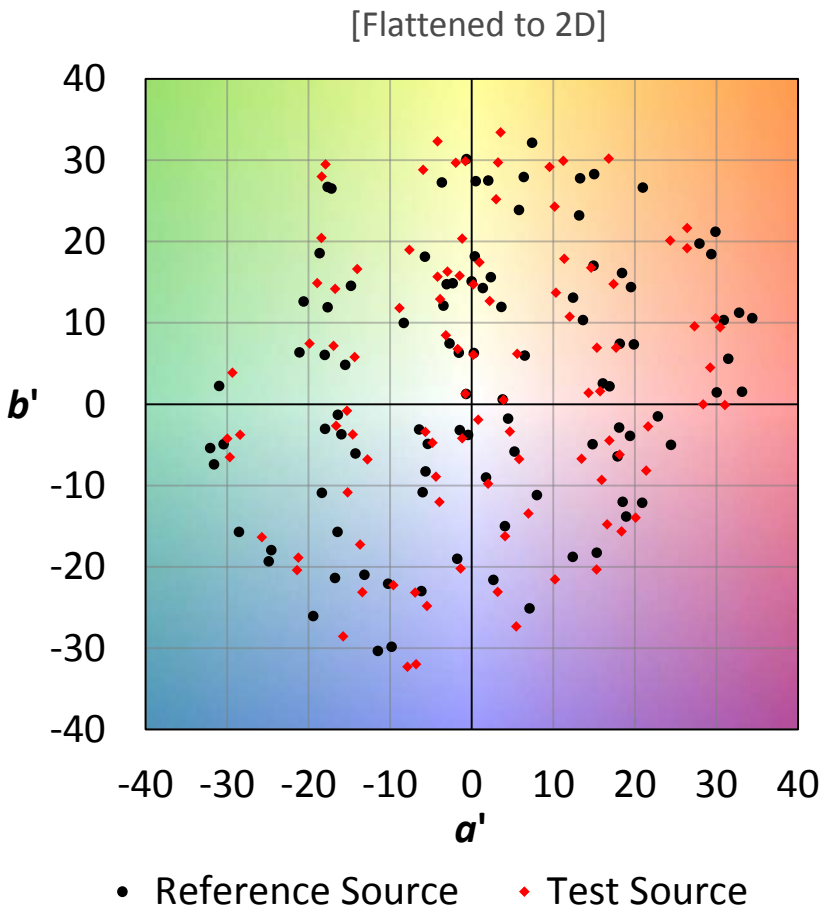
Graphics

Visual description of hue and saturation changes.

Color Vector Graphic

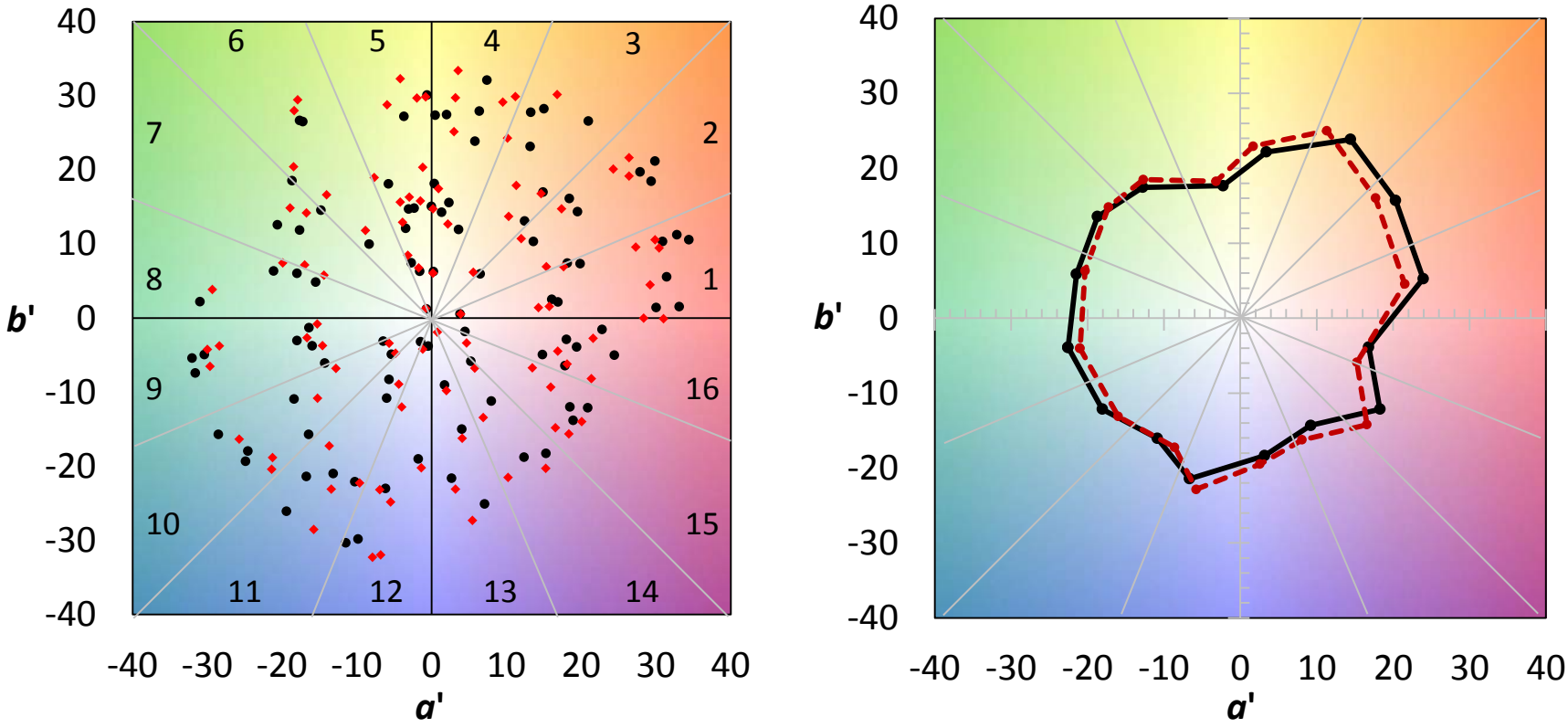


Fidelity Index: R_f



- Average similarity in appearance of test and reference sources
- Analogous to CIE R_a, greater accuracy
- Scores 0 to 100
- Scale similar to CIE R_a, but high scores harder to achieve
- Equal weight to all directions of shift
- Should not be expected to correlate with any single object

Relative Gamut Index: R_g



An R_g value greater than 100 indicates an average increase in saturation and an R_g value less than 100 indicates an average decrease in saturation.

(Theoretical)

Original

CRI = 95

R_f = 93

R_g = 100

Desaturated

CRI = 80

R_f = 78

R_g = 90

Red-Enhanced

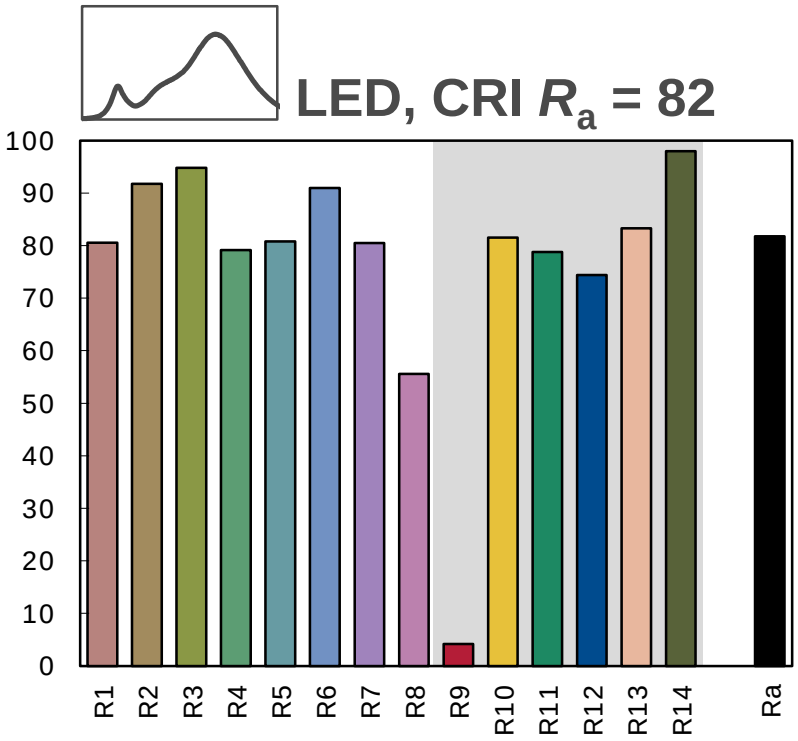
CRI = 80

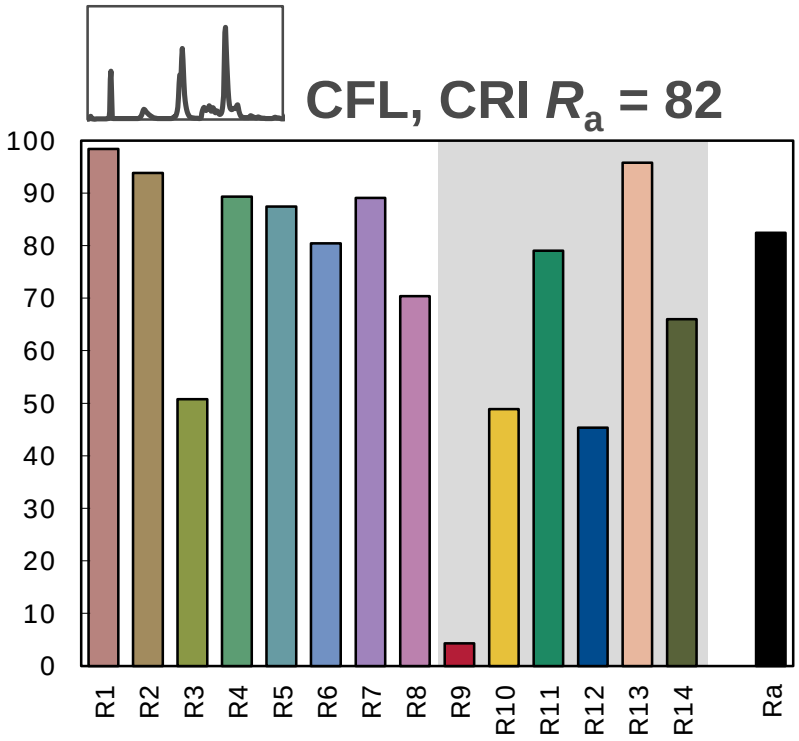
R_f = 78

R_g = 110

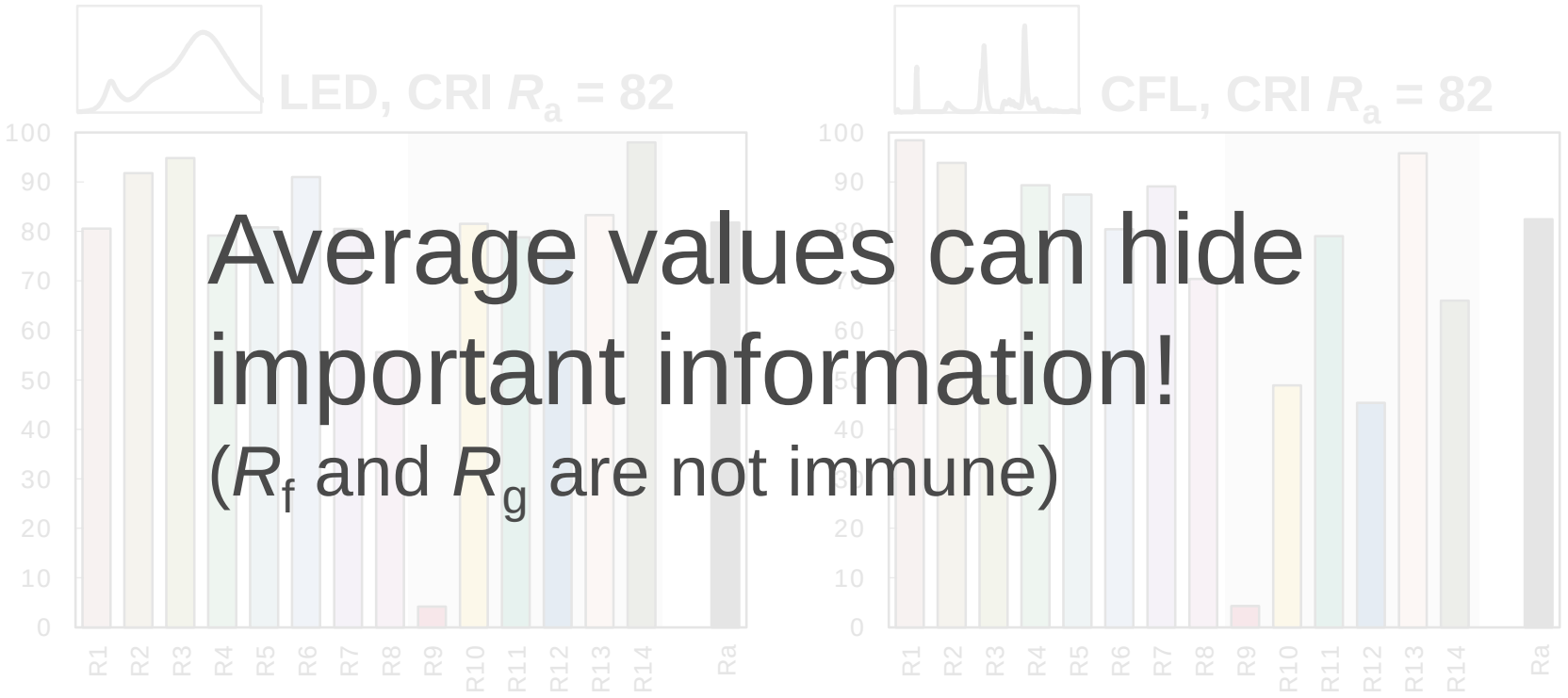
Images courtesy of Randy Burkett Lighting Design

Limitation of Average Values





Limitation of Average Values

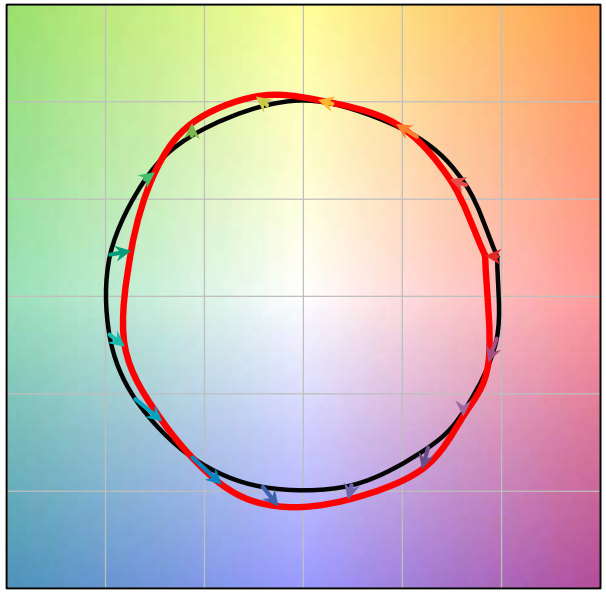


Average values can hide important information!

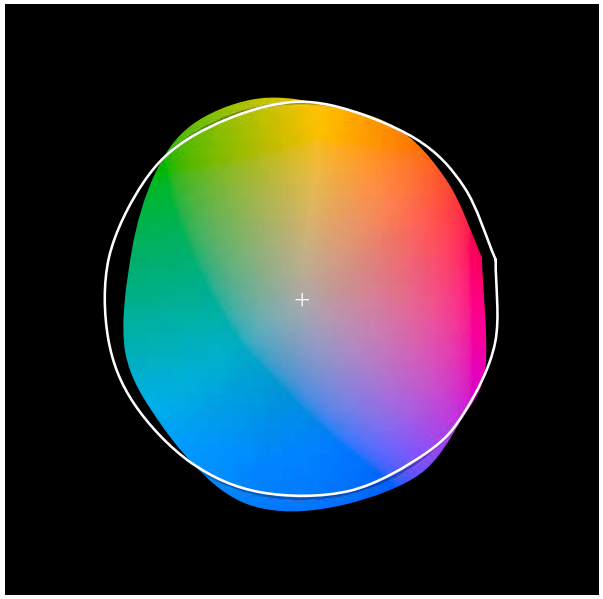
(R_f and R_g are not immune)

Color Vector Graphic

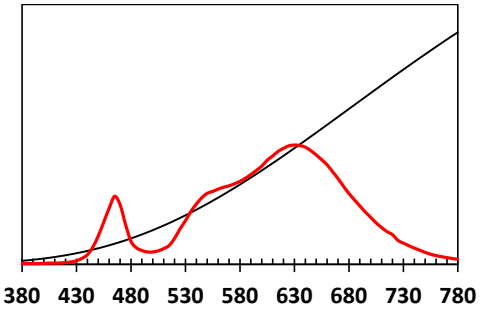
“Gamut” is not a dimension of perception. It is best interpreted with reference to a complementary graphic.



Color Vector Graphic



Color Distortion Graphic

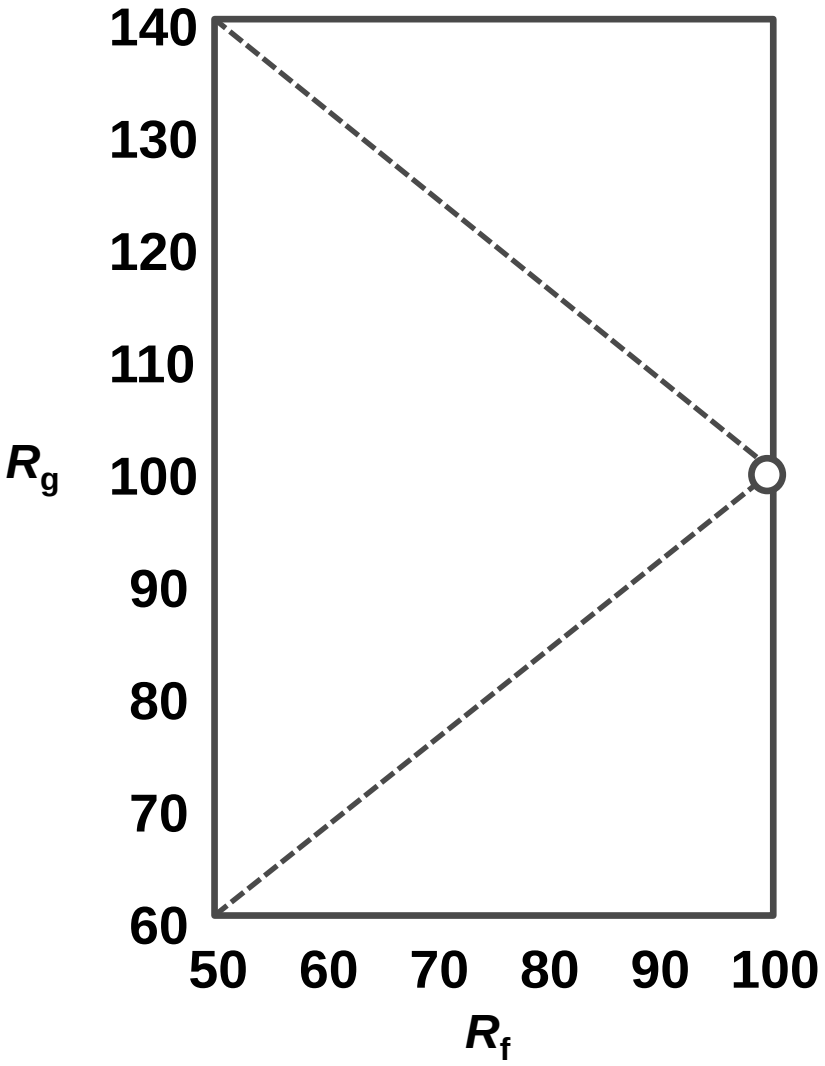


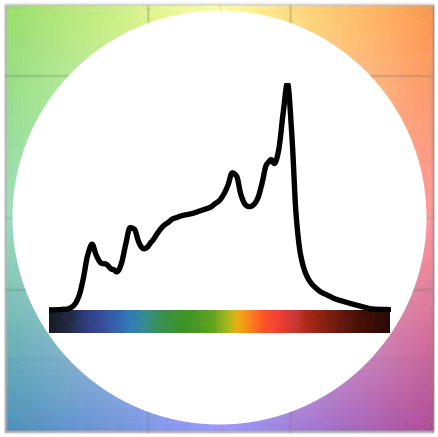
R_f	=	81
R_g	=	101
CCT	=	2496 K
R_a	=	88

(Source No. 286)

R_f, R_g and Color Vector Graphic

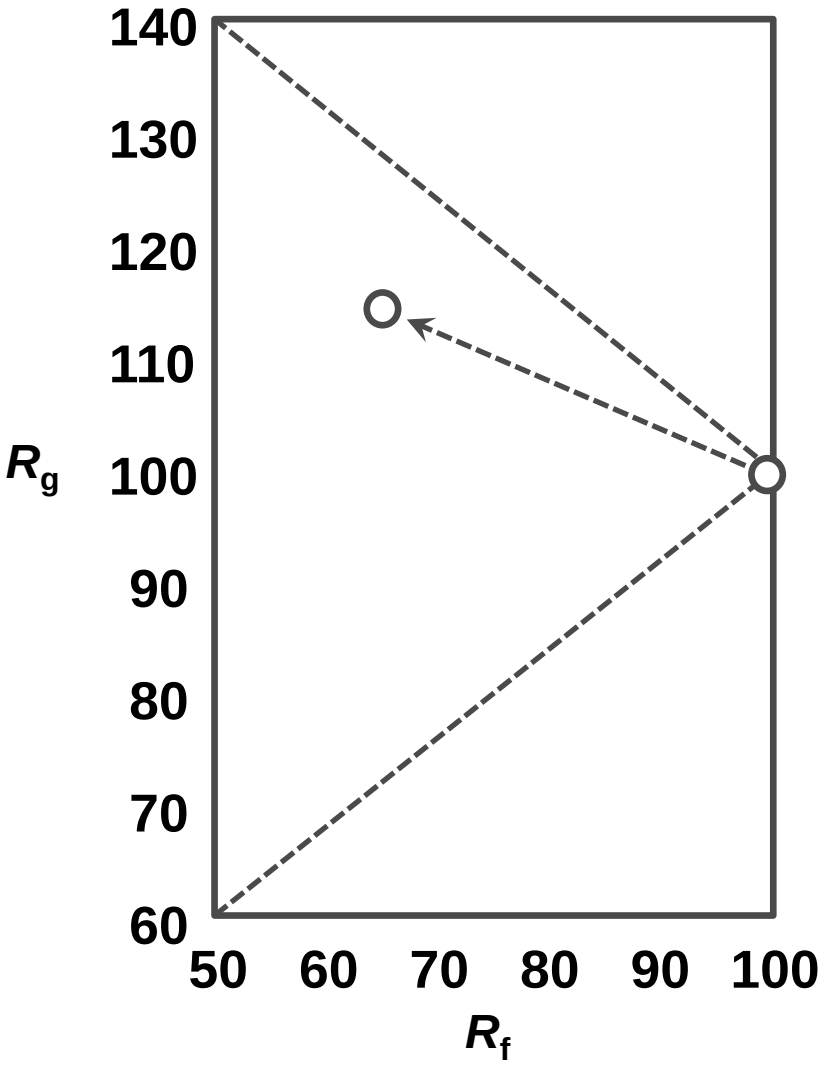
CCT = 3500 K, R_f = 100, R_g = 100

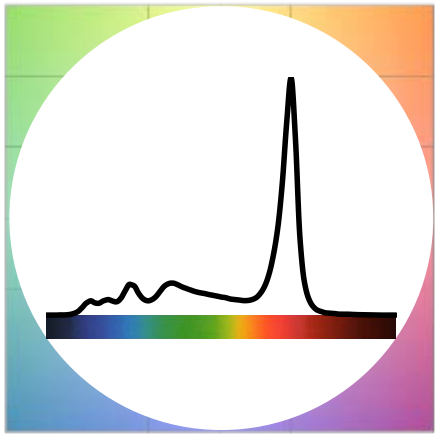


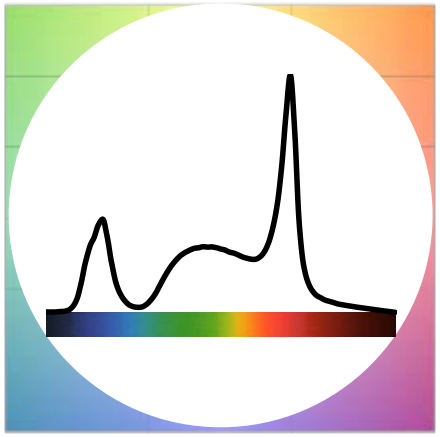


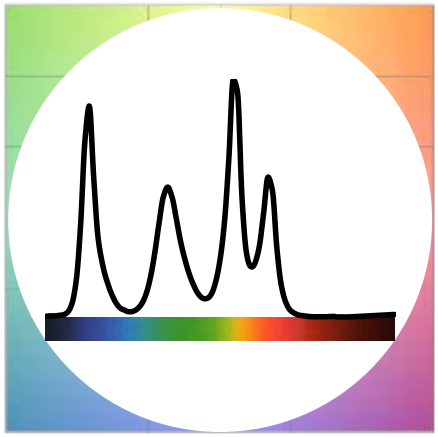
R_f, R_g and Color Vector Graphic

CCT = 3500 K, R_f = 65, R_g = 115







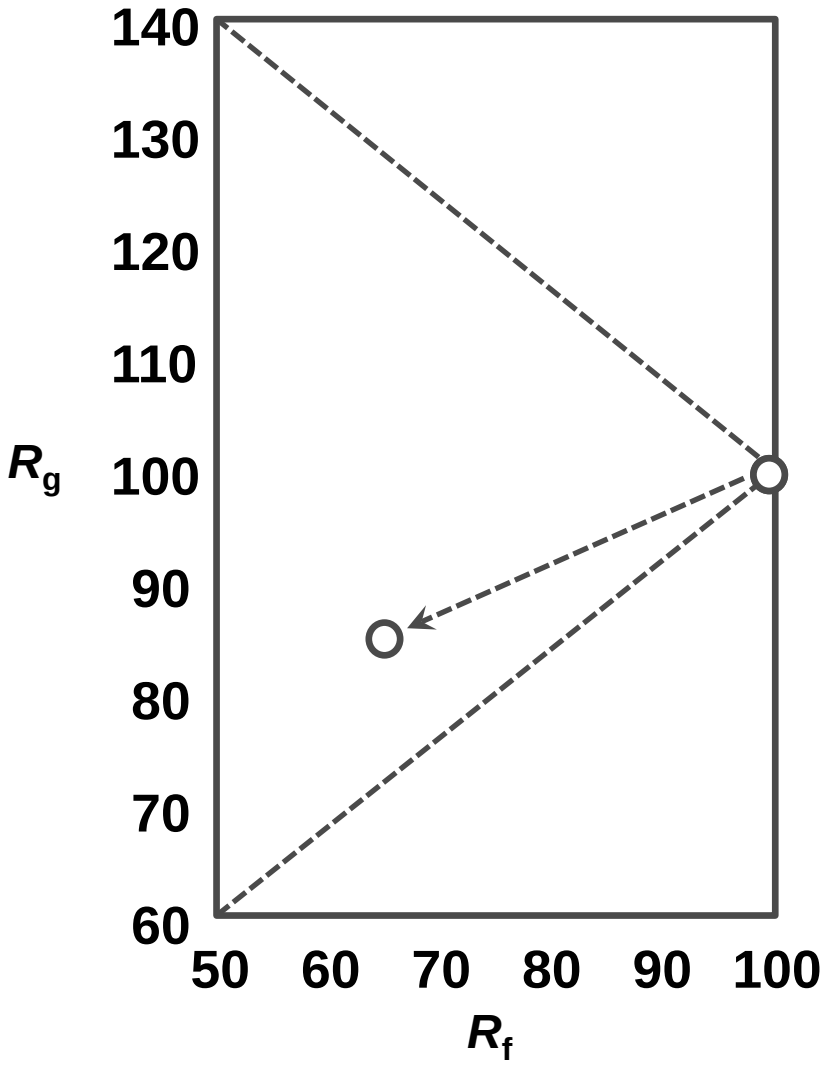


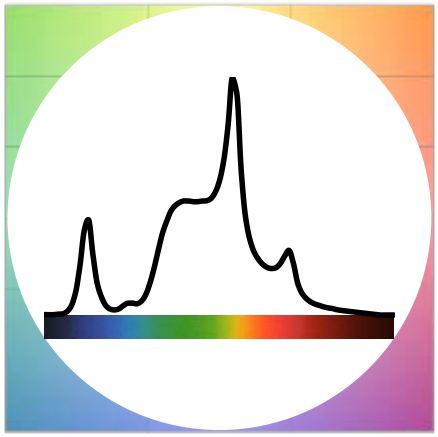
Color Vector Graphic analyses and plots courtesy of Tony Esposito, PhD Candidate, Penn State University.

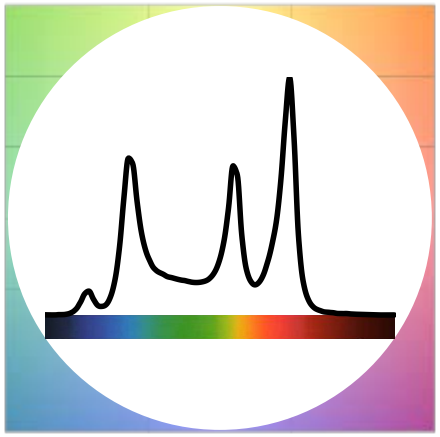
Based on simulations using 11-channel LED Cube.

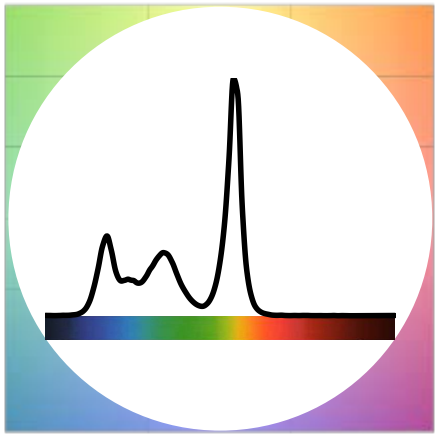
R_f, R_g and Color Vector Graphic

CCT = 3500 K, R_f = 65, R_g = 85





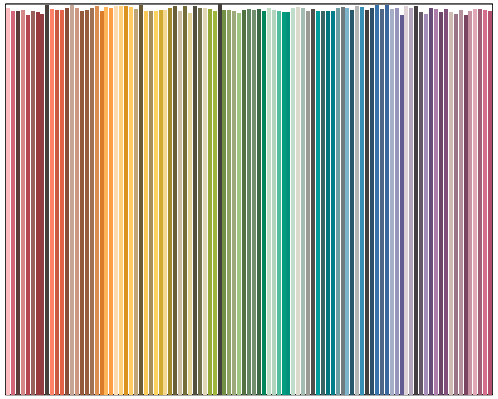


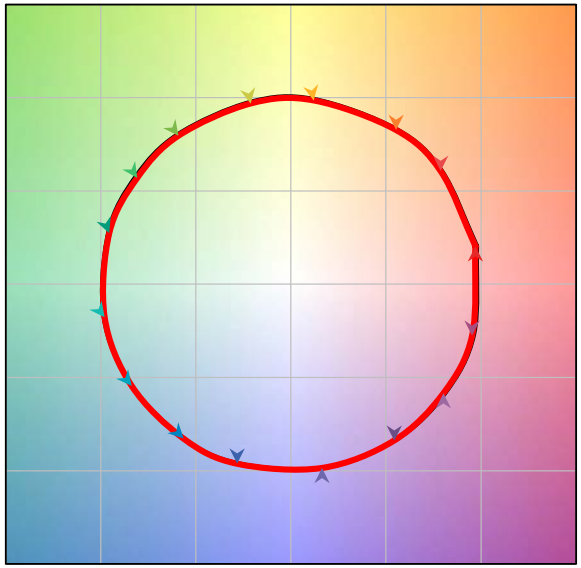


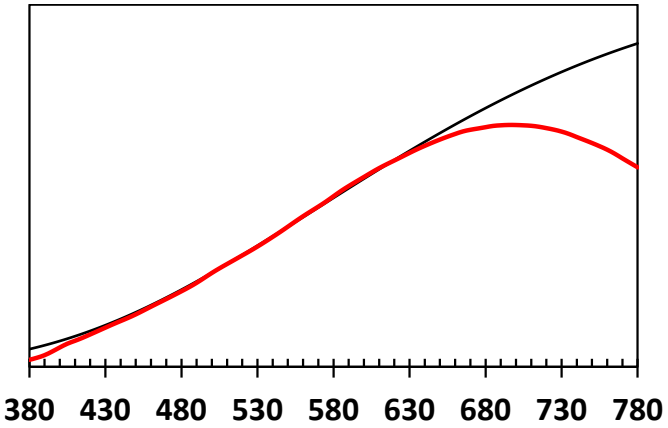
Color Vector Graphic analyses and plots courtesy of Tony Esposito, PhD Candidate, Penn State University.

Based on simulations using 11-channel LED Cube.

Halogen MR16, 3000 K (Source No. 80)

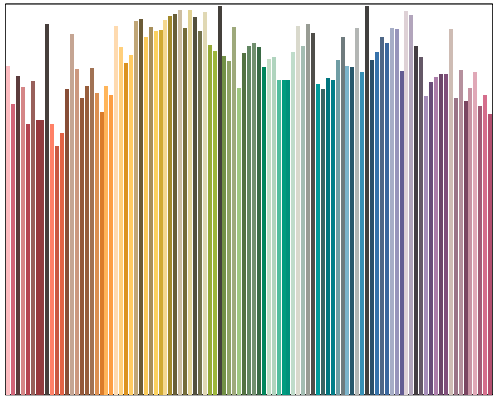


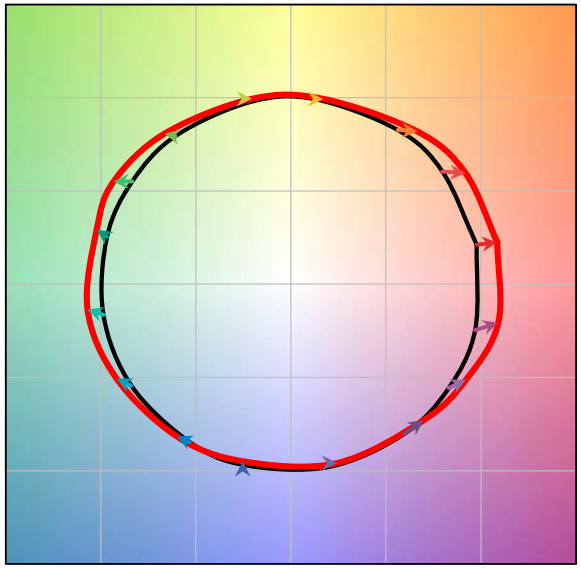


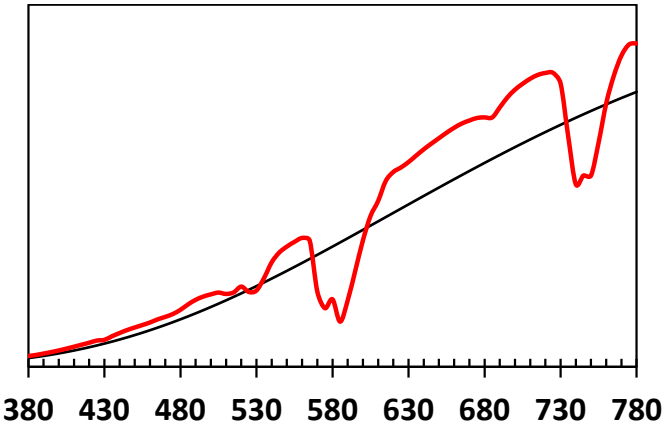


R_f	=	99
R_g	=	99
$R_{f,skin}$	=	99
CCT	=	2988 K
D_{uv}	=	0.0010
R_a	=	99
R_9	=	93

Neodymium Incandescent (Source No. 88)

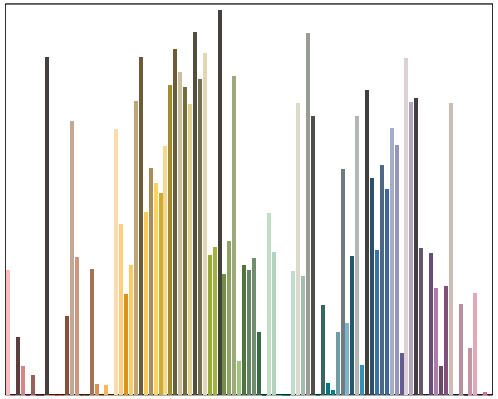


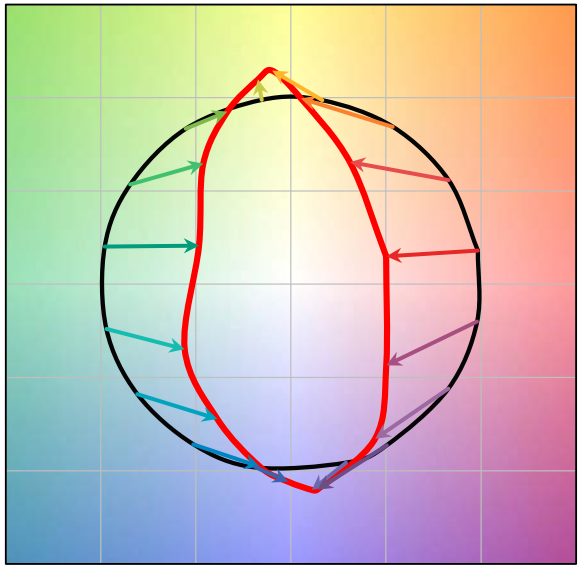


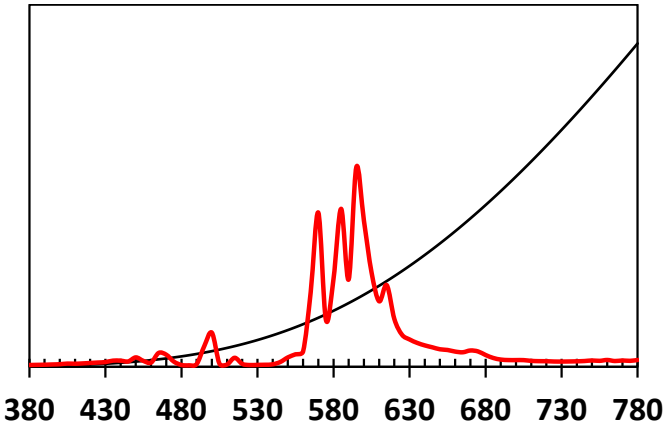


R_f	=	86
R_g	=	109
$R_{f,skin}$	=	83
CCT	=	2757 K
D_{uv}	=	-0.0048
R_a	=	77
R_9	=	15

High Pressure Sodium (Source No. 56)

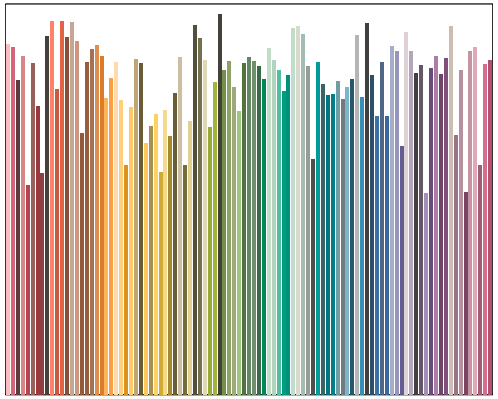


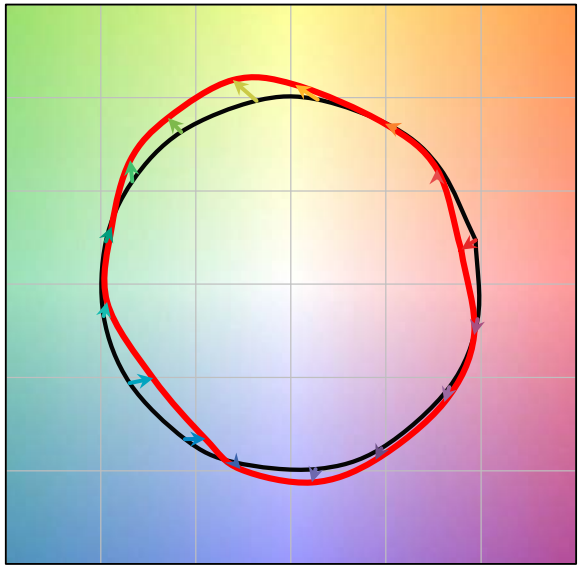


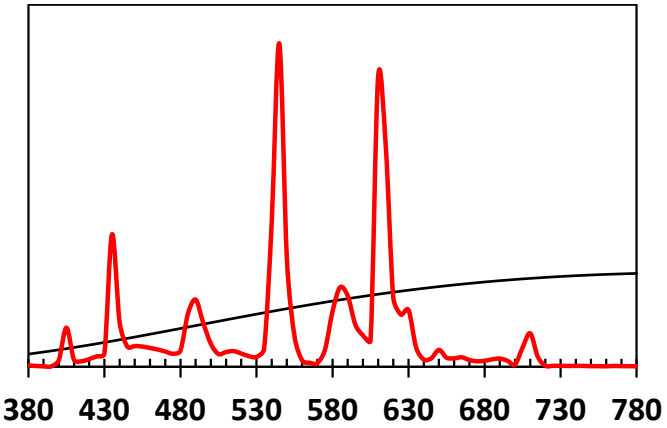


R_f	=	32
R_g	=	61
$R_{f,skin}$	=	34
CCT	=	1967 K
D_{uv}	=	-0.0002
R_a	=	16
R_9	=	-226

F32T8 835 (Source No. 37)

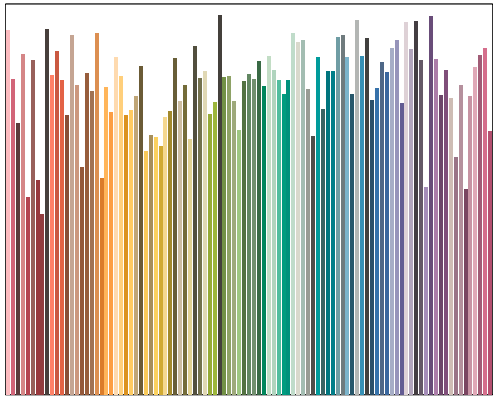


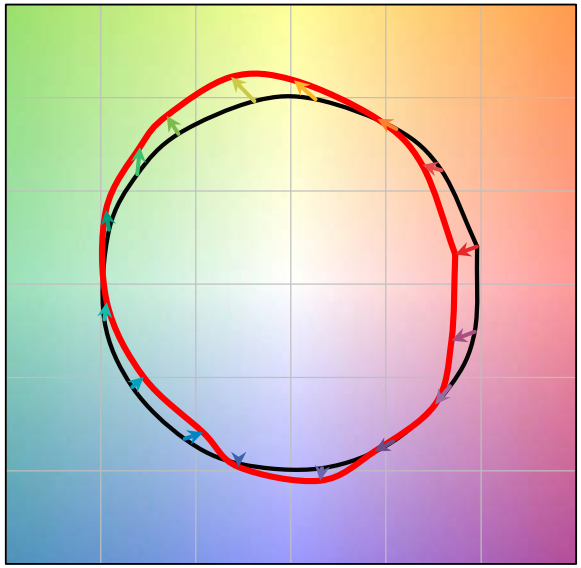


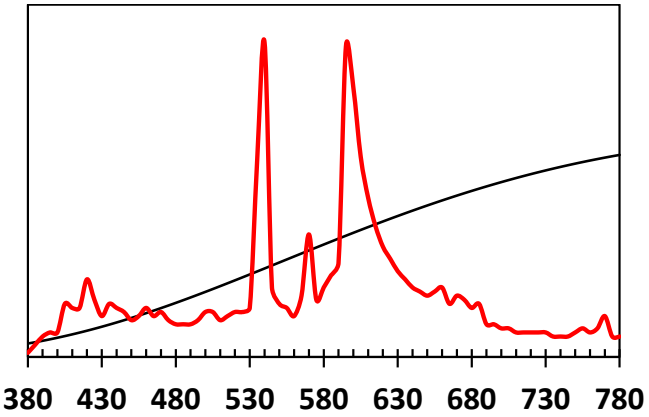


R_f	=	80
R_g	=	102
$R_{f,skin}$	=	89
CCT	=	3480 K
D_{uv}	=	0.0007
R_a	=	86
R_9	=	15

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





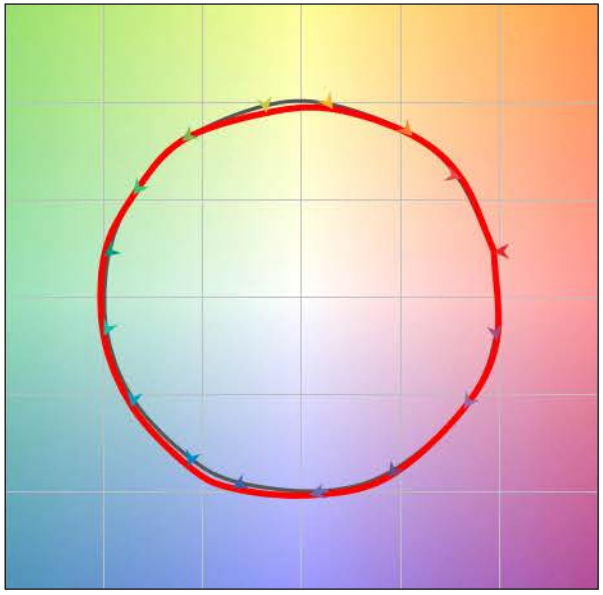


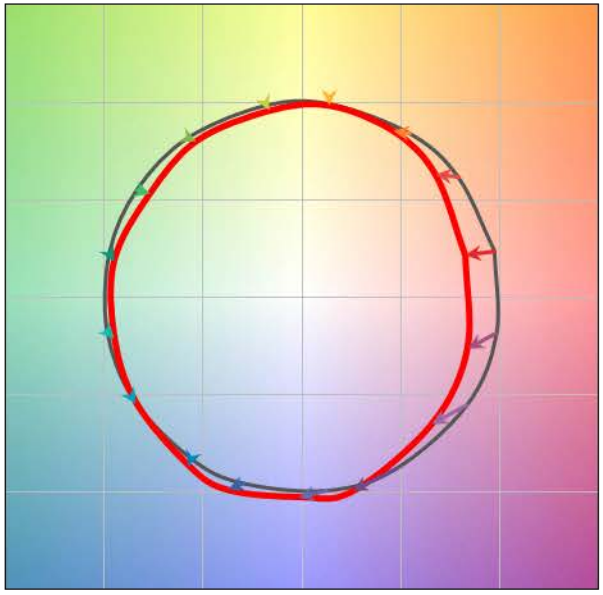
R_f	=	79
R_g	=	100
$R_{f,skin}$	=	78
CCT	=	3080 K
D_{uv}	=	-0.0024
R_a	=	84
R_9	=	-30

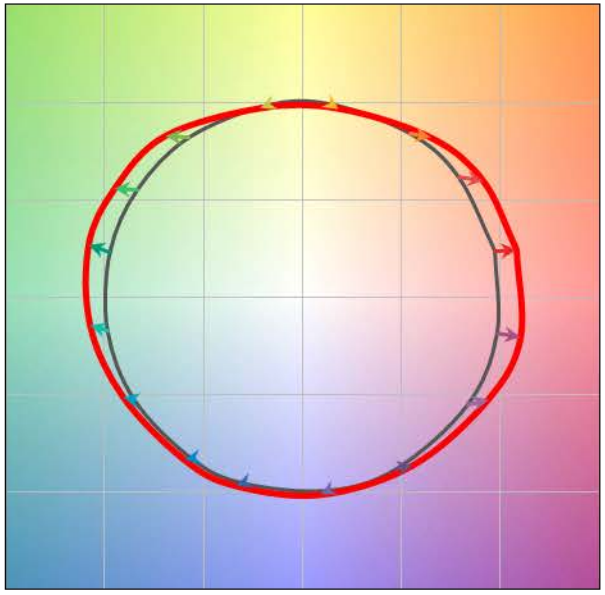
Original

Desaturated

Red-Enhanced

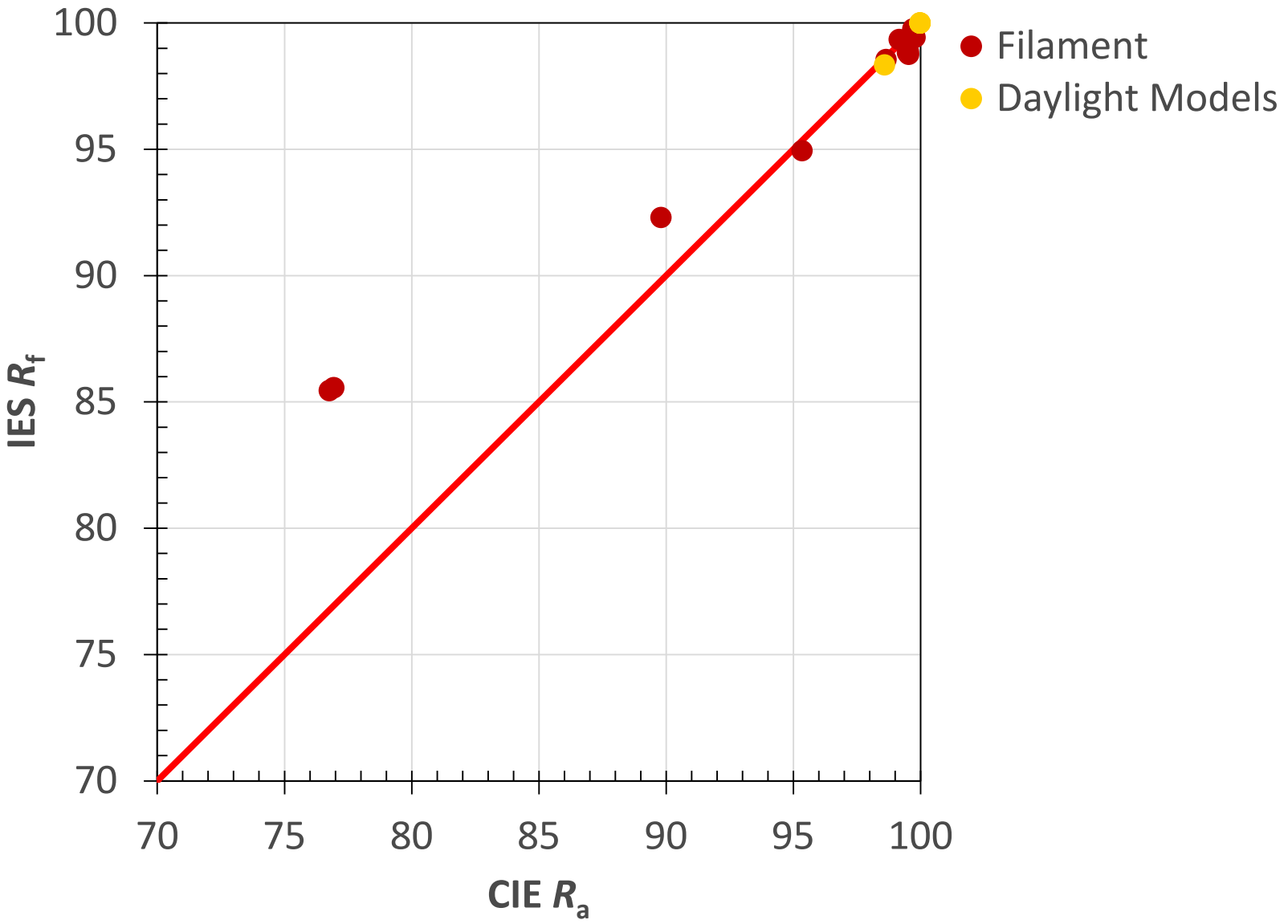




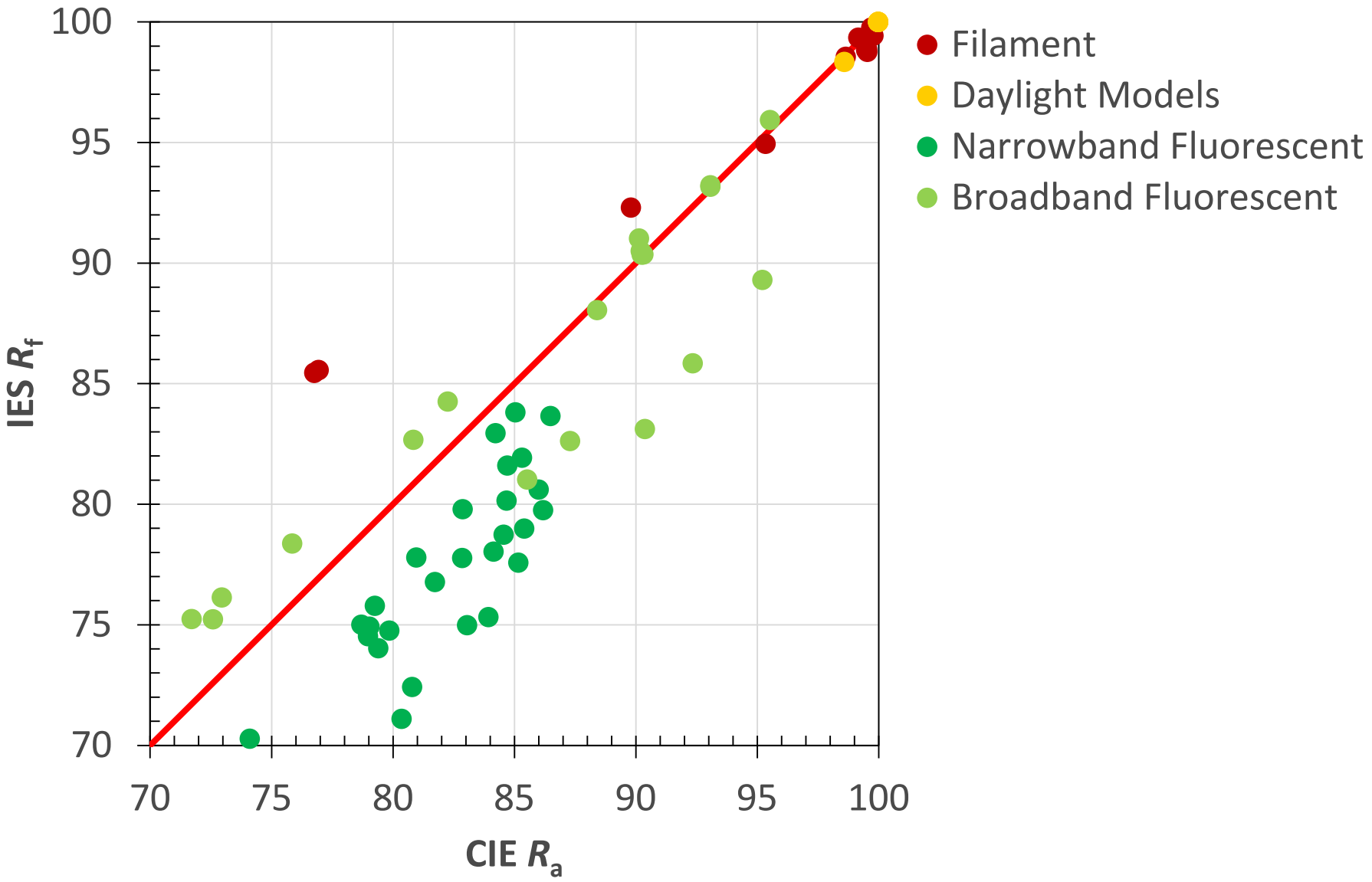


Part 3:
IES R_f versus CIE R_a

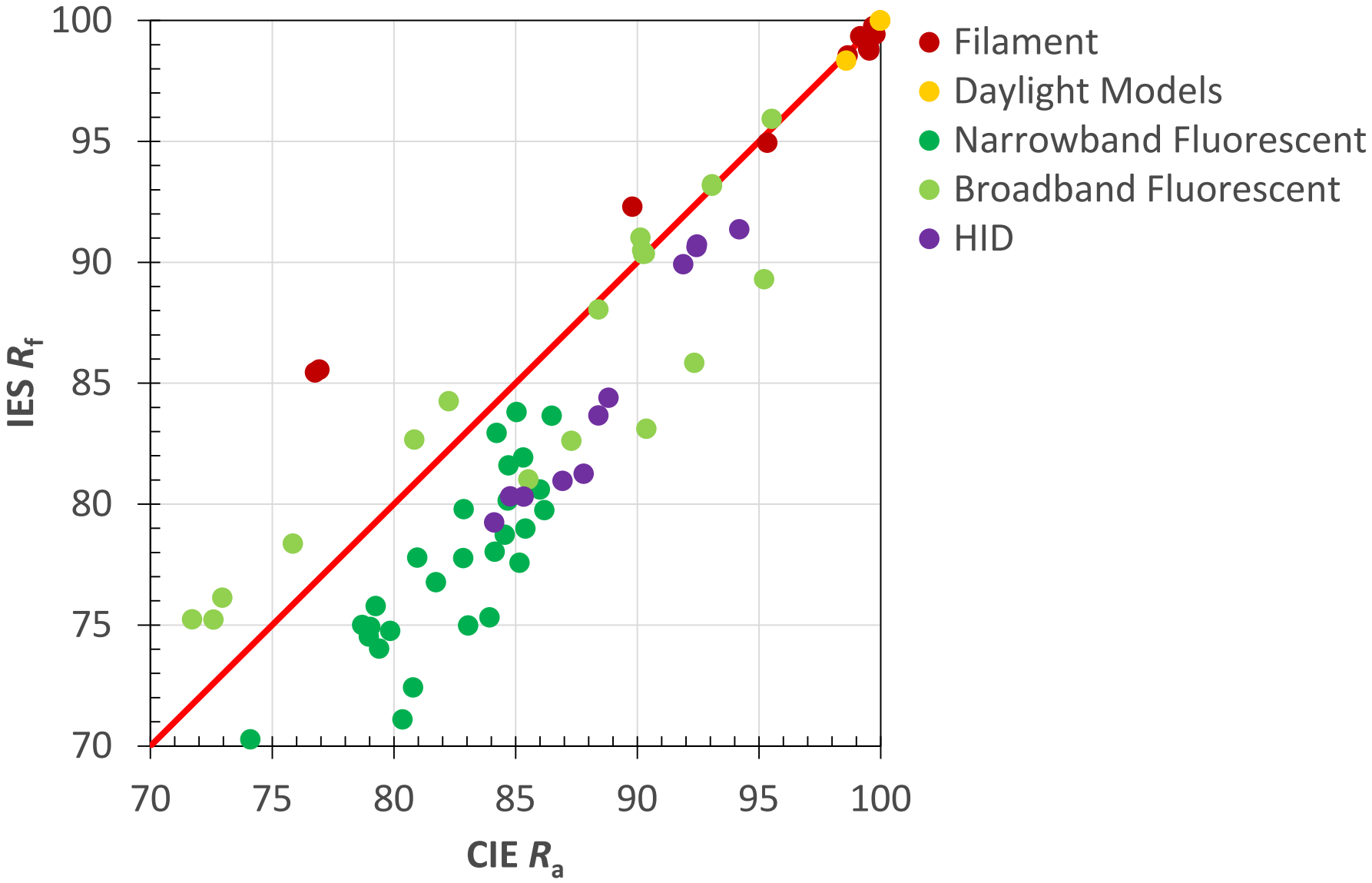
IES R_f versus CIE R_a



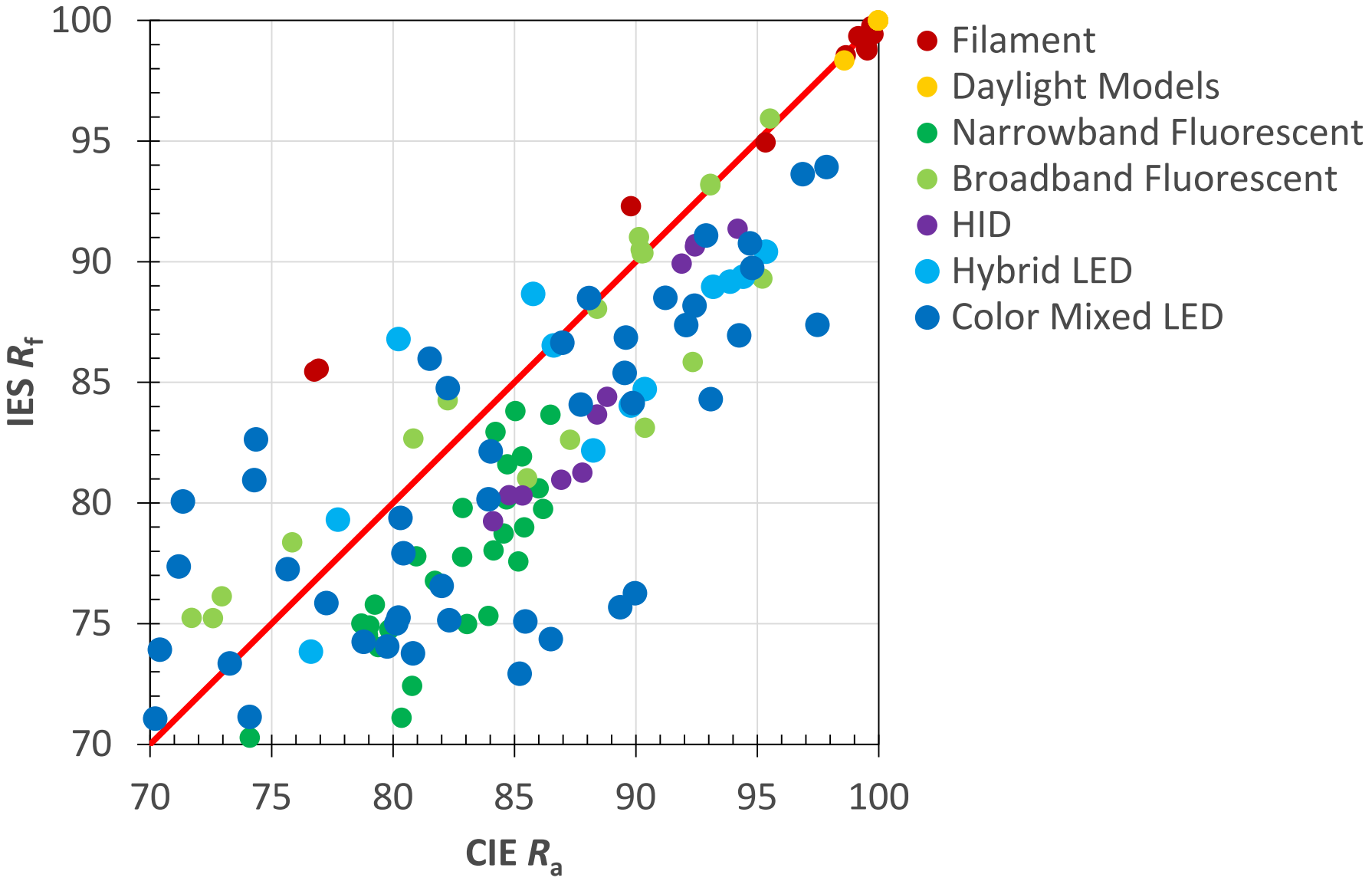
IES R_f versus CIE R_a



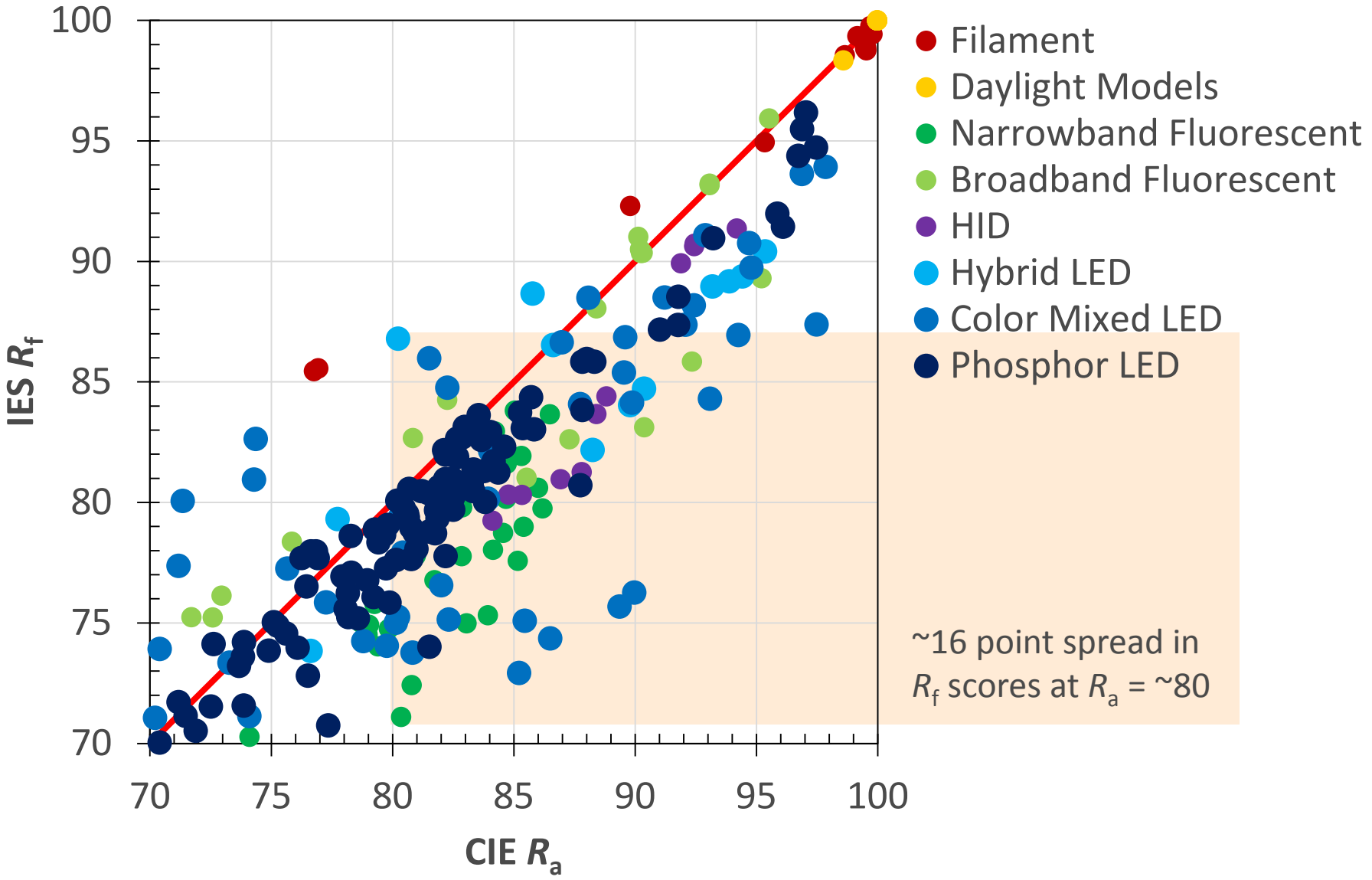
IES R_f versus CIE R_a



IES R_f versus CIE R_a



IES R_f versus CIE R_a



Questions?

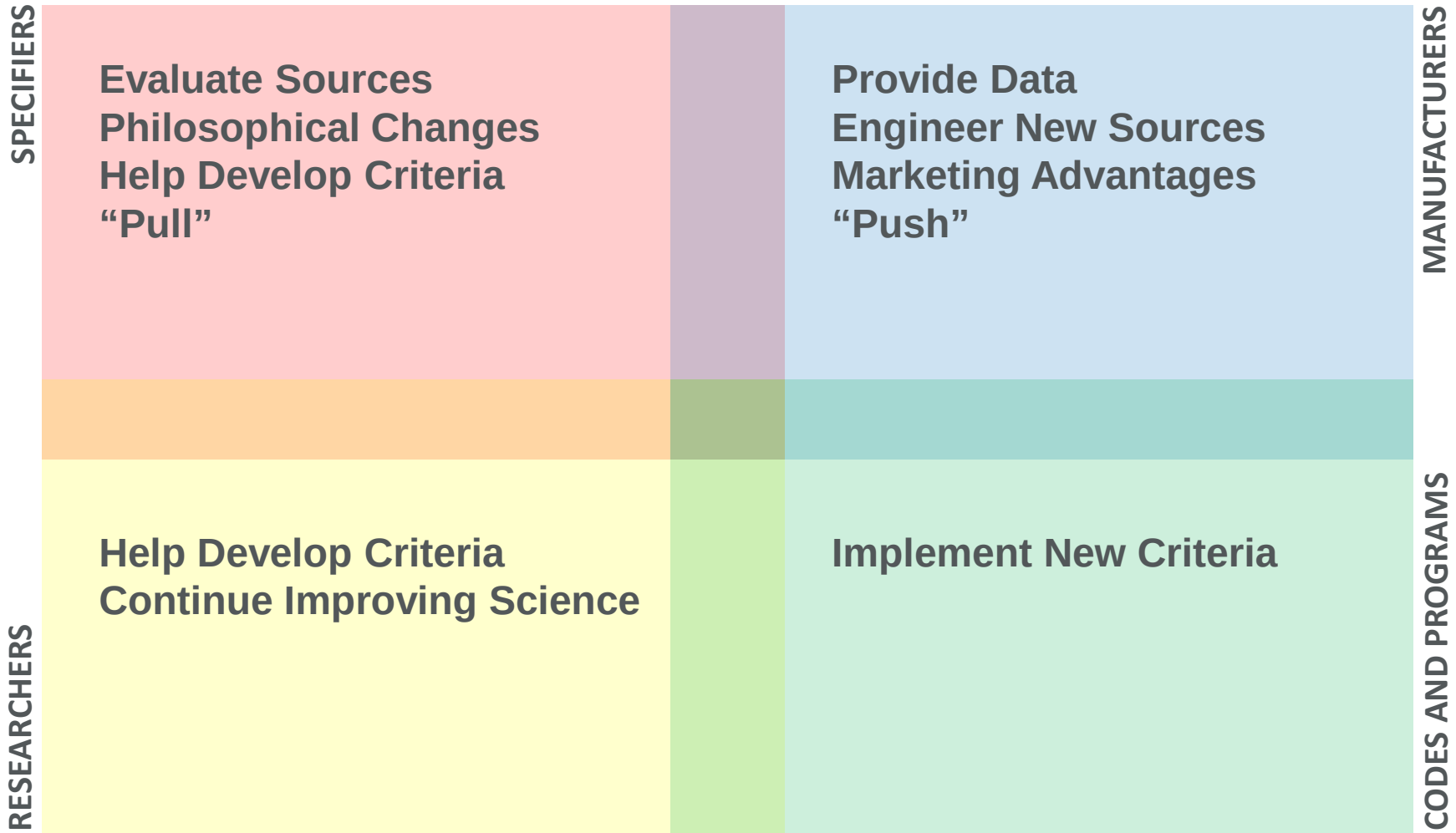
Part 4:
Excel Tool Live Demo

Kevin Houser

Part 5:
TM-30-15 Adoption Considerations

Michael Royer

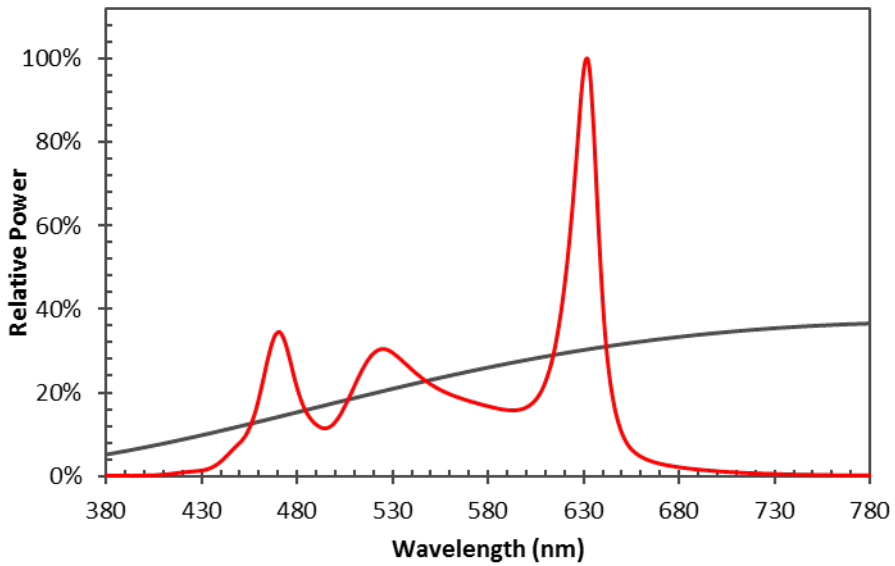
Adoption Stakeholders

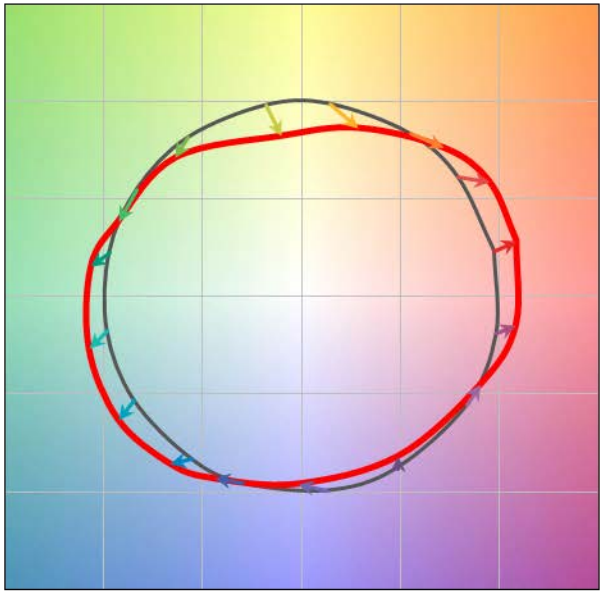


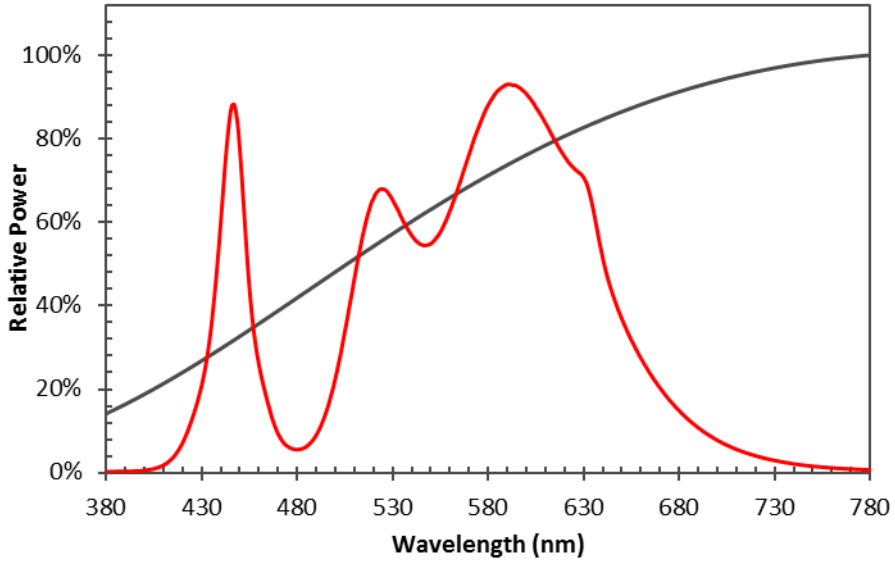
Manufacturers

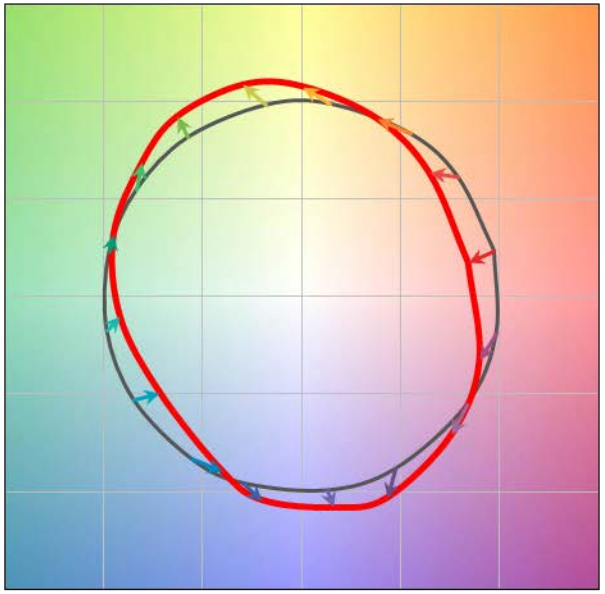
Manufacturers have explored tradeoffs between fidelity and gamut in the past.

Manufacturers









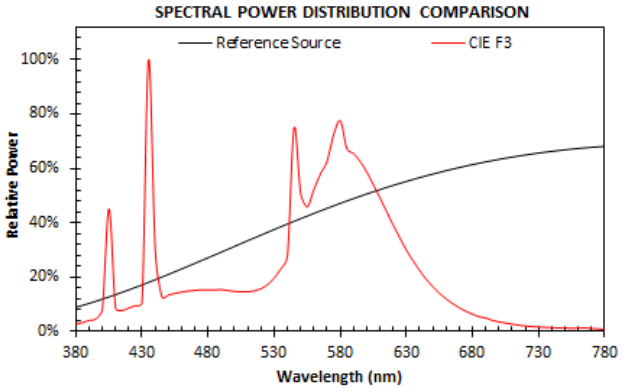
Manufacturers

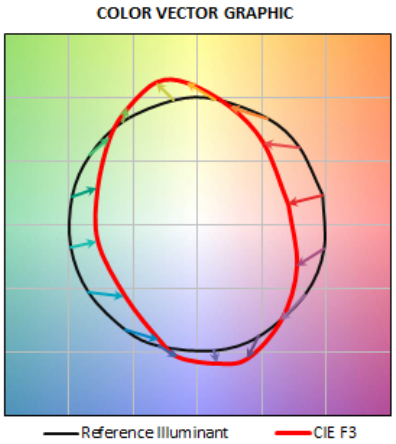
Source:

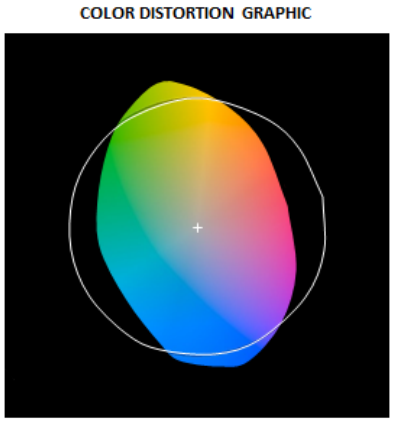
CIE F3

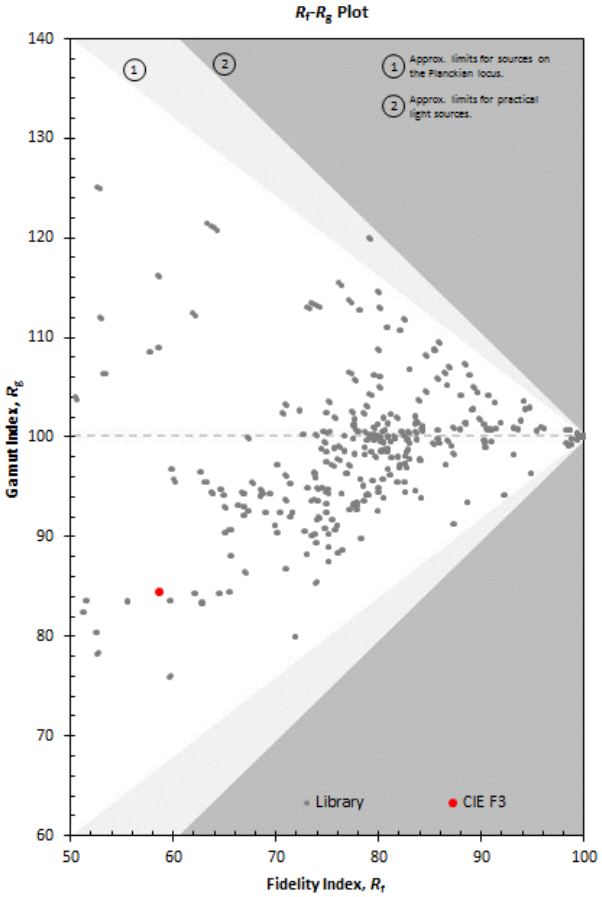
R_f	59
R_g	84
CCT (K)	3446
D_{uv}	0.0007
x	0.4091
y	0.3941
CIE R_a	57

0









Specifiers

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

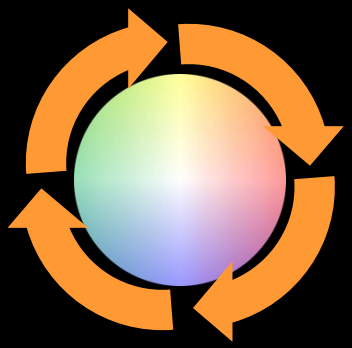
Measure	Scale	Comparisons
CIE R_a	? – 100	Higher may be "better"
TM-30 R_f	0 – 100	Higher may be "better"
TM-30 R_g	60 – 140 (Approx.)	Varies
TM-30 Icon	None (Visual)	Varies


Complex Chemistry
DESIGNATE PAINT CHIP

“Original” Baseline

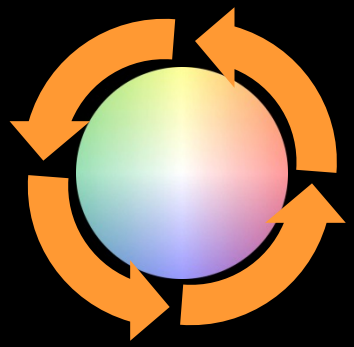
Image courtesy of Randy Burkett Lighting Design

“CRI = 80” + Hue Shift



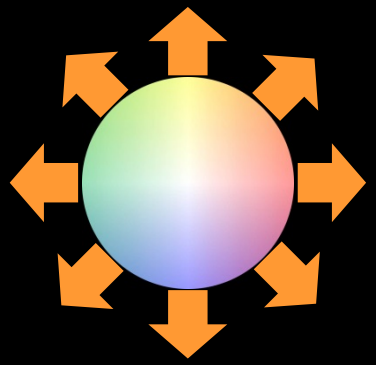
“R_f = 75, R_g = 100”

“CRI = 80” - Hue Shift



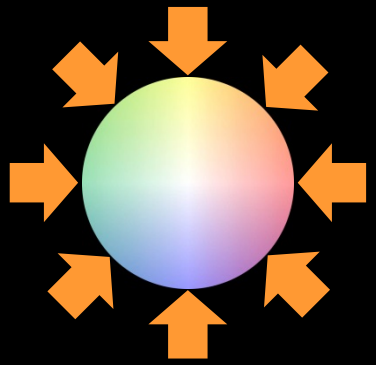
“R_f = 75, R_g = 100”

“CRI = 80” Saturated



“R_f = 75, R_g = 120”

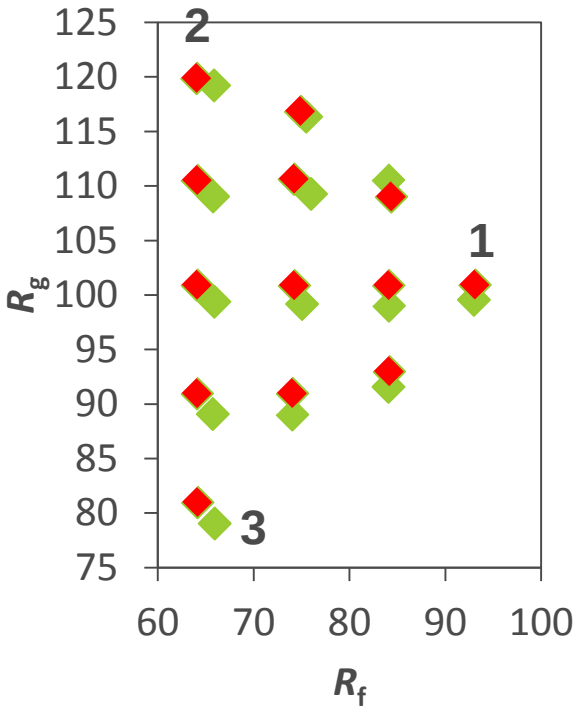
“CRI = 80” Desaturated

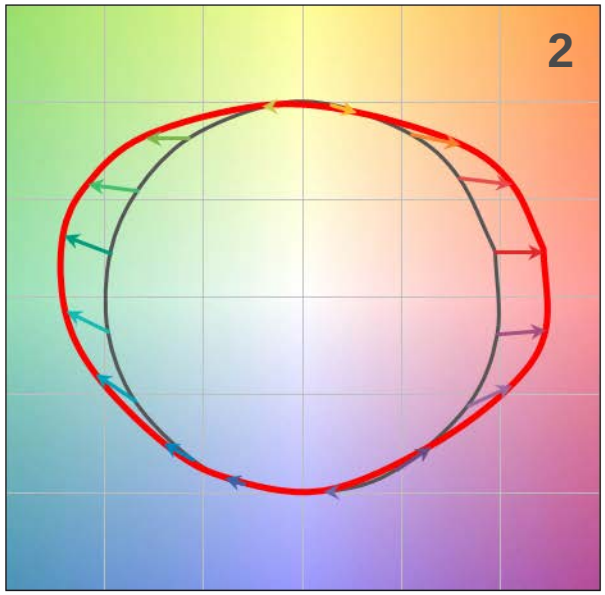


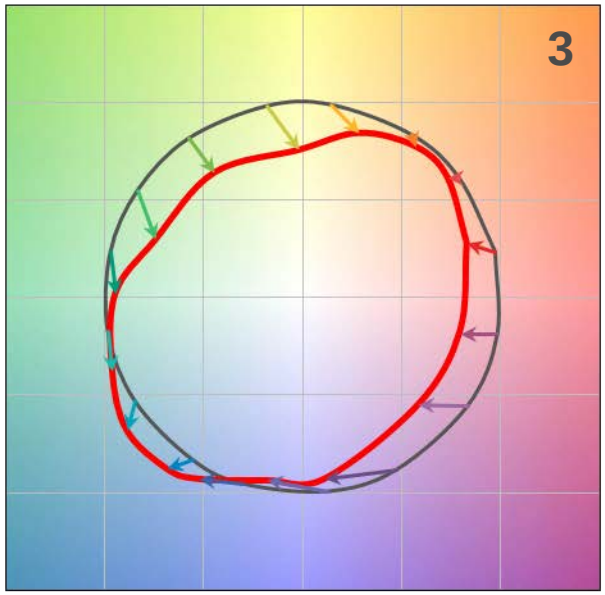
“R_f = 75, R_g = 80”

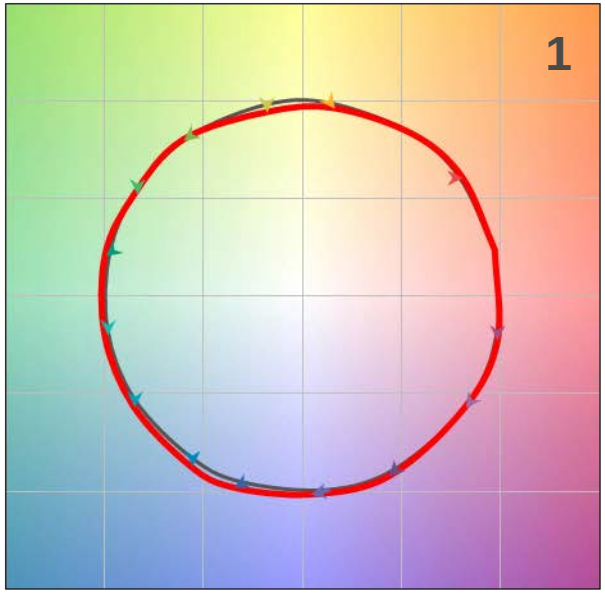
Research

Some Preliminary Data (in one space)

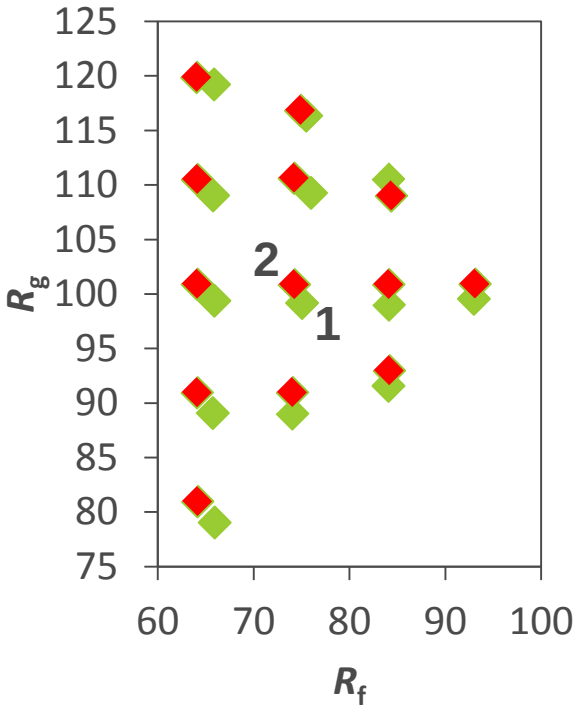


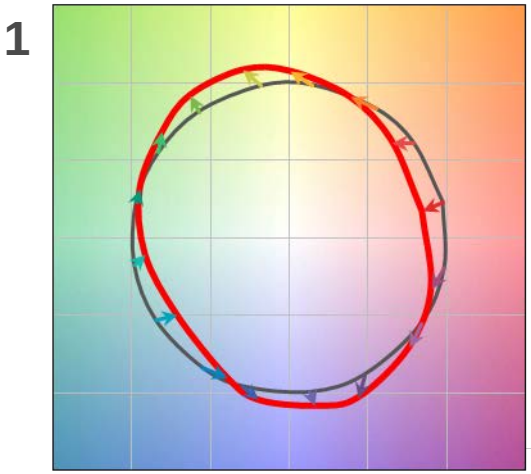


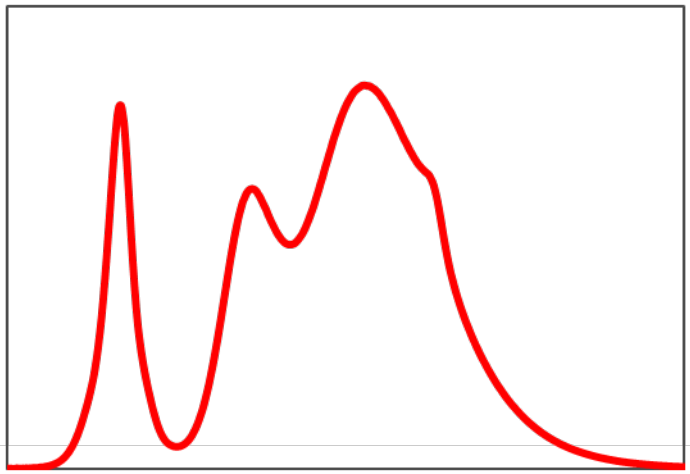


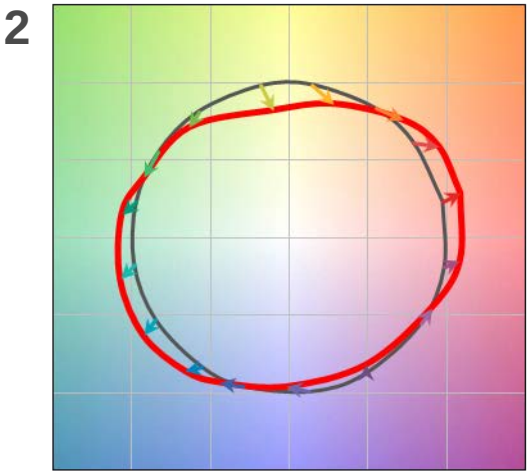


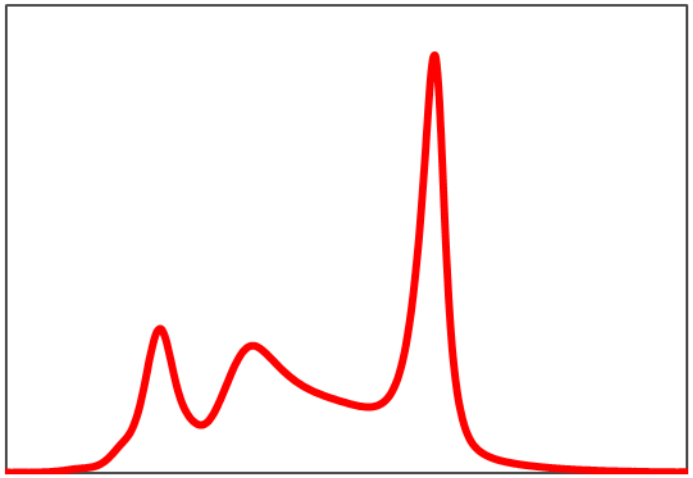
Some Preliminary Data (in one space)



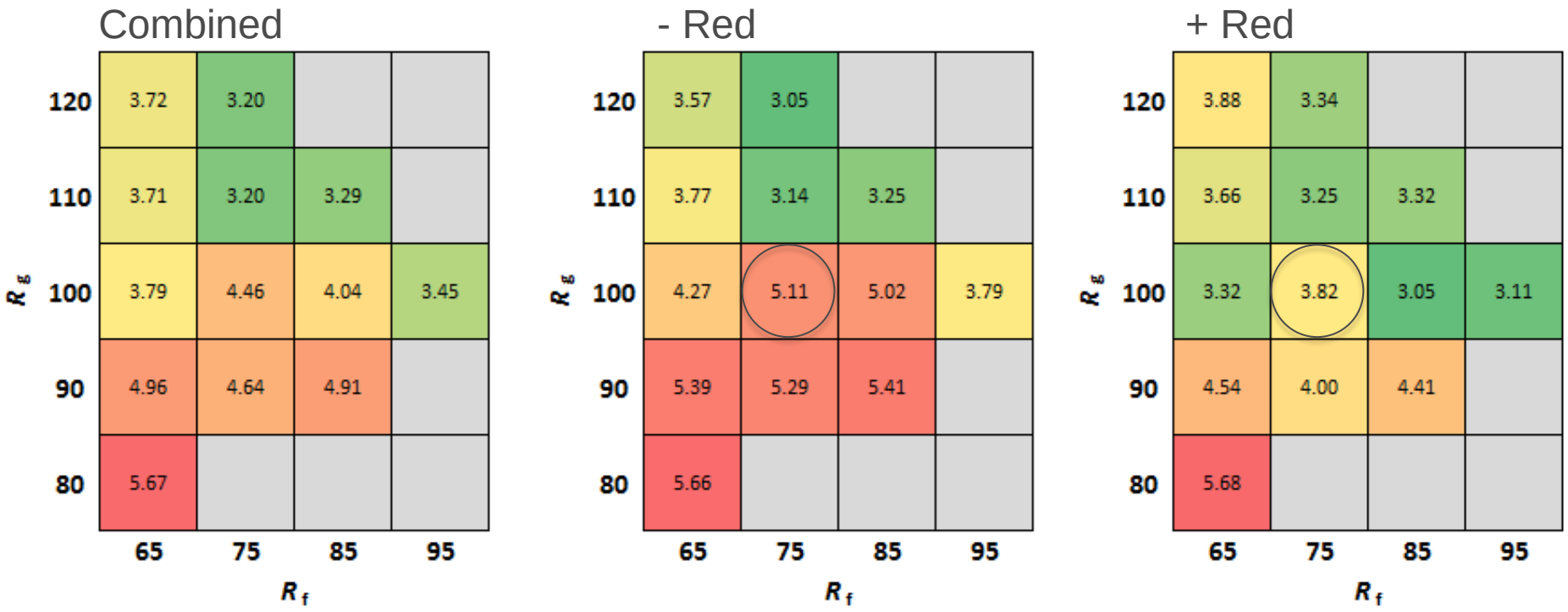




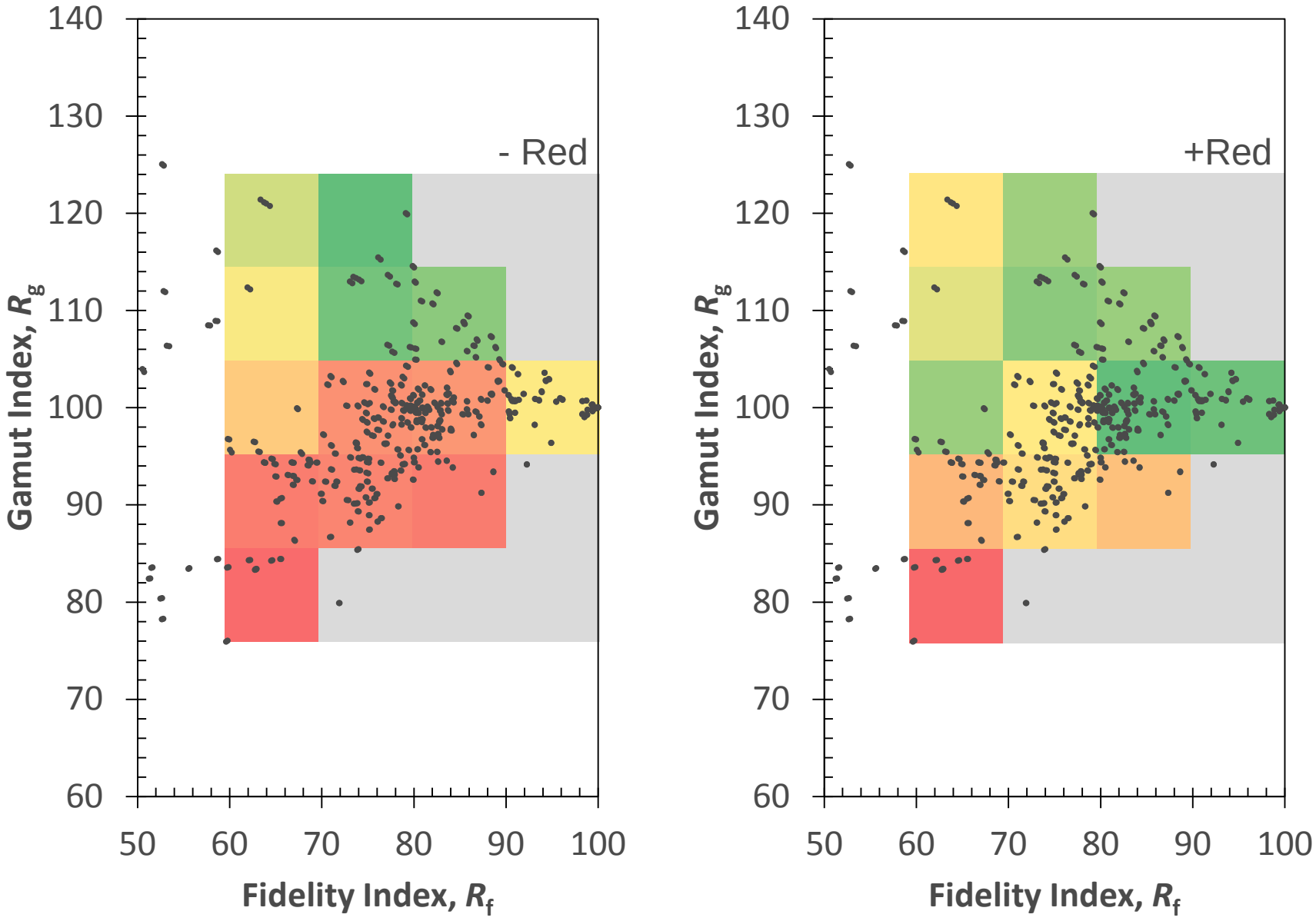




Some Preliminary Data (in one space)



Some Preliminary Data (in one space)



Efficiency and Incentive Programs

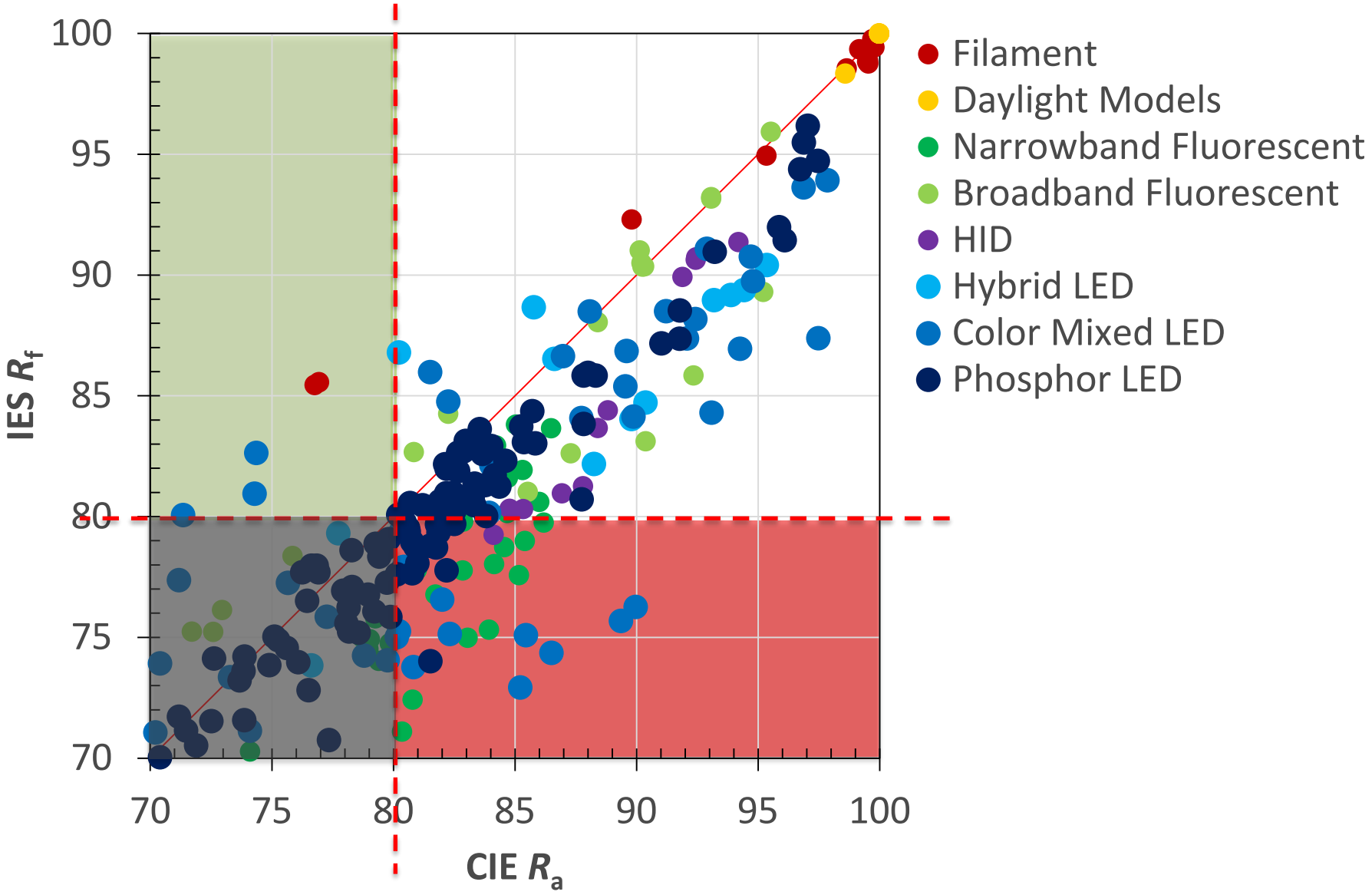
1. **Keep using CRI**
   - \- Uses an inaccurate metric, higher values not always better
   - \+ No disruption to existing system

2. **Replace CRI R_a with R_f, do not specify R_g limits**
   - \- Higher R_f not always better
   - \+ Relatively easy implementation, but not a direct change [see next slide]
     Mandatory reporting of R_g? Color Graphics?
     What about R_9?

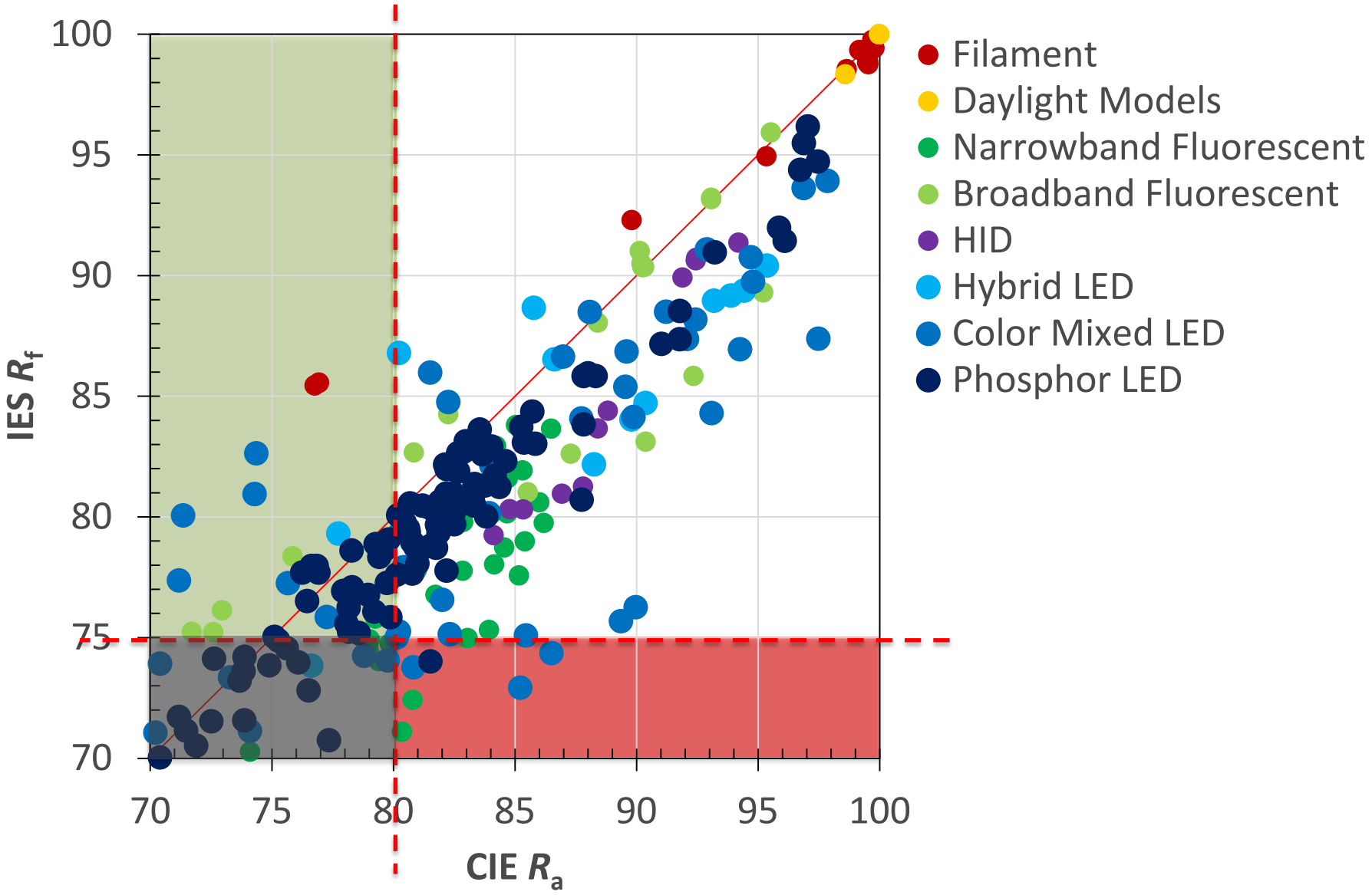
3. **Replace CRI R_a with both R_f and R_g limits**
   - \- May start to regulate quality/preference
   - \+ More thorough specification. Limits for R_g could only preclude extreme sources (e.g., ≤70, ≥130)

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

Changing from R_a to R_f



Changing from R_a to R_f



Additional Resources

IES Technical Memorandum (TM) 30-15:
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

Questions?