A new measure of color discrimination

Tony Esposito, PhD
Tony.Esposito@Philips.com
0000-0002-0308-6191

October 3, 2017

ORCID

Background

This work was performed as part of my doctoral dissertation at Pennsylvania State University, The Graduate School, College of Engineering

Title: MODELING COLOR RENDITION AND COLOR DISCRIMINATION WITH AVERAGE FIDELITY, AVERAGE GAMUT, AND GAMUT SHAPE

Download doctoral dissertation at:
https://etda.libraries.psu.edu/catalog/13478txe136

Esposito T, Houser KW. 2017. *A new measure of color discrimination for LEDs and other light sources*. Lighting Research and Technology. Available online before print. DOI: 10.1177/1477153517729200

Background: color rendering

Fidelity

Degree of similarity to a defined reference light source

Objective measure of color difference

Metrics such as:

CIE R_a, CQS Q_f, IES R_f, etc.

Preference

Rendition of objects such that they appear pleasant, vivid, or flattering

Goal: quantify repeatable user preferences

Metrics such as:

R_f (flattery), CQS Q_p, CPI, Often linked to increased gamut area, etc.

Discrimination

The ability of a source to reveal slight hue variations of objects (when viewed simultaneously)

Goal: to maximize

Previously quantified with gamut indices:

CDI, GAI, FMG, IES R_g, etc.

Background: color rendering

Fidelity

Degree of similarity to a defined reference light source

Objective measure of color difference

Metrics such as:

CIE R_a, CQS Q_a, IES R_f, etc.

Preference

Rendition of objects such that they appear pleasant, vivid, or flattering

Goal: quantify repeatable user preferences

Metrics such as:

R_f (flattery), CQS Q_p, CPI, Often linked to increased gamut area, etc.

Discrimination

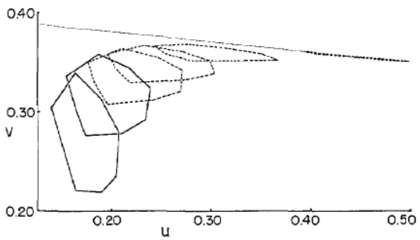
The ability of a source to reveal slight hue variations of objects (when viewed simultaneously)

Goal: to maximize

Previously quantified with gamut indices:

CDI, GAI, FMG, IES R_g, etc.

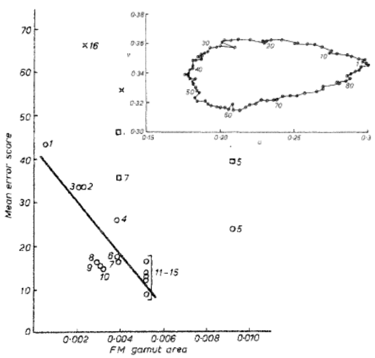
Background: previous research



WA Thorton [1972] – Color Discrimination Index

“…the extent to which the illumination allows the observer to discriminate among a large variety of object colors simultaneously viewed.”

Gamut area as a predictor of discrimination ability, CDI

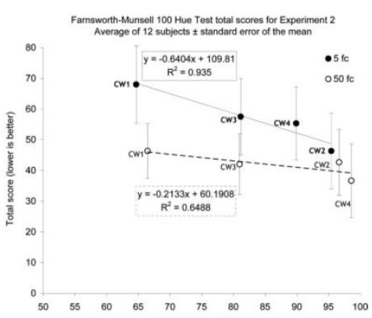


Boyce, Boyce and Simons [1976, 1977]

R_a (“CRI”) and CDI are approximate predictors

Above 300 lux, lamp type is more important than illuminance

Age is a significant factor



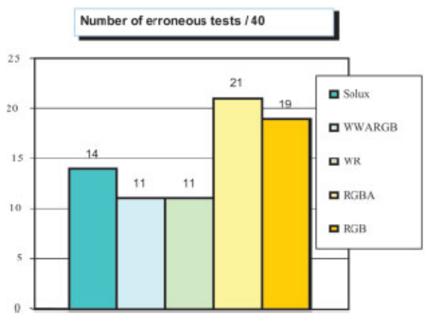
Rea and Freyssinier-Nova [2007]

Evaluated *cool white* and *warm white* sources

Color discrimination better (i.e. error scores consistently lower) at higher illuminances

GAI is a better, and more consistent predictor than CIE R_a

Background: previous research

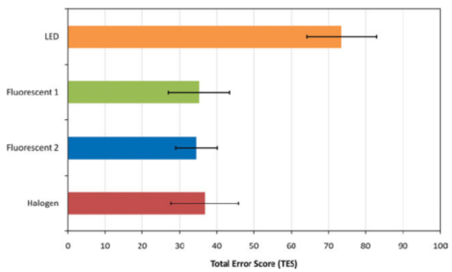


Mahler and Others [2008]

CRI correlates well with discrimination for LED sources

Increasing chroma (saturation) doens't imply improved Color Discrimination

Color discrimination ability of "…RGB LED illumination is reduced precisely for the falsely saturated colors."



Royer and Others [2011]

CRI, CDI, and FM Gamut all fail to predict (or correctly rank order) the four experimental SPDs

Gamut measures "…are not accurate predictors of color discrimination capability when highly structured SPDs are included."

Background: summary

Available fidelity and gamut indices cannot predict a light source's ability to permit the accurate discrimination of colors.

Past research highlights this problem specifically for highly structured spectra (e.g. sharp peaks and valleys).

PROBLEM

We don’t have an accurate and reliable CD metric for applied lighting

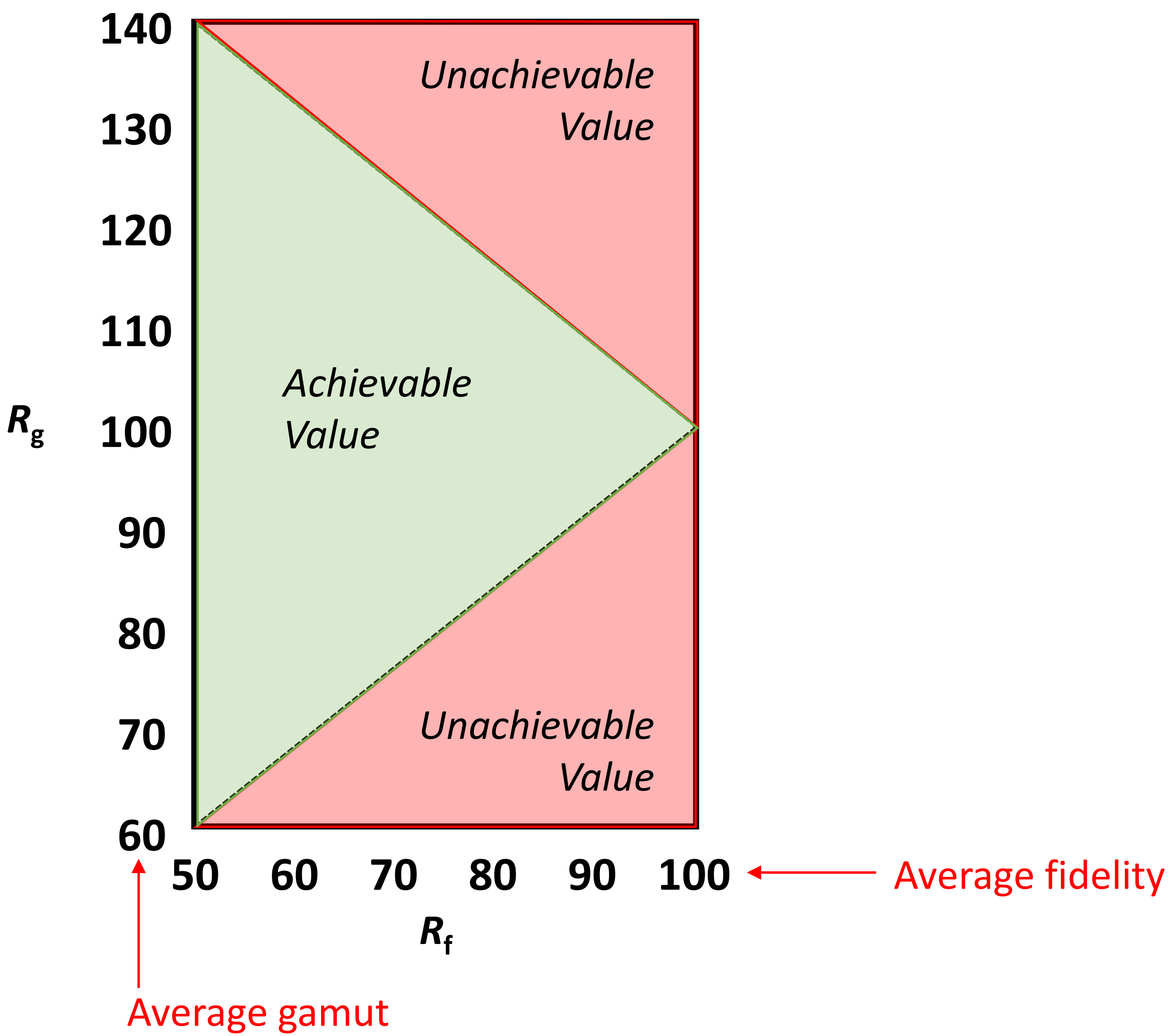
GOAL

To develop a generalizable method for quantifying a light source's CD ability:

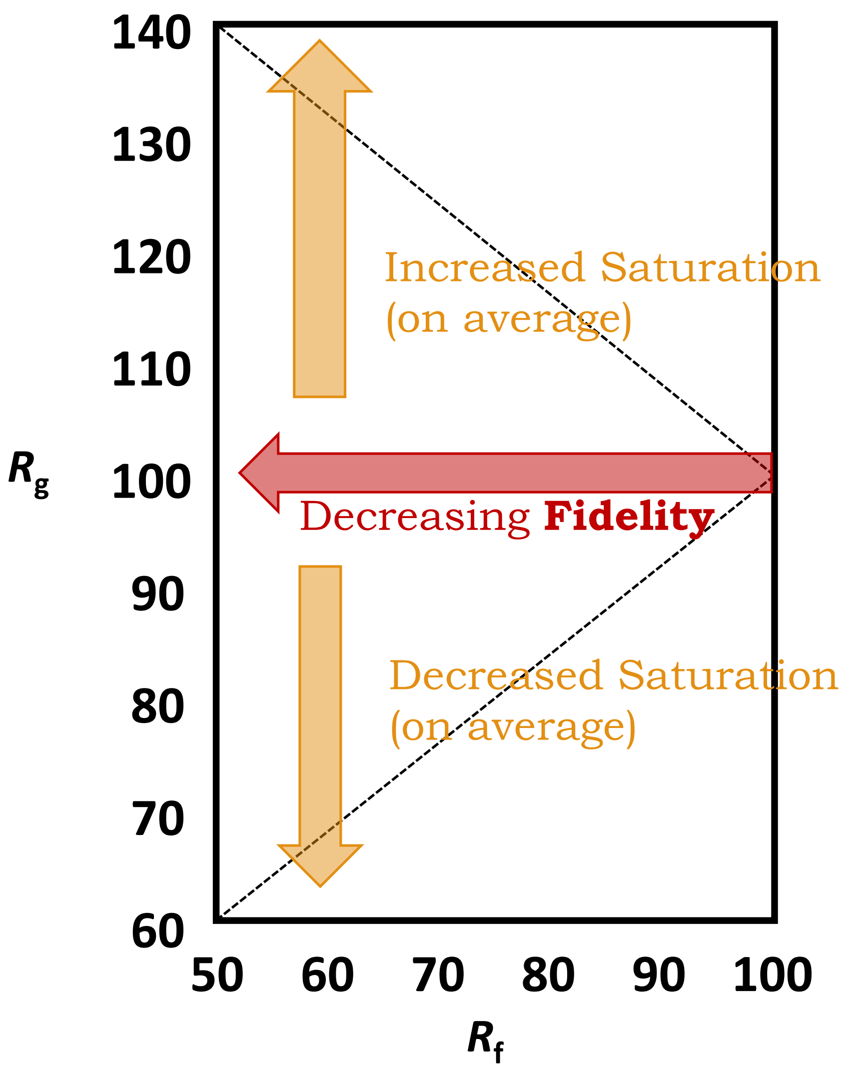
- A large number of sources
- Systematically varies spectra over a wide range of average fidelity and average gamut values
- Considers gamut shape
- Accounts for the interaction between source SPD and object SRD.

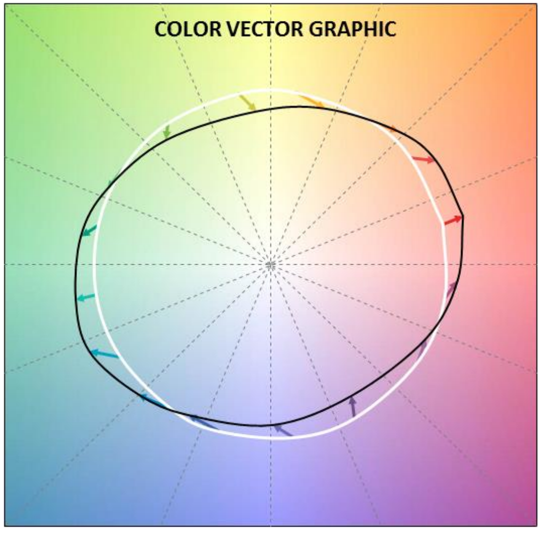
Methodology

Method: IES TM-30-15 review



Method: IES TM-30-15 review

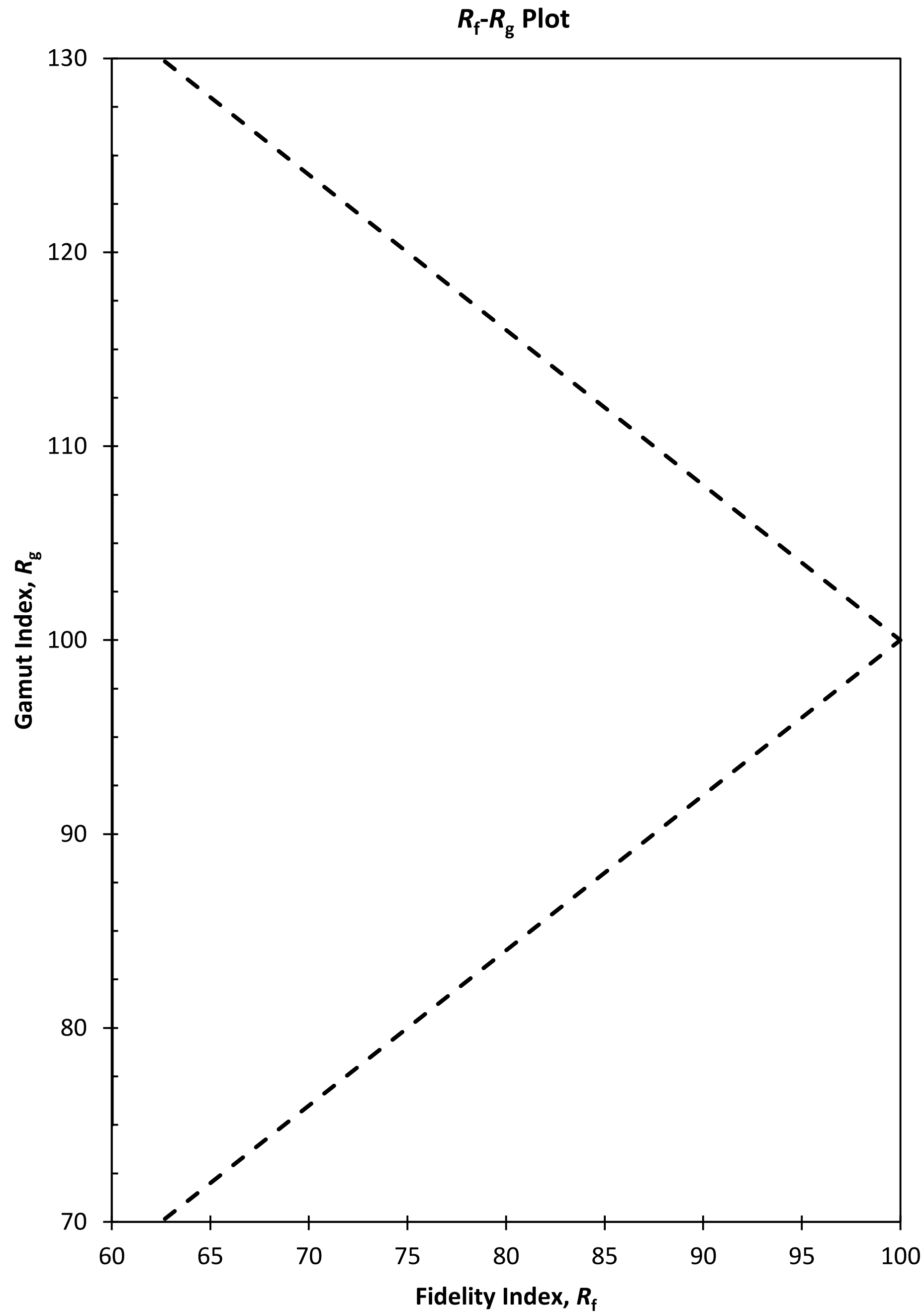




Color Vector Graphic
Shows inc/dec saturation relative to reference source

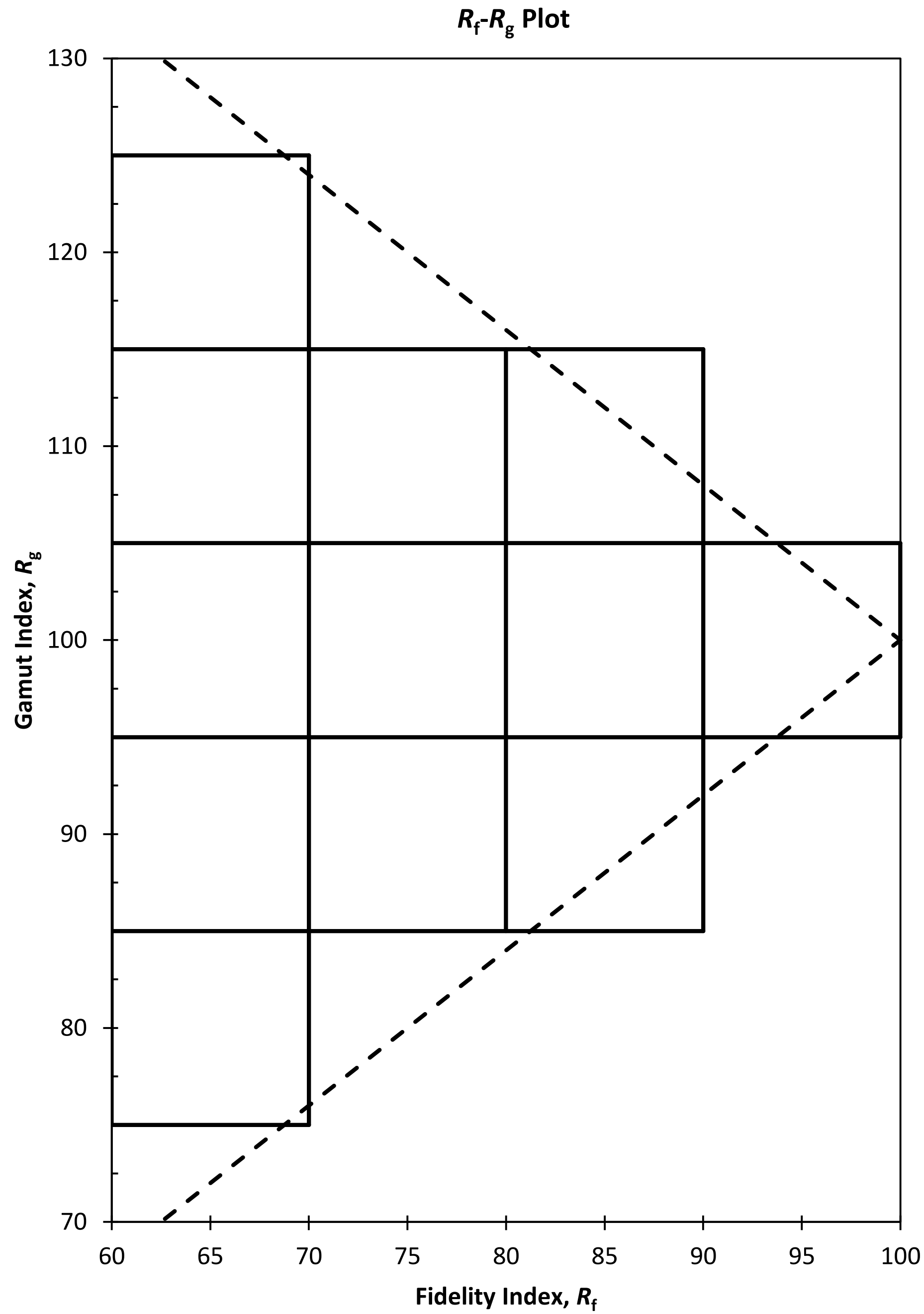
Method: SPDs

- CCT = 3500 K
- D_{uv} = 0.000
- E = 600 lx



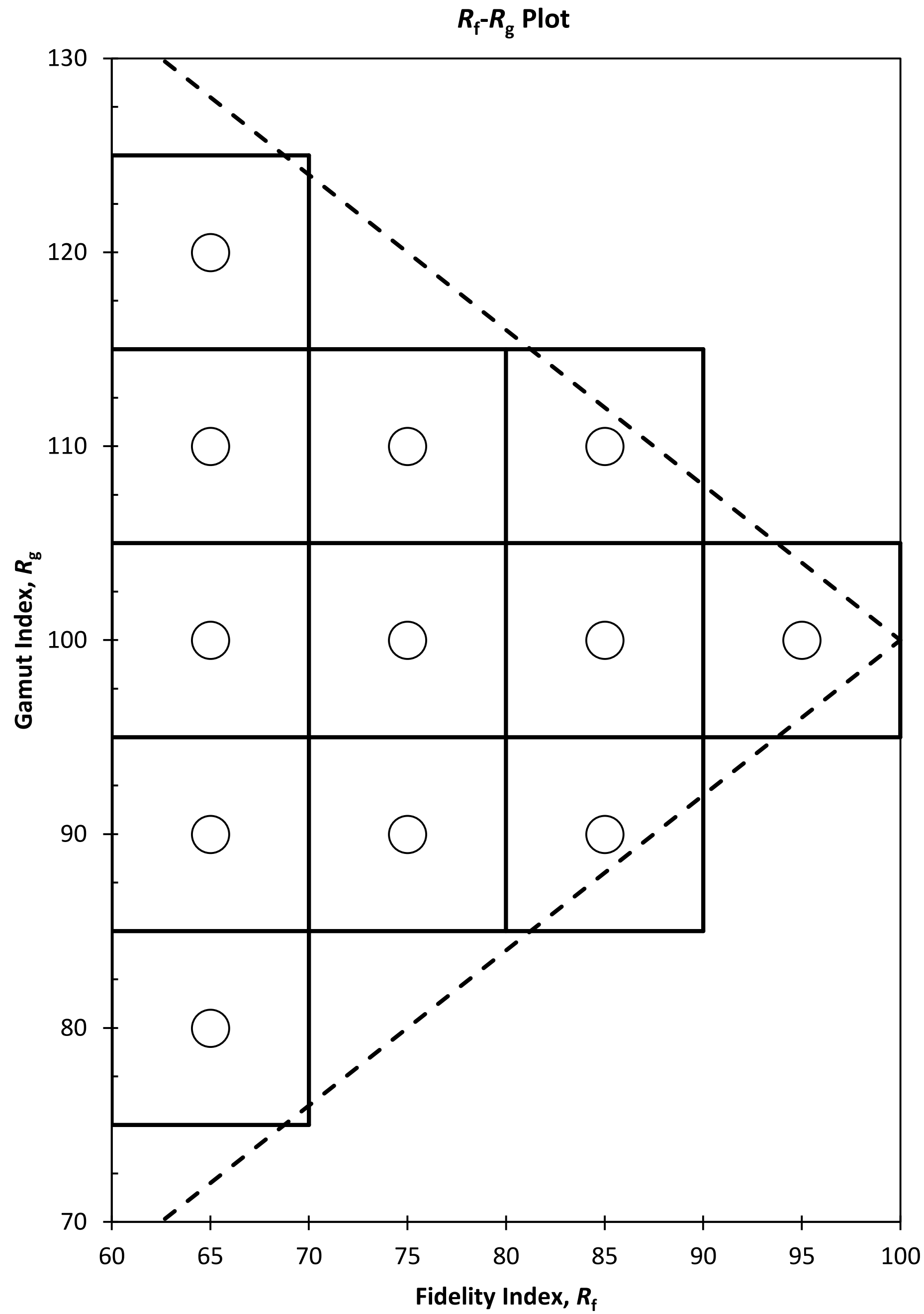
Method: SPDs

- CCT = 3500 K
- D_{uv} = 0.000
- E = 600 lx



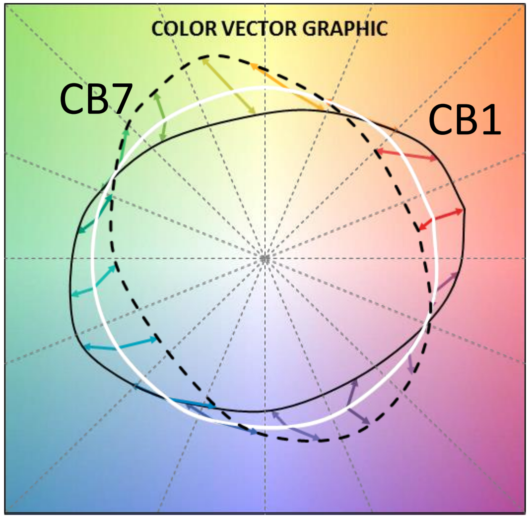
Method: SPDs

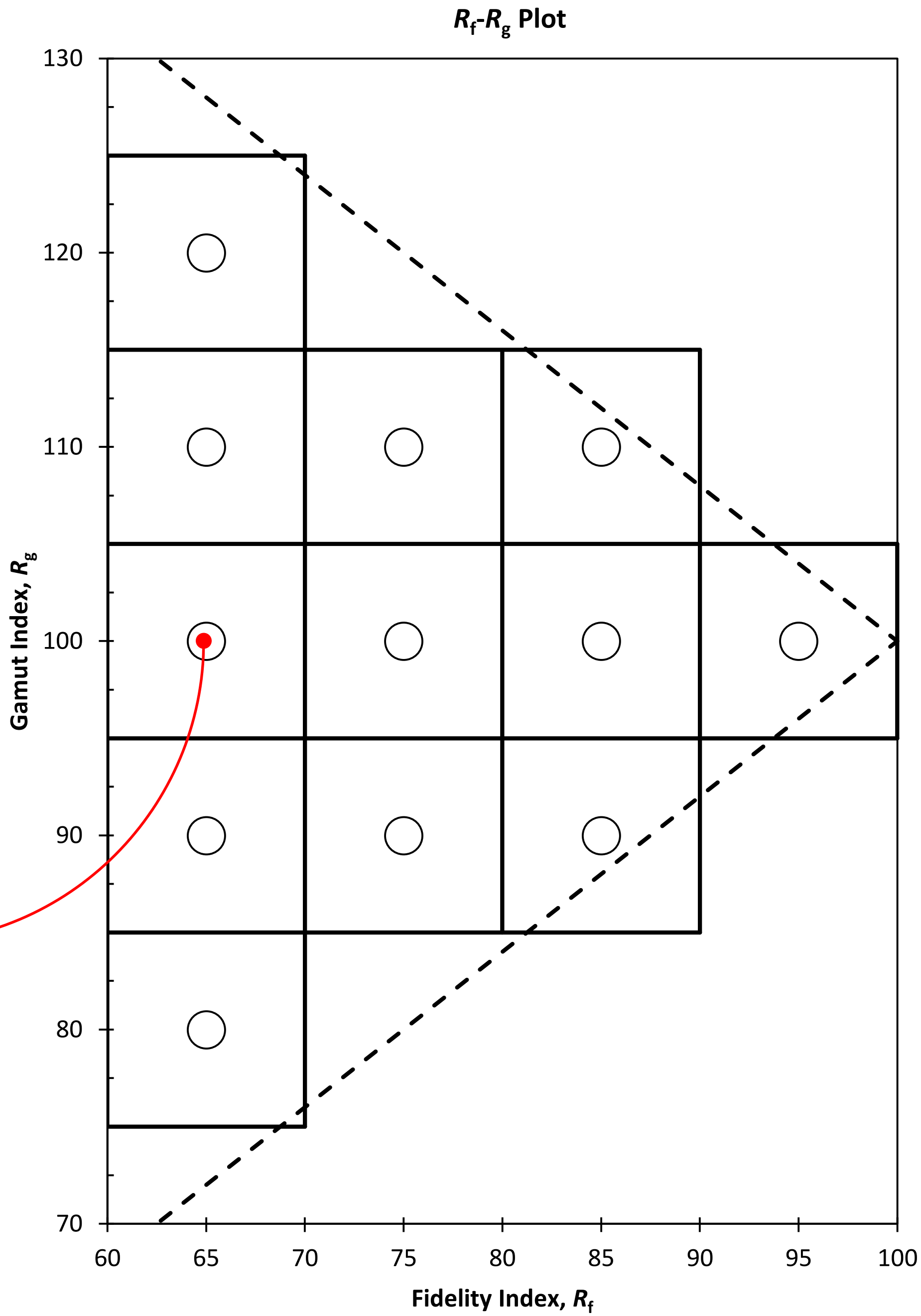
- CCT = 3500 K
- D_{uv} = 0.000
- E = 600 lx



Method: SPDs

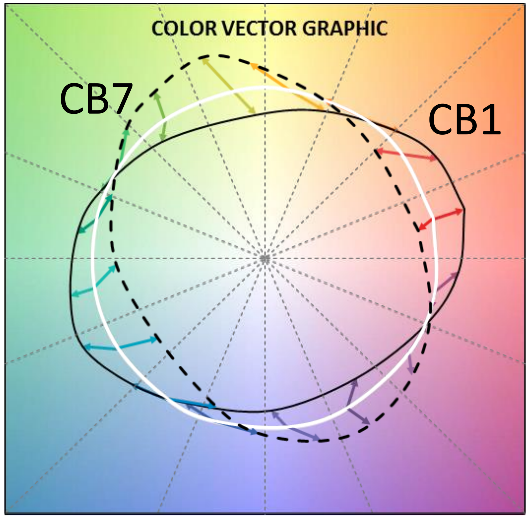
- CCT = 3500 K
- D_{uv} = 0.000
- E = 600 lx





Method: SPDs

- CCT = 3500 K
- D_{uv} = 0.000
- E = 600 lx



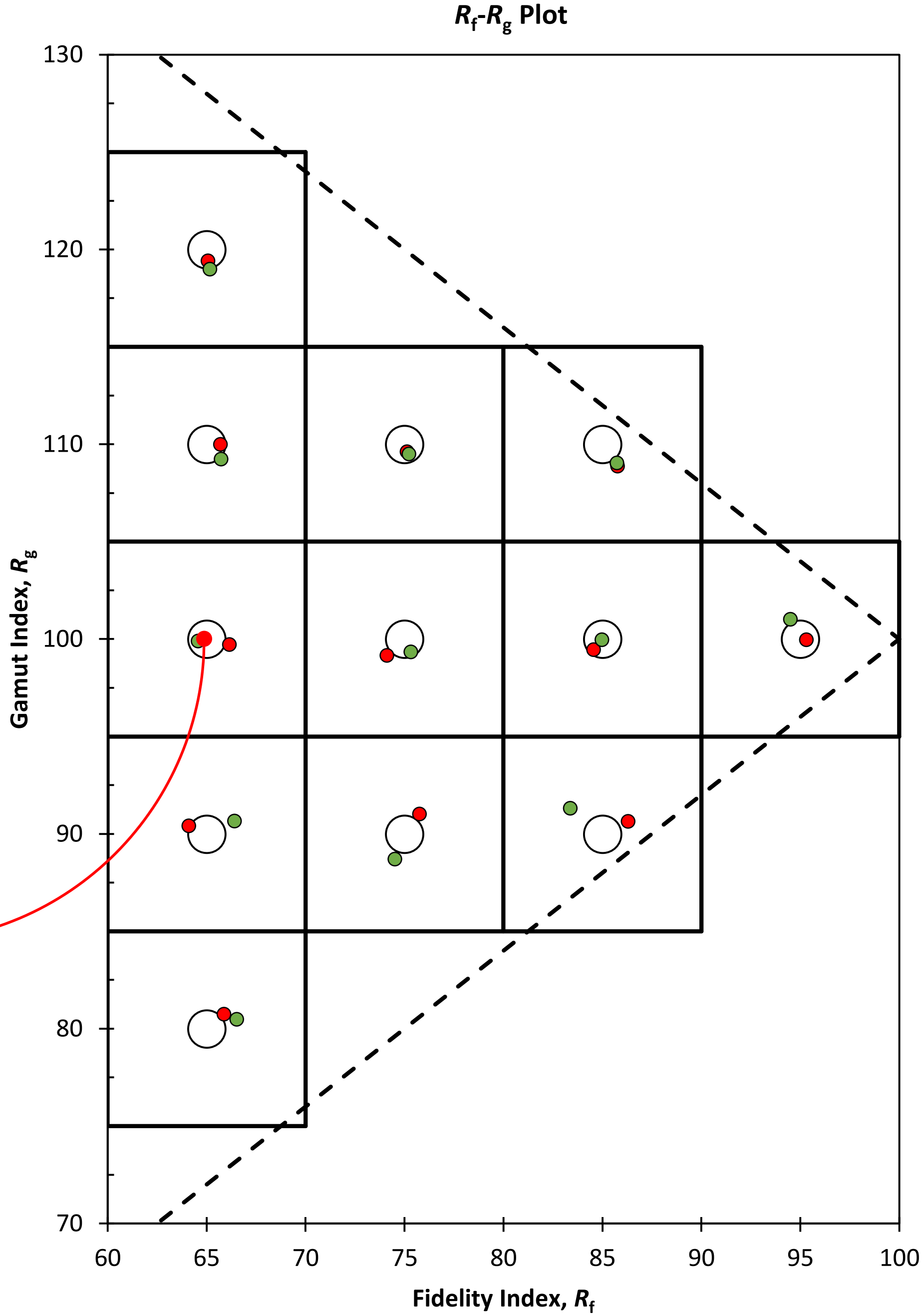
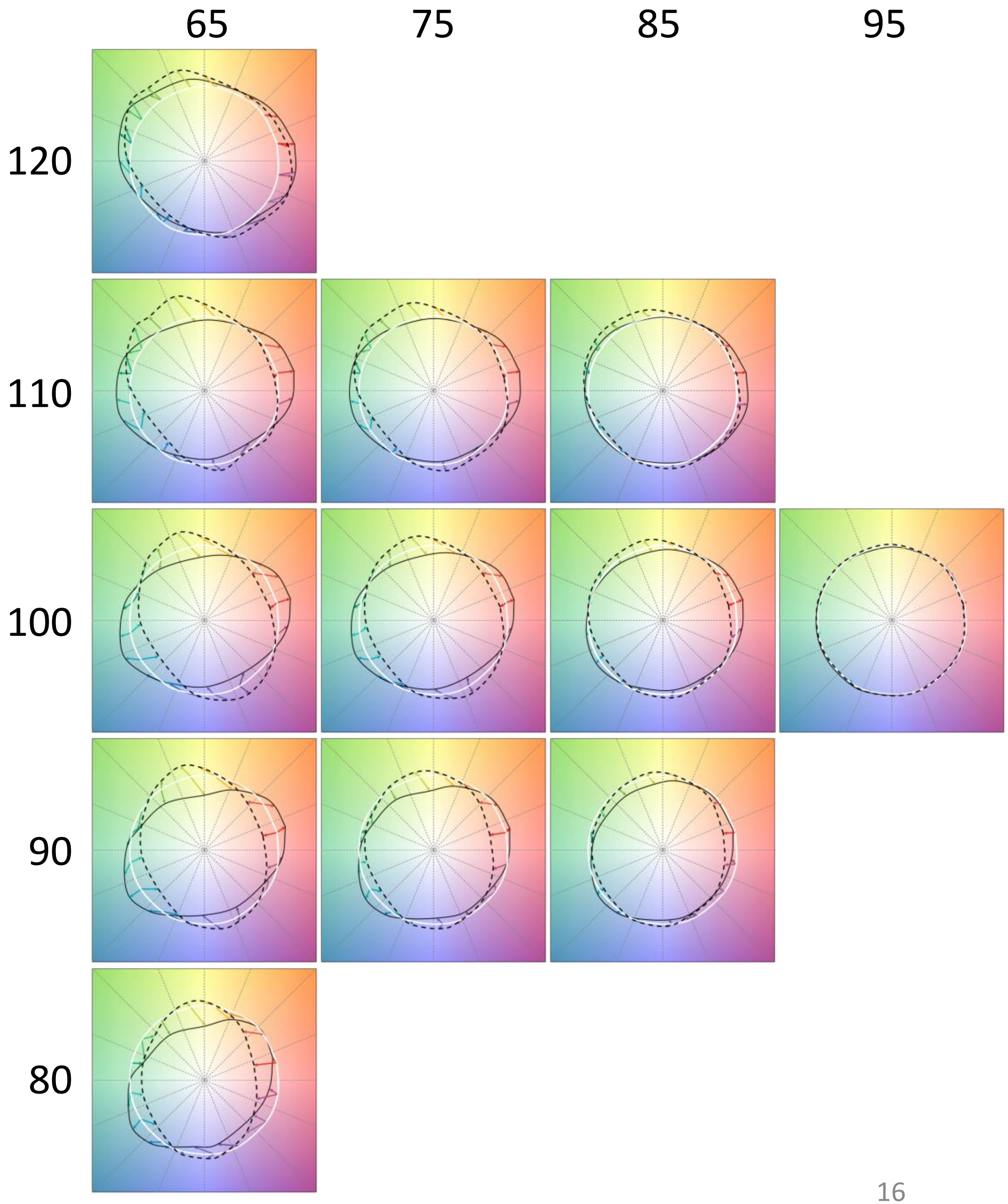


Figure reproduced from Esposito and Houser 2017

Method: CVGs

- CCT = 3500 K
- D_{uv} = 0.000
- E = 600 lx

- 24 total spectra
- 4 nominal R_f values
- 5 nominal R_g values
- 2 CVG orientations (CB)



Method: quantifying color discrimination

Farnsworth-Munsell 100 Hue Test

Method: FM-100 error score

A  0

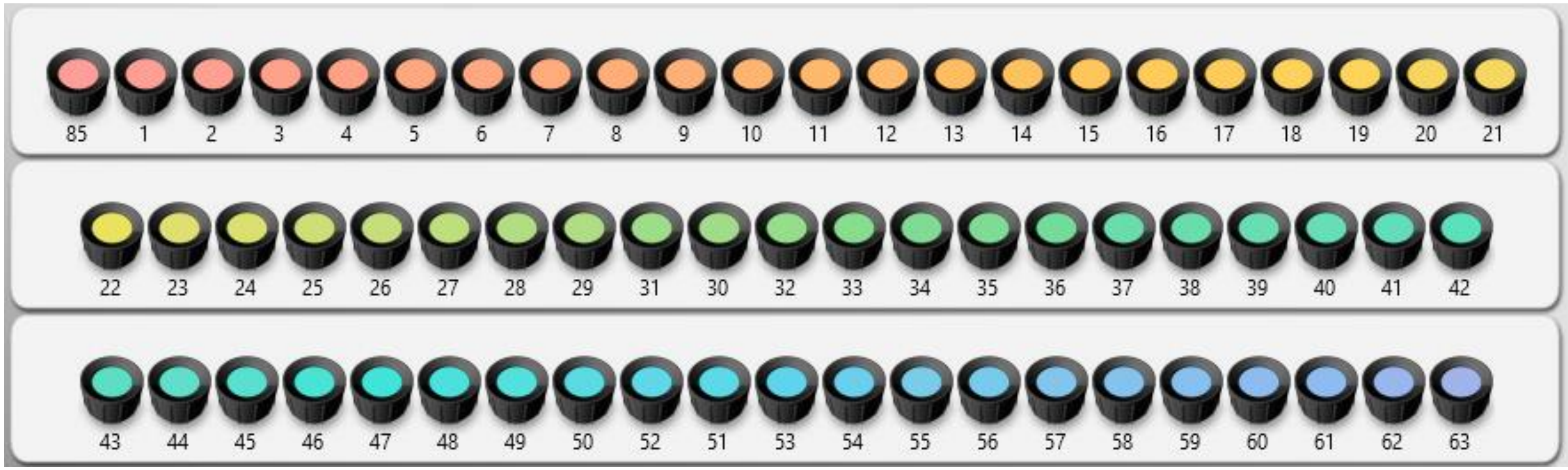
Method: FM-100 error score

B  12

28 **31** **29** **30** 32

Method: FM-100 error score

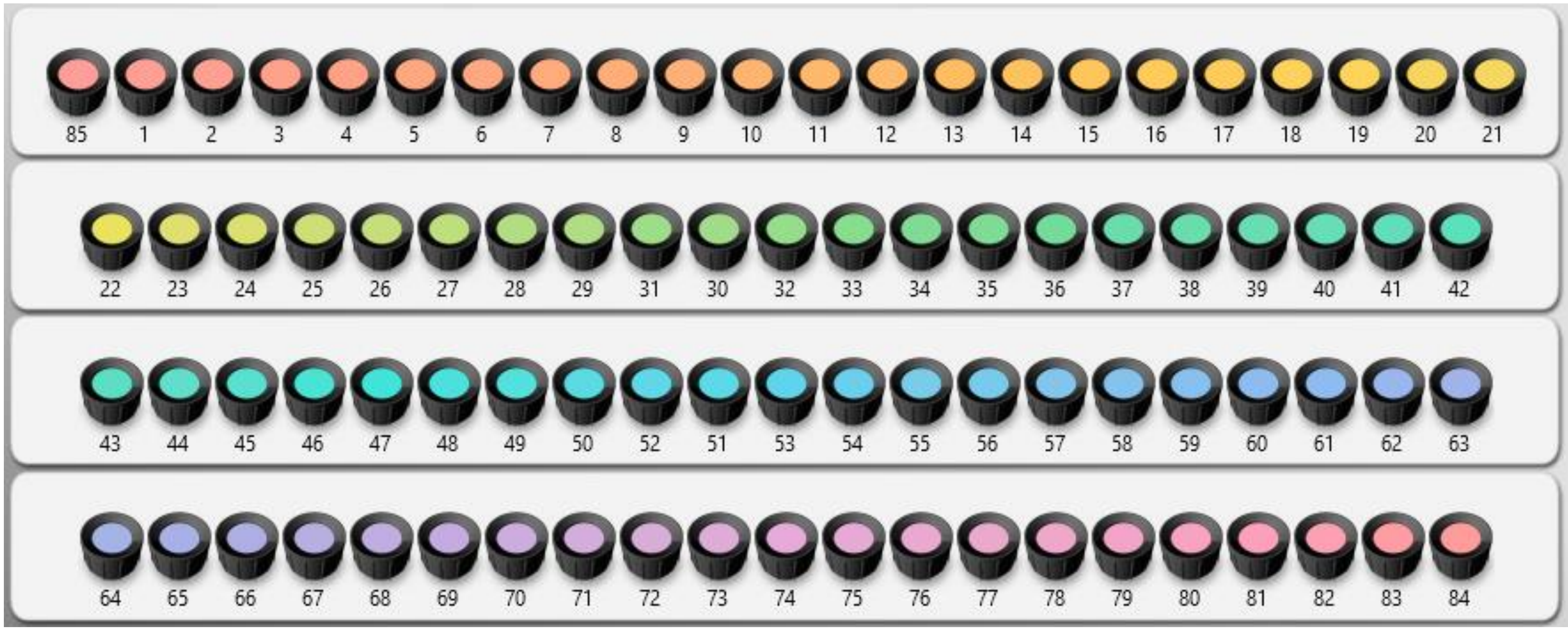
C



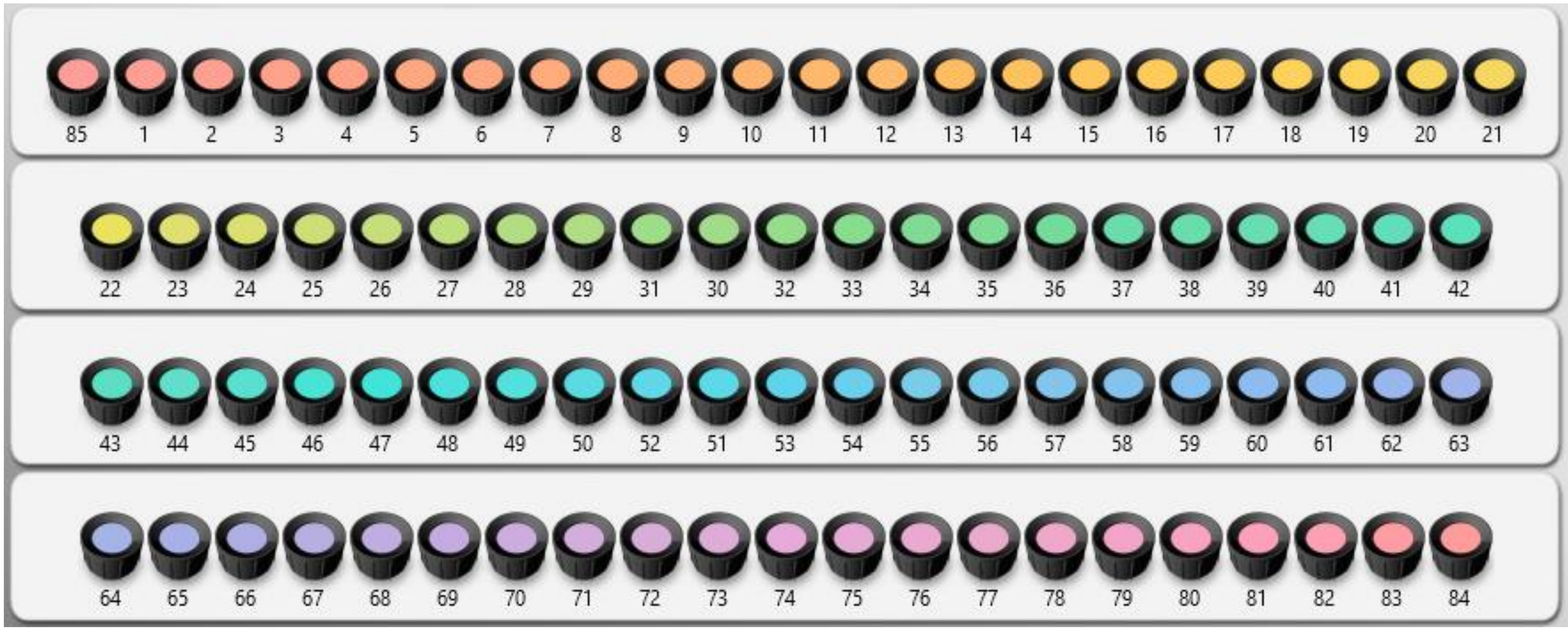
4

50 **52** **51** 53

Method: FM-100 error score

D  0

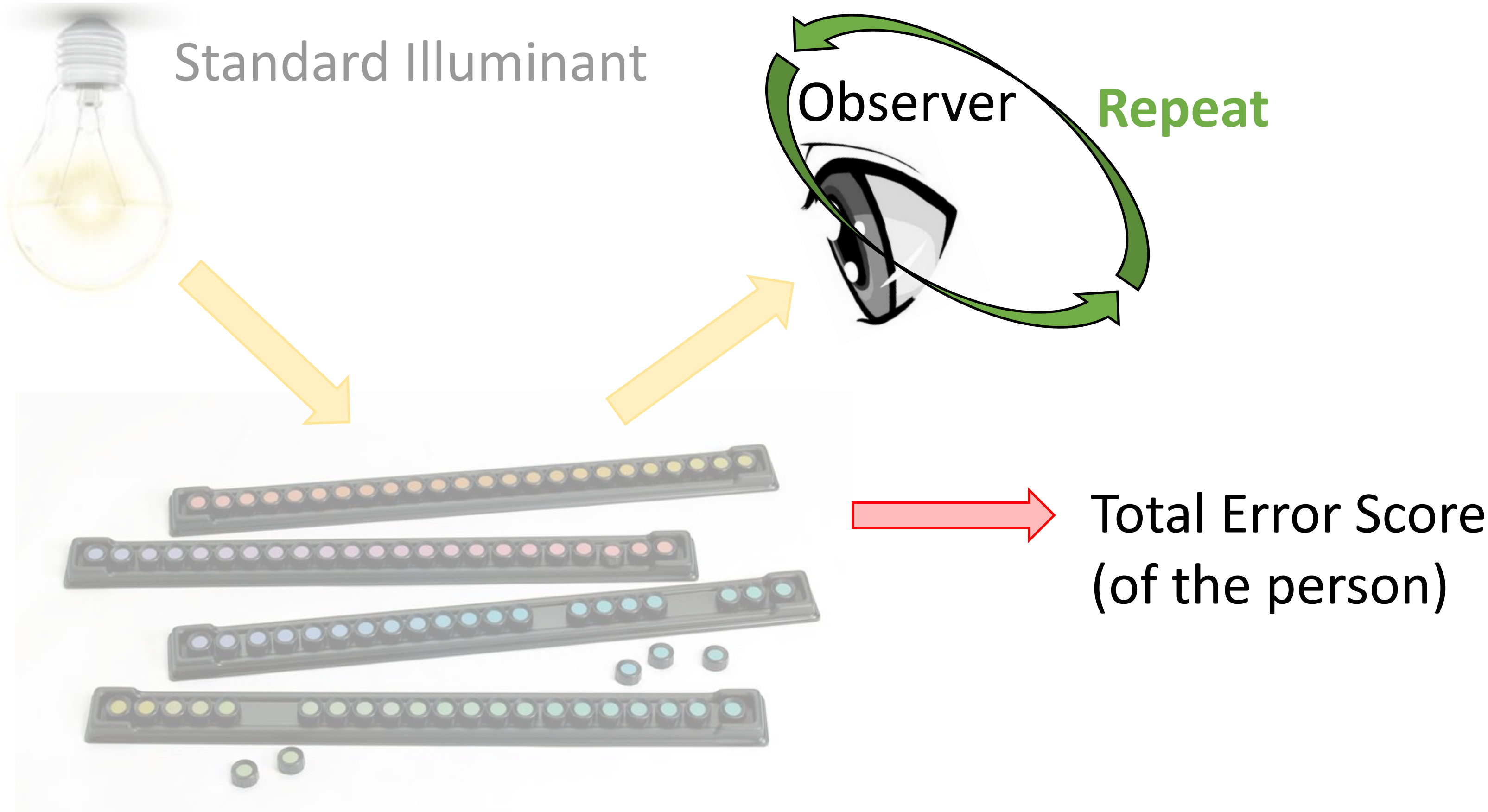
Method: FM-100 error score



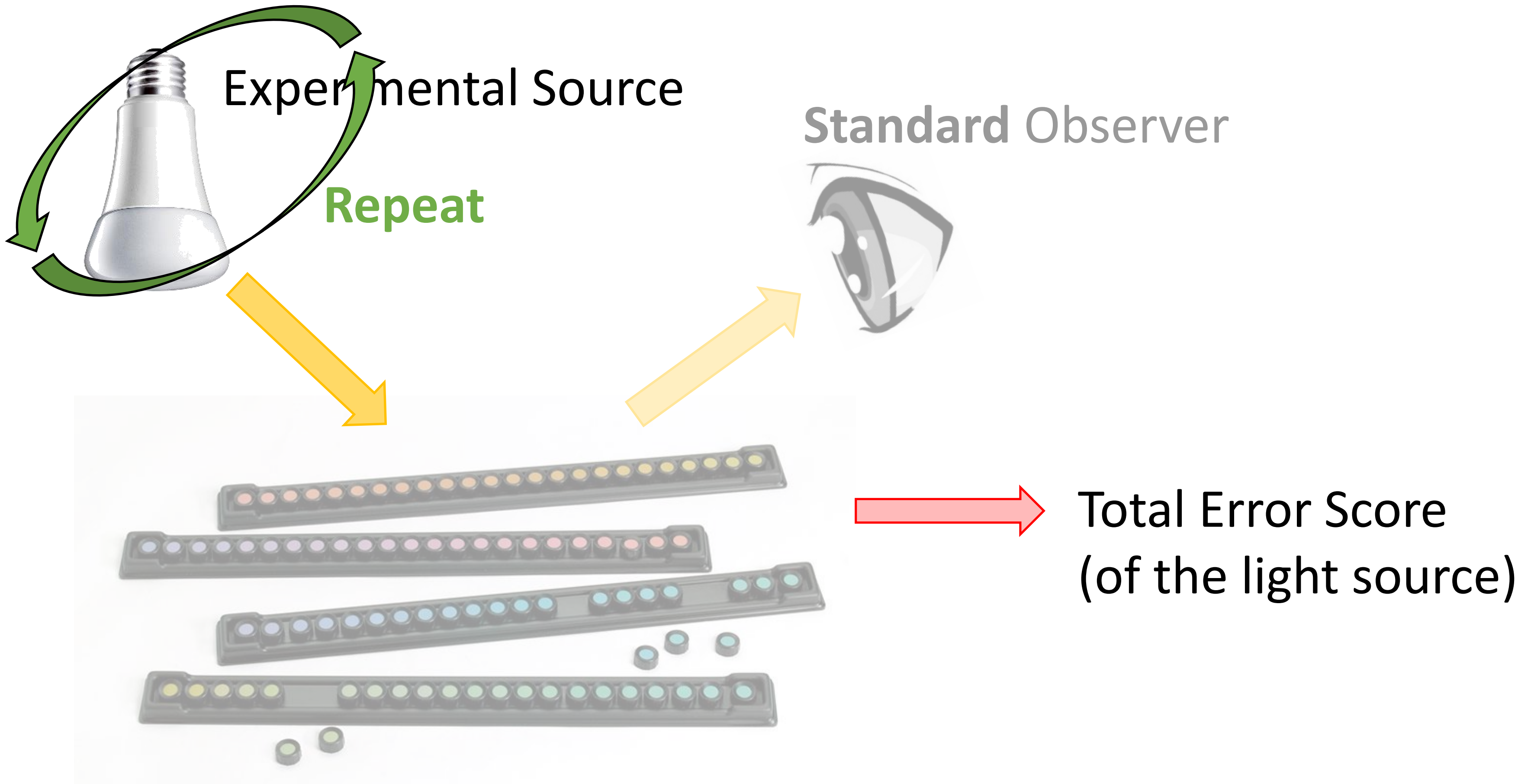
A	0
B	12
C	4
D	0
	16

Total Error Score (*TES*) = 16

Method: FM-100 error score

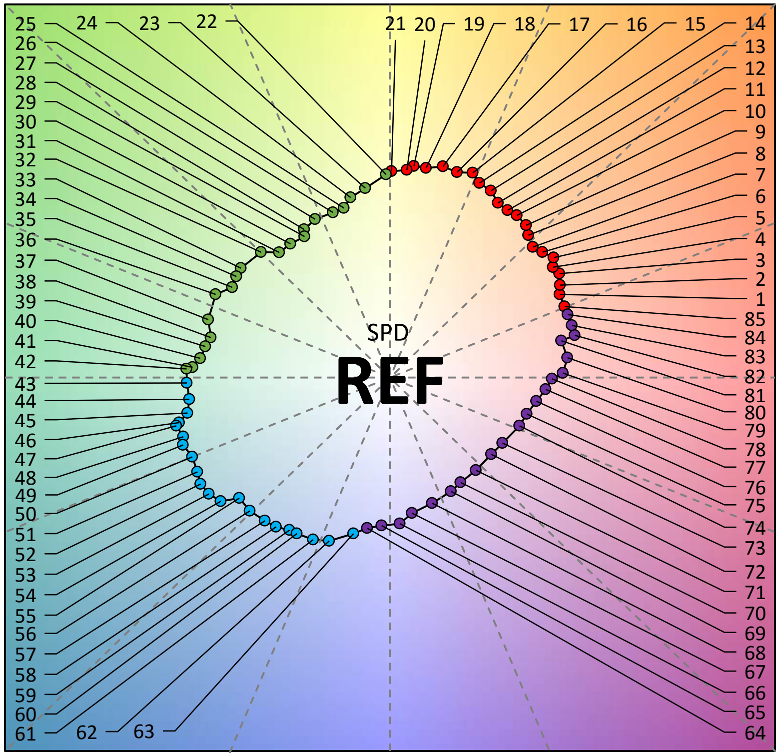


Method: FM-100 error score



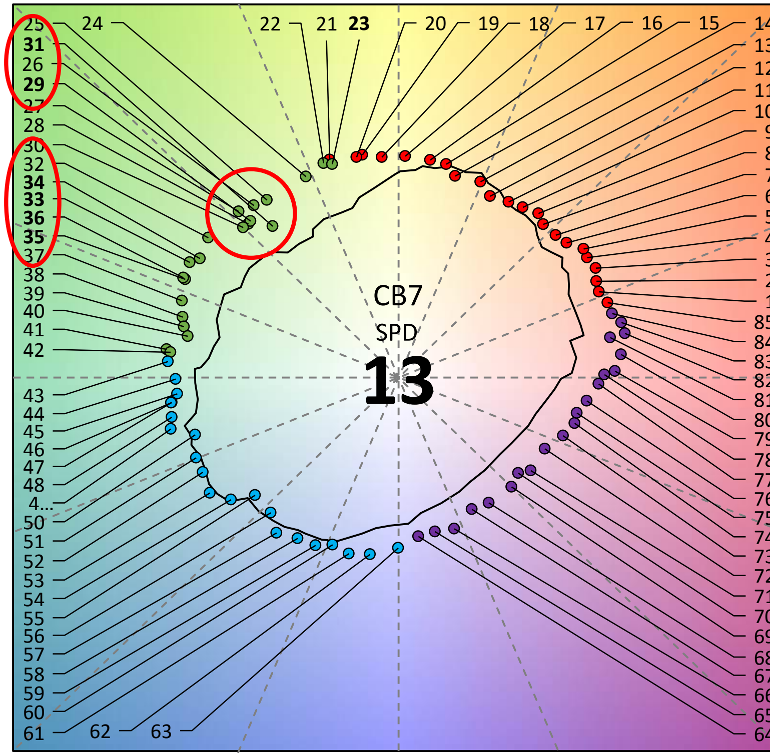
Method: FM-100 error score

Standard Illuminant



● A ● B ● C ● D

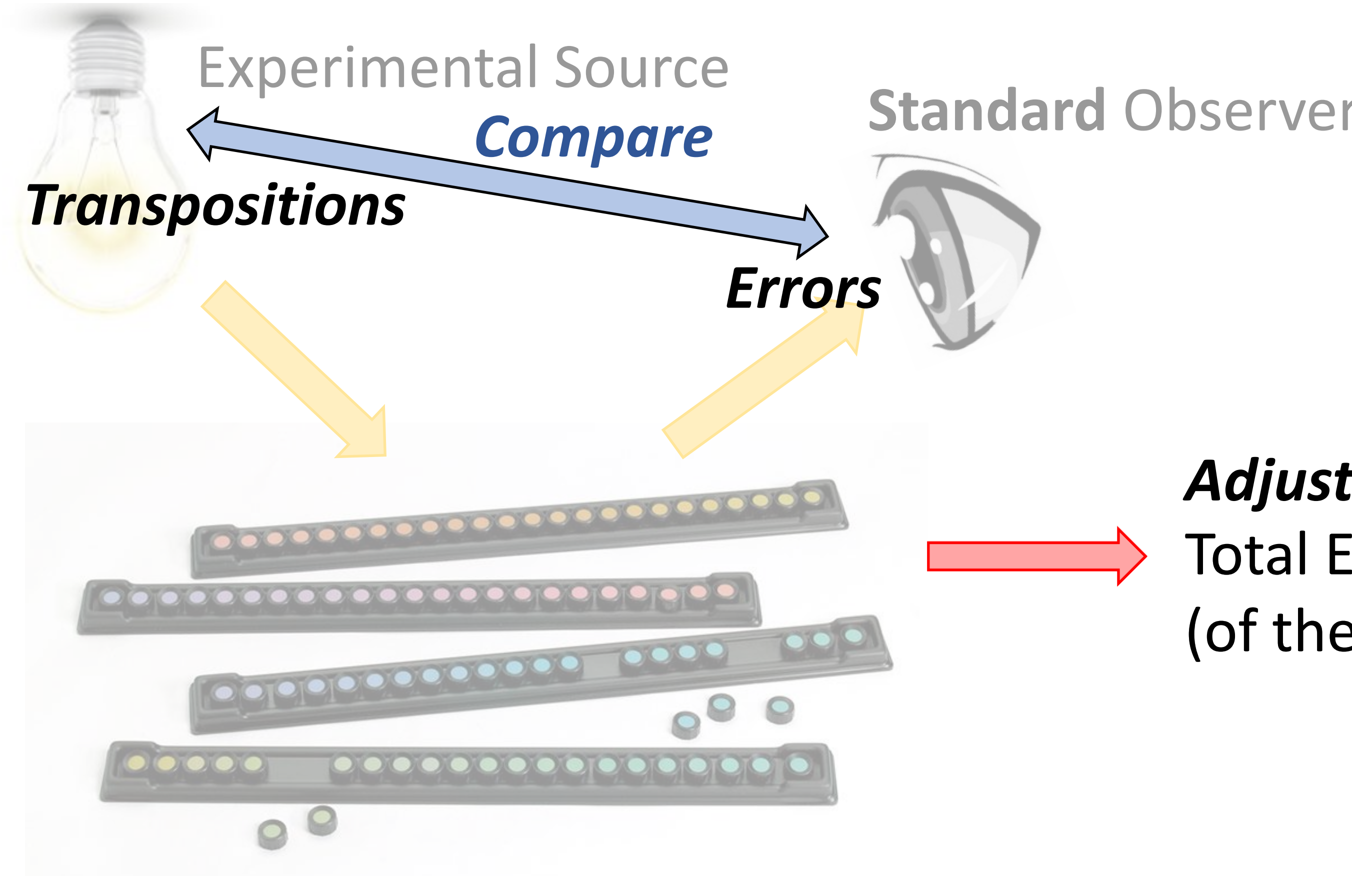
Experimental Source



● A ● B ● C ● D

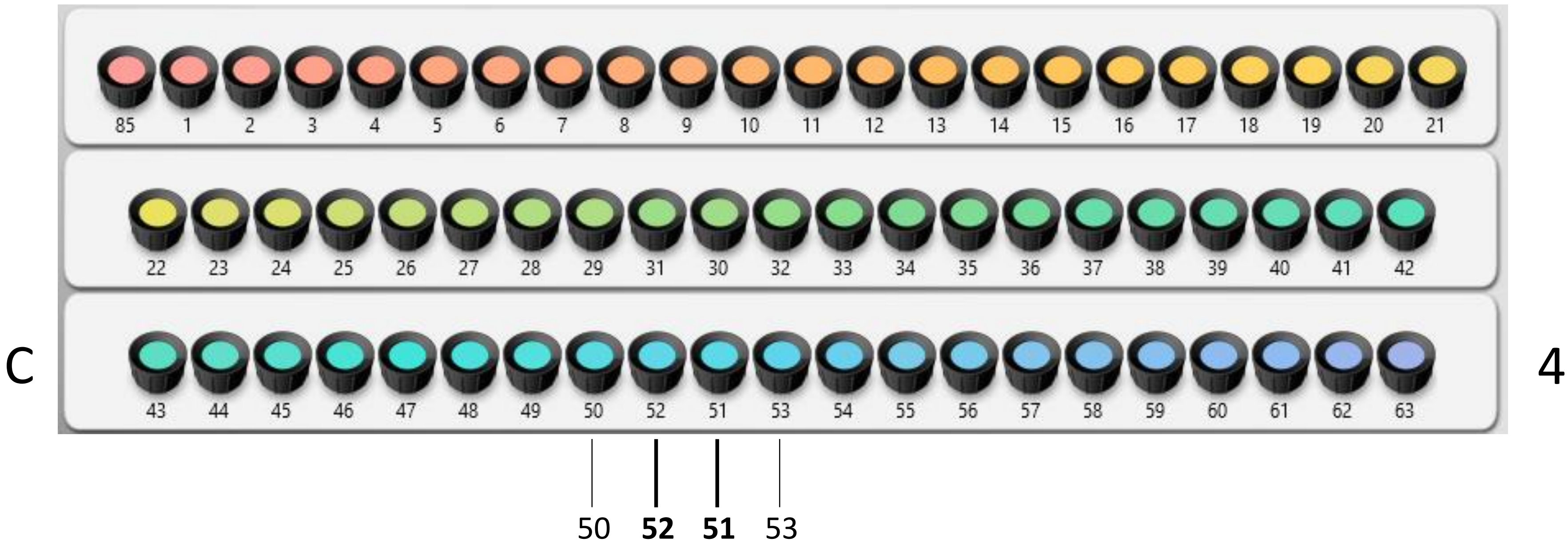
Figure (right) reproduced from Esposito and Houser 2017

Method: FM-100 error score



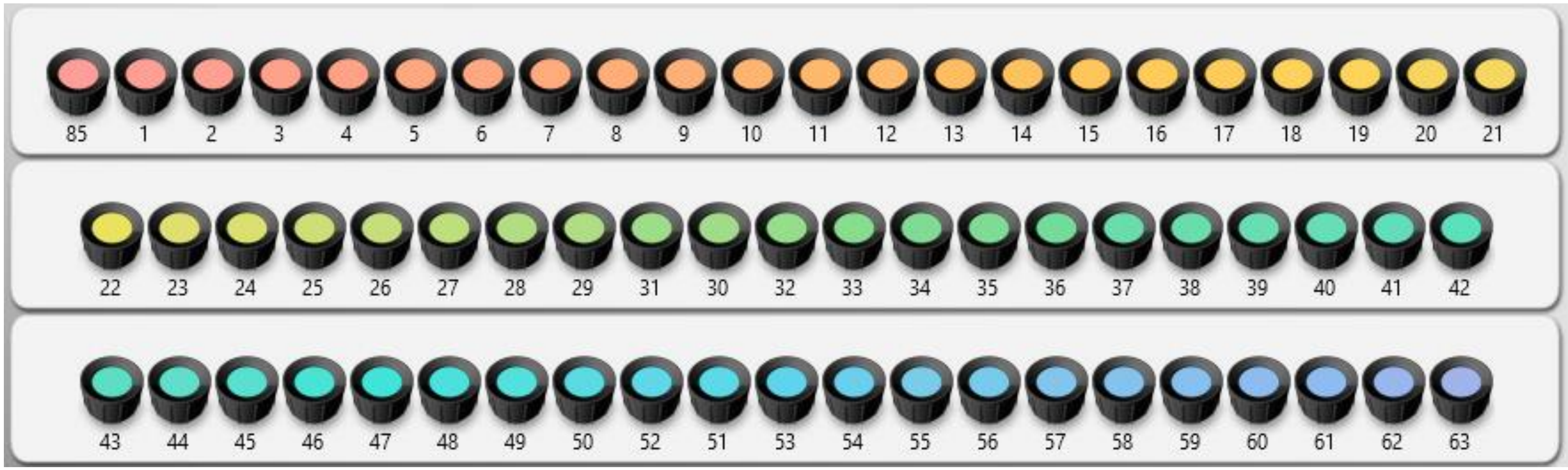
Adjusted
Total Error Score
(of the light source)

Method: FM-100 error score



Method: FM-100 error score

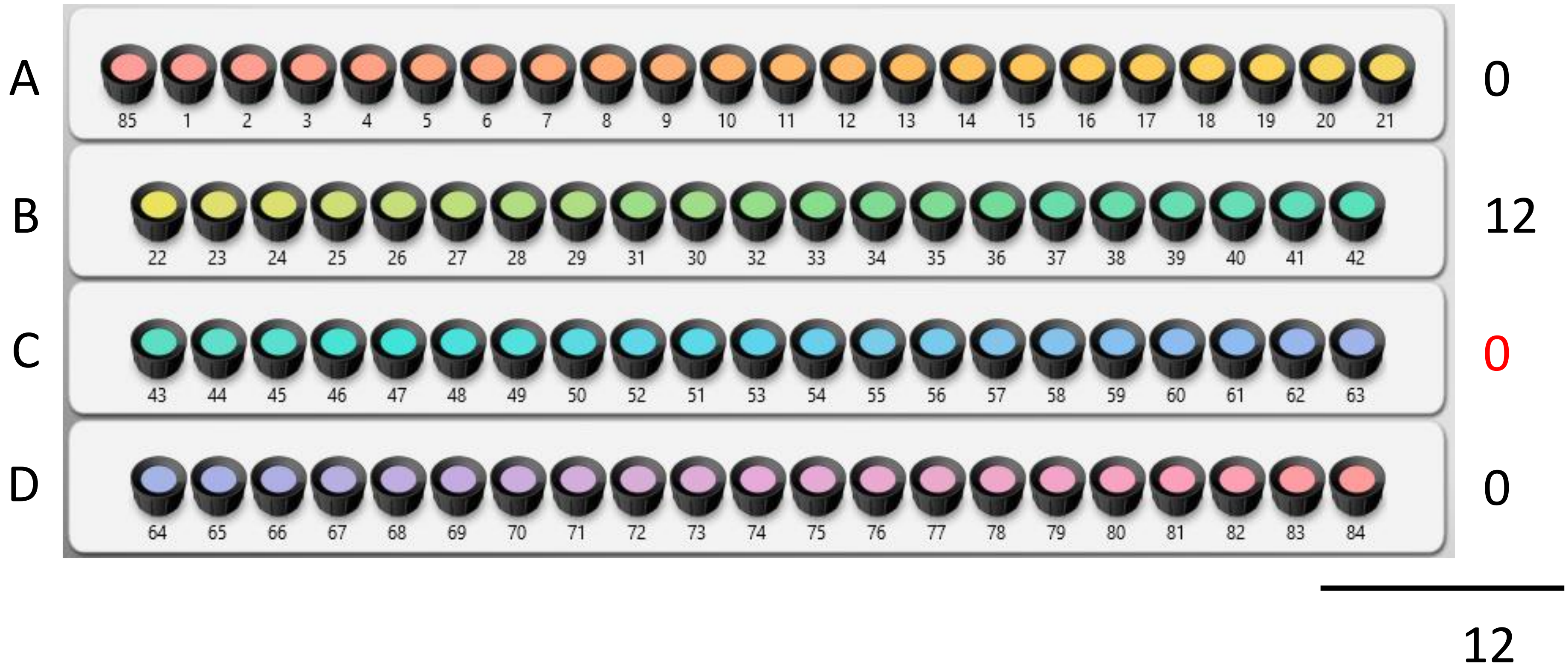
C



0

50 52 51 53

Method: FM-100 error score



***Adjusted* Total Error Score (*TES*$_{adj}$) = 12**

Total Error Score (*TES*) = 16

Method: $\mathit{TES}_{\mathrm{adj}}$

The *adjusted* Total Error Score ($\mathit{TES}_{\mathrm{adj}}$) compares the order of caps under the *test* illuminant to the order of caps performed by the participant

$\mathit{TES}_{\mathrm{adj}}$ reconciles the light source-induced cap transpositions and participant performance

Participants should not be penalized (i.e. attributed an error) for correctly responding to hue transpositions caused by the light source

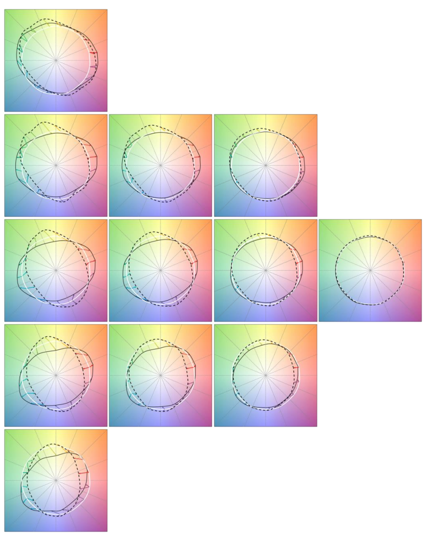
Method: Summary

24 spectra

4 nominal R_f values

5 nominal R_g values

2 CVG orientations



20 participants per spectra

Average TES_{adj}

480 FM-100 tests

Results/Analysis

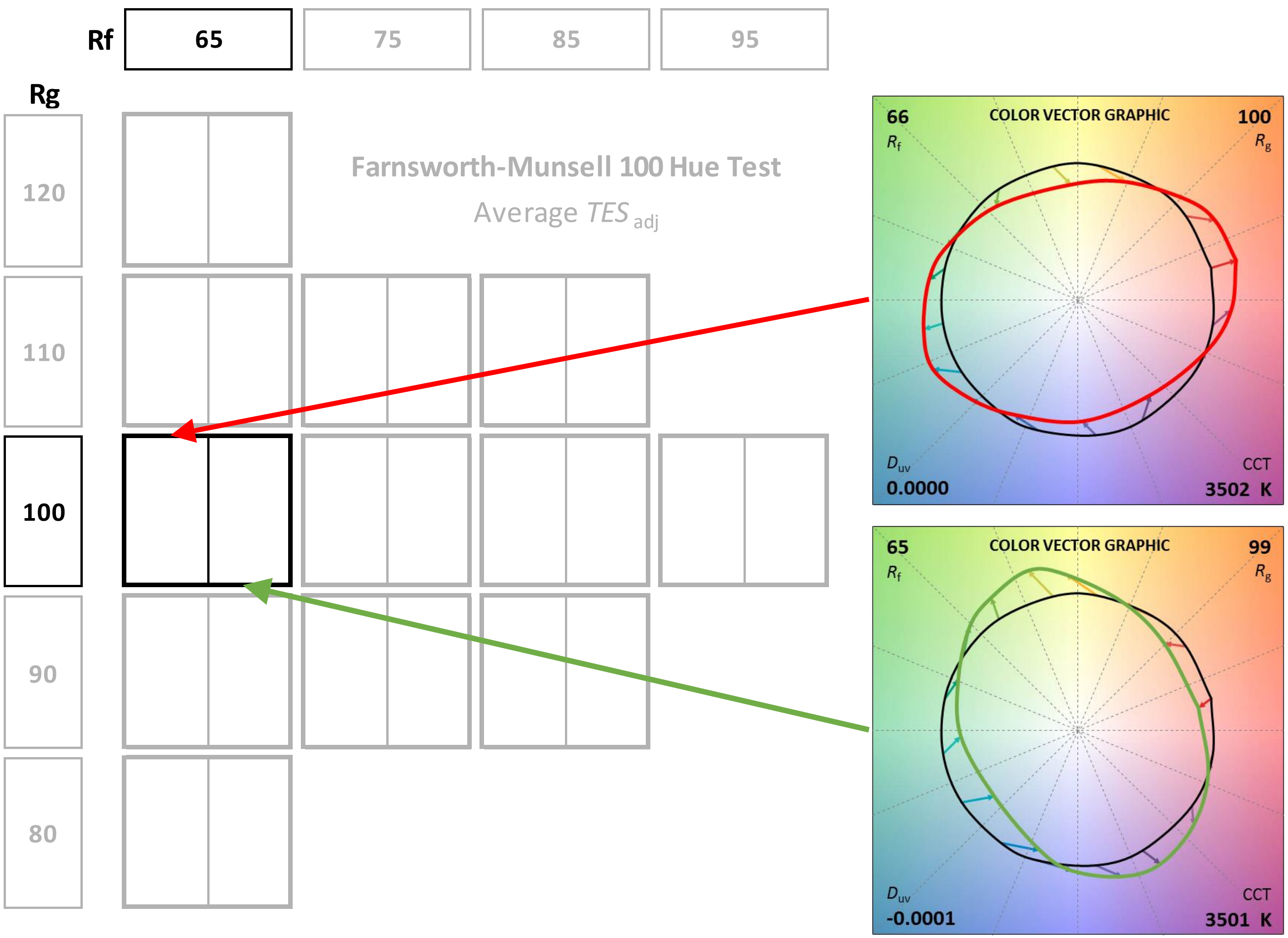
Results: average fidelity

Farnsworth-Munsell 100 Hue Test

Average TES_{adj}

Rg \ Rf	65	75	85	95
120				
110				
100				
90				
80				

Results: average fidelity



Results: average fidelity

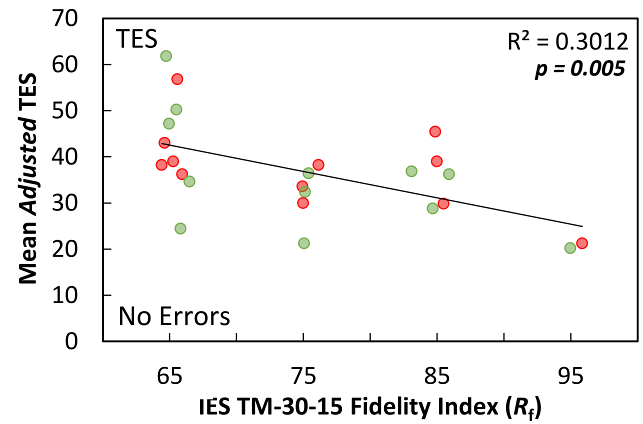
Farnsworth-Munsell 100 Hue Test

Average TES_{adj}

Rg \ Rf	65		75		85		95	
120	56.8	61.8						
110	38.2	50.2	33.6	36.4	45.4	36.2		
100	36.2	47.2	30	32.4	39	28.8	21.2	20.2
90	43	34.6	38.2	21.2	29.8	36.8		
80	39	24.4						

$r^2 = 0.30$

$\boldsymbol{p = 0.005}$



Figures reproduced from Esposito and Houser 2017

Results: average gamut

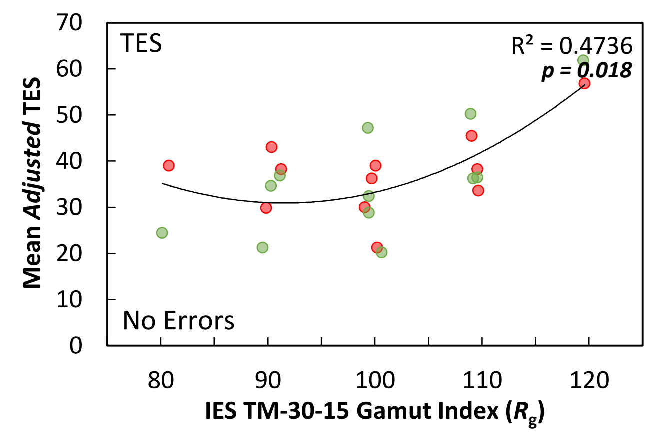
Farnsworth-Munsell 100 Hue Test

Average TES_{adj}

Rg \ Rf	65		75		85		95	
120	56.8	61.8						
110	38.2	50.2	33.6	36.4	45.4	36.2		
100	36.2	47.2	30	32.4	39	28.8	21.2	20.2
90	43	34.6	38.2	21.2	29.8	36.8		
80	39	24.4						

$r^2 = 0.47$

$\boldsymbol{p = 0.018}$



Figures reproduced from Esposito and Houser 2017

Results: gamut shape

Farnsworth-Munsell 100 Hue Test

Average TES_{adj}

Rg \ Rf	65		75		85		95	
120	56.8	61.8						
110	38.2	50.2	33.6	36.4	45.4	36.2		
100	36.2	47.2	30	32.4	39	28.8	21.2	20.2
90	43	34.6	38.2	21.2	29.8	36.8		
80	39	24.4						

$r^2 = 0.01$

$p = 0.704$

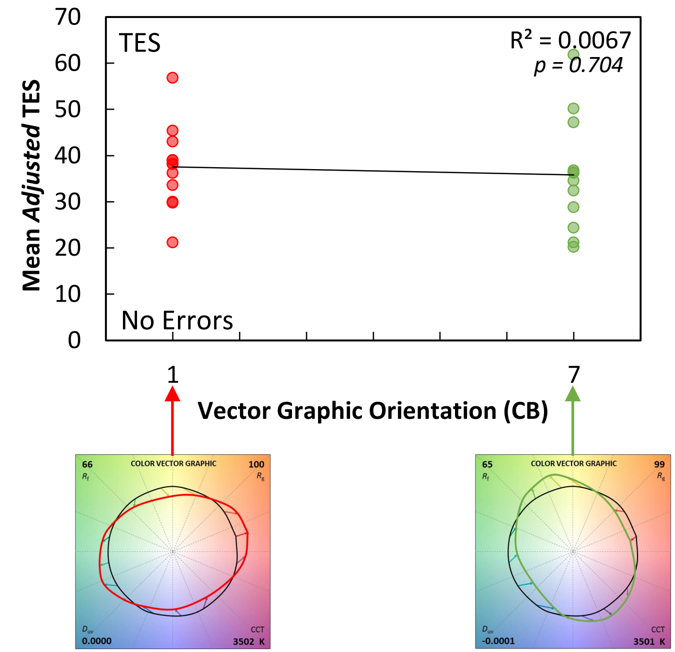


Figure (left) reproduced from Esposito and Houser 2017

Results: various gamut indices

	Linear Fit		Quadratic Fit	
Metric	***r^2***	***p-value***	***r^2***	***p-value***
R_g	30.75	**0.005**	47.36	**0.018**
Q_a	5.55	0.268	23.56	**0.037**
Q_g	35.75	**0.002**	44.93	0.075
GAI	34.68	**0.002**	42.82	0.099
FMG	34.04	**0.003**	40.91	0.133
FMG (CIE CAM02)	31.27	**0.005**	48.52	**0.015**
CDI	34.67	**0.002**	42.78	0.099

Gamut area is not predictive of TES_{adj}

Results: gamut/fidelity models

Model	r^2	*p-value*	
		Gamut	***Fidelity***
$R_g + R_f$	61.07	**0.001**	**0.001**
$Q_a + Q_f$	56.20	**0.000**	**0.000**
$Q_g + Q_f$	48.16	**0.002**	**0.036**
$GAI + R_a$	42.31	**0.004**	0.111
$FMG + R_a$	40.98	**0.005**	0.131
FMG (CIE CAM02) + R_a	41.72	**0.004**	0.066
$CDI + R_a$	42.29	**0.004**	0.111

Gamut area is not predictive of TES_{adj}

Even when paired with an average fidelity metric

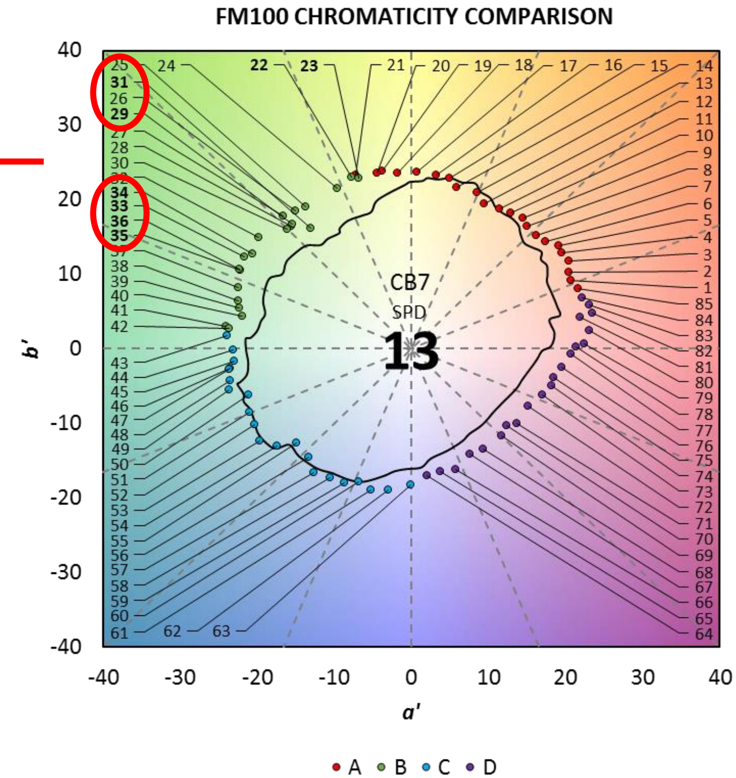
Results: overall

Rg \ Rf	65		75		85		95	
120	56.8	61.8						
110	38.2	50.2	33.6	36.4	45.4	36.2		
100	36.2	47.2	30	32.4	39	28.8	21.2	20.2
90	43	34.6	38.2	21.2	29.8	36.8		
80	39	24.4						

Results: transpositions

Rg \ Rf	65		75		85		95	
120	56.8	61.8						
110	38.2	50.2	33.6	36.4	45.4	36.2		
100	36.2	47.2	30	32.4	39	28.8	21.2	20.2
90	43	34.6	38.2	21.2	29.8	36.8		
80	39	24.4						

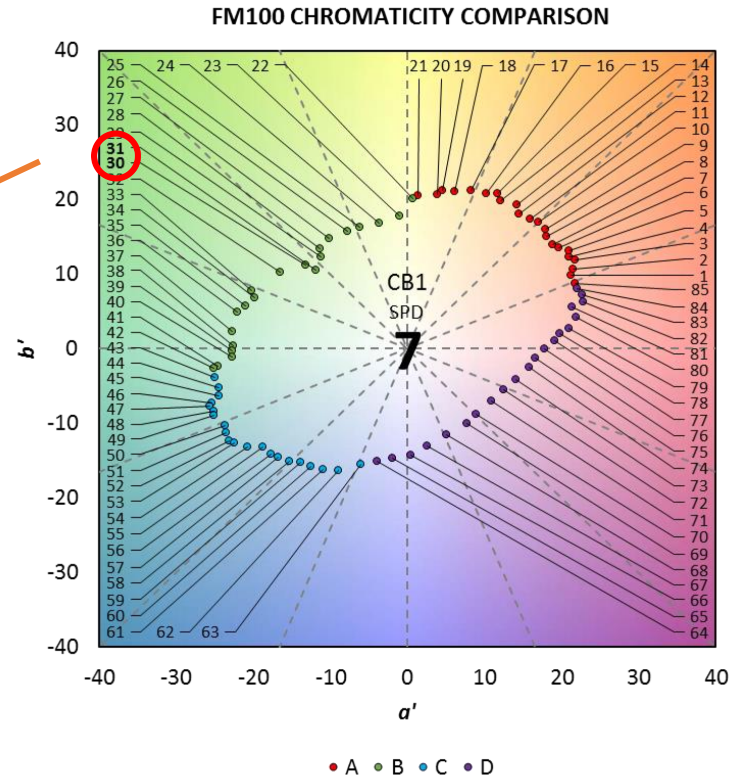
SPD transposes MANY caps



Results: transpositions

Rg \ Rf	65		75		85		95	
120	56.8	61.8						
110	38.2	50.2	33.6	36.4	45.4	36.2		
100	36.2	47.2	**30**	32.4	39	28.8	21.2	20.2
90	43	34.6	38.2	21.2	29.8	36.8		
80	39	24.4						

SPD transposes ONE cap

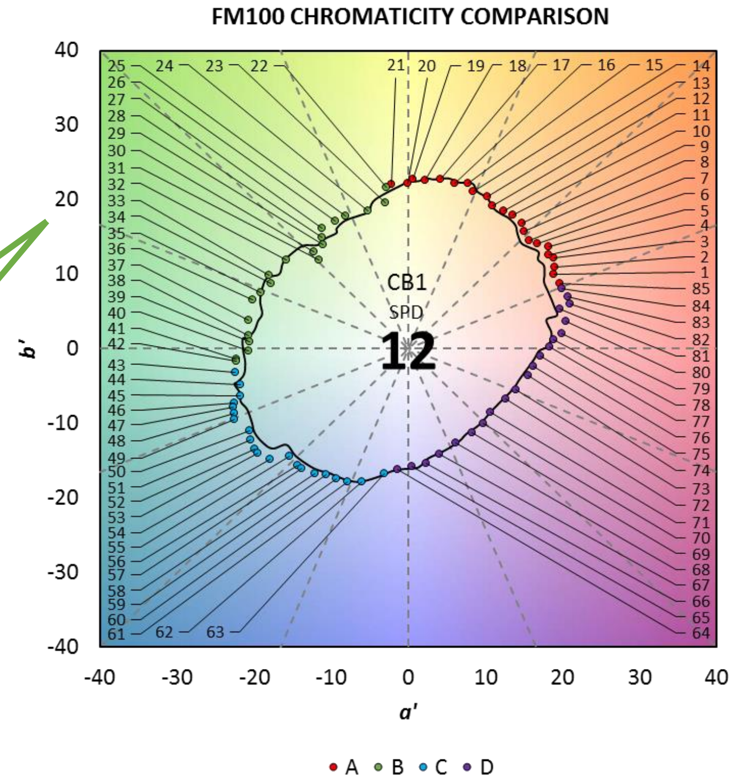


42

Results: transpositions

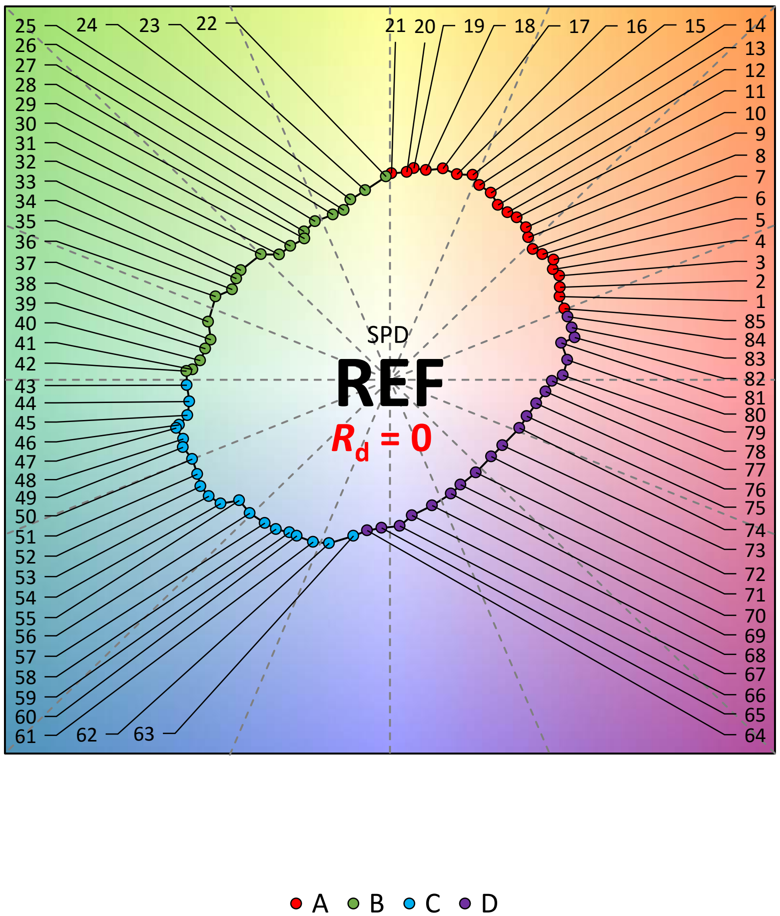
SPD transposes NO caps

Rg \ Rf	65		75		85		95	
120	56.8	61.8						
110	38.2	50.2	33.6	36.4	45.4	36.2		
100	36.2	47.2	30	32.4	39	28.8	21.2	20.2
90	43	34.6	38.2	21.2	29.8	36.8		
80	39	24.4						

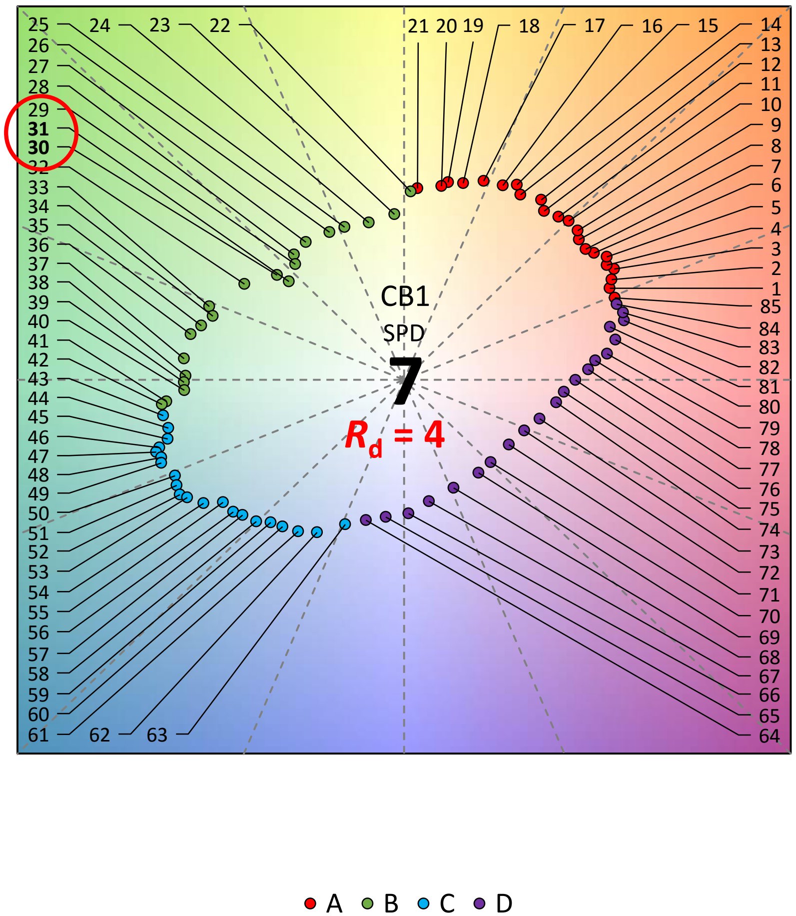


Results: Light Source Error Score, R_d

Standard Illuminant

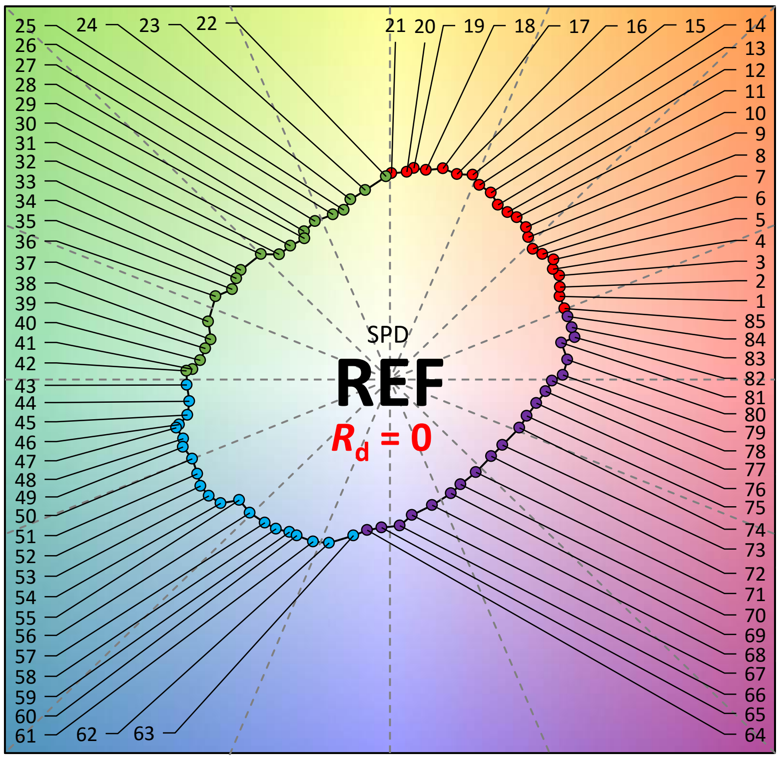


Experimental Source



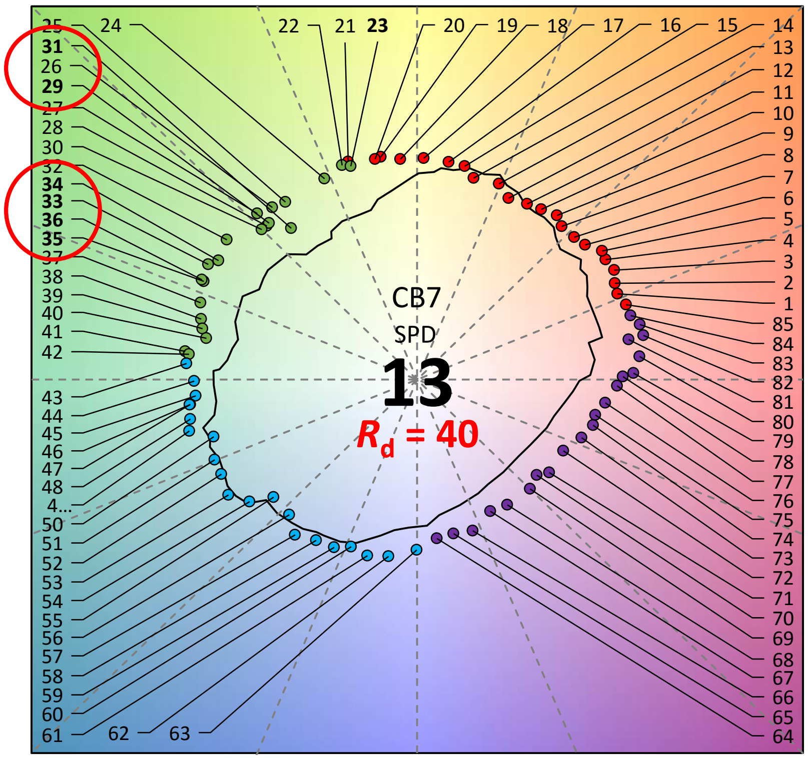
Results: Light Source Error Score, R_d

Standard Illuminant



● A ● B ● C ● D

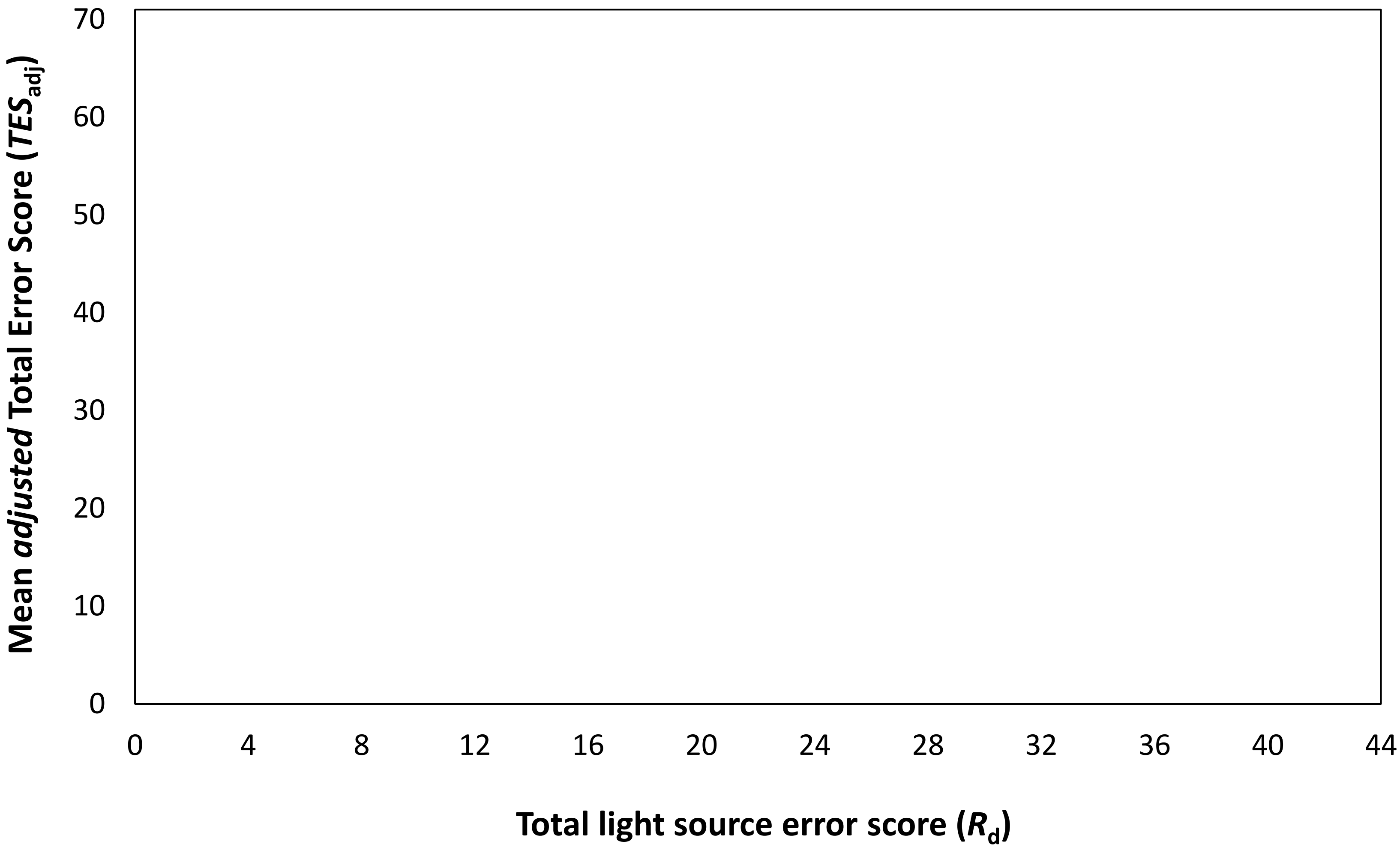
Experimental Source



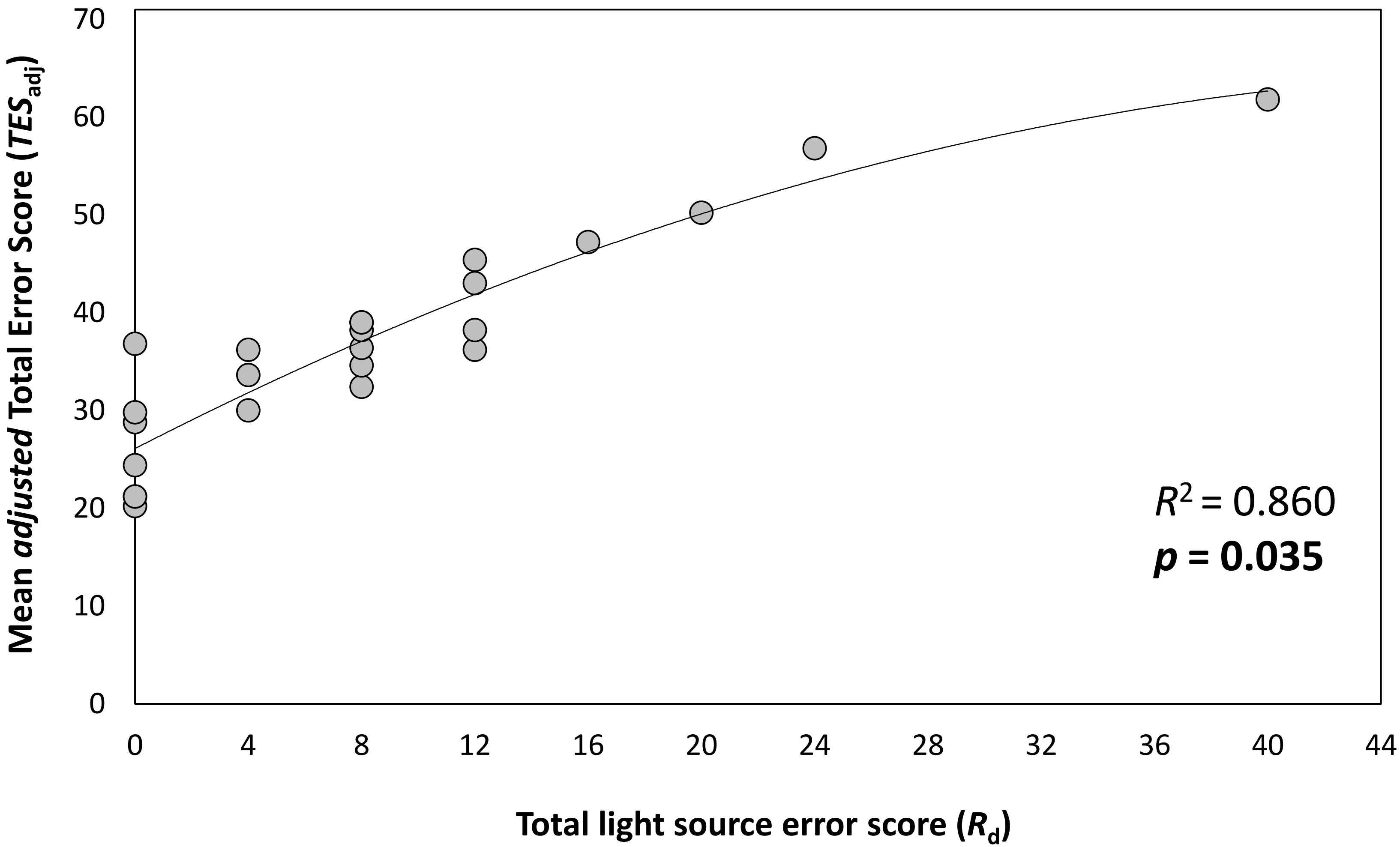
● A ● B ● C ● D

Figure (right) reproduced from Esposito and Houser 2017

Results: Light Source Error Score, R_d



Results: Light Source Error Score, R_d



Results: Light Source Error Score, R_d

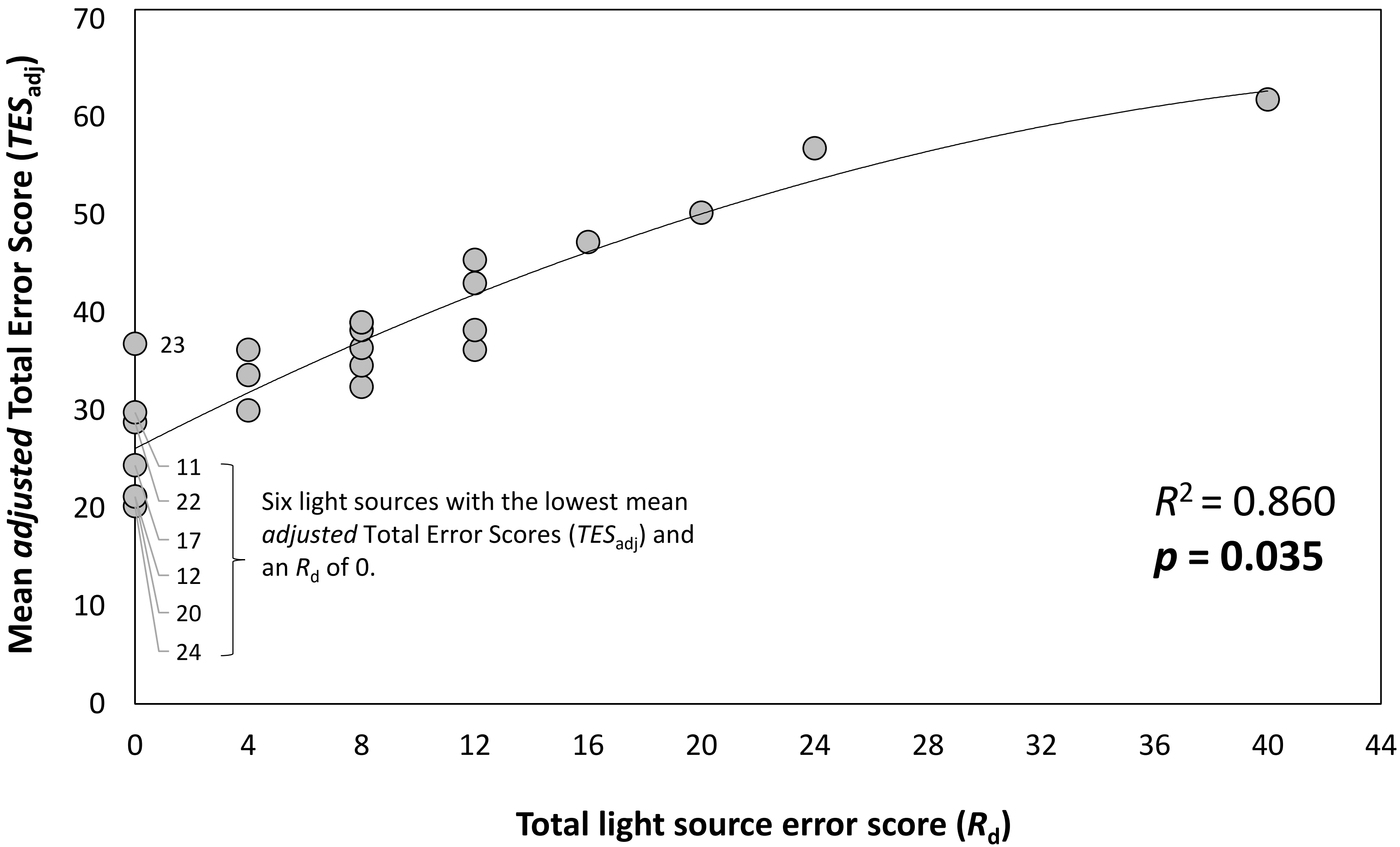


Figure reproduced from Esposito and Houser 2017

Results: Light Source Error Score, R_d

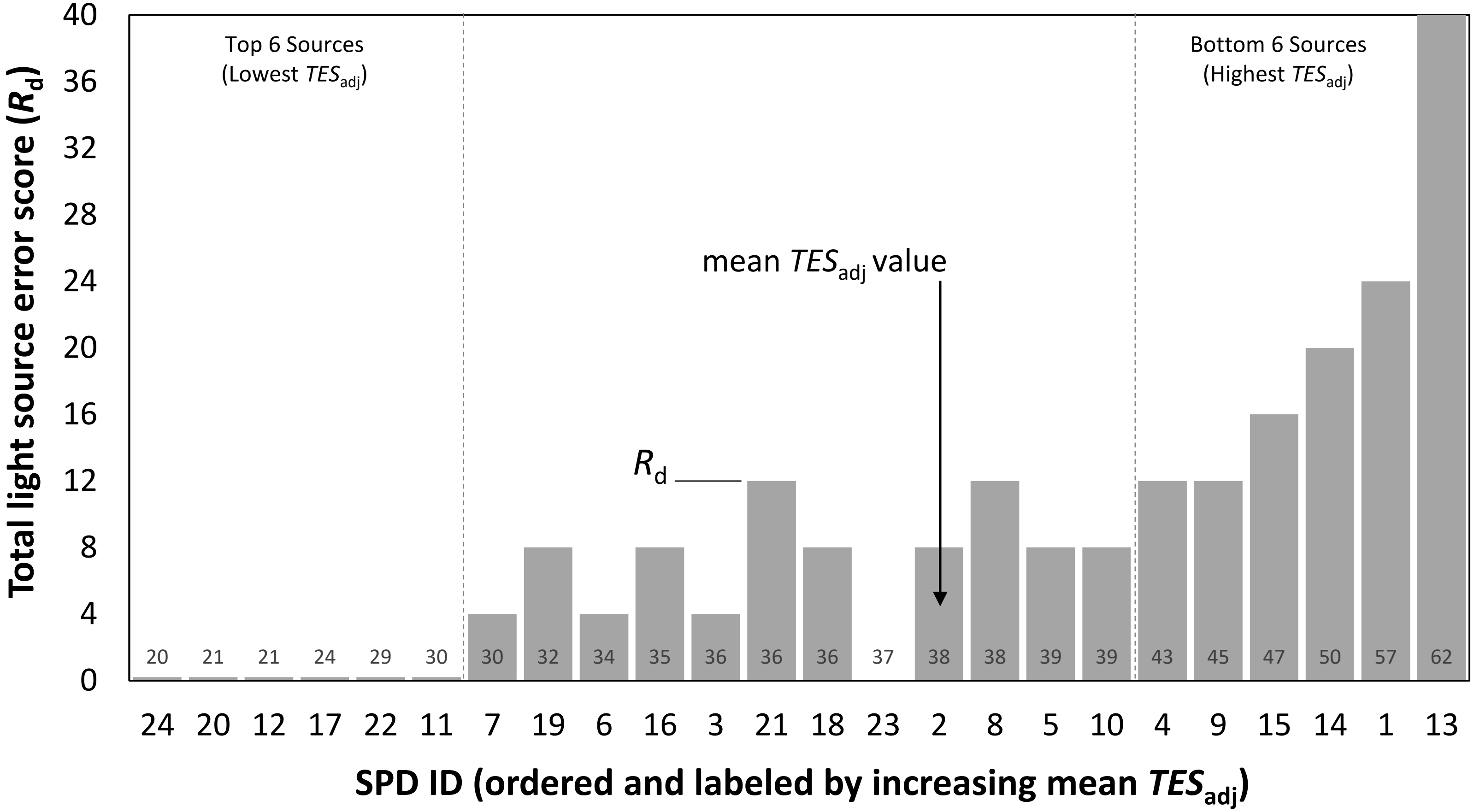


Figure reproduced from Esposito and Houser 2017

Results: Light Source Error Score, R_d

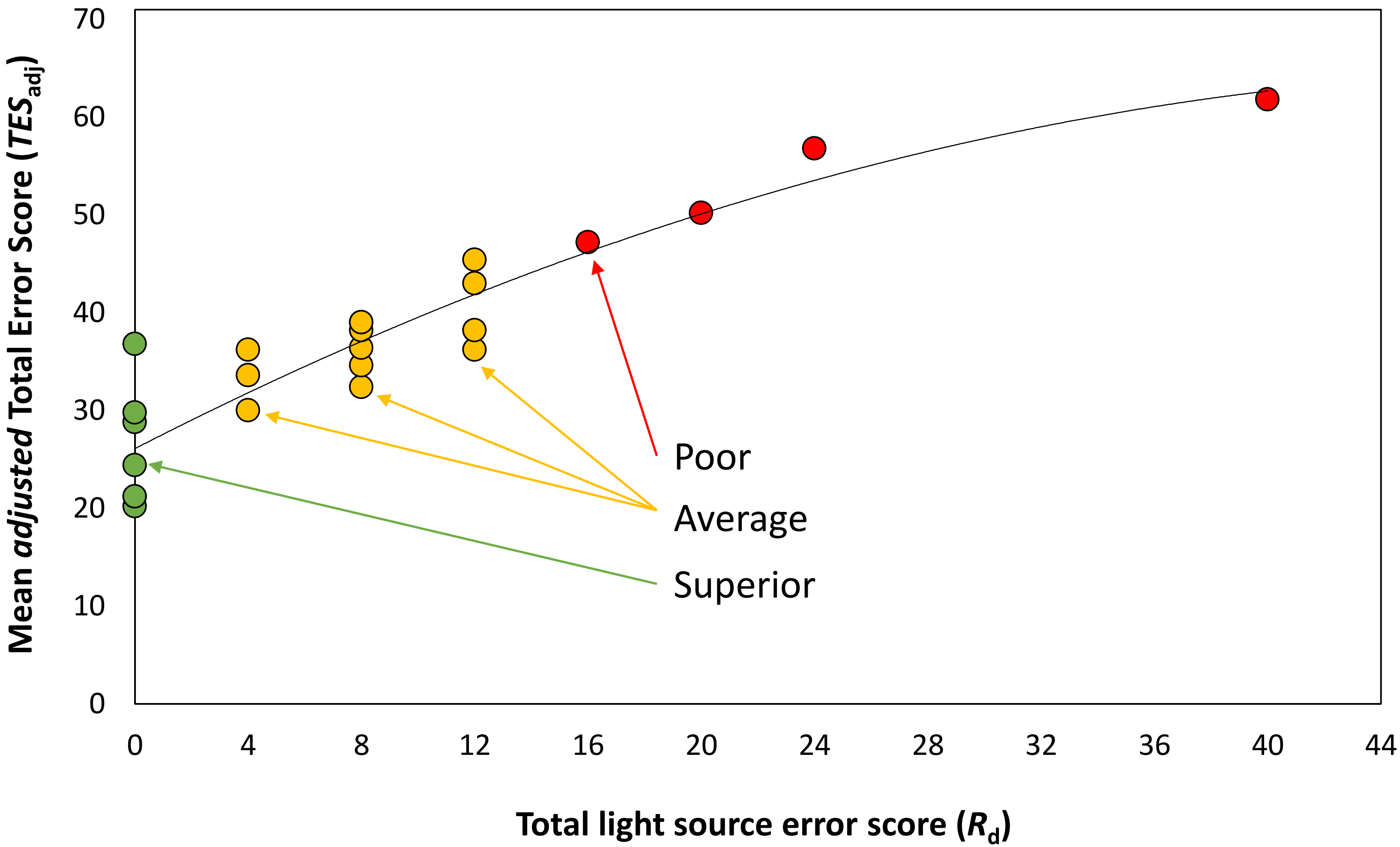


Figure reproduced from Esposito and Houser 2017

Results: R_d, common light sources

Source Type	Source Name	R_d	Discrimination
Incandescent	75WA19 Neodymium	12	Average
Incandescent	Halogen/Halogen MR16	4, 8	Average
Incandescent	Filtered Halogen	0	Superior
HID	HPS Standard	40, 48	Poor
HID	HPS Deluxe	36	Poor
HID	Super HPS	40	Poor
HID	Mercury	36, 44, 52	Poor
HID	CDM940 - Metal Halide	0	Superior
HID	CDM830, MHC100/U/MP/3K	4, 8	Average
LED	Mixed (Experimental)	0-40	Superior, Average, Poor
LED	Hybrid (Commercial)	0-16	Superior, Average, Poor
LED	Phosphor	0-28	Superior, Average, Poor
Fluorescent	Narrowband - F32T8/7XX	8, 12, 24	Average, Poor
Fluorescent	Narrowband - F32T8/8XX	0-16, 24	Superior, Average, Poor
Fluorescent	Narrowband - F32T8/9XX	0, 8	Superior, Average
Fluorescent	Narrowband - F40T12/XXU	8, 12, 24	Average, Poor
Fluorescent	Broadband	0, 4, 8, 20	Superior, Average, Poor
Model	CIE D65	0	Superior
Model	Equal Energy	0	Superior
Model	Ideal Prime Color	60	Poor

Table reproduced from Esposito and Houser 2017

CONCLUSIONS

Previous literature suggests the inability of available indices to predict color discrimination

Current study designed to objectively evaluate CD

Proposed *adjusted* TES (TES_{adj}) to reconcile source-participant

Results show that gamut area cannot predict TES_{adj}

- This is true for all gamut indices considered
- Adding a fidelity metric improved prediction, but still weak

New measure of color discrimination is proposed

- R_{d} is an objective measure of source-induced transpositions
- R_{d} is a strong predictor of TES_{adj}

R_{d} may be used to specify *poor*/*average*/*superior* performance

R_{d} corresponds well to anecdotal evidence

Thank you!

BIO

Tony graduated from Penn State University in 2016 with a PhD in Architectural Engineering and a minor in statistics. His dissertation explored human responses to various light spectra with strategically varied average fidelity, average gamut, and gamut shape. His research offers an improved method for predicting color discrimination, validation of several trends in color research, and a simplified method for the quantification and specification of gamut shape.

Tony has won the Robert J. Besal Scholarship four times, received EP funding to attend the IES and IALD annual conferences, and previously served as a graduate fellow on an education grant from the National Science Foundation. He has delivered several guest lectures on lighting fundamentals and design, and has lectured nationally and internationally on color science.

Tony currently serves as a voting member on the IES Color Committee and IES Educational Material Review Committee, and works as a *Lighting Quality Researcher* at Philips Lighting Research North America.

Contact information

Tony Esposito
Tony.Esposito@Philips.com
0000-0002-0308-6191