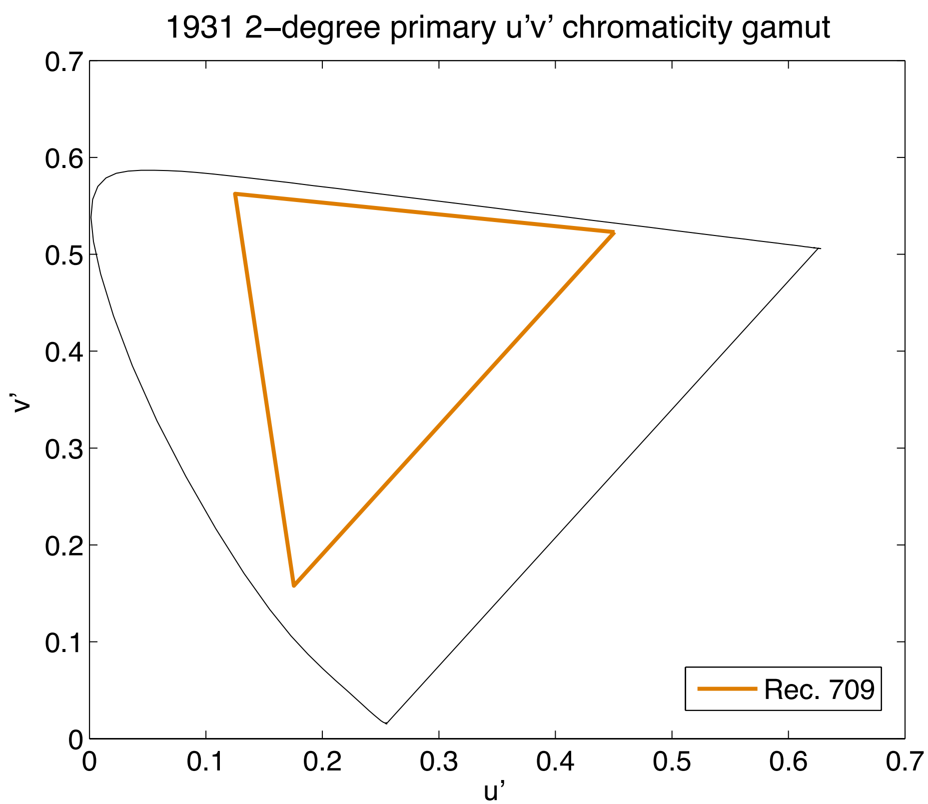
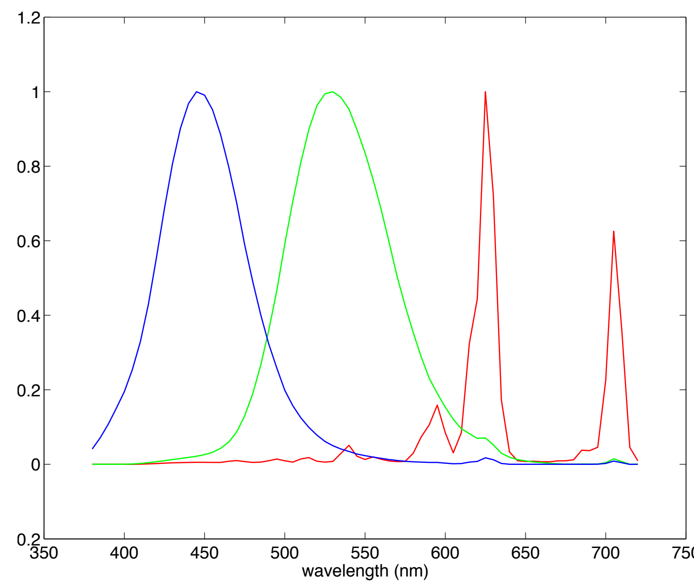
David Long
Rochester Institute of Technology
Program of Color Science | Munsell Color Science Laboratory

NAVIGATING BIG COLOR

Big

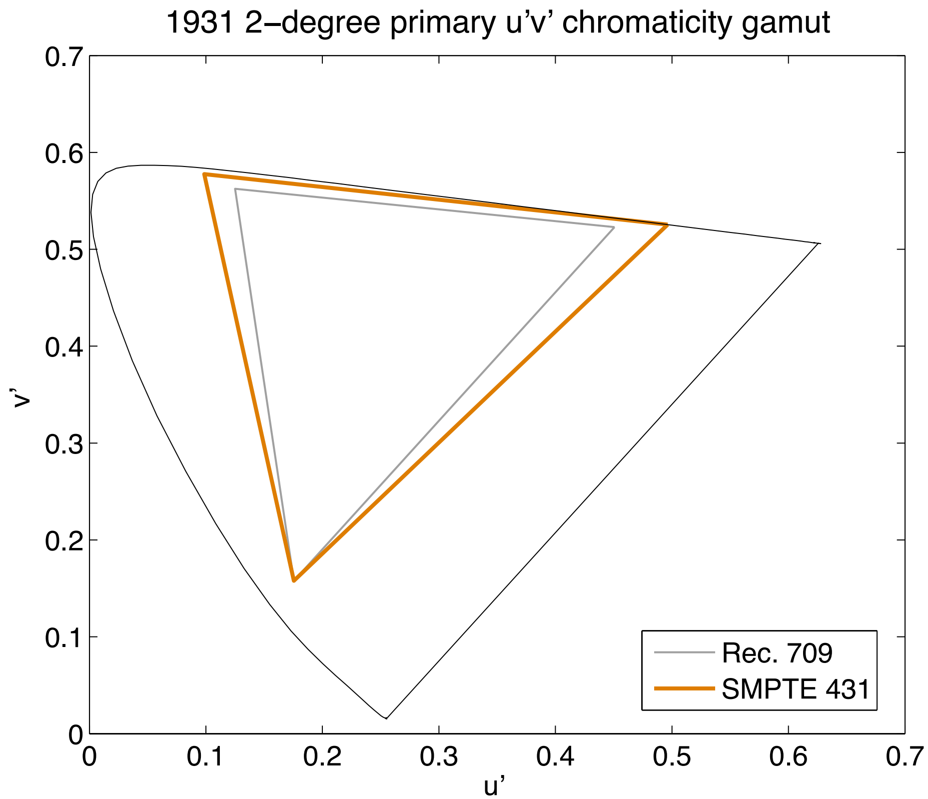
ITU-R Rec. 709

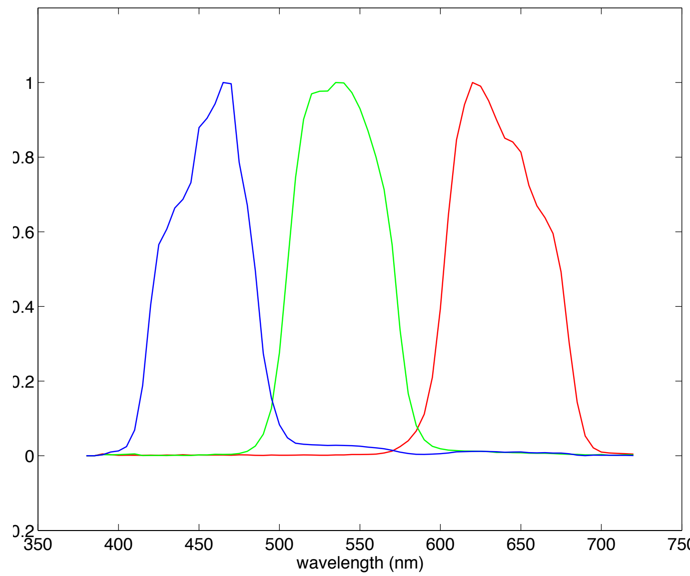


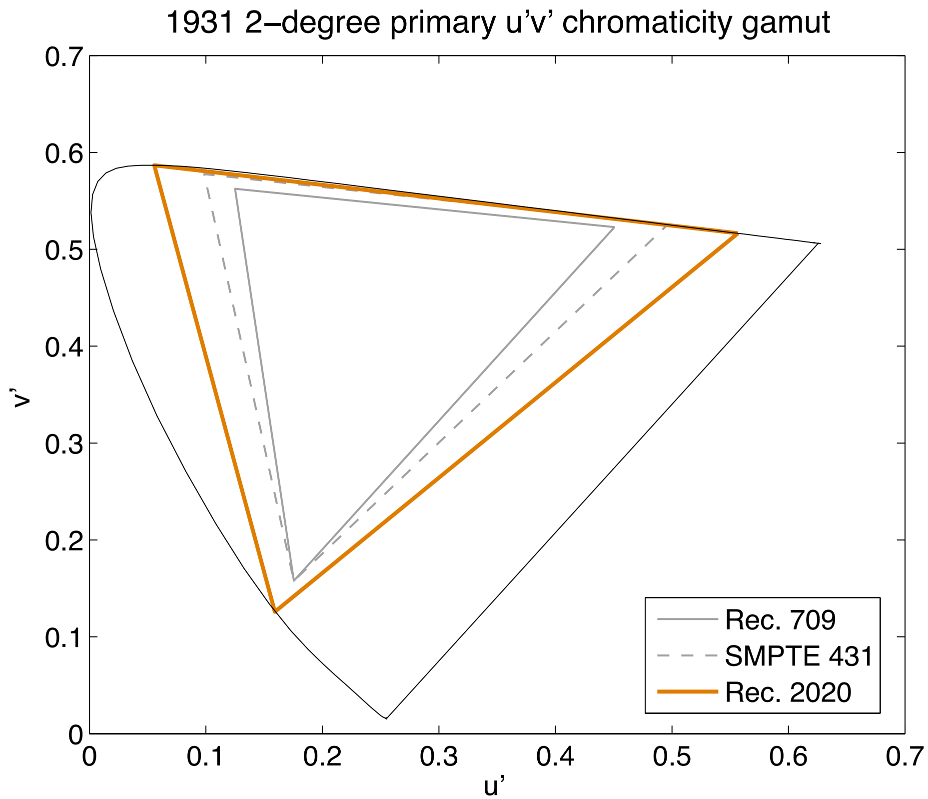


Bigger

SMPTE 431 “DCI P3”

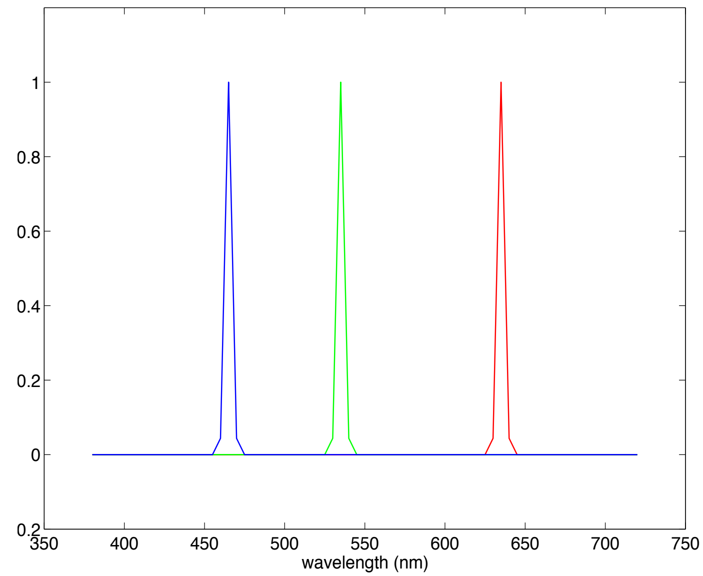


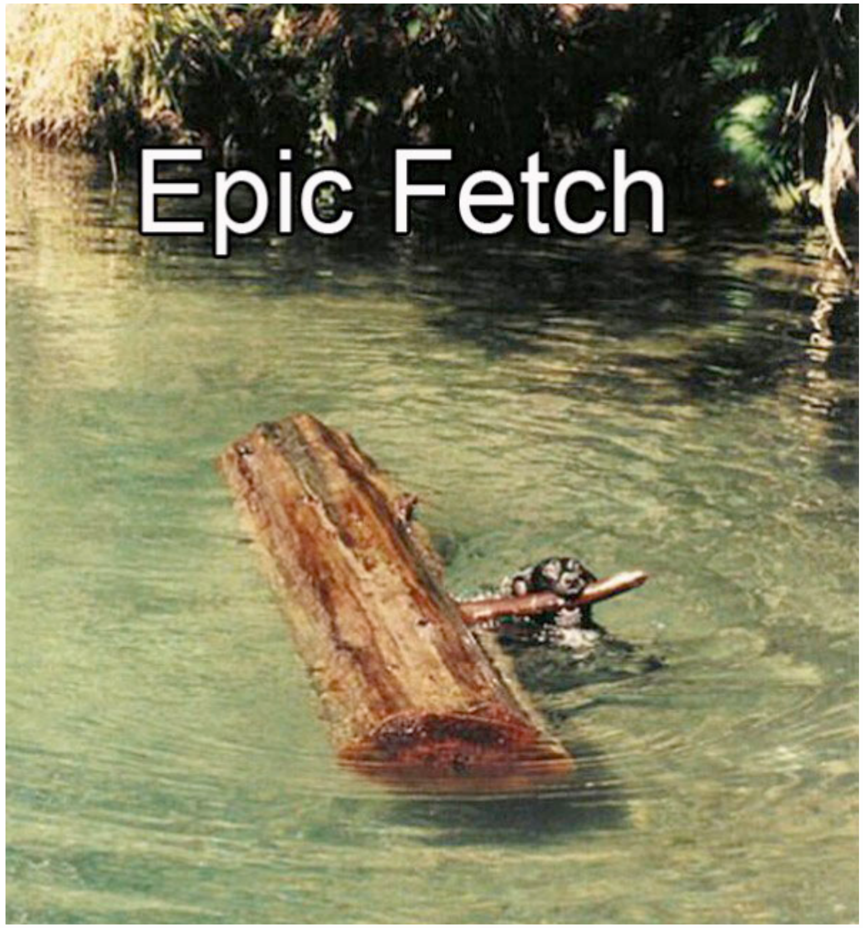


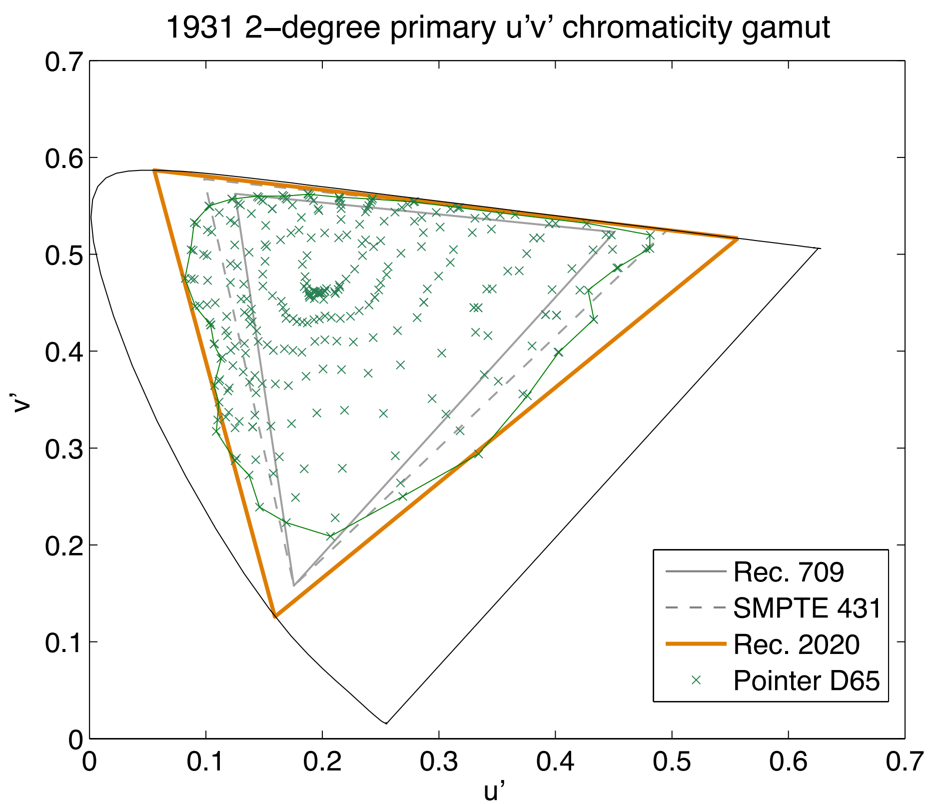


Biggest

ITU-R Rec. 2020

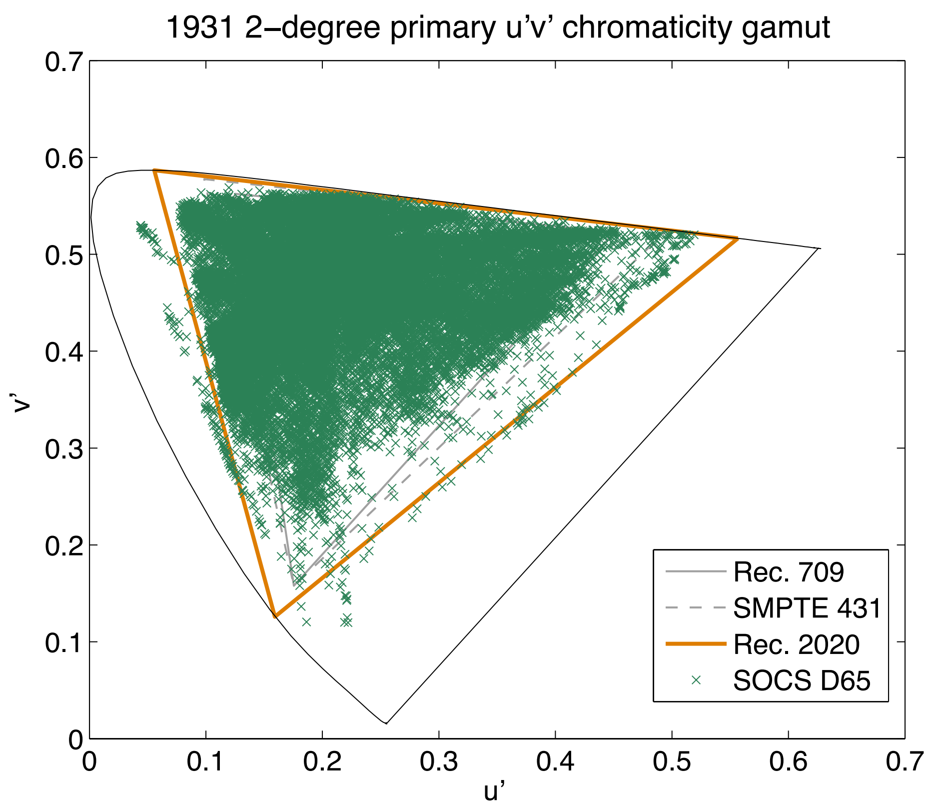



Epic Fetch



Scene Gamuts

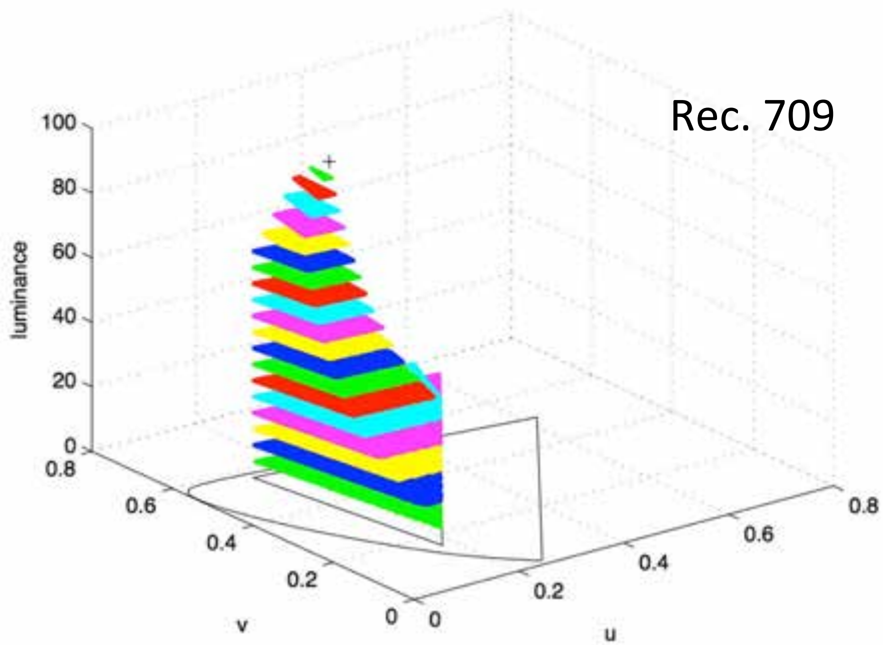
Pointer surface color gamut shows value of Rec. 2020 for display

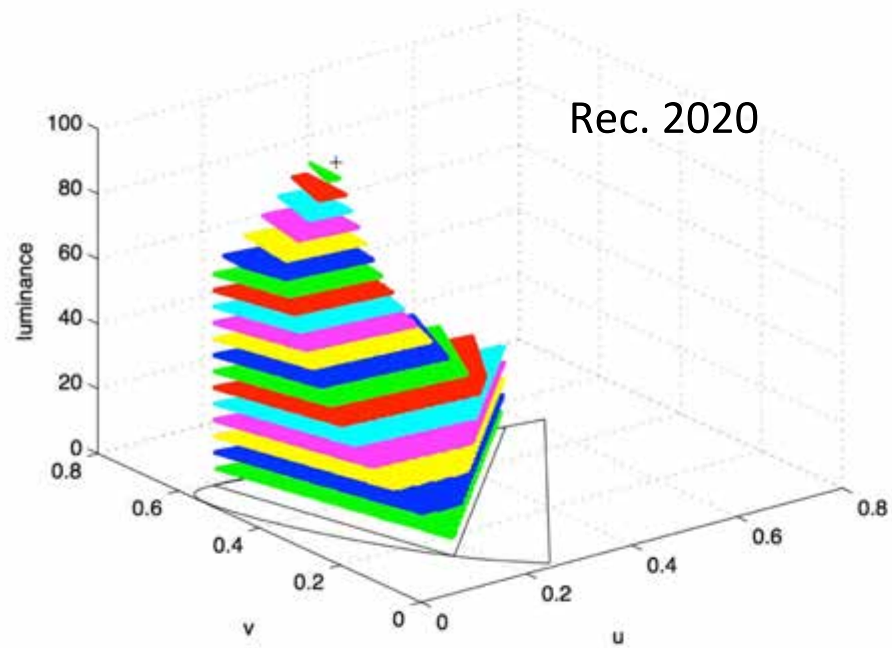


Scene Gamuts

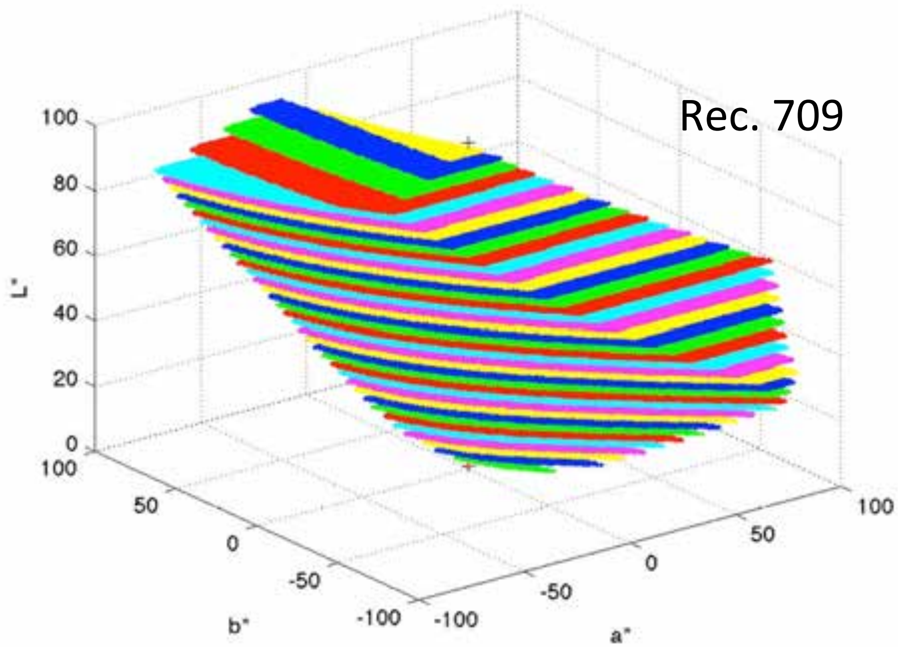
SOCS is another popular scene gamut set

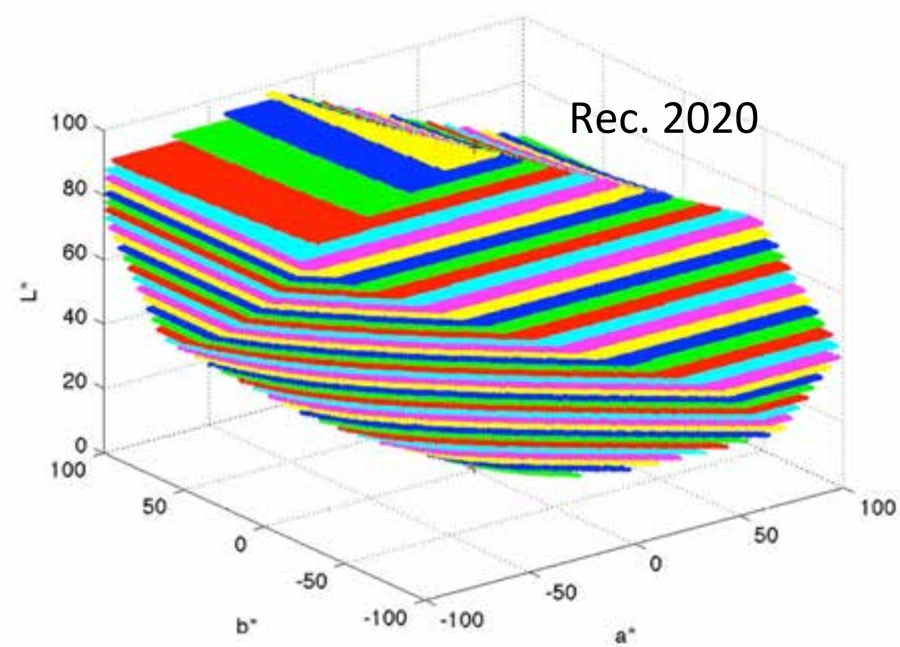
Gamut is 3 Dimensional (Yu’v’)





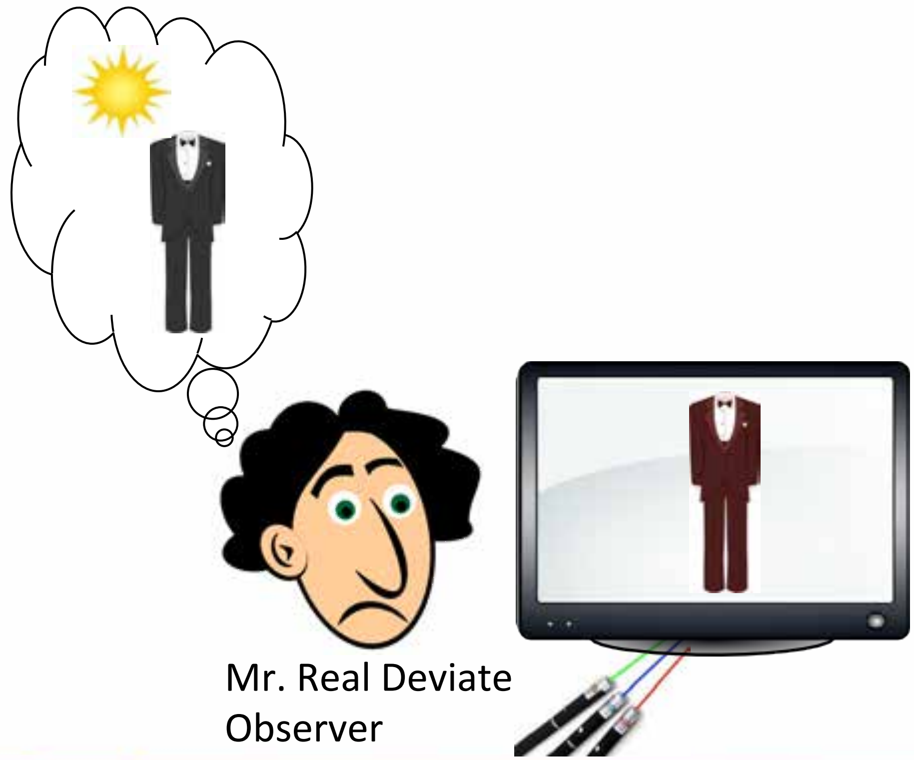
Gamut is 3 Dimensional (L*a*b*)





Observer metamerism can result from narrower primary spectra

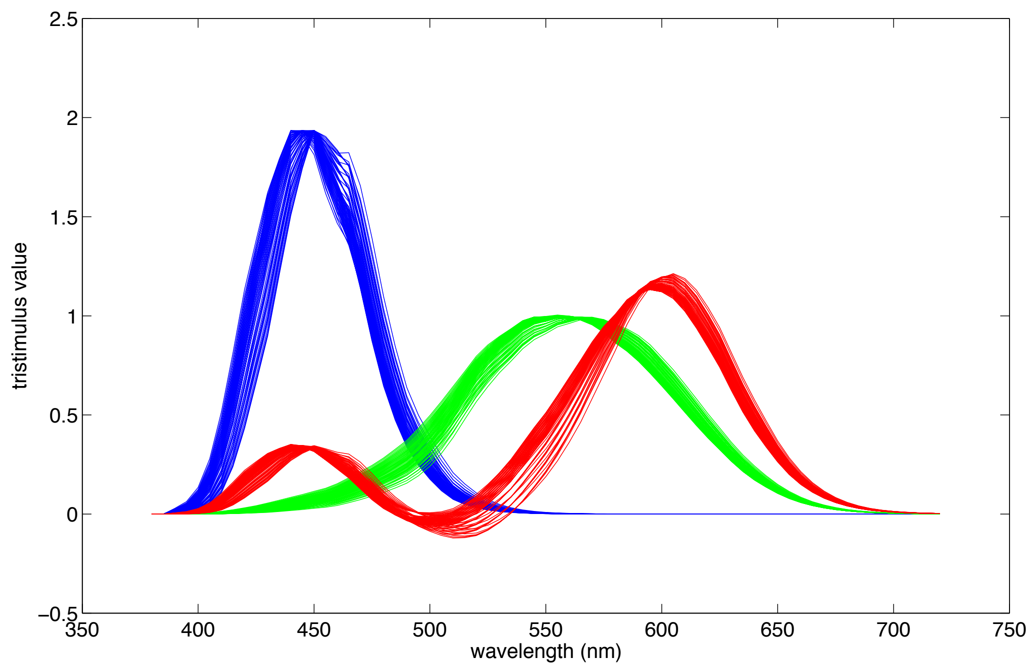
Mr. 1931 2°
Standard Observer



Mr. Real Deviate
Observer

Observer Models

CIE 2006 TC1-36 LMS cone fundamentals transformed to color-matching functions



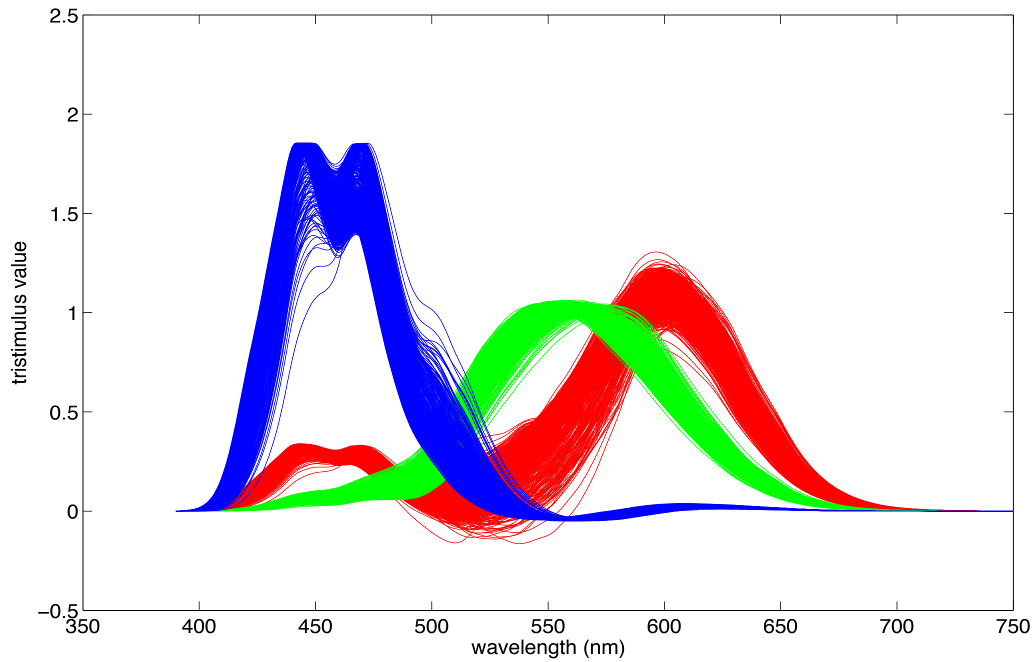
$$\bar{l}_\lambda = \alpha_{i,l,\lambda} \cdot 10^{-D_{\tau,max,macula} \cdot D_{macula\ relative,\lambda} - D_{\tau,ocul,\lambda}}$$

$$\bar{m}_\lambda = \alpha_{i,m,\lambda} \cdot 10^{-D_{\tau,max,macula} \cdot D_{macula\ relative,\lambda} - D_{\tau,ocul,\lambda}}$$

$$\bar{s}_\lambda = \alpha_{i,s,\lambda} \cdot 10^{-D_{\tau,max,macula} \cdot D_{macula\ relative,\lambda} - D_{\tau,ocul,\lambda}}$$

Observer Models

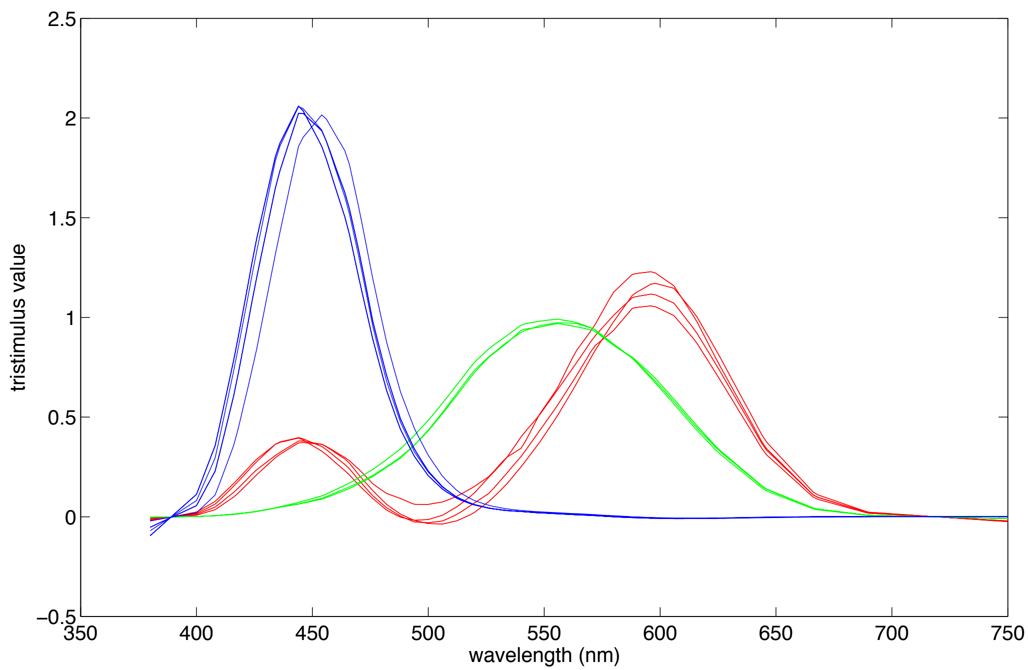
Heckaman / Fairchild Monte Carlo color matching functions



M.D. Fairchild and R.L. Heckaman, "Metameric Observers: A Monte Carlo Approach,: Proc. CIC21 (2013)

Observer Models

Sarkar/Fedutina, et al. color-matching functions



M. Fedutina, A. Sarkar, P. Urban and P. Moran, "How Do Observer Categories Based on Color Matching Functions Affect the Perception of Small Color Differences?" IS&T/SID Color Imaging Conference, 2-7, San Jose (2011)

Indices for Observer Metamerism

Color Difference

$$OM_x = max(\overline{\Delta E_{y,P,\iota}})$$

for each observer, ***i***, in the CMF set, ***x***, across ***P*** patches utilizing $y = \Delta E_{ab}$ or ΔE_{94} or ΔE_{2000}

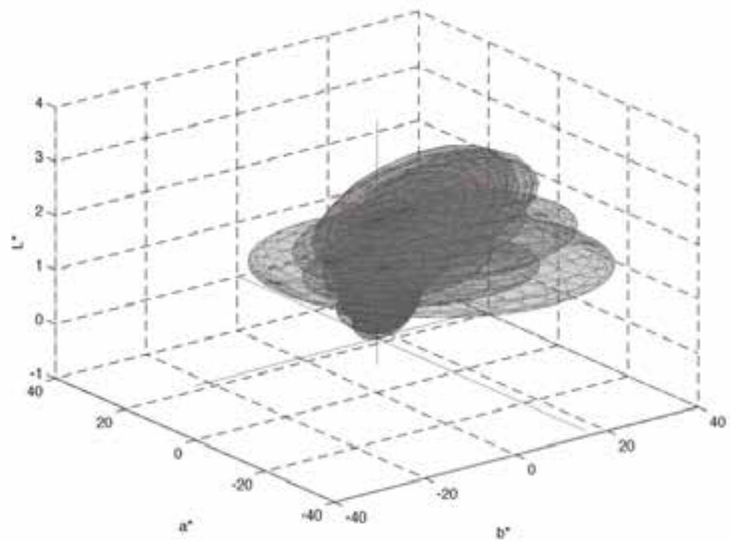
Treating CIELAB as an elementary color appearance model for individual observer color-matching functions encompassing chromatic adaptation, lightness adaptation and perception scaling

Indices for Observer Metamerism

Color Variability

$$\boldsymbol{OM_{x,var}} = \overline{\boldsymbol{Vol}(\Delta(\boldsymbol{L^* a^* b^*})_{\boldsymbol{P}})}$$

for the CMF set, ***x***, across ***P*** patches



*NOTE: x = Sarkar/Fedutina CMF set (s) for following simulations

Observer Metamerism Simulations

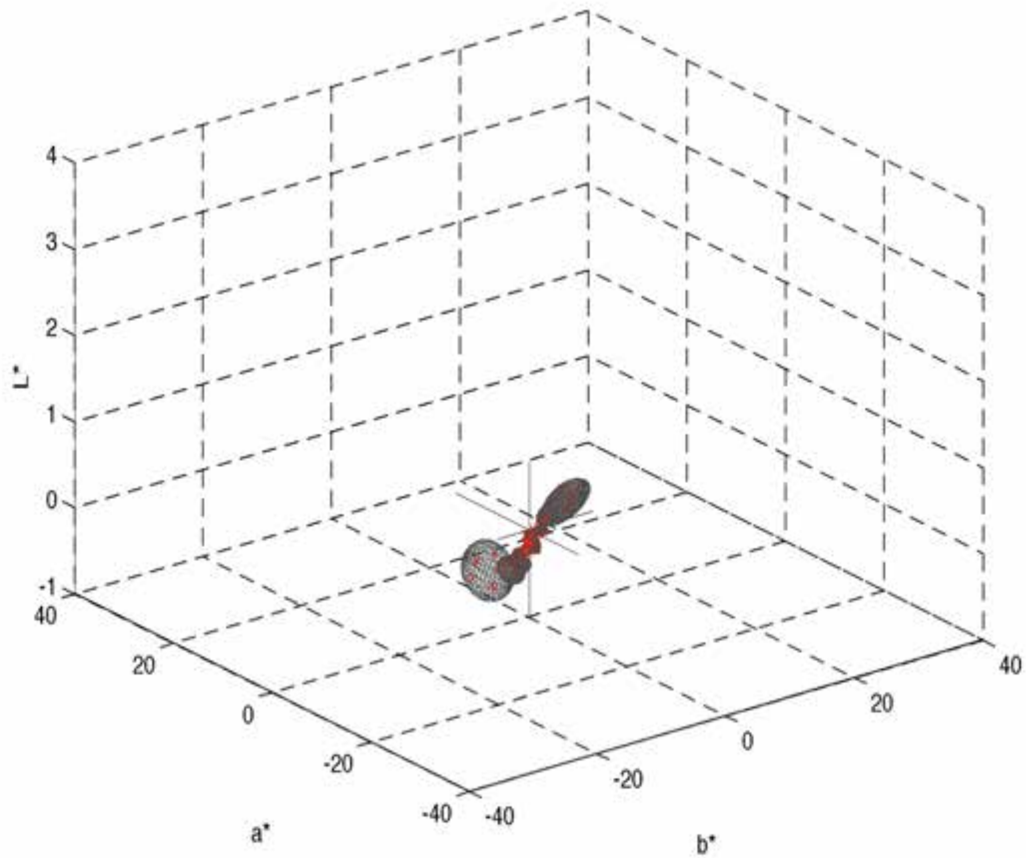
enforcing 1931 2° color match to aim stimuli

CIE D65	OM_s	$OM_{s,var}$	max DE00(31)
MacBeth24			
Sony CRT (Rec. 709)	2.15	2.6E-03	0.44
NEC DLP (P3)	1.83	2.8E-04	0.00
Panasonic DLP (P3)	2.49	1.0E-03	0.00
Laser (Rec. 2020)	5.50	2.6E-01	0.00

D. Long and M.D. Fairchild, “Modeling observer variability and metamerism failure in electronic displays,” Proc. CIC22 (2014)

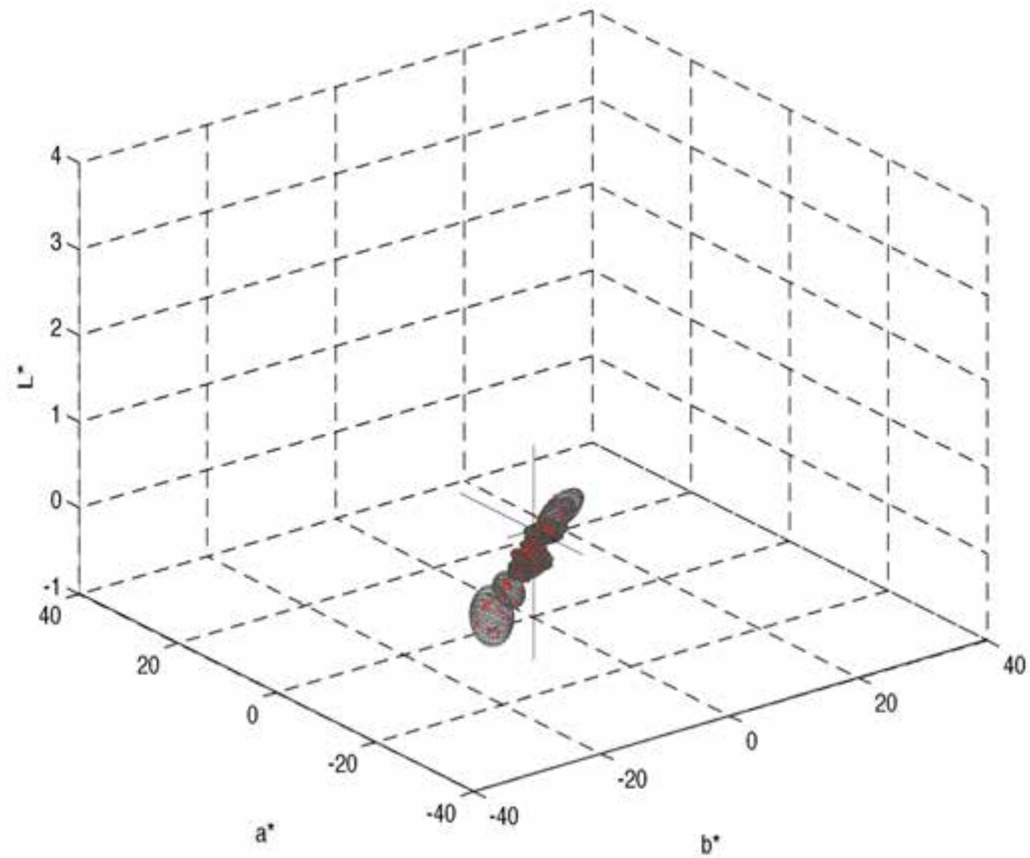
CRT $OM_{s,var}$

- ITU-R Rec. 709
- MacBeth 24
- Illuminated by CIE D65
- 1931 2° color match
- Sarkar/Fedutina CMFs



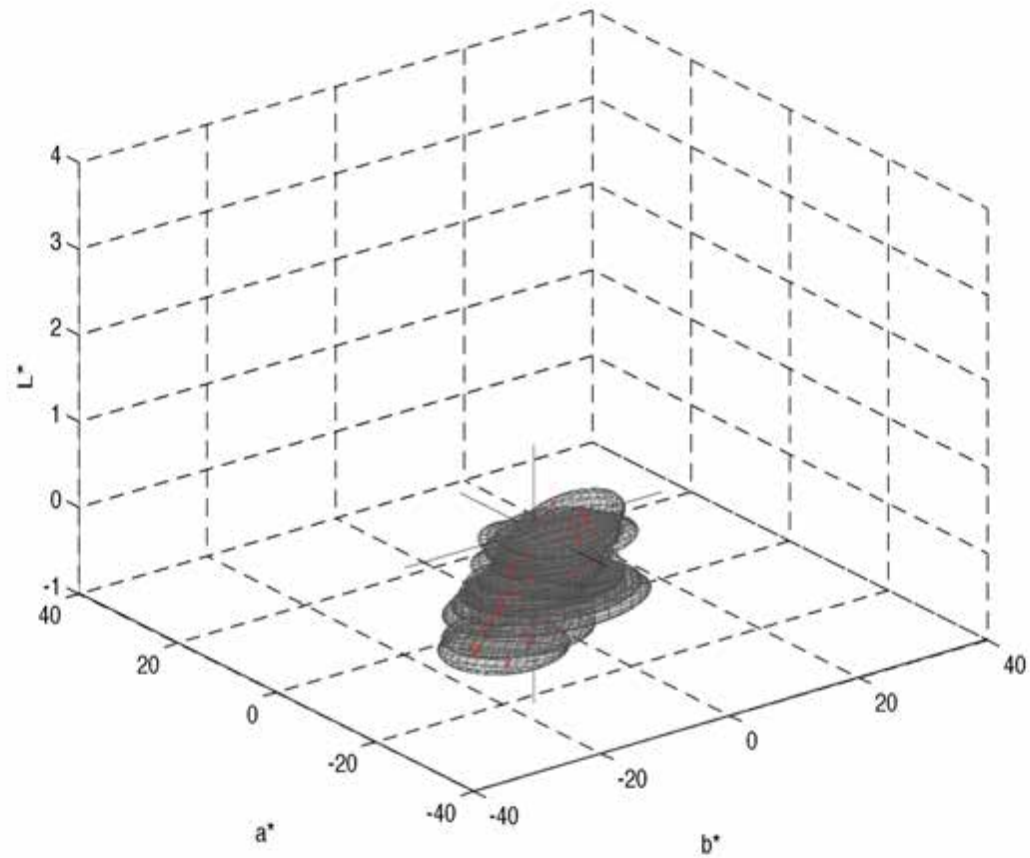
DLP $OM_{s,var}$

- SMPTE 431 “P3”
- MacBeth 24
- Illuminated by CIE D65
- 1931 2° color match
- Sarkar/Fedutina CMFs



RGB Laser $OM_{s,var}$

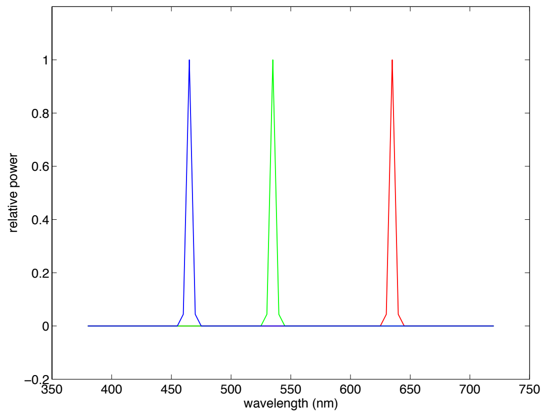
- ITU-R Rec. 2020
- MacBeth 24
- Illuminated by CIE D65
- 1931 2° color match
- Sarkar/Fedutina CMFs

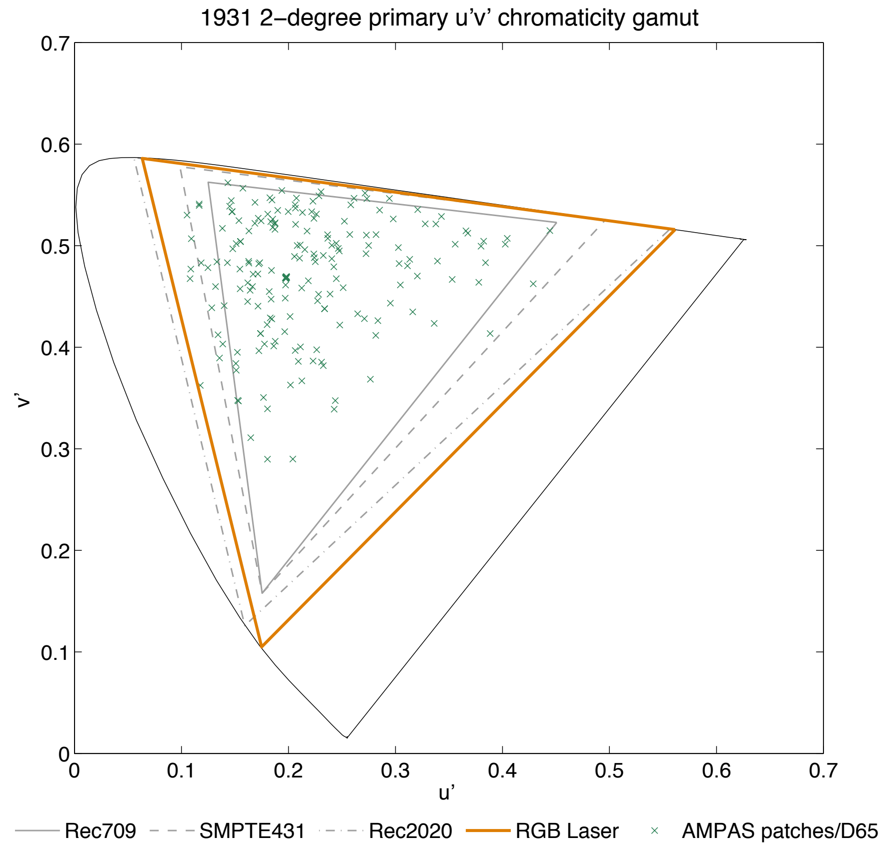


?

Modeling Displays

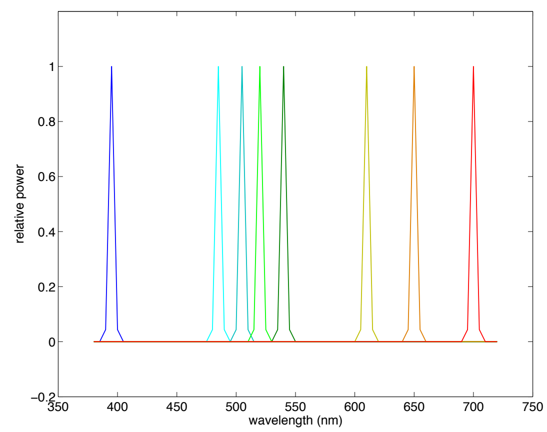
RGB Laser

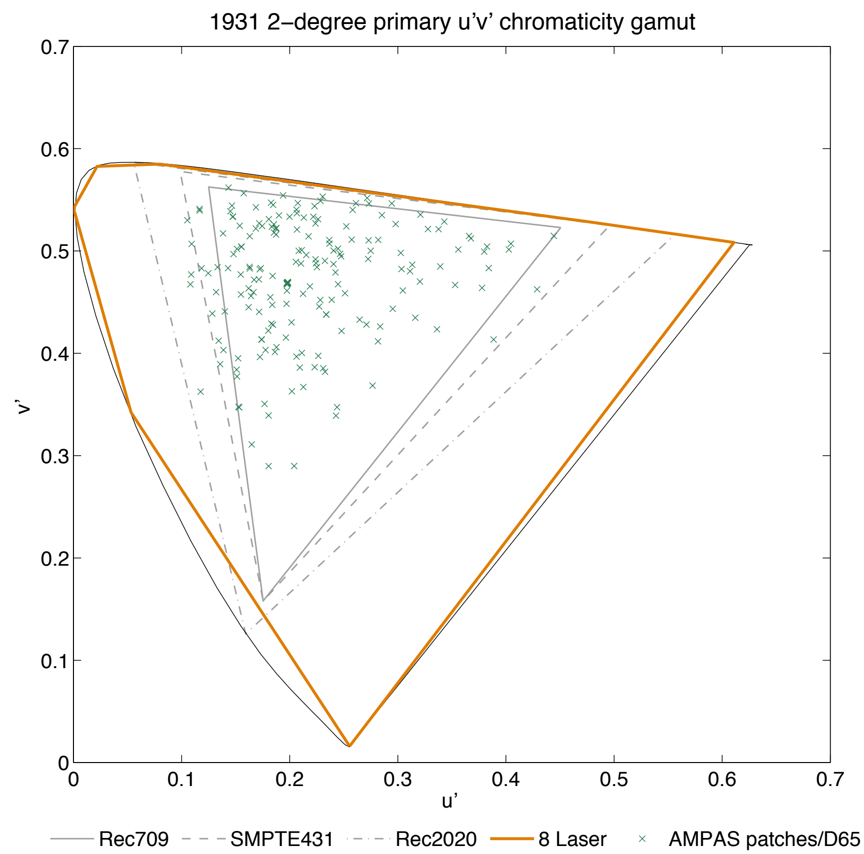




More Lasers!

Hypothetical 8 Laser



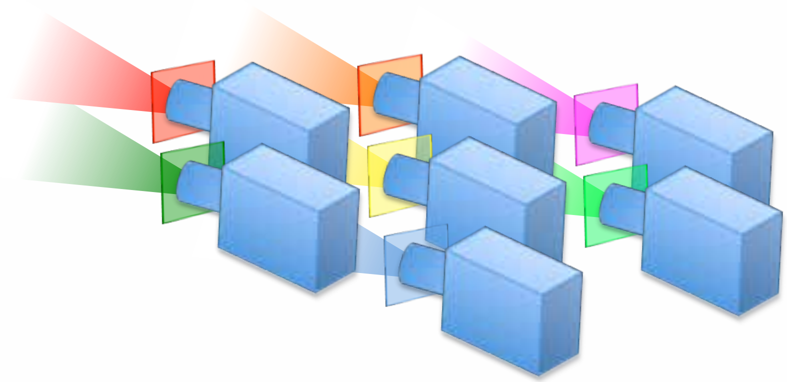


"The Octochromator"

- maximized chromaticity gamut

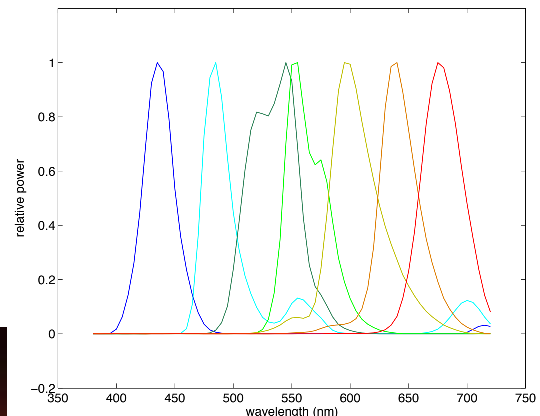
RIT Multi-Primary Display (MPD)

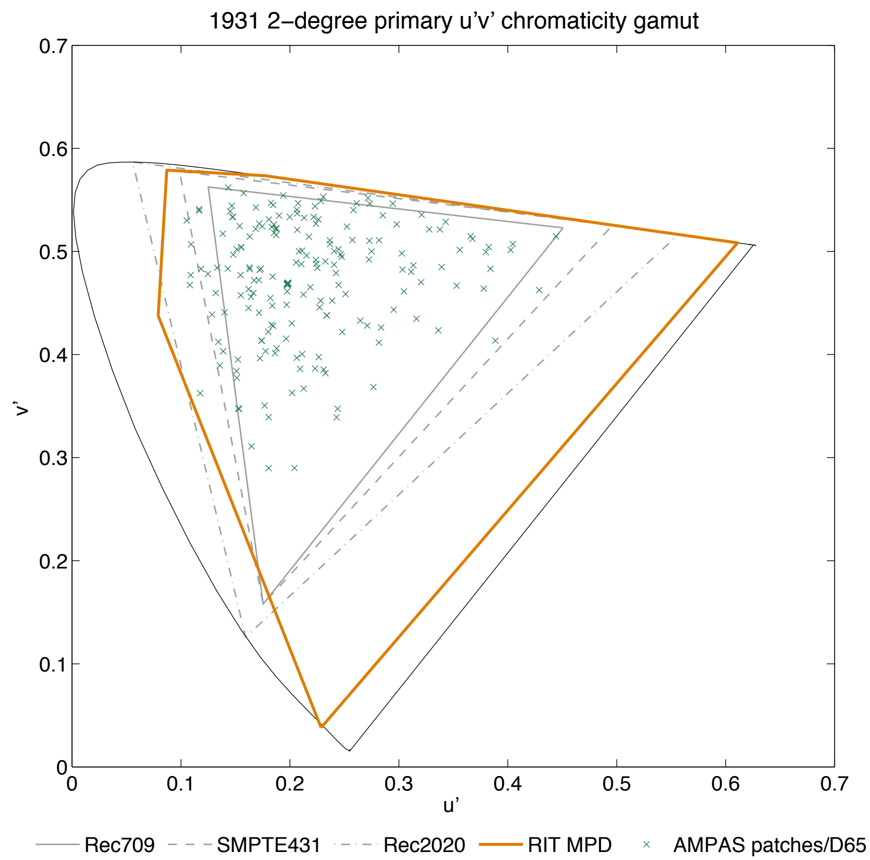
Designed explicitly via optimization in 7 channels to minimize OM_s



Modeling Displays

RIT MPD





Observer Metamerism Simulations

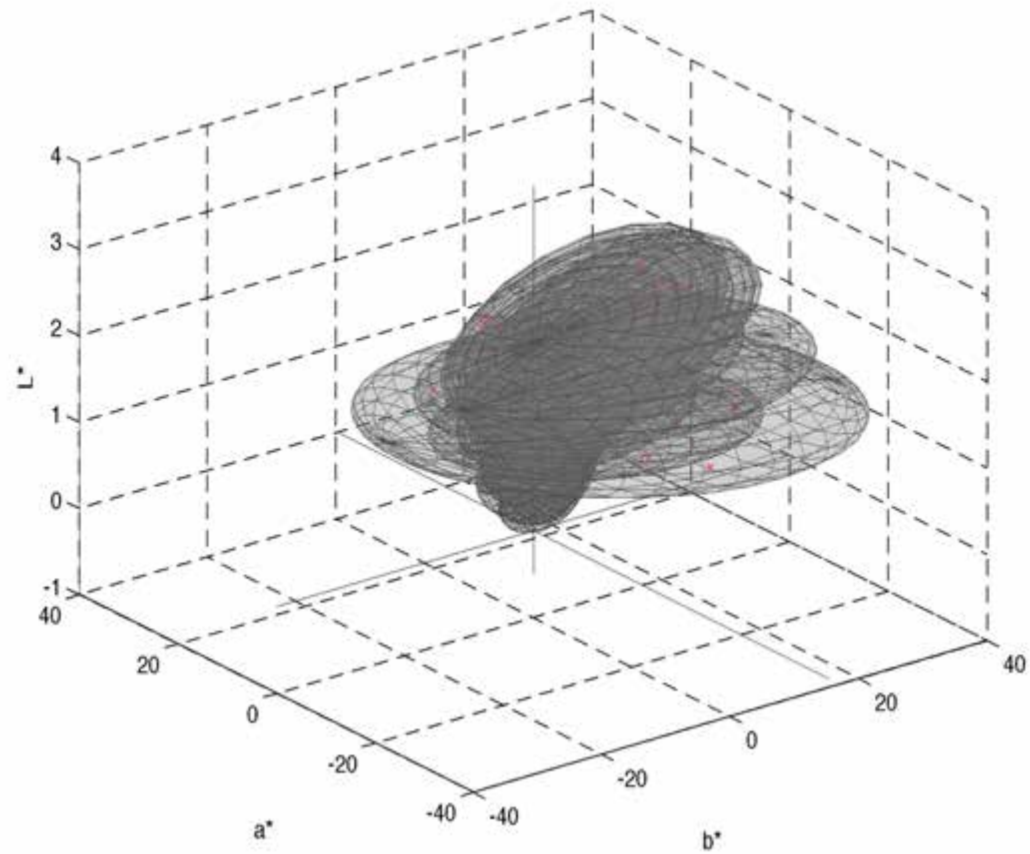
enforcing 1931 2° color match to aim stimuli

CIE D65	**OM_s**	**$OM_{s,var}$**	**max DE00(31)**
MacBeth24			
Sony CRT (Rec. 709)	2.15	2.6E-03	0.44
NEC DLP (P3)	1.83	2.8E-04	0.00
Panasonic DLP (P3)	2.49	1.0E-03	0.00
Laser (Rec. 2020)	5.50	2.6E-01	0.00
8 laser	11.61	3.1E+02	0.00
RIT MPD	0.78	6.2E-06	0.00

*NOTE: Extra degrees of freedom used to further minimize OM_s for 8-laser and RIT MPD

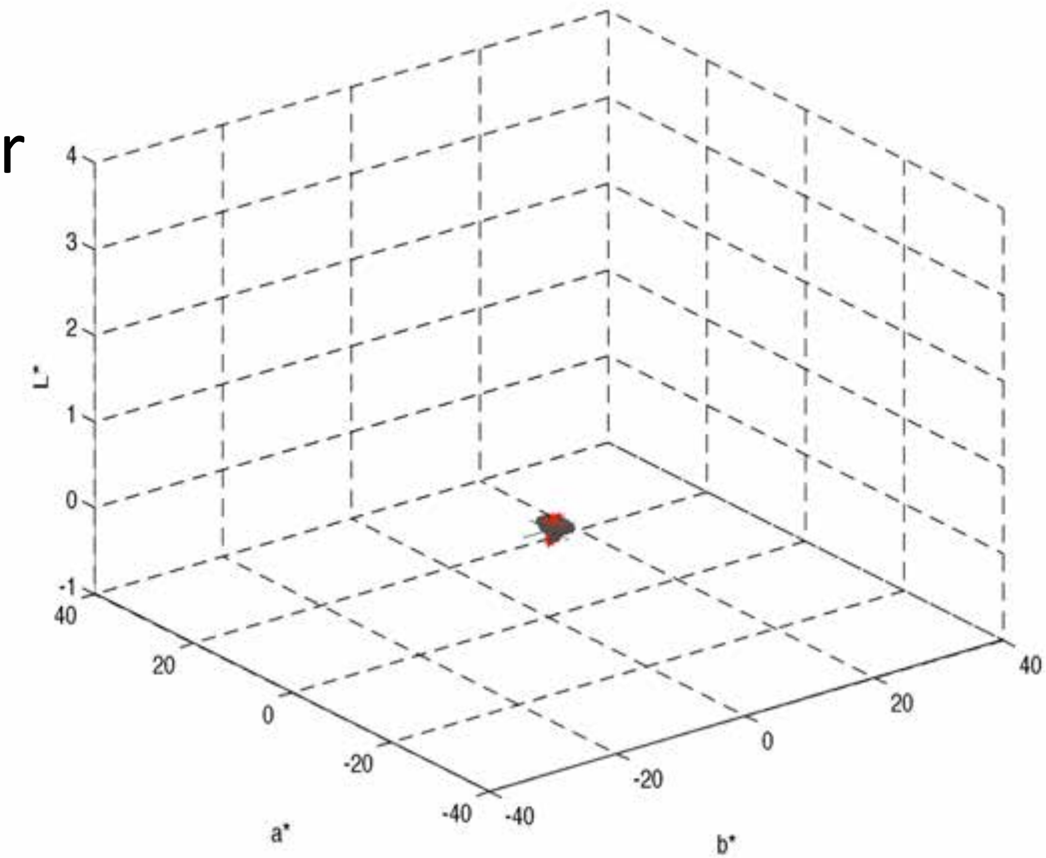
8 Laser $OM_{s,var}$

- Maximum chromaticity gamut
- MacBeth 24
- Illuminated by CIE D65
- 1931 2° color match
- Sarkar/Fedutina CMFs



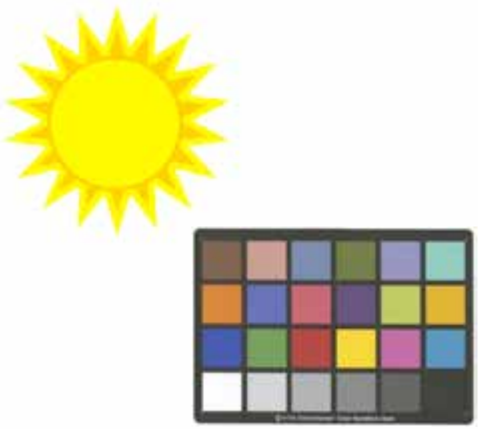
RIT MPD $OM_{s,var}$

- Optimized for Observer Metamerism, OM_s
- MacBeth 24
- Illuminated by CIE D65
- 1931 2° color match
- Sarkar/Fedutina CMFs



Observer Metamerism Simulations

a better 8-laser design?



CIE D65	OM_s	$OM_{s,var}$	max DE00(31)
MacBeth24			
Laser (Rec. 2020)	5.50	2.6E-01	0.00
8 laser	11.61	3.1E+02	0.00
8 laser + Rec. 2020	2.09	3.2E-03	0.00
RIT MPD	0.78	6.2E-06	0.00

*NOTE: Extra degrees of freedom used to further minimize OM_s for 8-laser and RIT MPD

Metamerism in Color Correction

Color image matching experiment (not patches!)

- conventional media (LCD monitor) & laser projector viewed in practical condition (side-by-side comparison)

Microvision SHOWWX+
Laser Pico Projector

Apple Cinema HD LCD

Y. Asano, et al., "Observer variability in Color Image Matching on a LCD monitor and a Laser Projector," Proc. CIC22 (2014)

Metamerism in Color Correction

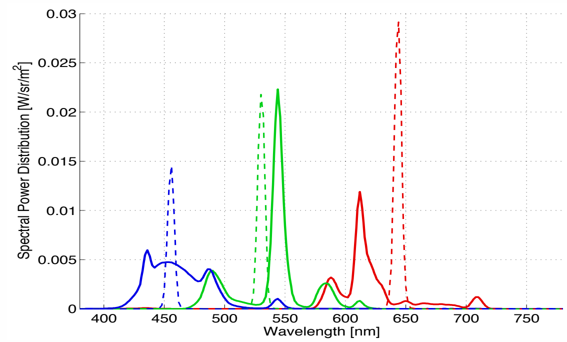


Image: 01

Image: 02

Image: 03

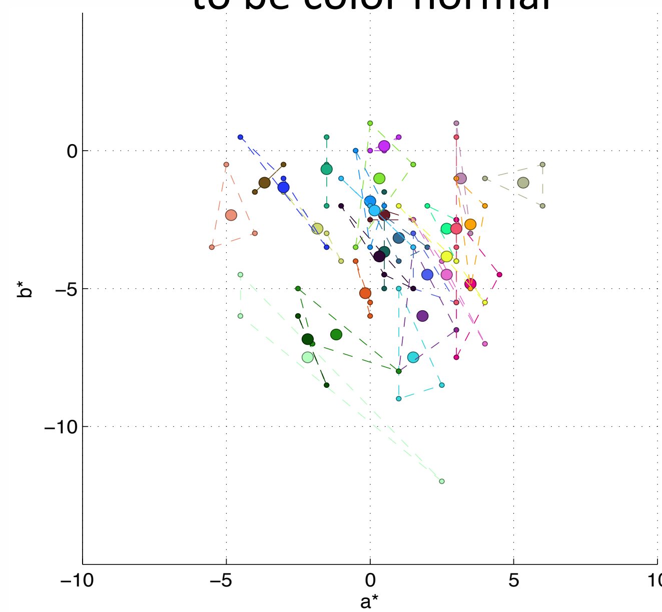
Reference Image on laser display

Global L*a*b* adjustments of LCD image to match

Metamerism in Color Correction

Extreme Observers, Image 01

All observers screened to be color normal

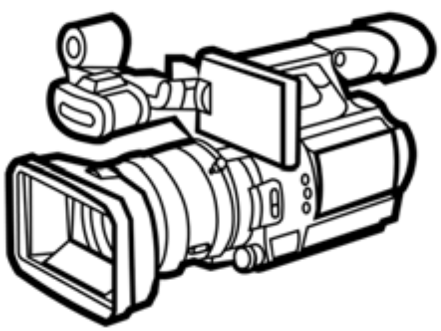


Metamerism in Color Correction

Extreme Observers, Image 03

Ideal Camera Spectral Sensitivity

- Traditional color camera designs operate under presumption of fixed output colorspace



aka, ITU-R Rec. 709

Ideal Camera Spectral Sensitivity

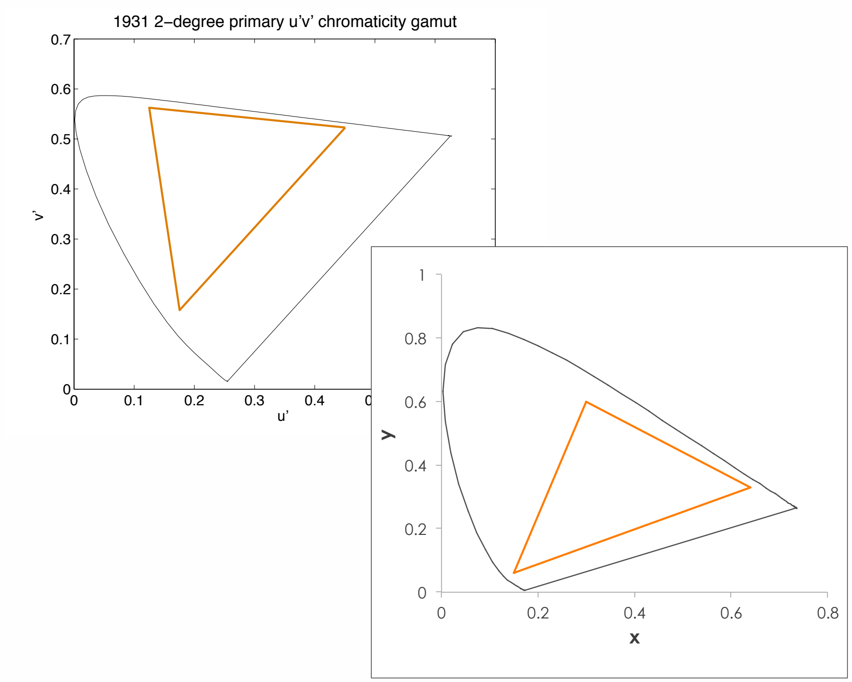
- Start by generating a primary matrix of a display

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \bullet \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{0-1}$$

$$PM = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix}$$

Determined under established white point (D65 for sRGB/709) and typically built presuming luminance normalization

Ideal Camera Spectral Sensitivity



	x	y
Red	0.64	0.33
Green	0.30	0.60
Blue	0.15	0.06
White	0.3127	0.329

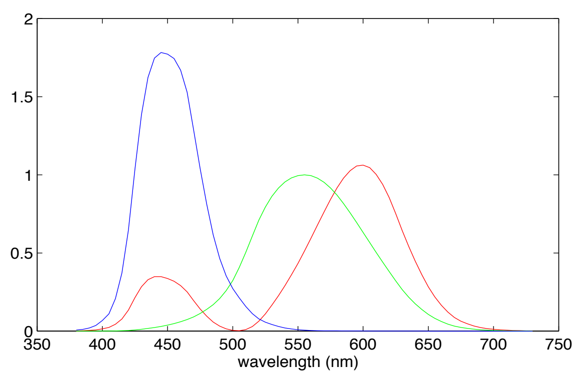
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4125 & 0.3576 & 0.1804 \\ 0.2127 & 0.7152 & 0.0722 \\ 0.0193 & 0.1191 & 0.9502 \end{bmatrix} \bullet \begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix}_{0-1}$$

ITU-R Rec. 709 / IEC 61966-2-1 “sRGB”

Ideal Camera Spectral Sensitivity

Enforce the Luther condition in camera design for exact colorimetric reproduction

$$\begin{bmatrix} \overline{r_{\lambda 1}} & \overline{g_{\lambda 1}} & \overline{b_{\lambda 1}} \\ \dots & \dots & \dots \\ \overline{r_{\lambda n}} & \overline{g_{\lambda n}} & \overline{b_{\lambda n}} \end{bmatrix}^T = [PM]^{-1} \begin{bmatrix} \overline{x_{\lambda 1}} & \overline{y_{\lambda 1}} & \overline{z_{\lambda 1}} \\ \dots & \dots & \dots \\ \overline{x_{\lambda n}} & \overline{y_{\lambda n}} & \overline{z_{\lambda n}} \end{bmatrix}^T$$

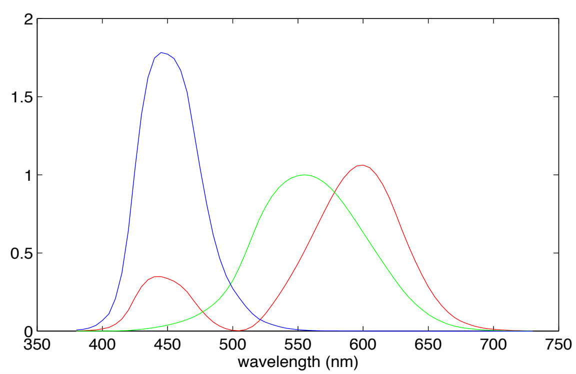


1931 2° standard observer

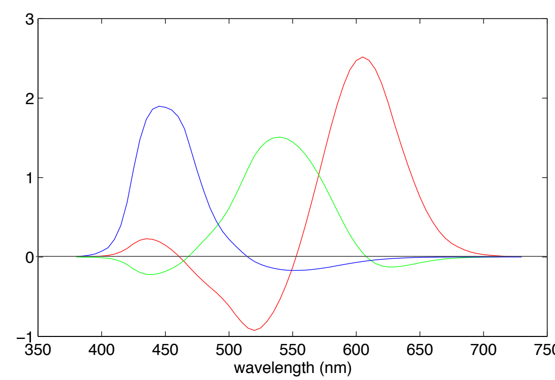
Ideal Camera Spectral Sensitivity

Enforce the Luther condition in camera design for exact colorimetric reproduction

$$\begin{bmatrix} \overline{r}_{\lambda 1} & \overline{g}_{\lambda 1} & \overline{b}_{\lambda 1} \\ \cdots & \cdots & \cdots \\ \overline{r}_{\lambda n} & \overline{g}_{\lambda n} & \overline{b}_{\lambda n} \end{bmatrix}^T = [PM]^{-1} \begin{bmatrix} \overline{x}_{\lambda 1} & \overline{y}_{\lambda 1} & \overline{z}_{\lambda 1} \\ \cdots & \cdots & \cdots \\ \overline{x}_{\lambda n} & \overline{y}_{\lambda n} & \overline{z}_{\lambda n} \end{bmatrix}^T$$



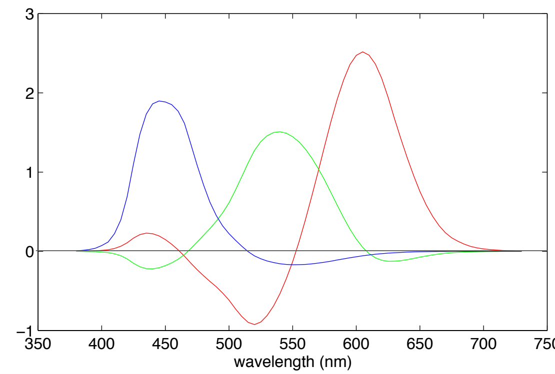
1931 2° standard observer



Rec. 709 Spectral Sensitivity

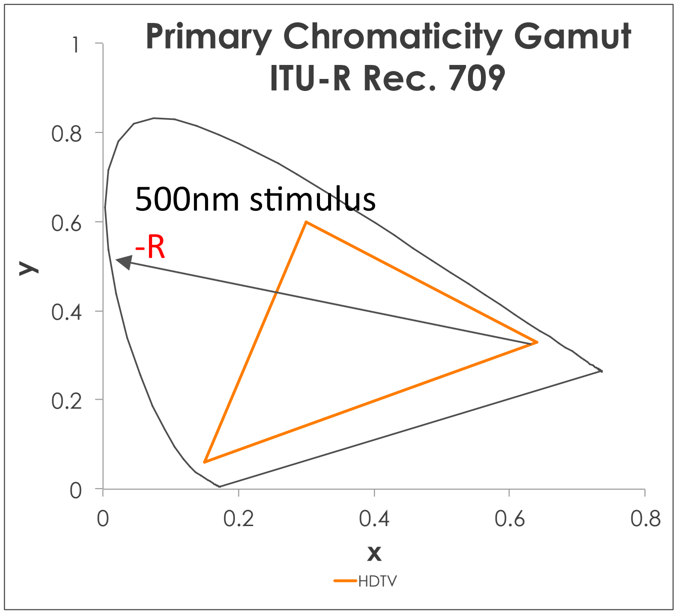
Ideal Camera Spectral Sensitivity

But how can camera physics deliver negative response to incident light?

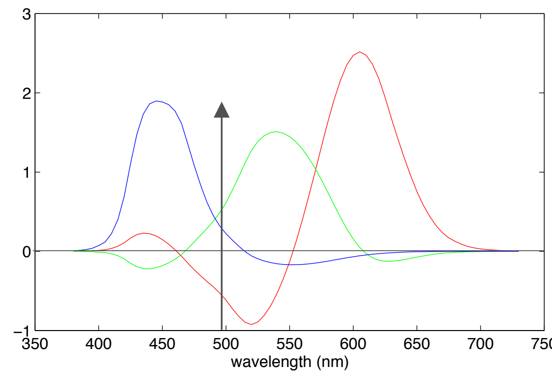


Rec. 709 Spectral Sensitivity

Ideal Camera Spectral Sensitivity

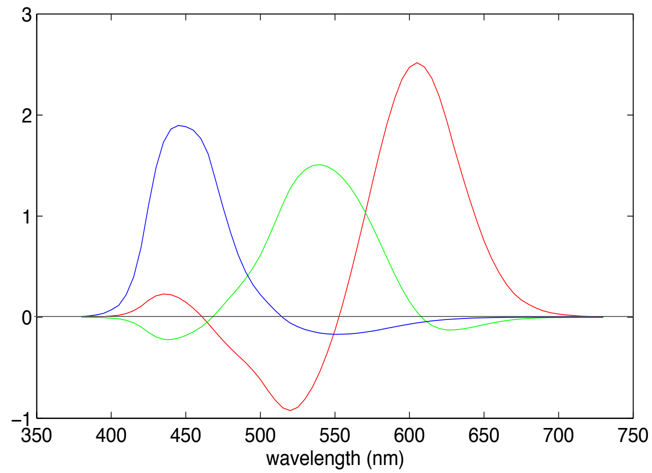


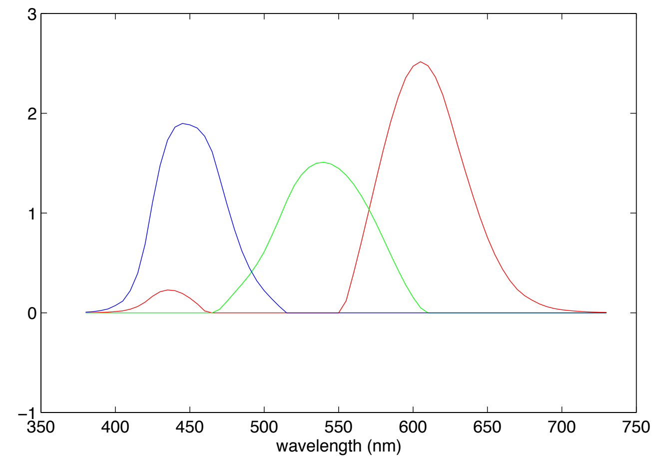
It can't – this is a mathematical idealization and results from the display colorspace being smaller gamut than the spectral locus



Rec. 709 Spectral Sensitivity

How Do We Actually Build This?

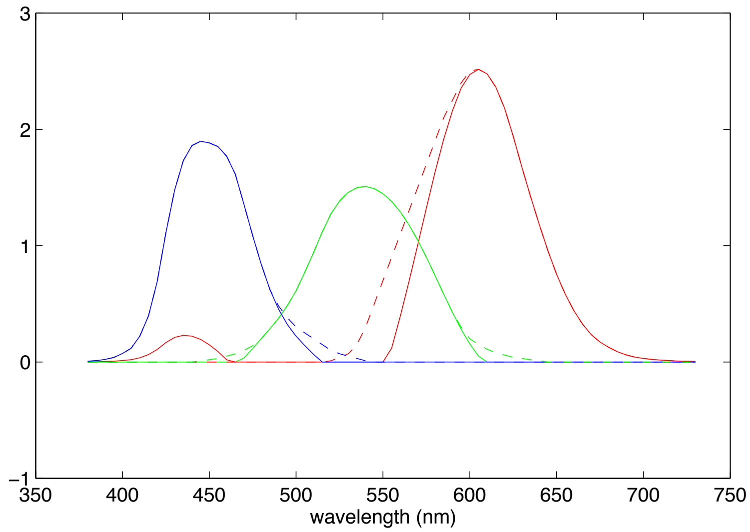




At this point, there are a lot of strategies to consider…

…we could chop off the negative parts…

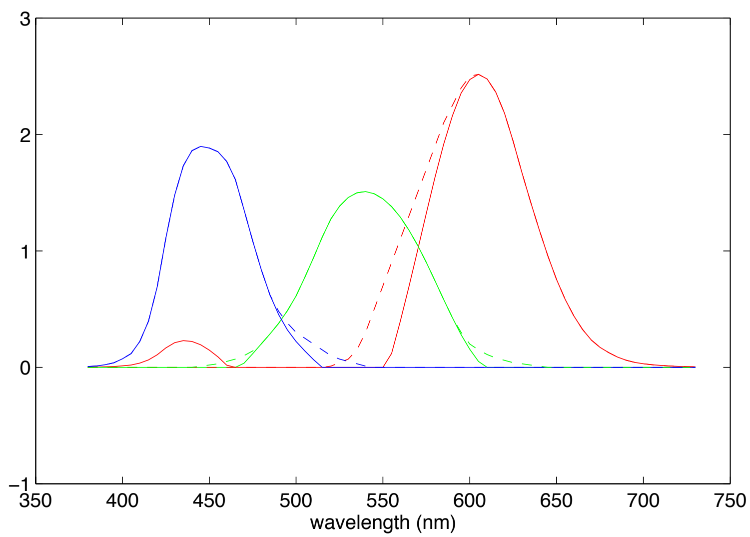
Ideal Camera Spectral Sensitivity



…but we also might need to smooth the edges we just chopped off to reflect the reality of available color filter array materials

We might also compromise shape to ensure minimum quantum detection and electronic noise!

Ideal Camera Spectral Sensitivity

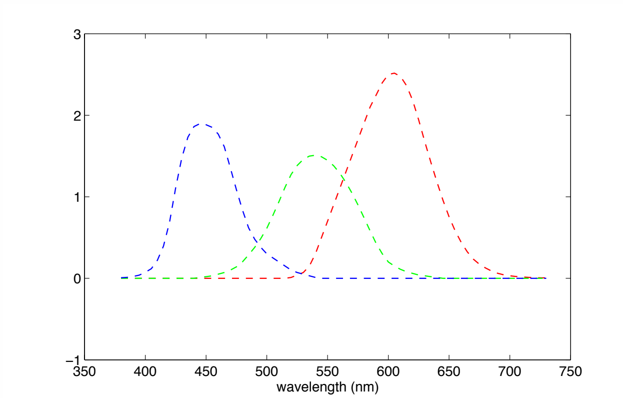


We have now fully perturbed our spectral sensitivity away from the Luther ideal – can we get back to it?

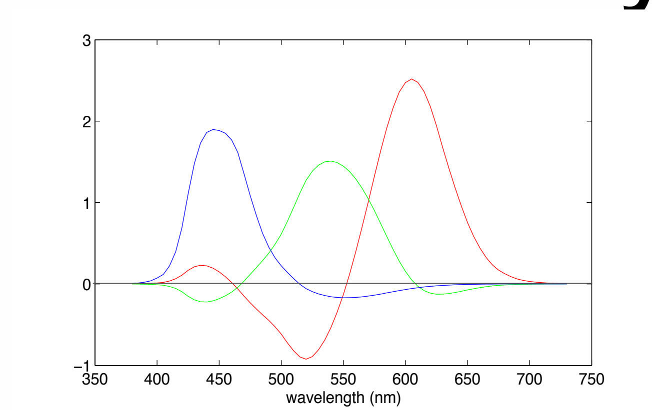
We can try optimizing a linear (or other) transform

We can try doing this with the spectral sensitivity curves themselves (typically a bad idea!) or we can regress a model of important scene colors

Ideal Camera Spectral Sensitivity



$$\begin{bmatrix} c_1 & c_2 & c_3 \\ c_4 & c_5 & c_6 \\ c_7 & c_8 & c_9 \end{bmatrix}_{SS\_opt}$$



$$\begin{bmatrix} c'_1 & c'_2 & c'_3 \\ c'_4 & c'_5 & c'_6 \\ c'_7 & c'_8 & c'_9 \end{bmatrix}_{patches\_opt}$$

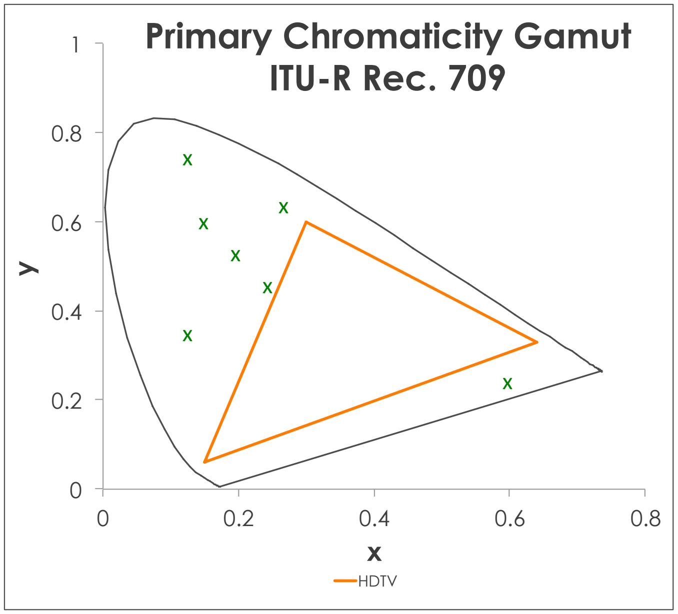
Ideal Camera Spectral Sensitivity

Parameters for optimization

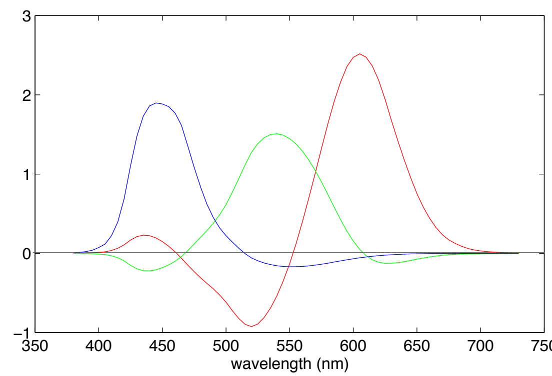
1. Which patches do you regress? Are some more important than others? Do you restrict optimization to patches within the display gamut? What illumination?
2. Optimization metric? Colorimetry or Color Appearance? CIELAB? CIECAM?
3. Transform complexity?

$$\begin{bmatrix} c'_1 & c'_2 & c'_3 \\ c'_4 & c'_5 & c'_6 \\ c'_7 & c'_8 & c'_9 \end{bmatrix}_{patches\_opt}$$

Ideal Camera Spectral Sensitivity



Of course, if we actually re-predict the Luther response, out-of-gamut scene colors WILL STILL give negative R or G or B camera signals



Rec. 709 Spectral Sensitivity

Ideal Camera Spectral Sensitivity

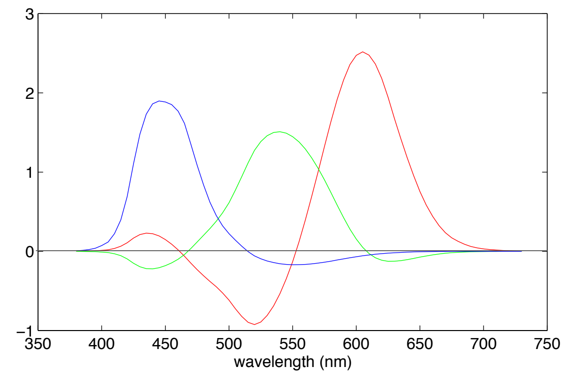
There are solution options that work seamless for direct-displayed color…

1. Constrain the optimization matrix to not permit creation of negative effective spectral sensitivity (trading colorimetric accuracy)

2. Employ in-camera processing to clip or intelligently gamut-map negative RGB

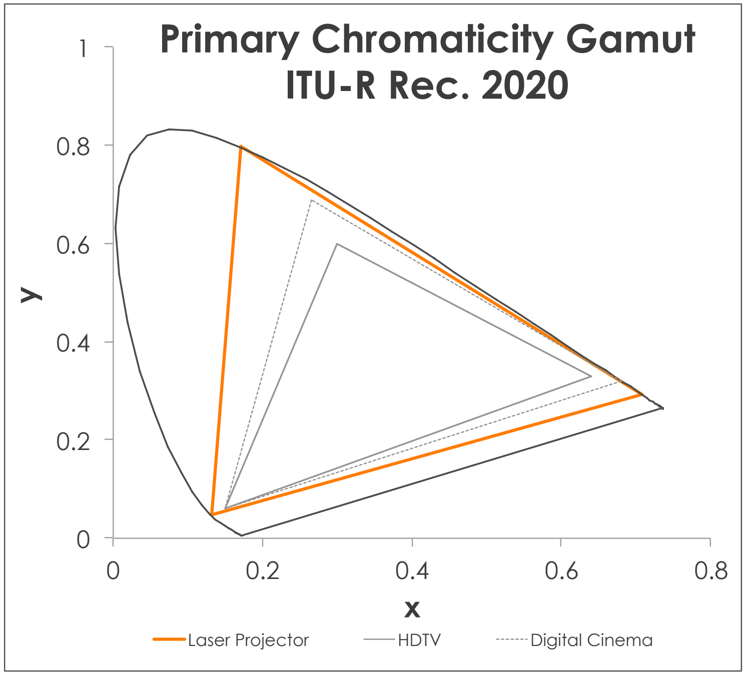
…or an option that preserves scene colorimetry by <u>encoding</u> negative values but requires intelligent display processing

3. xvYCC, ITU-R Rec.1361, etc.



Rec. 709 Spectral Sensitivity

Ideal Camera Spectral Sensitivity



	x	y	λ (nm)
Red	0.708	0.292	630
Green	0.170	0.797	532
Blue	0.131	0.046	467
White	0.3127	0.329	----

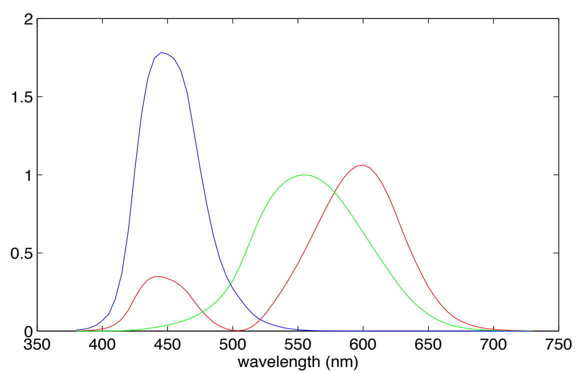
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.6370 & 0.1446 & 0.1689 \\ 0.2627 & 0.6780 & 0.0593 \\ 0.0 & 0.0281 & 1.0610 \end{bmatrix} \bullet \begin{bmatrix} R_{2020} \\ G_{2020} \\ B_{2020} \end{bmatrix}_{0-1}$$

Ideal Camera Spectral Sensitivity

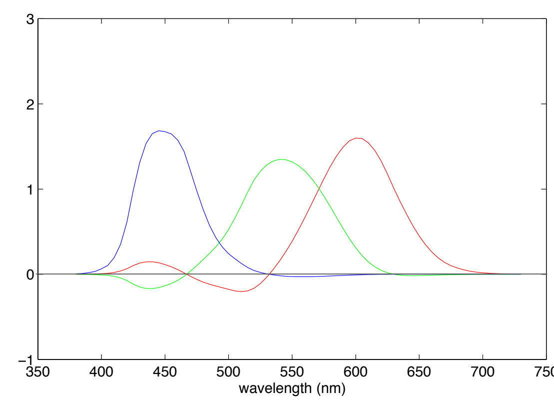
Bigger display gamuts have a lot less negative issues!

Luther optimization should be better

$$\begin{bmatrix} \overline{r}_{\lambda 1} & \overline{g}_{\lambda 1} & \overline{b}_{\lambda 1} \\ \cdots & \cdots & \cdots \\ \overline{r}_{\lambda n} & \overline{g}_{\lambda n} & \overline{b}_{\lambda n} \end{bmatrix}^T = [PM]^{-1} \begin{bmatrix} \overline{x}_{\lambda 1} & \overline{y}_{\lambda 1} & \overline{z}_{\lambda 1} \\ \cdots & \cdots & \cdots \\ \overline{x}_{\lambda n} & \overline{y}_{\lambda n} & \overline{z}_{\lambda n} \end{bmatrix}^T$$

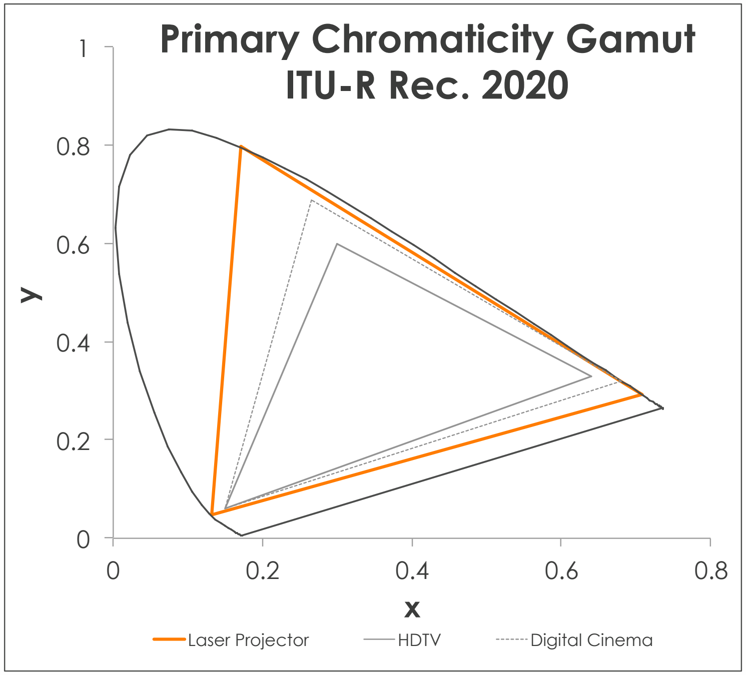


1931 2° standard observer



Rec. 2020 Spectral Sensitivity

Camera Gamut?

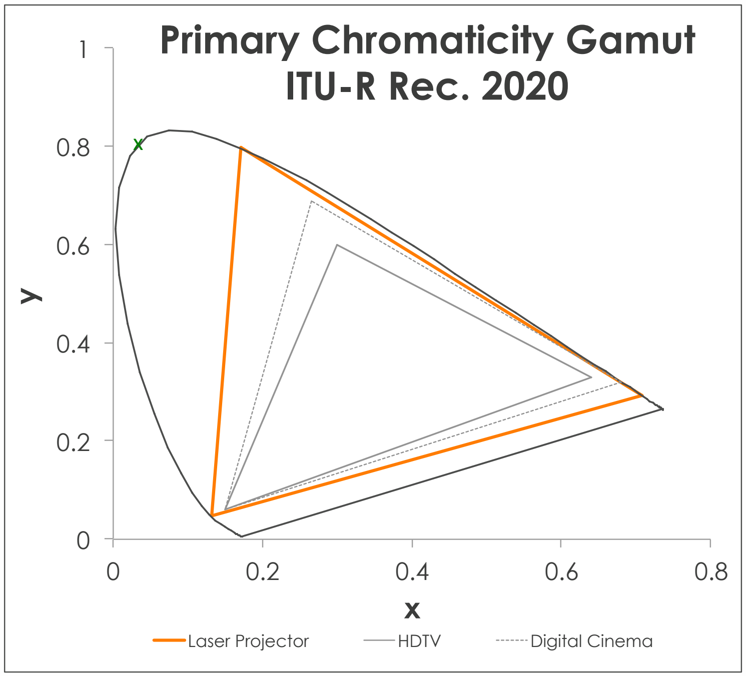


Some camera spec sheets seem to tout Rec2020 mode means they have a bigger camera gamut?

My triangle is bigger than yours?

My camera can "see" more colors than yours?

Camera Gamut?

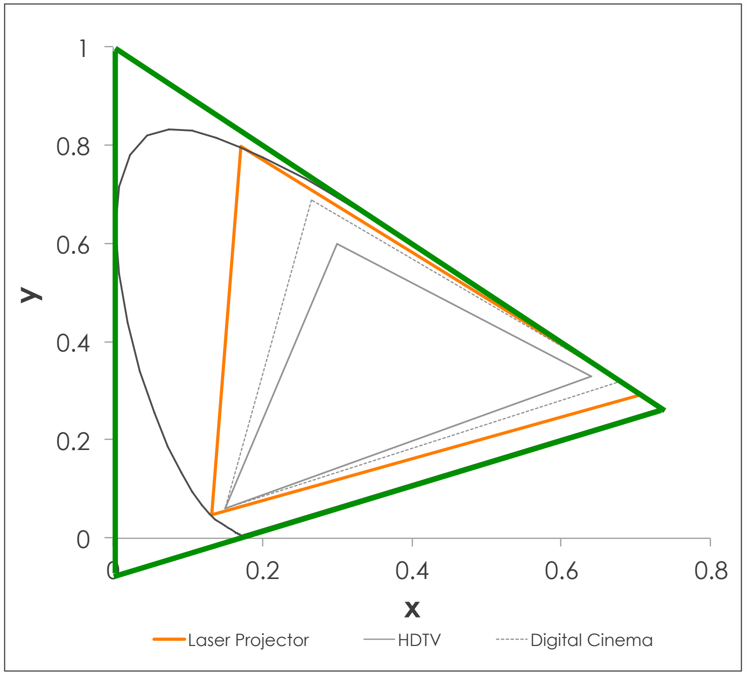


Gamut is a term appropriate to displays only! Color scientists don't talk about camera gamuts

Go ahead and take a picture with your phone – can you see my laser pointer?

When showing a chromaticity diagram for a camera, always interpret it as an optimized encoding space for the RGB color of the display (with all of the requisite constraints we've discussed)

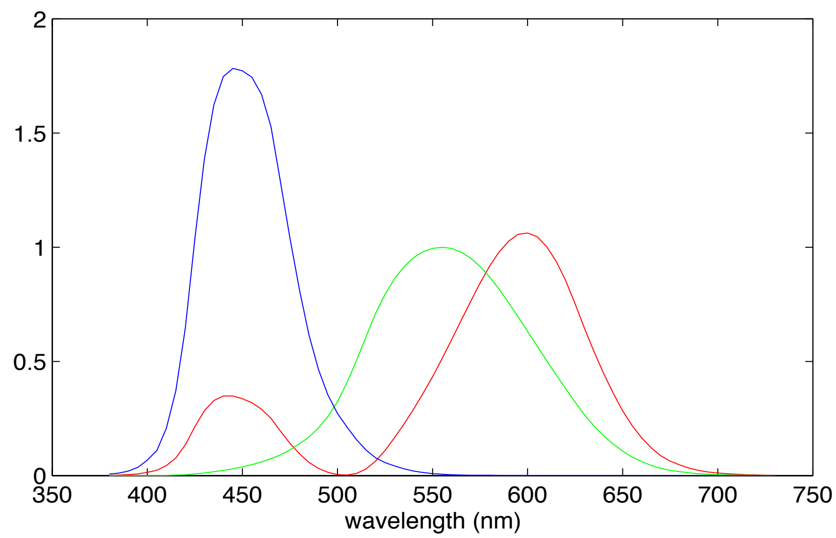
Camera Gamut?



If you really want to compare triangle sizes, consider that the Academy's ACES system provides a recipe for turning ANY camera into a full XYZ encoder!

With controlled optimization errors inferred of course if the camera isn't a Luther design

Camera Gamut?

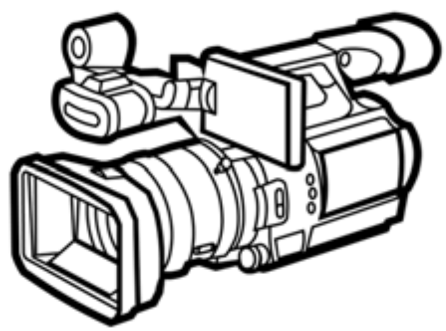


Or why not simply produce a camera with spectral sensitivities equivalent to the 1931 2° color-matching functions?

Or a linear combination thereof?

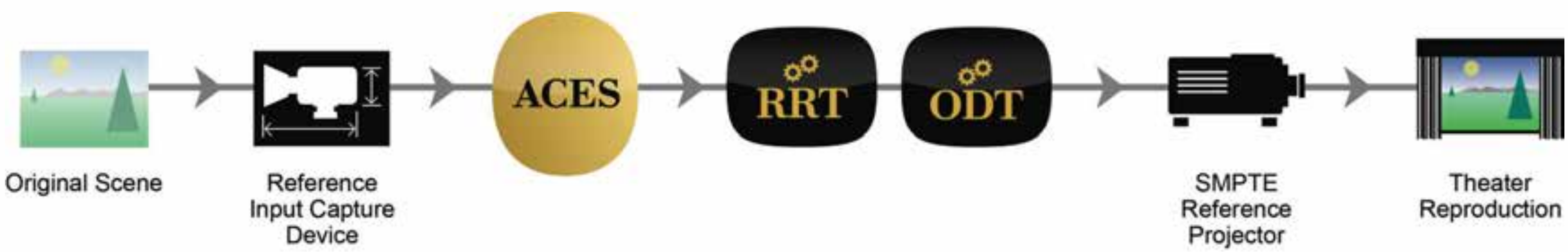
Do We Want a Luther Camera?

For direct-to-display workflows, it is the typical starting point in design



Do We Want a Luther Camera?

For workflows with extensive display image processing available, it can be extremely useful



Consider ACES scene-referred colorimetric encoding combined with reference rendering output

Historical Color Preference?

What about specific color reproduction preference?

Multiple studies at Kodak confirmed 100% accurate scene colorimetry is a fairly unpopular goal in motion media design

Is the neg-to-print "film look" actually a better aim? It does have the benefit of decades of in-the-field refinement

Film Look Colorspaces

LOG and RAW modes in cinema cameras are partly intended to permit seamless integration into the printing density ("film-look") paradigm of early digital intermediate

Thomson Viper and the "filmstream" mode (2004)

Is Colorimetry Color Appearance?

We must also acknowledge that human color vision is so much more than matching points on a chromaticity diagram between scene and screen

Stevens Effect: A screen luminance lower than scene luminance will lead to a low contrast perception despite equivalent relative colorimetry

Surround Illumination: Viewing content in dim or dark surround will lead to a low contrast perception despite equivalent relative colorimetry

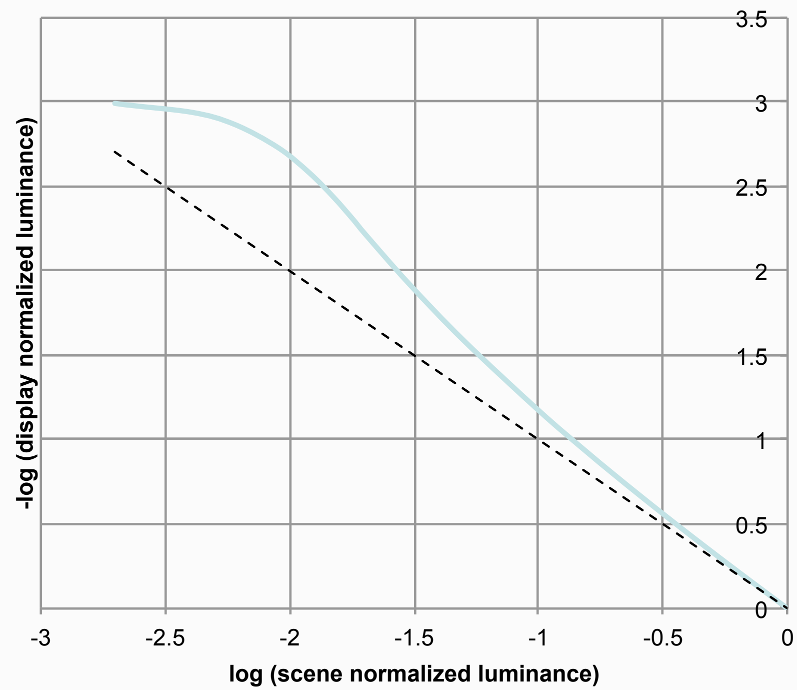
Is Colorimetry Color Appearance?

Hunt Effect: A screen luminance lower than scene luminance will lead to a low colorfulness perception despite equivalent relative colorimetry

White Balance & Chromatic Adaptation: Camera RGB is not the correct colorspace to mimic human chromatic adaptation to differing scene whites

Tone Rendering Beyond Colorimetry

We technically need HDR and wide color gamut displays just to accurately render the equivalent appearance of our typical scenes!



1000:1 scene mapped from Rec. 709 camera onto 1000:1 sRGB display

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NAVIGATING BIG COLOR