Versatile Color Space for Large Color Volumes

February 24, 2016

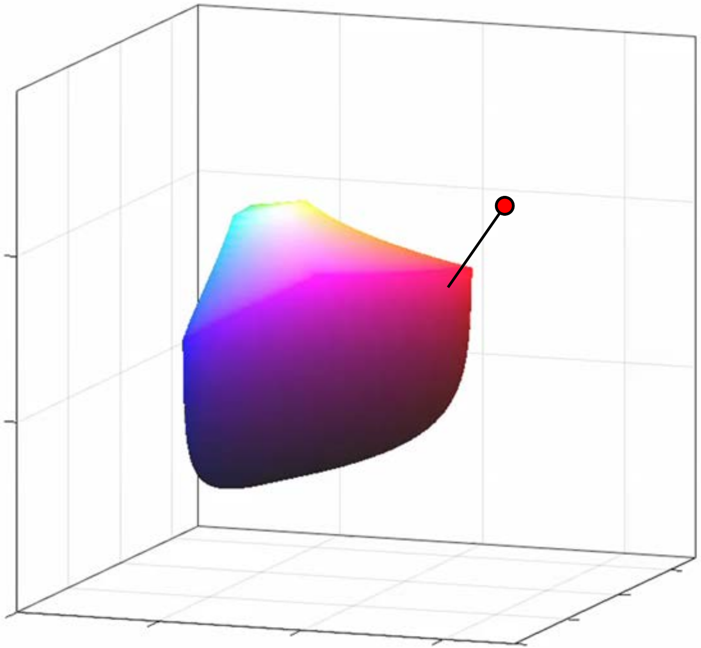
Applied Vision Science Group

Dolby Laboratories

Television Capabilities Today

- Standard Color Volume
  - ITU-R BT.709 Color Primaries
  - Standard Dynamic Range
- Good Old $Y'C_BC_R$
  - Separates chroma from luma (1)
  - Simple complexity
- Televisions are evolving
  - High dynamic range (HDR)
  - Wide primaries →

LARGE COLOR VOLUME

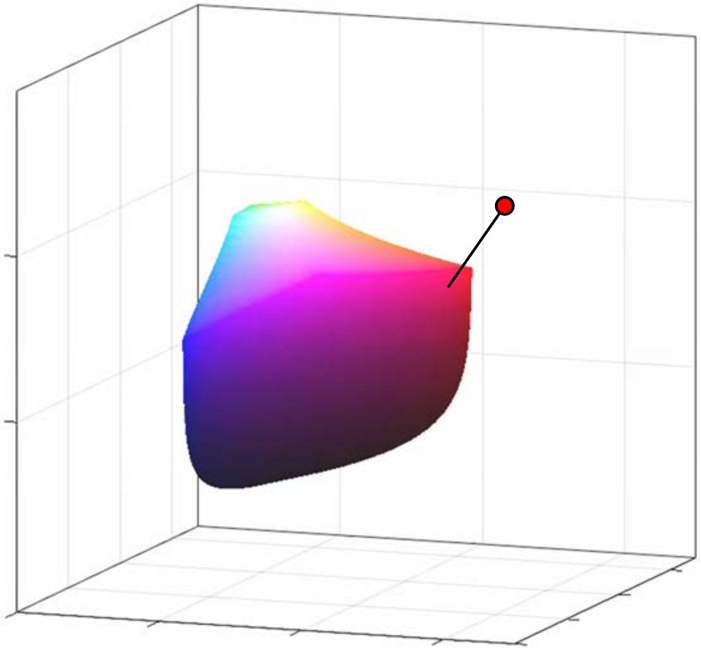


Television Capabilities Today

Need to transform between color volumes (Color Volume Mapping)

- Luminance Changes
- Hue Changes
- Saturation Changes

Starting to see shortcomings of $Y'C'_BC'_R$



Color Volume Mapping: Desaturation

1. Start with saturated color in $Y'C'_BC'_R$
2. Desaturate in increments of 25%
3. Compare hue and luminance rendering

$Y'C'_BC'_R$ Saturation Ramp:

0%	25%	50%	75%	100%
6 cd/m^2	7 cd/m^2	8 cd/m^2	12 cd/m^2	20 cd/m^2

Chroma Subsampling

Subsample Test:

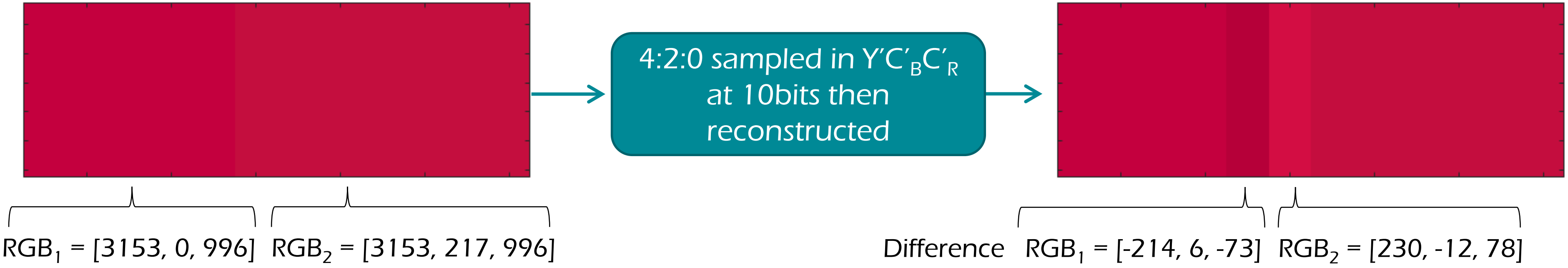
1. Two similar colors (ΔE=0.1)
2. Subsample and reconstruct in $Y'C'_BC'_R$

$Y'C'_BC'_R$: <u>non-constant luminance space</u>

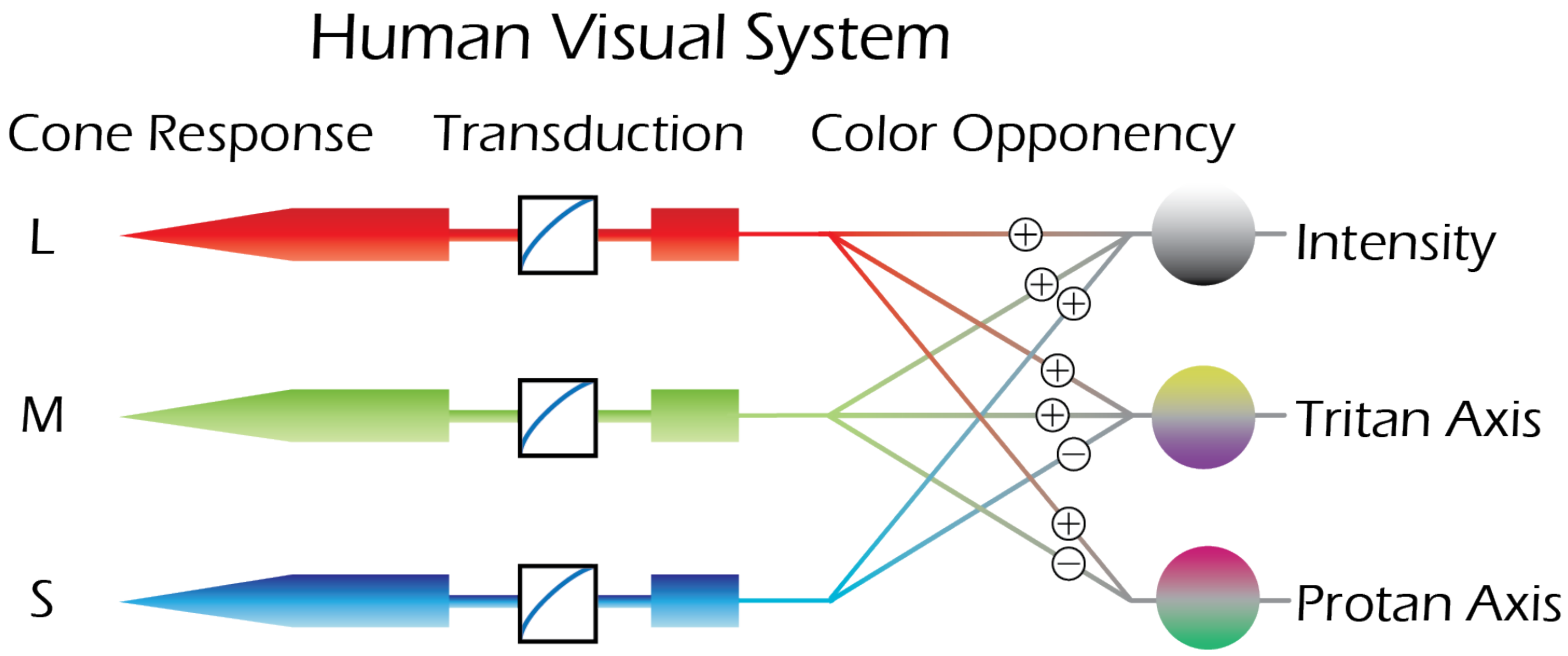
- Errors introduced in chroma (quantization, subsampling, compression) spread to luminance and become more visible (ΔE=4.0)

Original 2 Colors
(Below Visible Threshold):

$Y'C'_BC'_R$
(Above Visible Threshold):



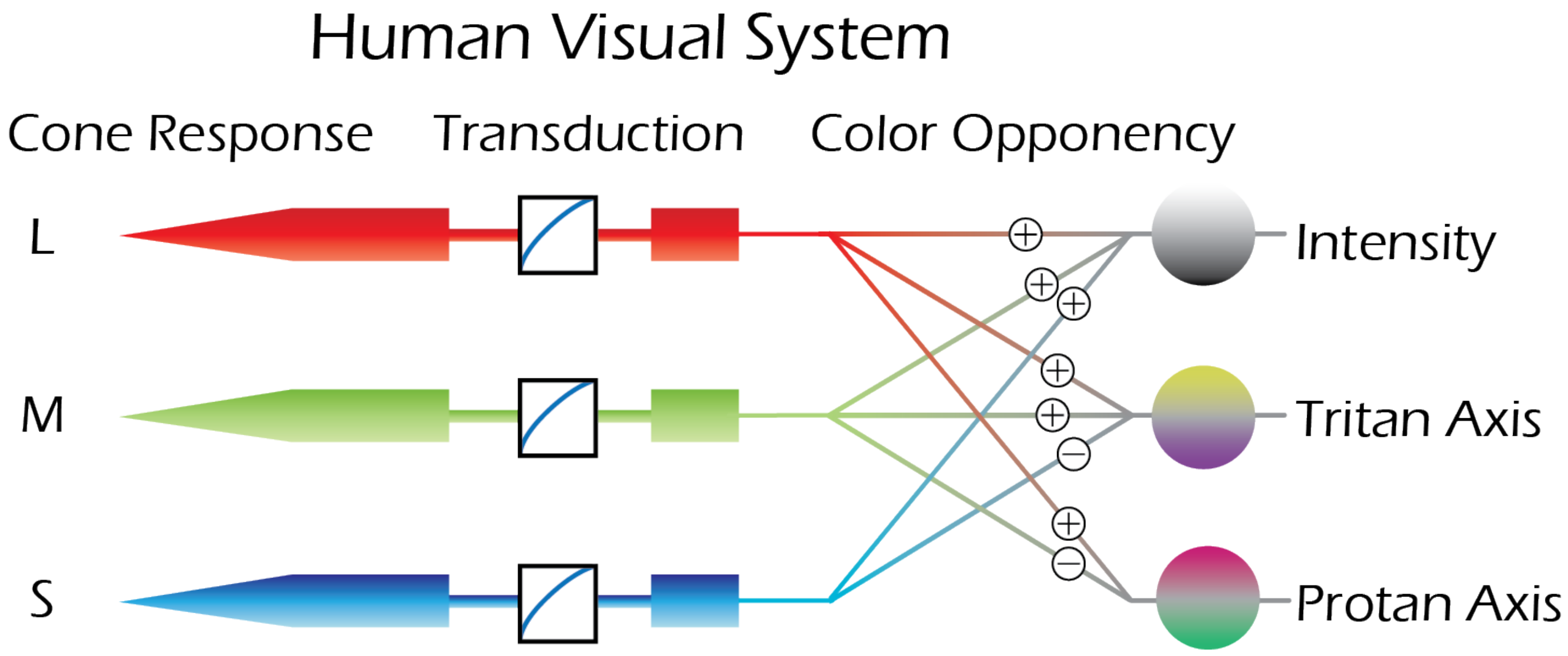
What Now?


Human Visual System
Cone Response
Transduction
Color Opponency
L
M
S
Intensity
Tritan Axis
Protan Axis

IC_TC_P Color Representation

- Better Performance for Large Color Volumes
  - Constant Intensity
  - Constant Hues
  - Perceptually Uniform
  - Improved Baseband Quantization
- Same Operations as $Y'C'_BC'_R$

What Now?



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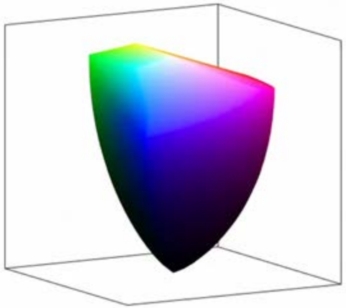
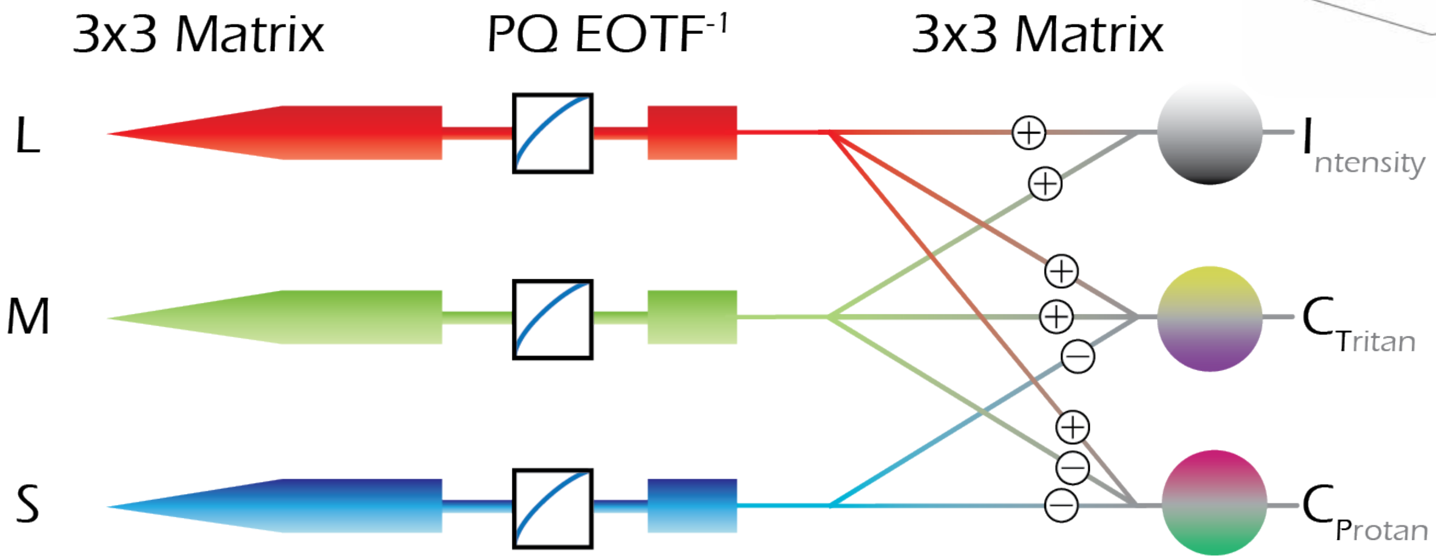


IC_TC_P Color Representation

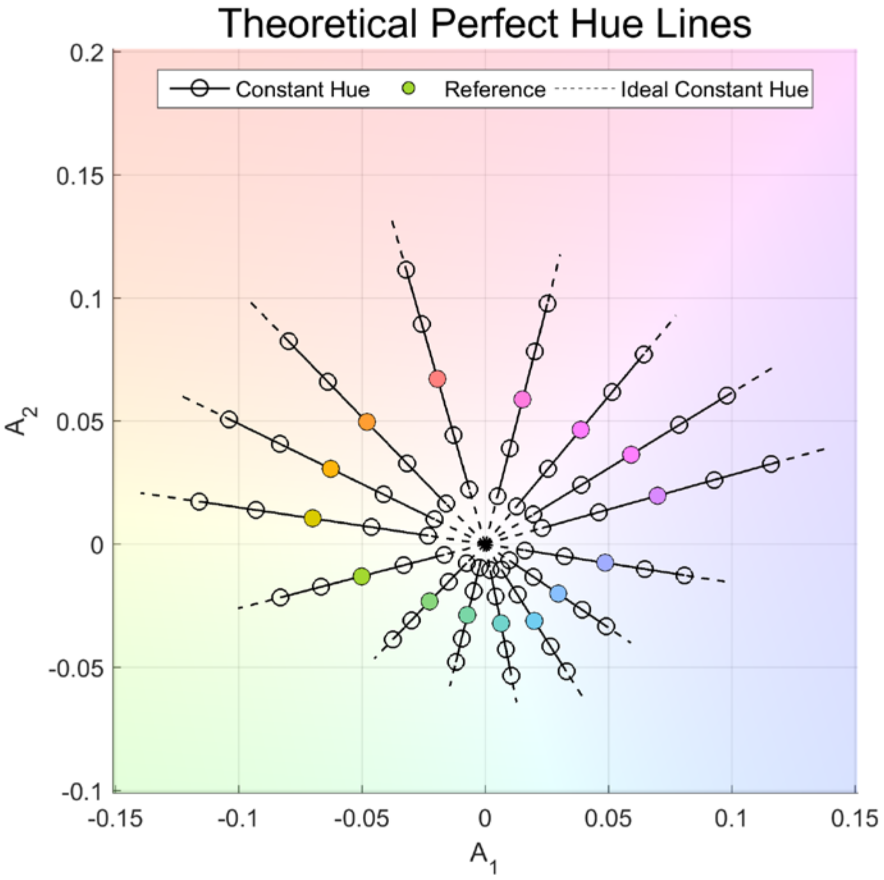


Hue Linearity

- Linear Hue: the hue remains constant as saturation is changed (on right)

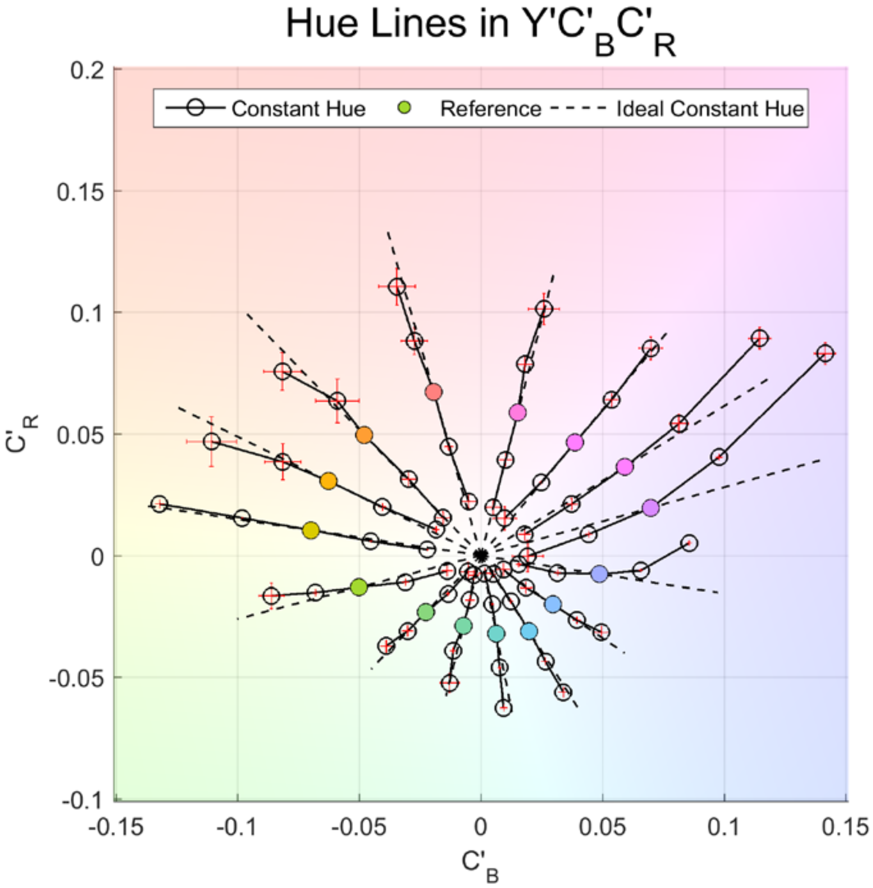
EXPERIMENT:

1. 15 hues matched at 4 saturation levels
2. Adjusted hue of test patch to match
3. Solid lines = Experimental Results
4. Dashed lines = Space Prediction



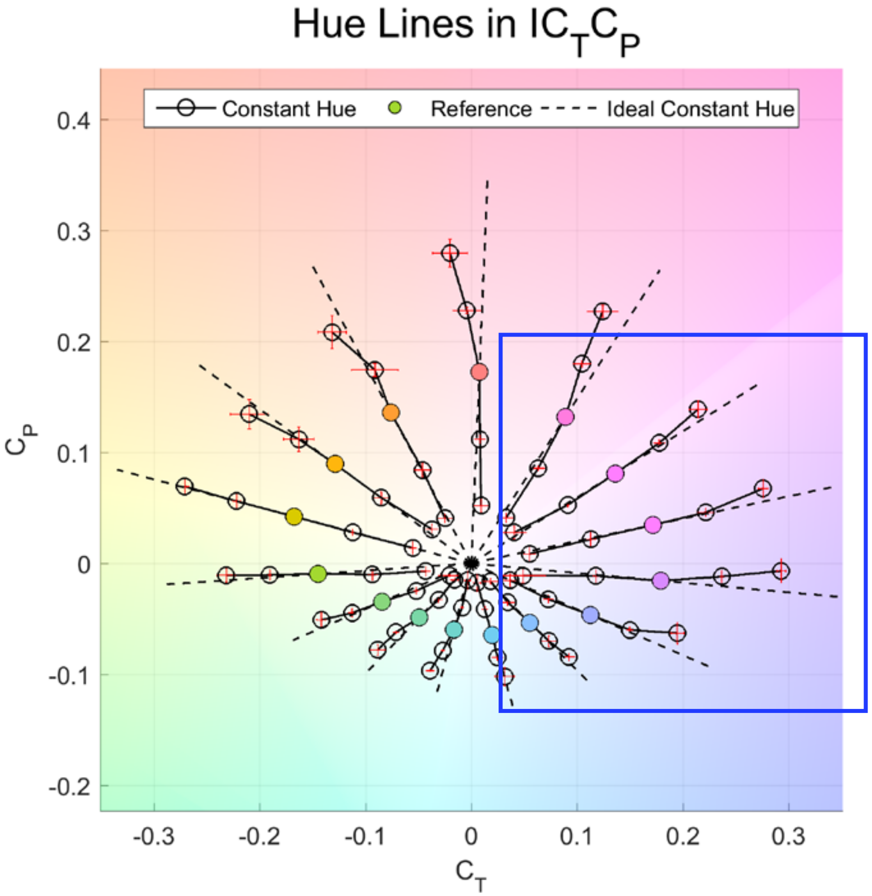
Hue Linearity

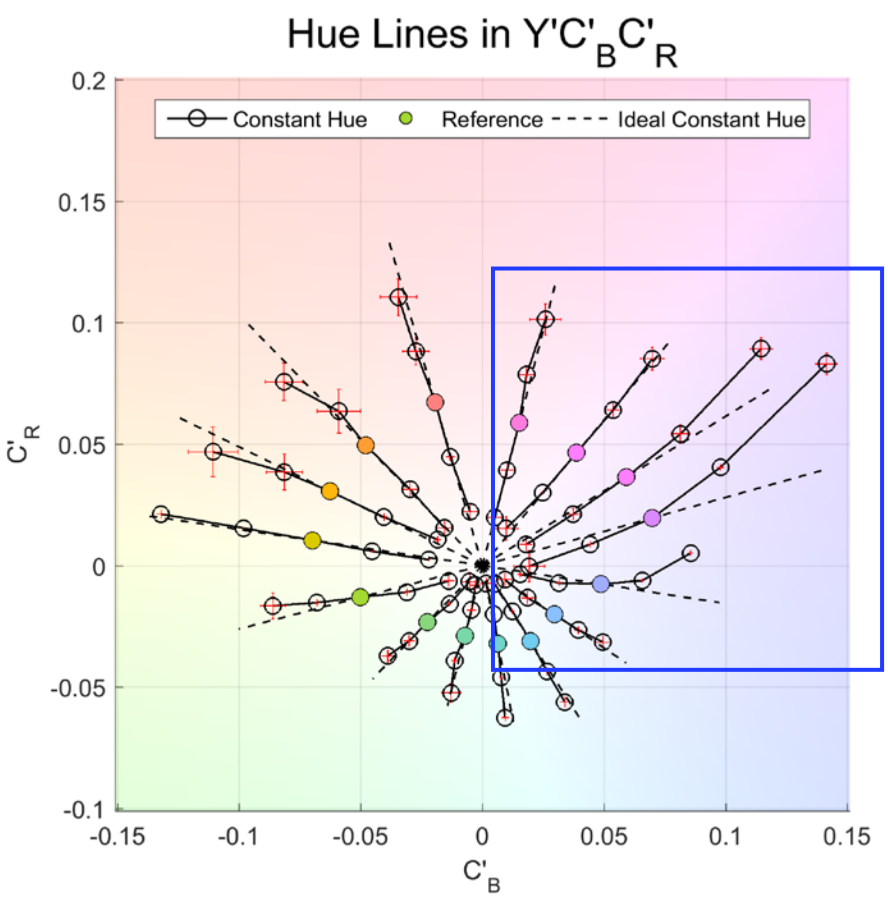
- Linear Hue: the hue remains constant as saturation is changed (on right)
- $Y'C'_BC'_R$: hue deviations greatest in blue
  - Out of context hues created during interpolation

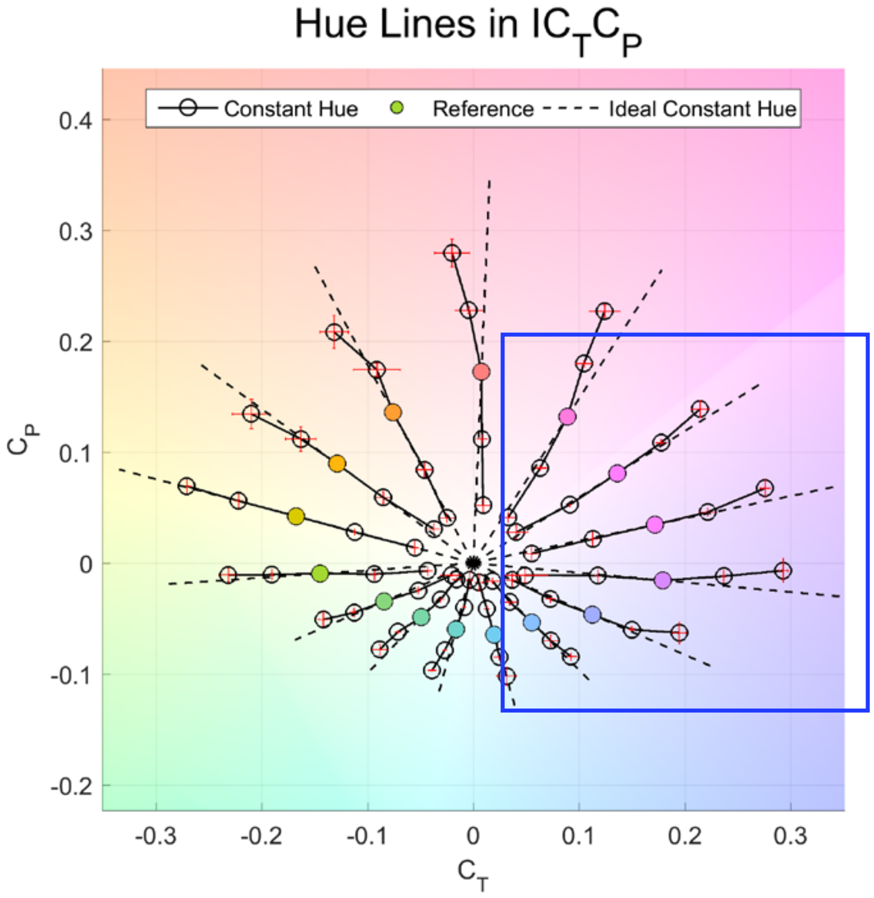


Hue Linearity

- Linear Hue: the hue remains constant as saturation is changed (on right)
- IC_TC_P: designed for hue linearity
  - Allows for simple radius changes when color volume mapping
  - Blending/fading doesn't create hues out of context

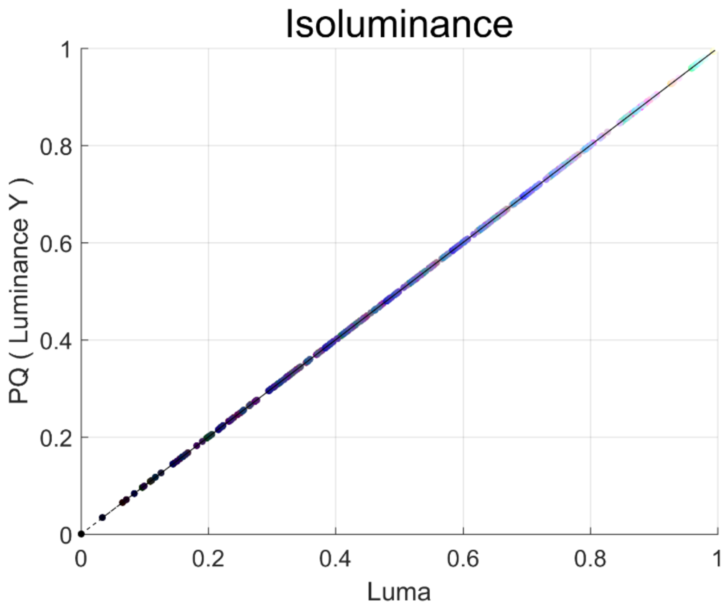



Hue Lines in Y'C'BC'R
Constant Hue
Reference
Ideal Constant Hue
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
C'R
C'B


Hue Lines in ICTCP
Constant Hue
Reference
Ideal Constant Hue
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
CP
CT

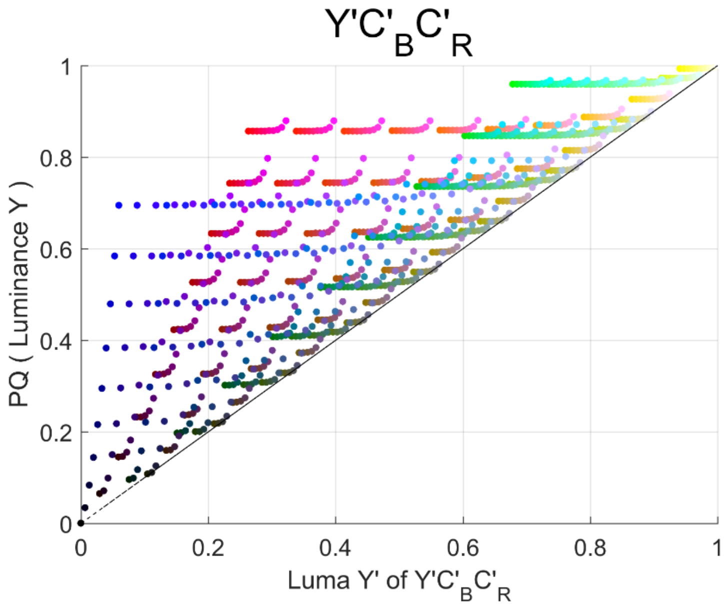
Isoluminance (Constant Intensity)

- Isoluminance: How well Luma corresponds to PQ encoded Luminance Y
  - Perfectly isoluminant space = 1:1 ratio (on right)
  - *Measures how well a color space decorrelates luma and chroma*



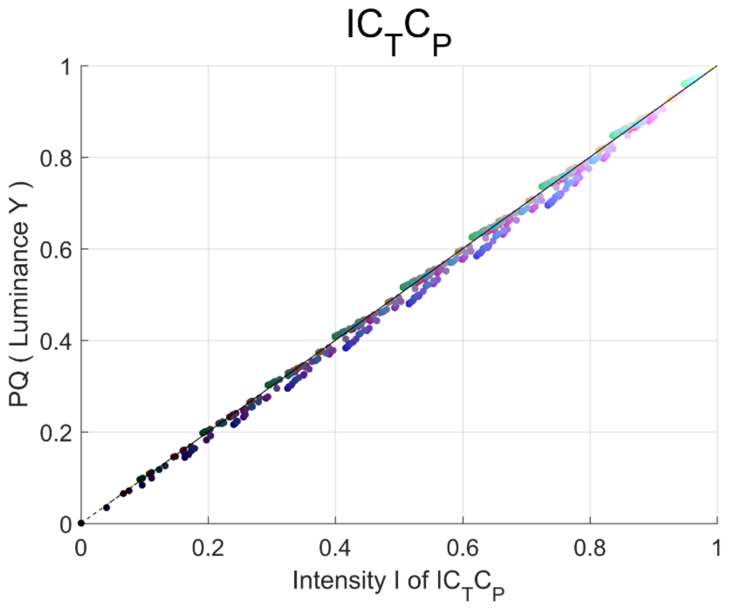
Isoluminance (Constant Intensity)

- Isoluminance: How well Luma corresponds to PQ encoded Luminance Y
- Y′ of $Y'C'_BC'_R$ varies significantly from PQ Luminance Y
- Saturated colors (red and blue especially) are rendered too bright

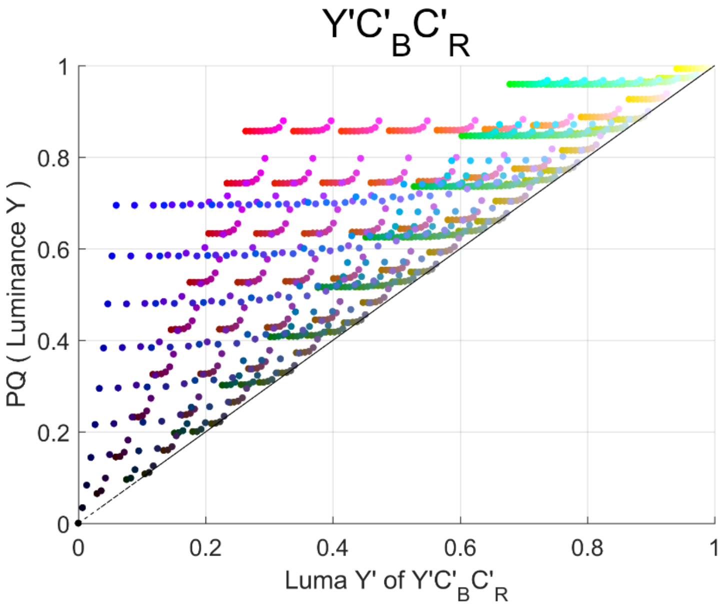


Isoluminance (Constant Intensity)

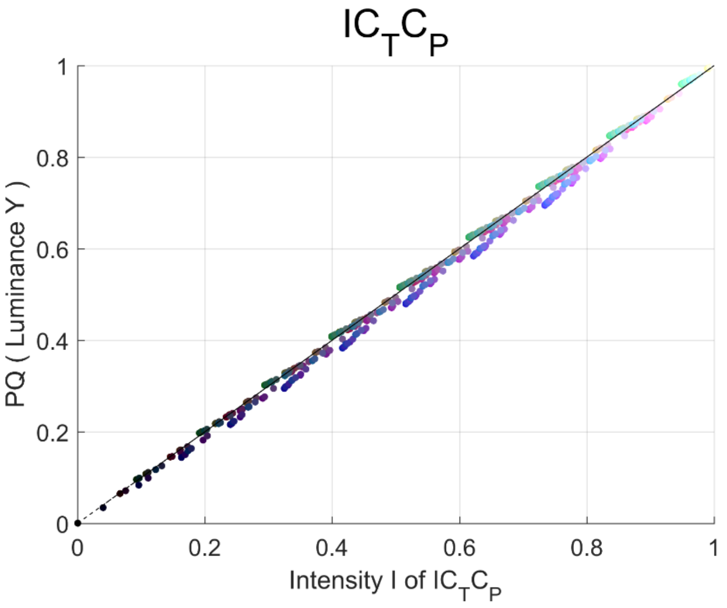
- Isoluminance: How well Luma corresponds to PQ encoded Luminance Y
- I of IC_TC_P corresponds closely to PQ Luminance Y
- IC_TC_P decorrelates Luma and Chroma



Isoluminance (Constant Intensity)



Pearson Correlation = 0.819



Pearson Correlation = 0.998

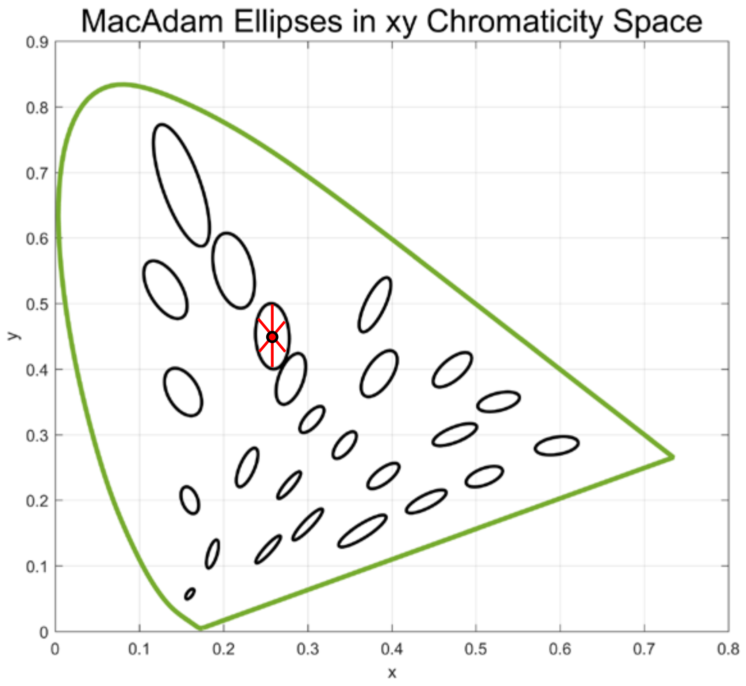
Color Volume Mapping: Desaturation

0%	25%	50%	75%	100%	
6 cd/m^2	7 cd/m^2	8 cd/m^2	12 cd/m^2	20 cd/m^2	$Y'C'_BC'_R$
20 cd/m^2	20 cd/m^2	22 cd/m^2	21 cd/m^2	20 cd/m^2	IC_TC_P

Just Noticeable Difference (JND) Uniformity

MacAdam Ellipses (3) show the JND from the center point of the ellipse

- YCbCr has non-circular ellipses
  - Inefficient use of code words (4)
  - Potential for introducing distortions
    - Chroma subsampling
    - Color Volume Mapping
    - Fading/Blending



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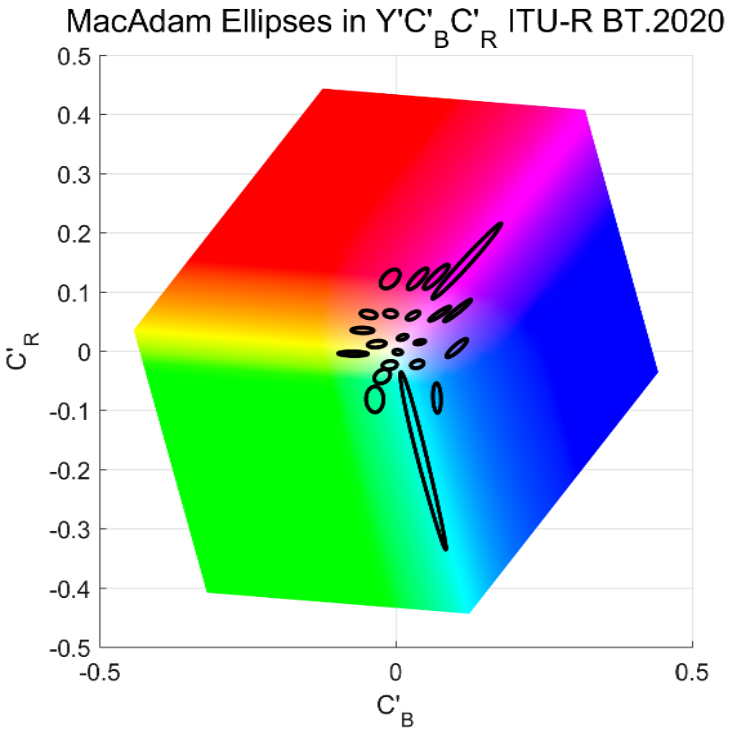

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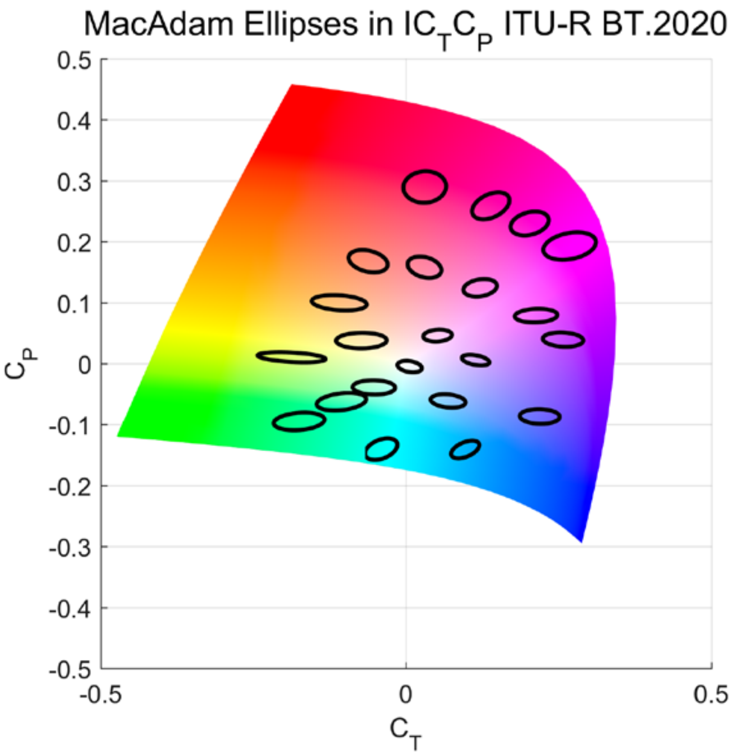
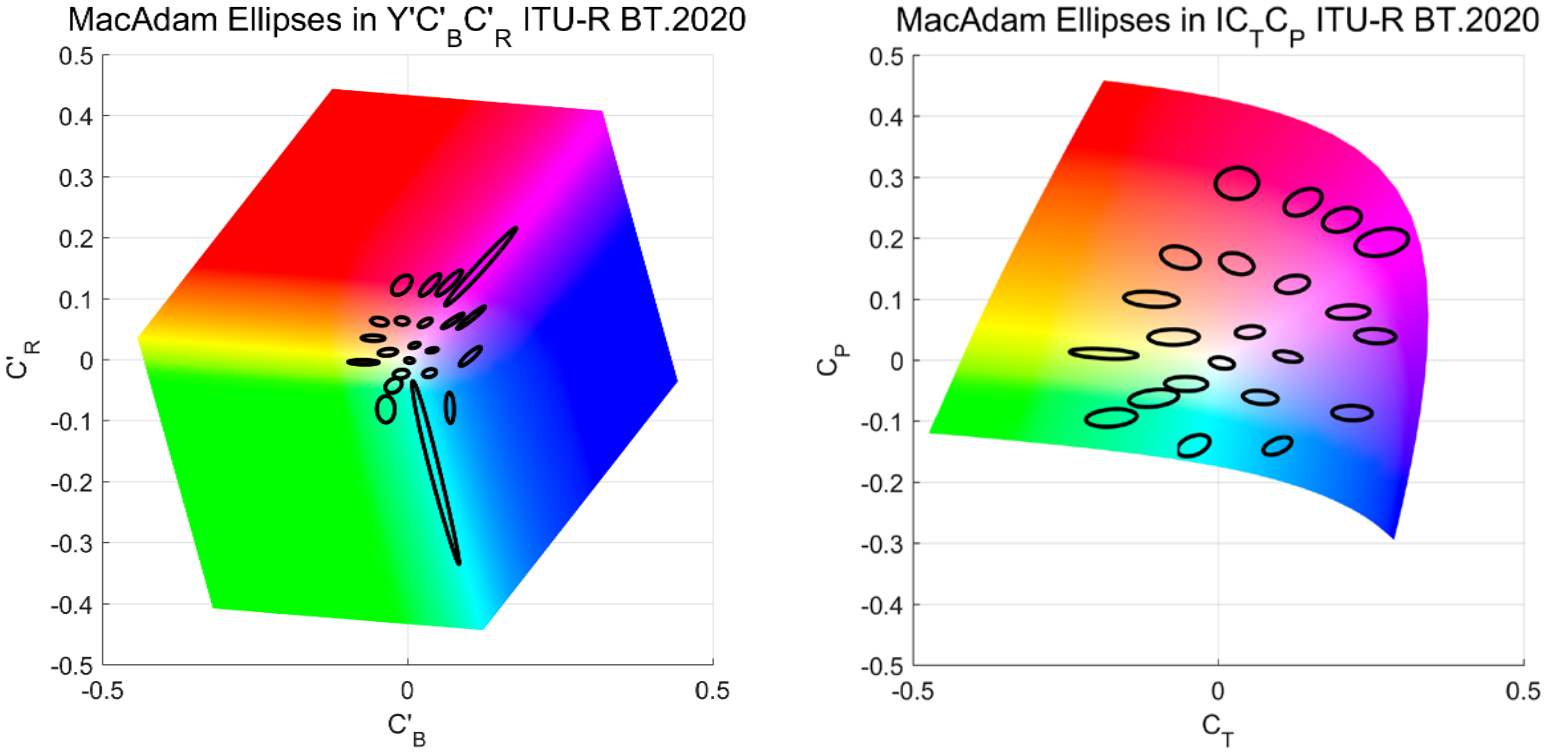
MacAdam Ellipses (3) show the JND from the center point of the ellipse

- YCbCr has non-circular ellipses
  - Inefficient use of code words (4)
  - Potential for introducing distortions
    - Chroma subsampling
    - Color Volume Mapping
    - Fading/Blending
- ITP has much more uniform JNDs

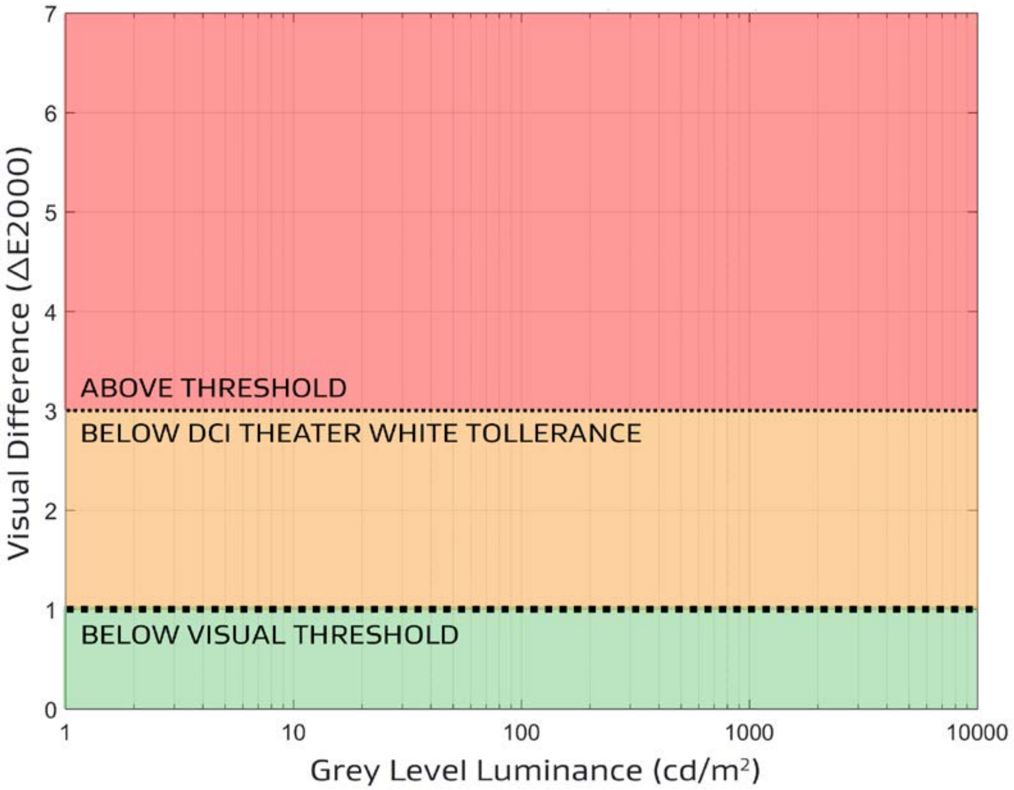


Just Noticeable Difference (JND) Uniformity



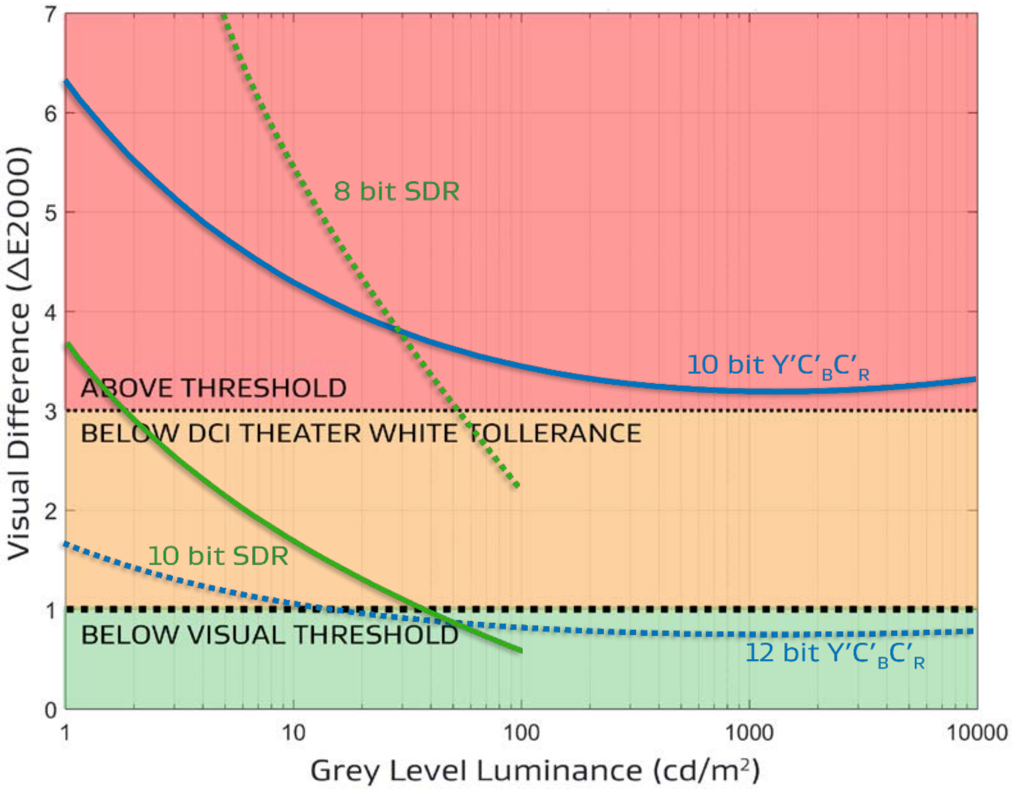
Baseband Quantization

- What error is introduced by quantizing a signal to N bits?
- The more perceptually uniform the space, the better the performance



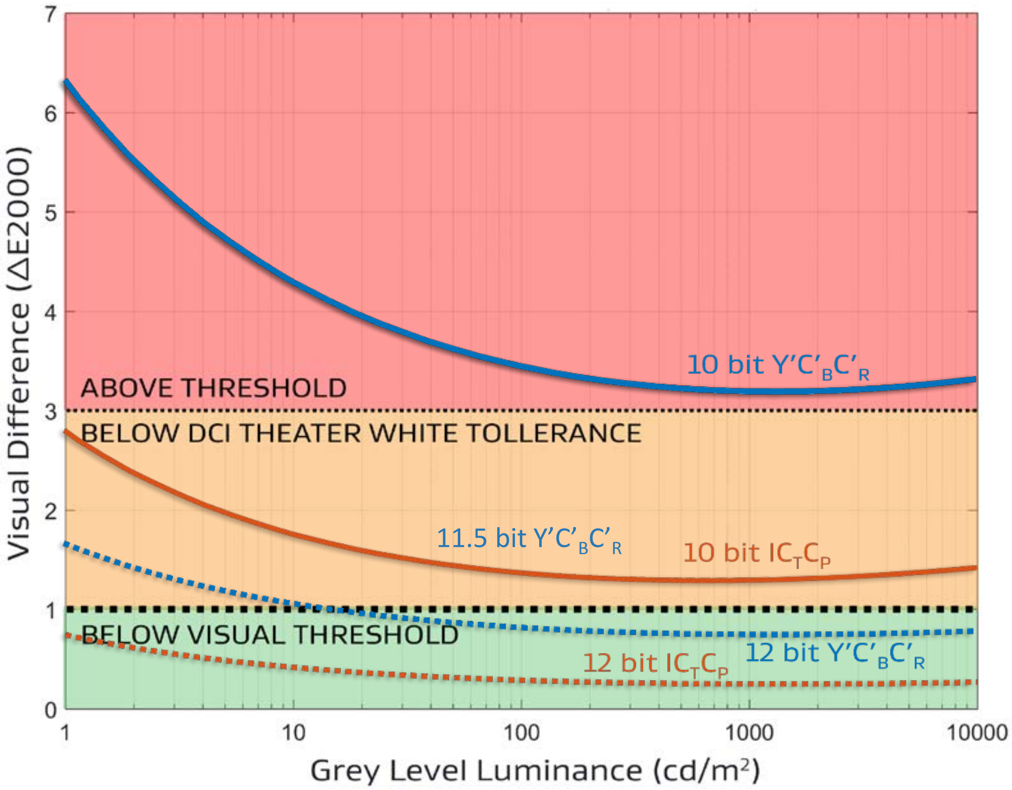
Baseband Quantization

- What error is introduced by quantizing a signal to N bits?
- The more perceptually uniform the space, the better the performance
- 10bit $Y'C'_BC'_R$ ΔE2000 is always >3
  - Visible quantization



Baseband Quantization

- What error is introduced by quantizing a signal to N bits?
- The more perceptually uniform the space, the better the performance
- 10bit $Y'C'_BC'_R$ ΔE2000 is always >3
  - Visible quantization
- 10bit IC_TC_P is ~1.5 bit more efficient than YC_BC_R for color



Implementation

IC_TC_P is easy to implement because

from a camera or to a display it uses the

SAME SEQUENCE OF OPERATIONS as $Y'C'_BC'_R$

IC_TC_P Implementation *(See Appendix A. for precise conversion to IC_TC_P)*

Camera RGB

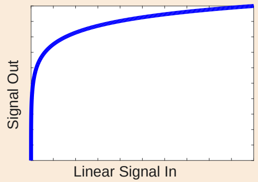
Example:
First Convert to XYZ

Camera to $Y'C'_BC'_R$

3x3 to R2020

1.717	-0.356	-0.253
-0.667	1.616	0.016
0.018	-0.043	0.942

OETF



3x3 to $Y'C'_BC'_R$

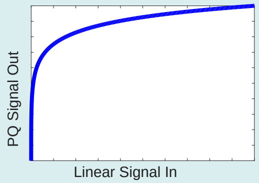
0.263	0.678	0.059
-0.140	-0.360	0.500
0.500	-0.460	-0.040

Camera to IC_TC_P

3x3 to LMS

0.359	0.696	-0.036
-0.192	1.100	0.075
0.007	0.075	0.843

PQ OETF



3x3 to IC_TC_P

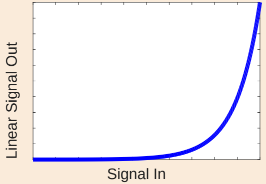
0.5	0.5	0
1.614	-3.323	1.710
4.378	-4.246	-0.135

IC_TC_P Implementation

$Y'C'_BC'_R$ to Display

3x3 from $Y'C'_BC'_R$ — **EOTF** — **3x3 R2020 to XYZ**

$$\begin{pmatrix} 1 & 0 & 1.47 \\ 1 & -0.165 & -0.571 \\ 1 & 1.88 & 0 \end{pmatrix}$$

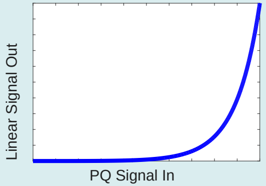


$$\begin{pmatrix} 0.637 & 0.145 & 0.169 \\ 0.263 & 0.678 & 0.059 \\ 0 & 0.028 & 1.061 \end{pmatrix}$$

IC_TC_P to Display

3x3 from IC_TC_P — **PQ EOTF** — **3x3 LMS to XYZ**

$$\begin{pmatrix} 1 & 0.009 & 0.111 \\ 1 & -0.009 & -0.111 \\ 1 & 0.56 & -0.321 \end{pmatrix}$$



$$\begin{pmatrix} 2.071 & -1.327 & 0.207 \\ 0.365 & 0.681 & -0.045 \\ -0.049 & -0.050 & 1.188 \end{pmatrix}$$

Display RGB

XYZ to Display Primaries(BT.709,etc)

Conclusion: Why IC_TC_P?

1) Improves color accuracy with fewer bits

2) Preserves artistic intent via improved hue linearity and constant intensity akin to the human visual system

3) Drop-in replacement for $Y'C'_BC'_R$ in cameras and displays

4) A future proof container for BT.2020 and beyond

Approved by ITU-R SG 6

References:

(1) C. Poynton. “Constant Luminance”. Online. 25 February 2004. <http://www.poynton.com/notes/video/Constant_luminance.html>.

(2) F. Ebner, “Derivation and Modelling of Hue Uniformity And Development of the IPT Color Space.” Rochester Institute of Technology, July 1998.

(3) D. MacAdam. “Visual Sensitivities to Color Differences in Daylight,” *Journal of the Optical Society of America*. Volume 32, Number 5. May 1942.

(4) Based on “Encoding Color Difference Signals for High Dynamic Range and Wide Gamut Imagery”, Froehlich et al., Color and Imaging Conference, Volume 2015, Number 1, October 2015, pp. 240-247(8)

(5) J. Pytlarz, R. Atkins, T. Lu, F. Pu, P. Yin, T. Chen, W. Husak, “Overview of IPT-PQ Color Space”, Doc. m37266, October 2015, Geneva, Switzerland.

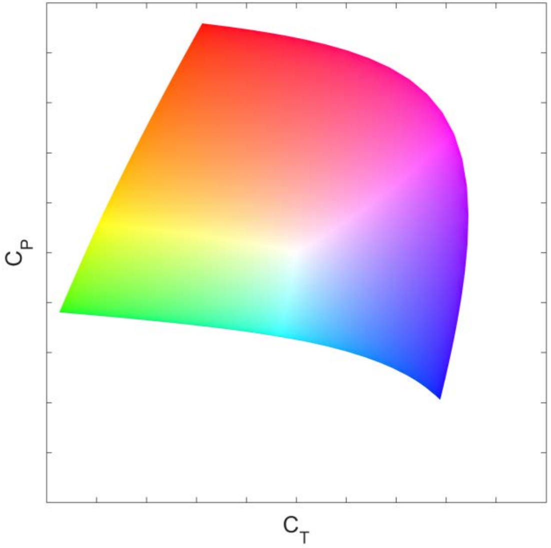
(6) "ST 2084:2014". Society of Motion Picture and Television Engineers. Retrieved 2016-01-11.

(7) “SMPTE 431-1-2006”. “SMPTE Standard for D-Cinema Quality – Screen Luminance Level, Chromaticity and Uniformity”.

Appendix

Appendix A.

Encoding IC_TC_P from ITU-R BT.2020:



$$M_1 = \begin{bmatrix} 1688 & 2146 & 262 \\ 683 & 2951 & 462 \\ 99 & 309 & 3688 \end{bmatrix} / 4096$$

$$LMS = M_1 * RGB_{ITU-R\ BT.2020}$$

$$L'M'S' = EOTF_{PQ}{}^{-1}[LMS]$$

$$M_2 = \begin{bmatrix} 2048 & 2048 & 0 \\ 6610 & -13613 & 7003 \\ 17933 & -17390 & -543 \end{bmatrix} / 4096$$

$$IC_TC_P = M_2 * L'M'S'$$