IMID 2025

HDR Display Picture Quality Assessment

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HDR problem statement

H-K effect revisited

Computational model 2D

Volumetric model

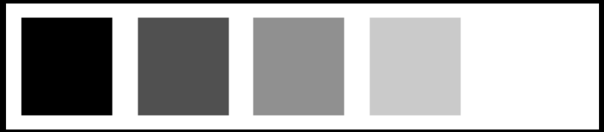
Perceptual attribute terminology

Relative scales

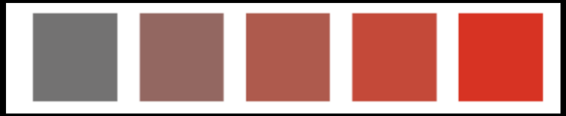
- **Lightness (*J*):** brightness of stimulus relative to scene white point.
- **Chroma (*C*):** colorfulness relative to scene white point.
- **Saturation (*s*):** colorfulness relative to stimulus brightness

Absolute scales

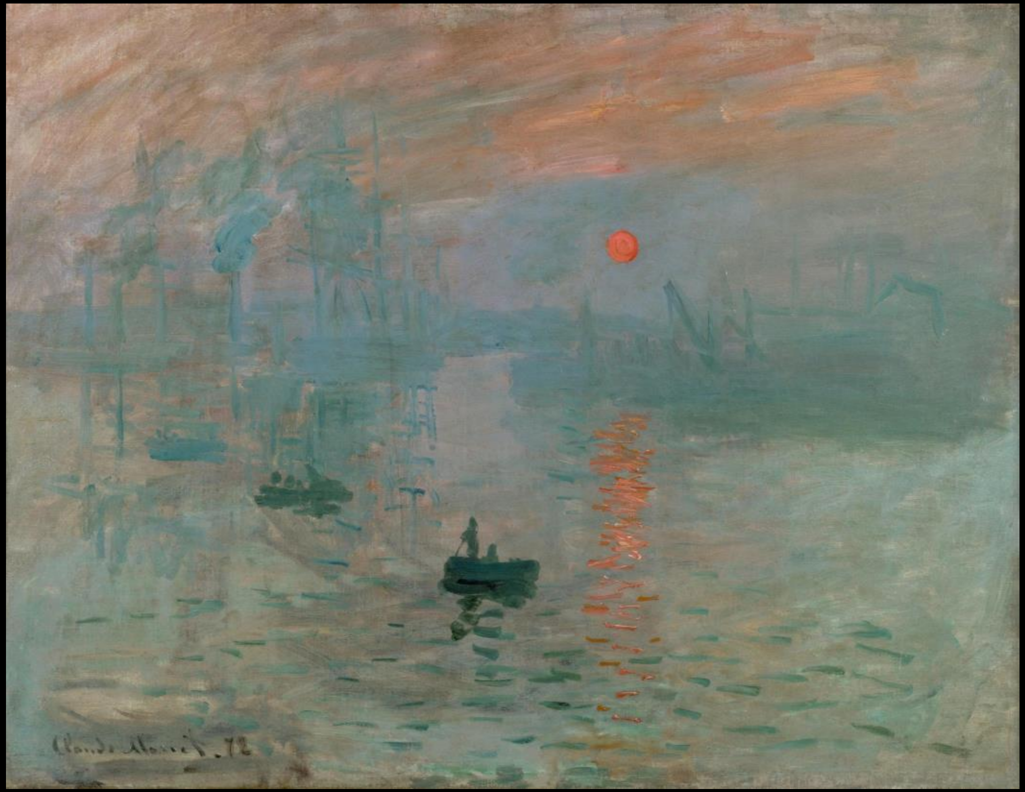
- **Brightness (*Q*):** perceived amount of light emitted by stimulus.



- **Colorfulness (*M*):** perceived chromaticness of stimulus

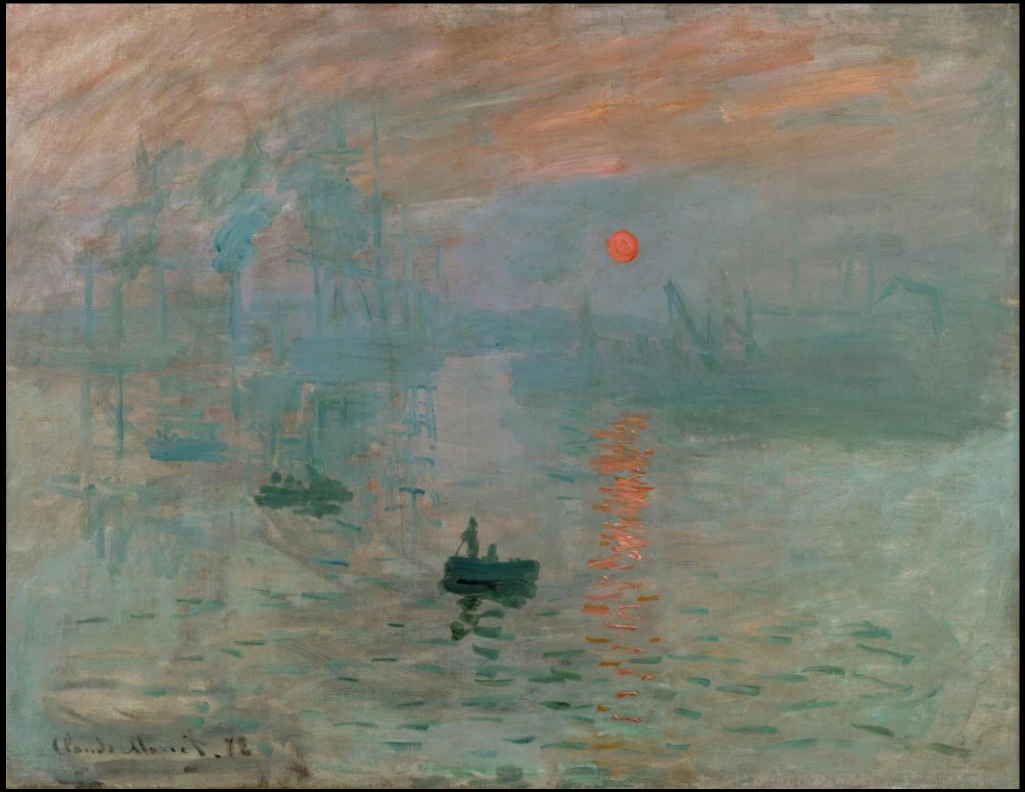


Hue:



Claude Monet, *Impression Sunrise*. Concept from Margaret Livingstone.

Failure of luminance to predict perceived colors

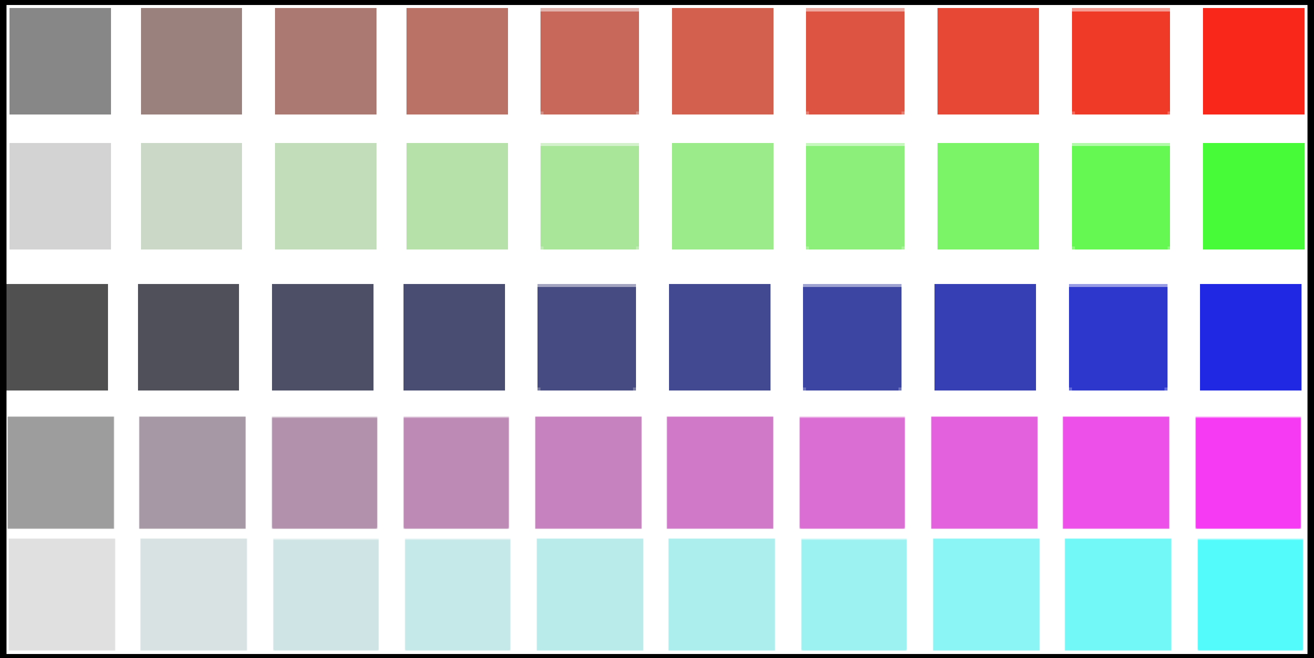


Claude Monet, *Impression Sunrise*. Concept from Margaret Livingstone.

Helmholtz-Kohlrausch Effect

At constant luminance, perceived brightness increases with increasing colorfulness or saturation

- **Well reported; only recently have HDR-appropriate models appeared**



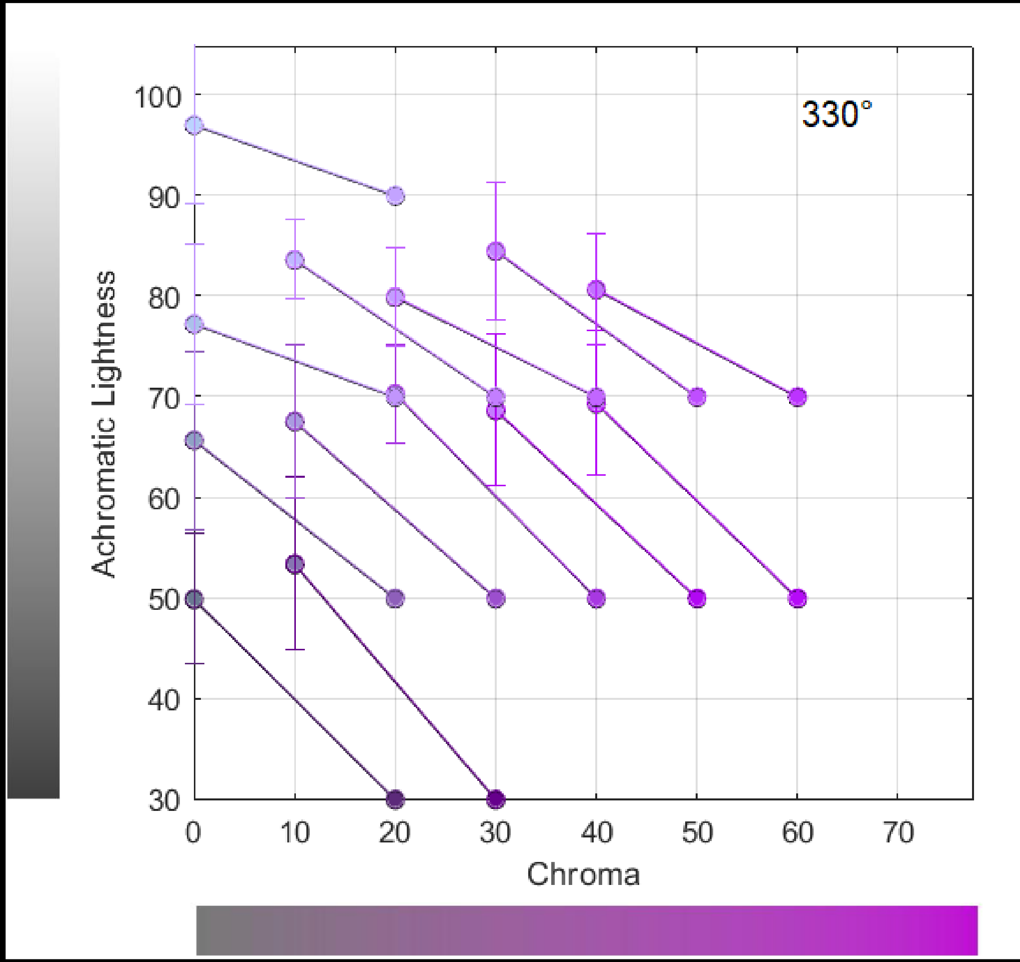
Decoding subjective data results for one hue (330°)

- Lines connect pairs of stimuli that were matched in brightness by observers (spacing by ΔChroma = 20)

- H-K Effect:

  Higher chroma, lower luminance stimuli are equally bright to **lower chroma, higher luminance** stimuli.

- **H-K strength ∝ negative slope of loci**



Data testing included 3 studies across 171 stimuli; viewed by 50 observers

modCAM16 model with H-K effect

Trends represented by a differential equation:

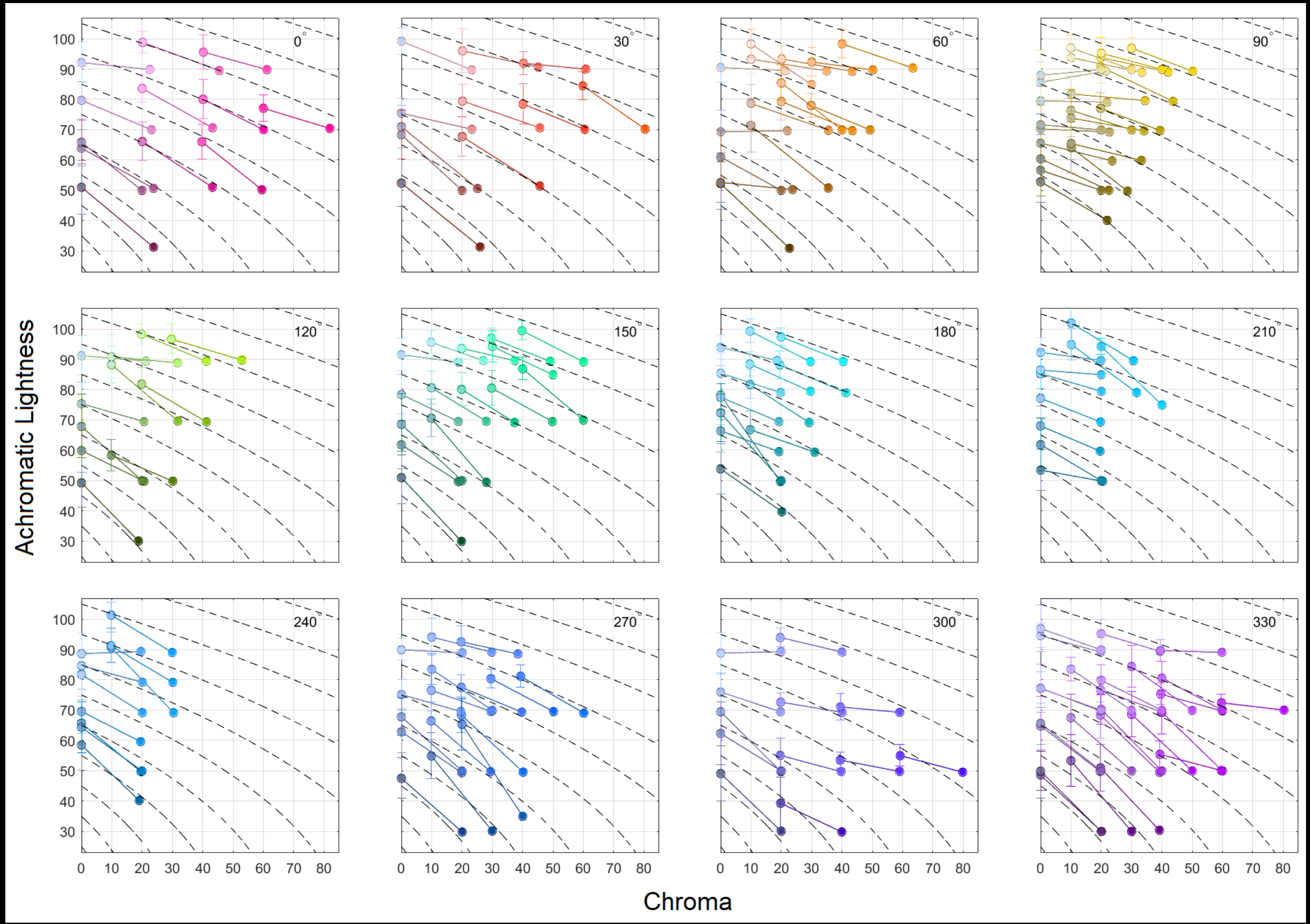
$$\frac{dJ_A}{dC} = \frac{-a}{J-b}$$

J_A: Achromatic lightness
C: Chroma

Proposed modCAM16 Model [1,2]

$$J_{HK} = \sqrt{J_A^2 + 66C}$$

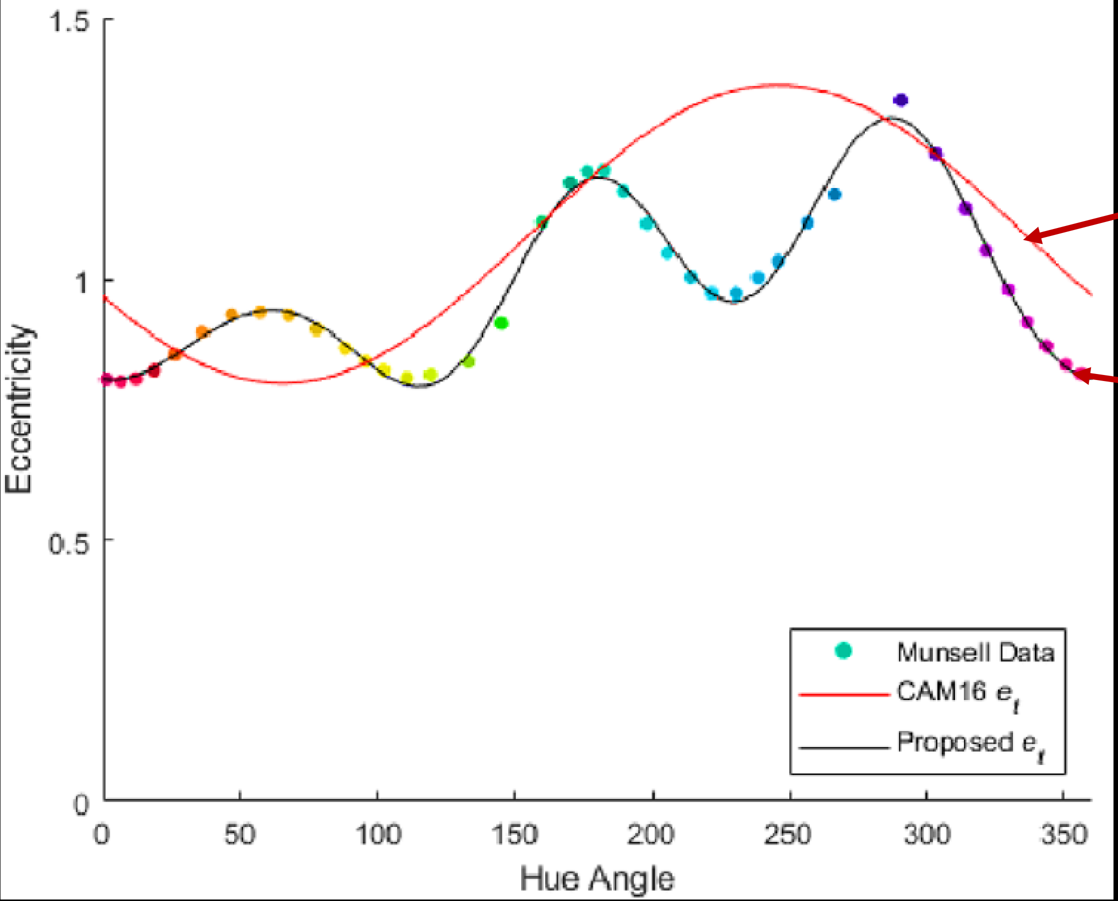
J_{HK}: Perceived lightness



1. Hellwig and Stolitzka, "An Advanced Color Model for Evaluating New Display Technologies, *Info. Disp., 39, #3 , pp 11-15* (May/June 2023).
2. Hellwig, Stolitzka and Fairchild, "The brightness of chromatic stimuli', *Color Res. Appl.*, ***49***, *#1, pp 113-123* (January 2024).

Hue dependency moved into modCAM16

Hue comparison CIECAM16 vs. modCAM16



- **CIECAM16**

$$e_t = \frac{1}{4}\cos\left(\frac{\pi}{180}h + 2\right) + 3.8$$

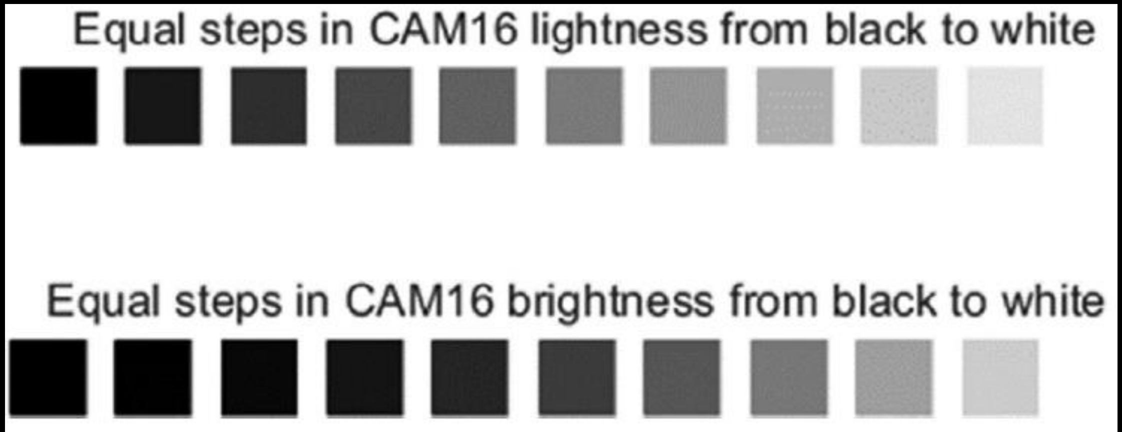
- **Proposed modCAM16**

$$e_t = -0.0582\cos h - 0.0258\cos 2h - 0.1347\cos 3h + 0.0289\cos 4h - 0.1457\sin h - 0.0308\sin 2h + 0.0385\sin 3h + 0.0096\sin 4h + 1$$

What about perceived brightness rather than lightness

CIECAM16

Average conditions
White background 400 cd/m^2



Warning:
$Q \propto f(\sqrt{J})$ has an intrinsic perception error

modCAM16 [3] brightness

- **modCAM16 conversion from lightness to brightness – linear**

modCAM16

$$Q = \left(\frac{2}{c}\right)\left(\frac{J}{100}\right)A_w$$

CIECAM16 & CIECAM02

$$Q = \left(\frac{4}{c}\right)\sqrt{\frac{J}{100}}\,(A_W + 4)$$

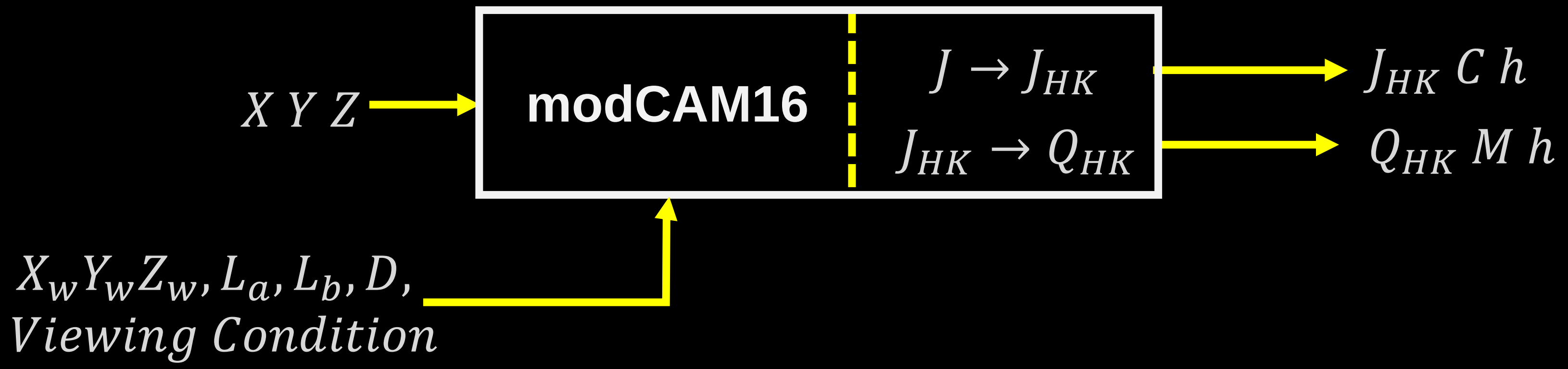
- **with H-K compensation**

$$Q_{HK} = \left(\frac{2}{c}\right)\left(\frac{J_{HK}}{100}\right)A_w$$

Q_{HK}: Perceived brightness
A_w: Brightness of white
c: Viewing conditions

3. Hellwig, Stolitzka and Fairchild, “Improvements to CIECAM16 and Future Directions”, *Proceedings of the 30th Session of the CIE* (Dec 2023).

eXperienced Color Range (XCR)



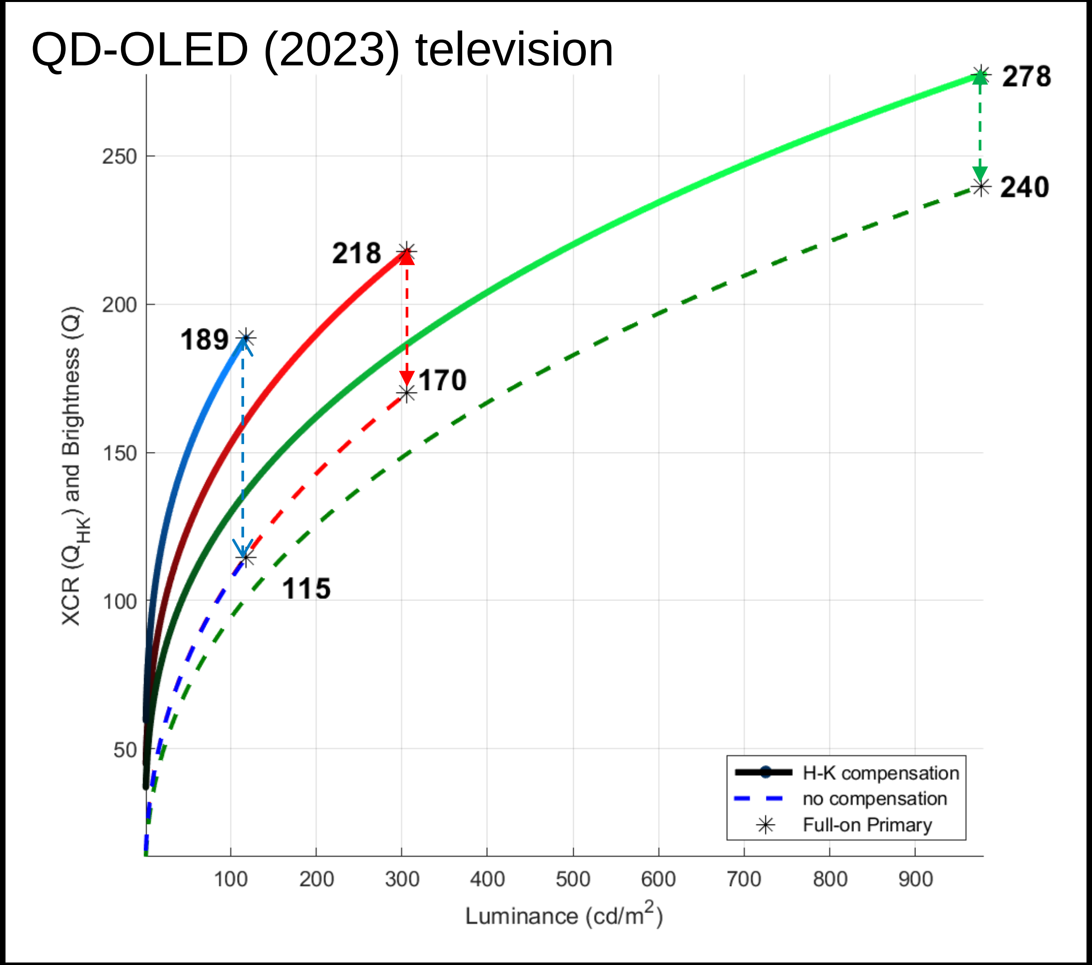
Example of applying XCR – 2D color attribute class

- **Accuracy**

	CIECAM16-based models			
Data set	**Proposed**	**Hellwig '22**	**Kim '19**	**CIECAM16**
Current	−0.37	−8.4	−2.3	−12
High '23	−0.087	−1.1	−3.4	−4.8
Seong '23	−4.7	−11.2	−21.5	−18.1
Xie '21	−3.0	−8.4	0.030	−14
Fairchild '91	5.6	1.2	5.4	−1.9
Wyszecki '67	3.7	−1.3	3.6	−4.3
Sanders '63	3.3	−1.6	4.4	−4.3

- **Tested in HDR conditions**

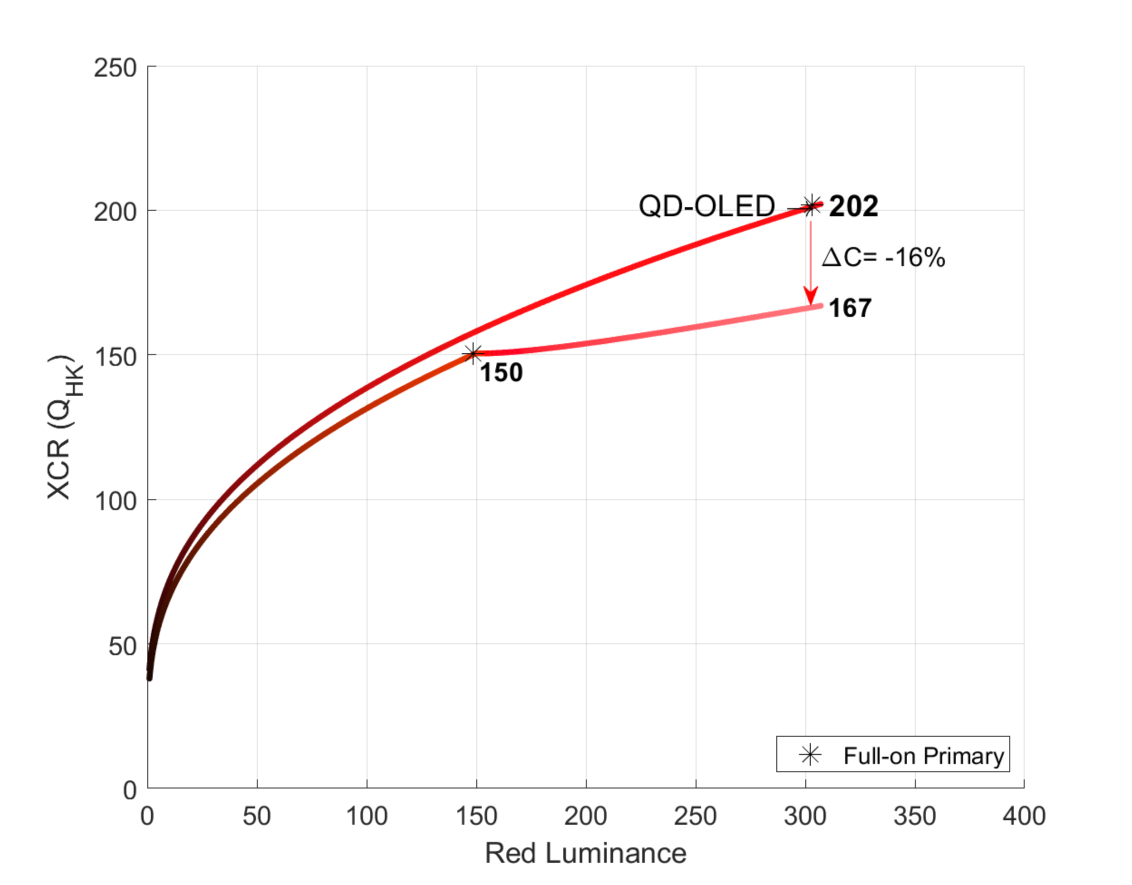
Data set	**Lightness range**	**White luminance (cd/m^2)**
Current	30–90	400, 500
High '23	80–100	120
Seong '23	100	30, 95, 300
Xie '21	100	50, 100, 200
Fairchild '91	30–70	382
Wyszecki '67	50	159
Sanders '63	50	100

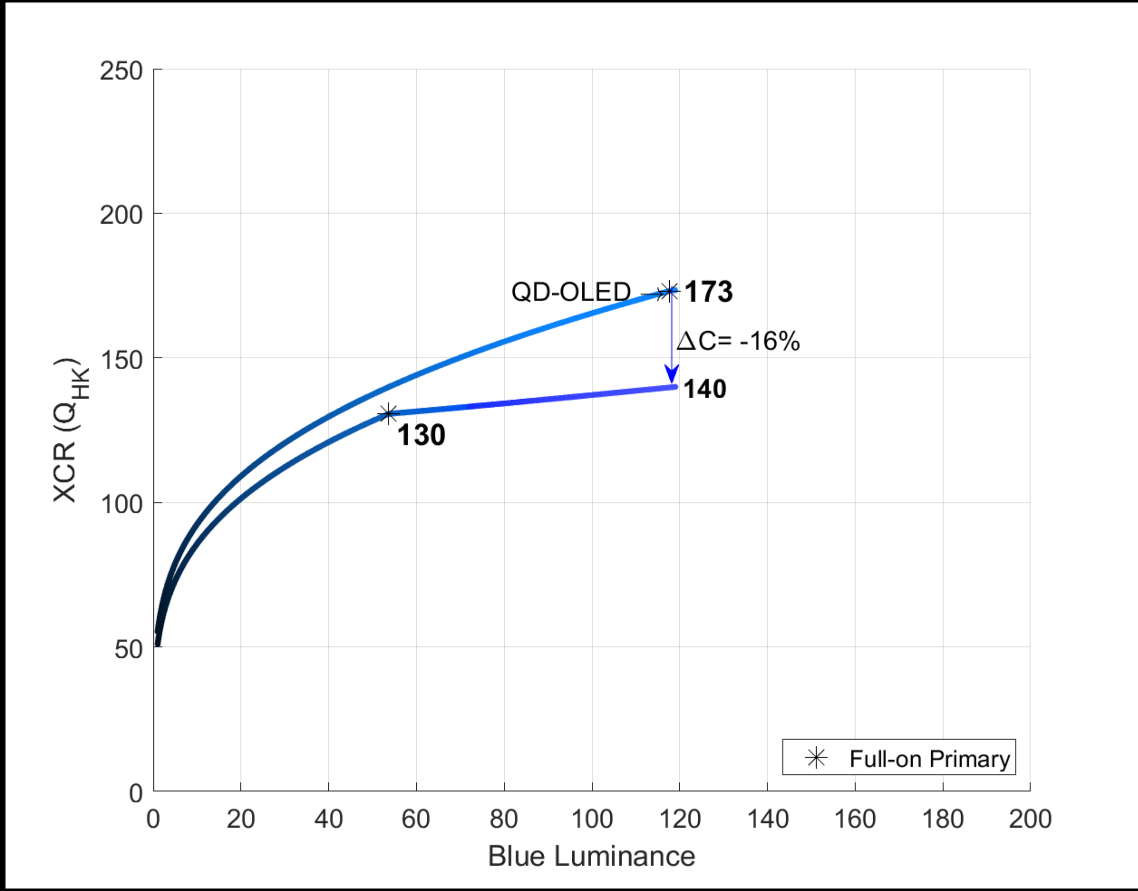


wp = 200 cd/m^2, condition "dark"

XCR showing desaturation

Effect when luminance is increased beyond one full primary toward the white point



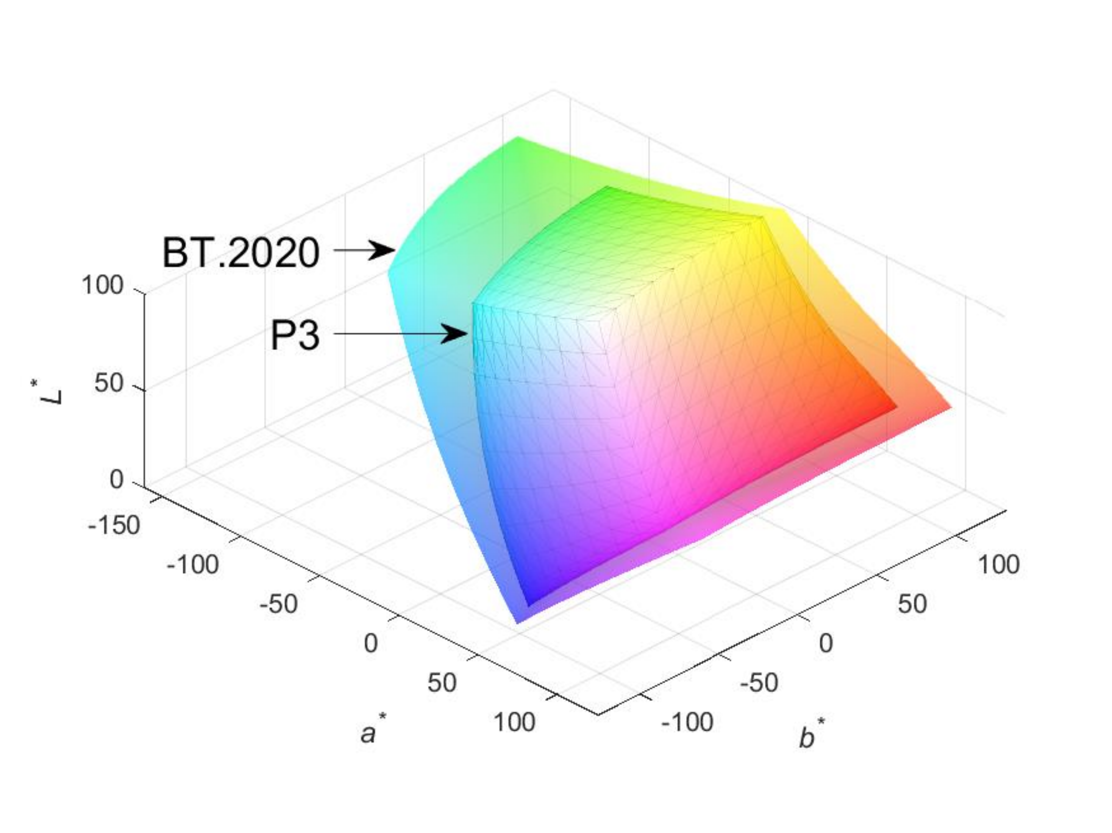


wp = 200 cd/m^2; Condition "dim"

Volumetric representations

SDR volumetric option using CIELAB

CIELAB (SDR)



E. Smith, Synthetic volume models

Underlying formulae

$$X\,Y\,Z \Rightarrow \begin{array}{l} L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16 \\ a^* \ldots \\ b^* \ldots \end{array}$$

- ☹ **luminance is not a good predictor of lightness**
- ☹ $\left(\frac{Y}{Y_n}\right)$ **≤ 1; no extension beyond ref. white**
- ☹ **$\Delta\, E_{ab}$ not competitive with the uniformity in ΔE_{00} & CAM16-UCS by weighted STRESS performance [4,5]**

Color Difference Metric	Color Difference Dataset				
	COM-BVD	RIT-DuPont	Witt	Leeds	BFD
Proposed *J'a'b'*	28.2	22.9	32.3	23.8	28.8
Proposed *Q'p't'*	28.6	22.5	31.7	24.5	28.5
CIEDE2000	<u>24.2</u>	<u>19.5</u>	30.1	<u>19.2</u>	<u>23.4</u>
CAM16-UCS	28.1	20.6	30.9	25.4	28.5
CIELAB ΔE_{ab}	*45.3*	*33.4*	*51.9*	*40.1*	*44.8*
DIN99	*31.8*	24.2	*36.3*	*29.8*	30.7

4. C. Li, M. R. Luo, G. Cui, “Colour-Differences Evaluation Using Colour Appearance Models” *Proc. 11th CIC* (2003): 127-131.
5. Hellwig, L., & Fairchild, M.D. (2022). Revising CAM16-UCS. 30th Color and Imaging Conference Final Paper and Proceedings. Scottsdale, Ariz.

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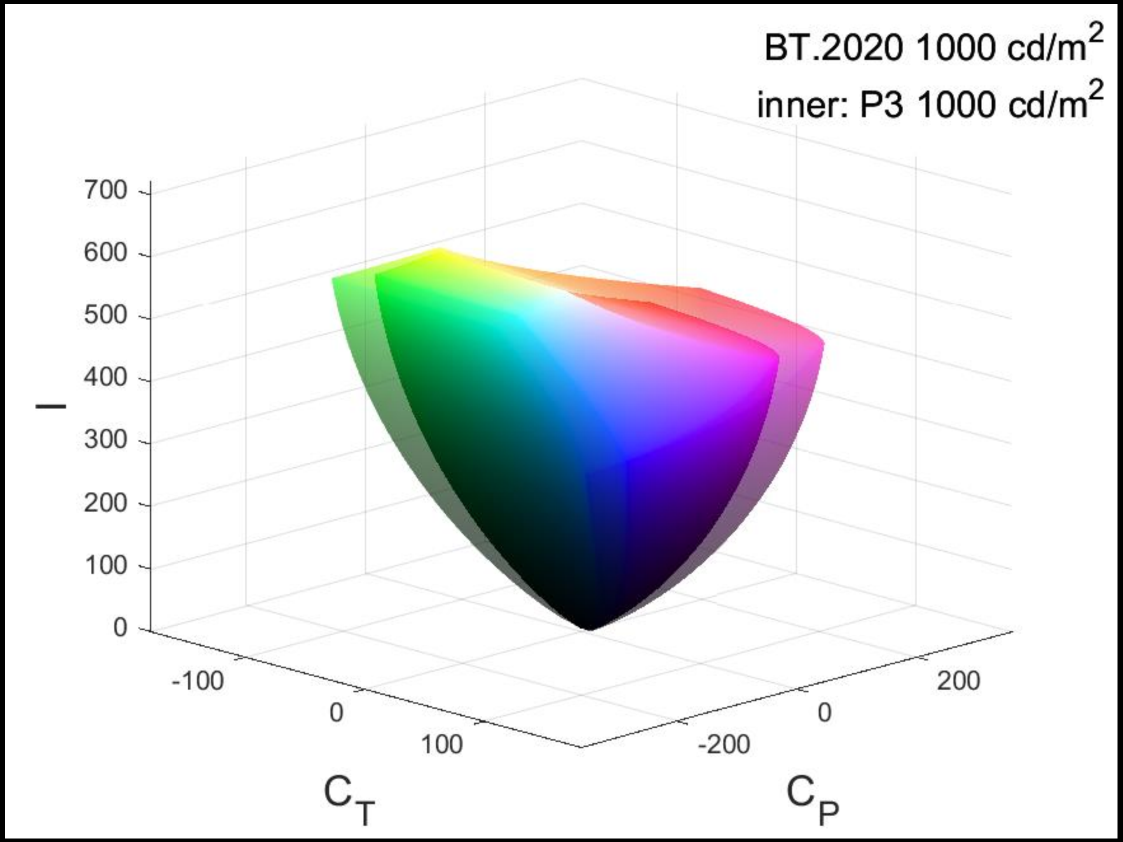
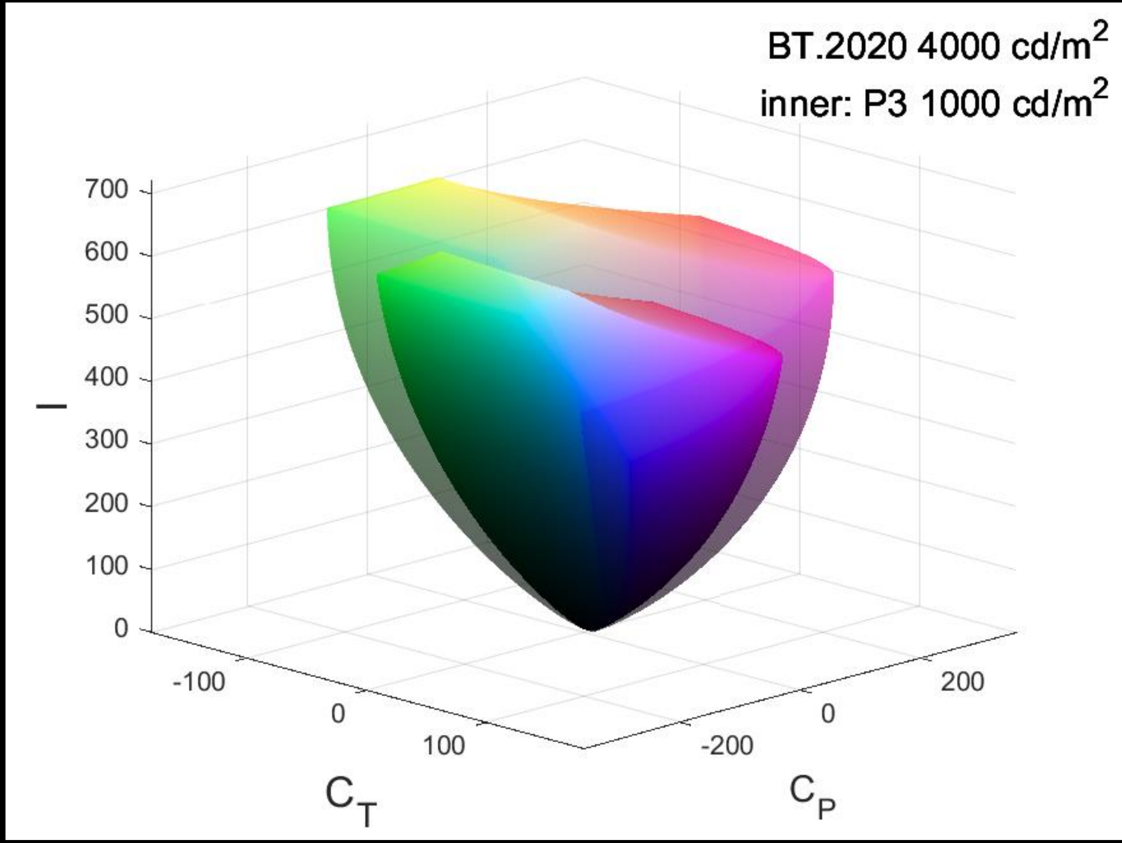
IC_TC_P behavior with expanding intensity and color

Larger gamut | **Larger intensity and gamut**

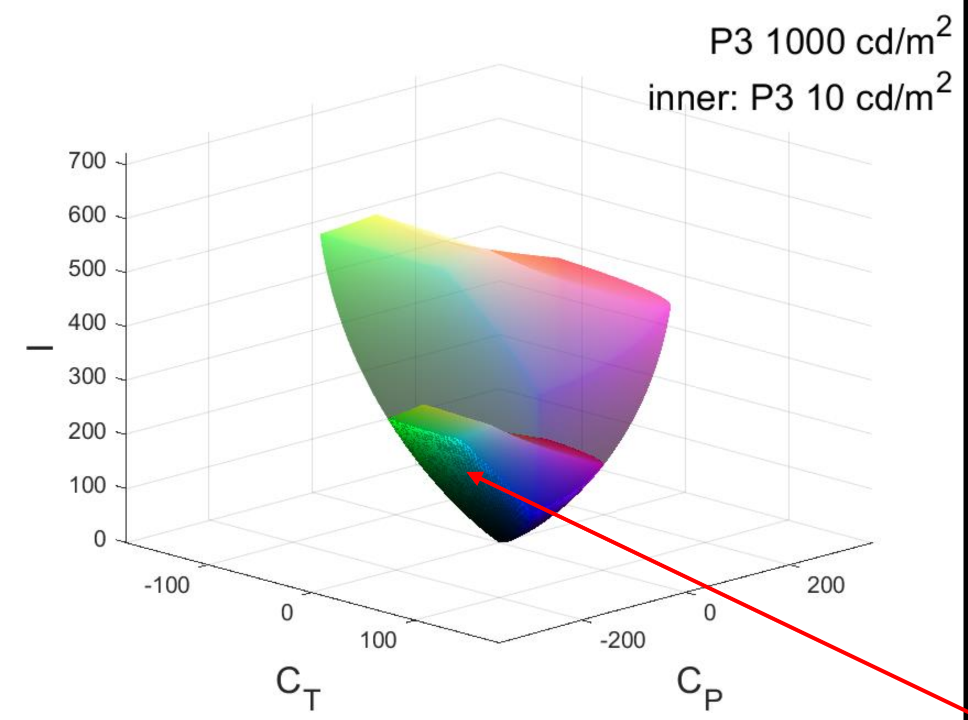




J. Pytlarz, Matlab code for calculating MDC“, v7.2 (2023)

P3 only viewed by IC_TC_P

Higher intensity



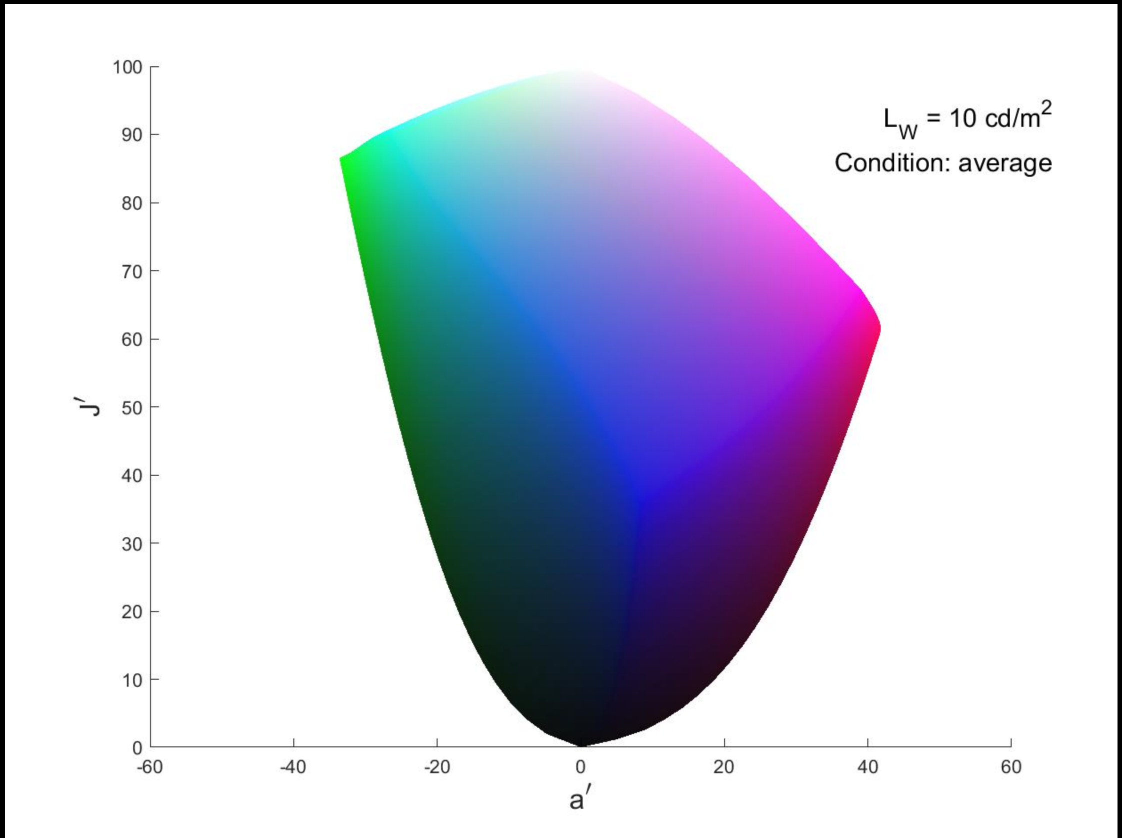
Coincident surfaces

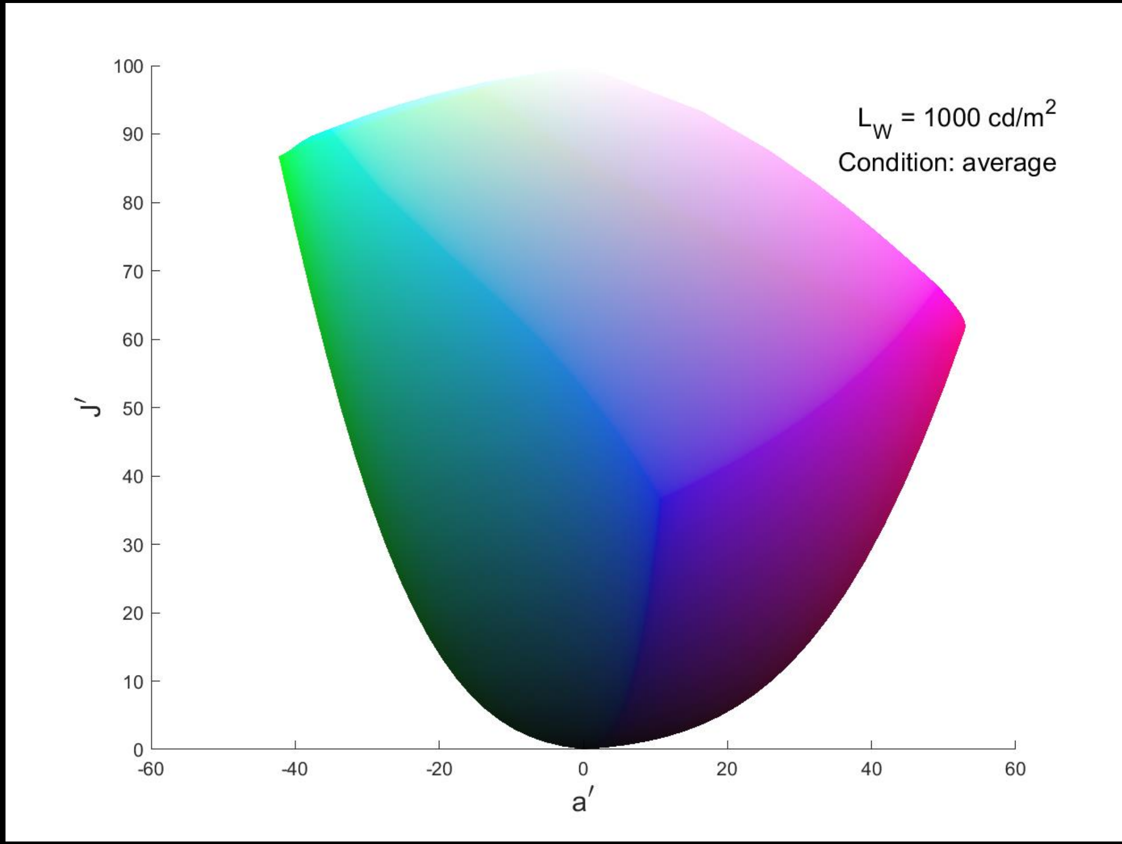
Issues also persist

- **ΔE_{ITP} recommended by BT.2124 for small color differences**
- **Lacks increasing colorfulness at low *I***
- **Nevertheless, the plots faithfully show an ability to render colors across a range of intensity**

CAM16-UCS J’ a’ b’ side view (sRGB / SDR example)

a’ and b’ grow relative to J’





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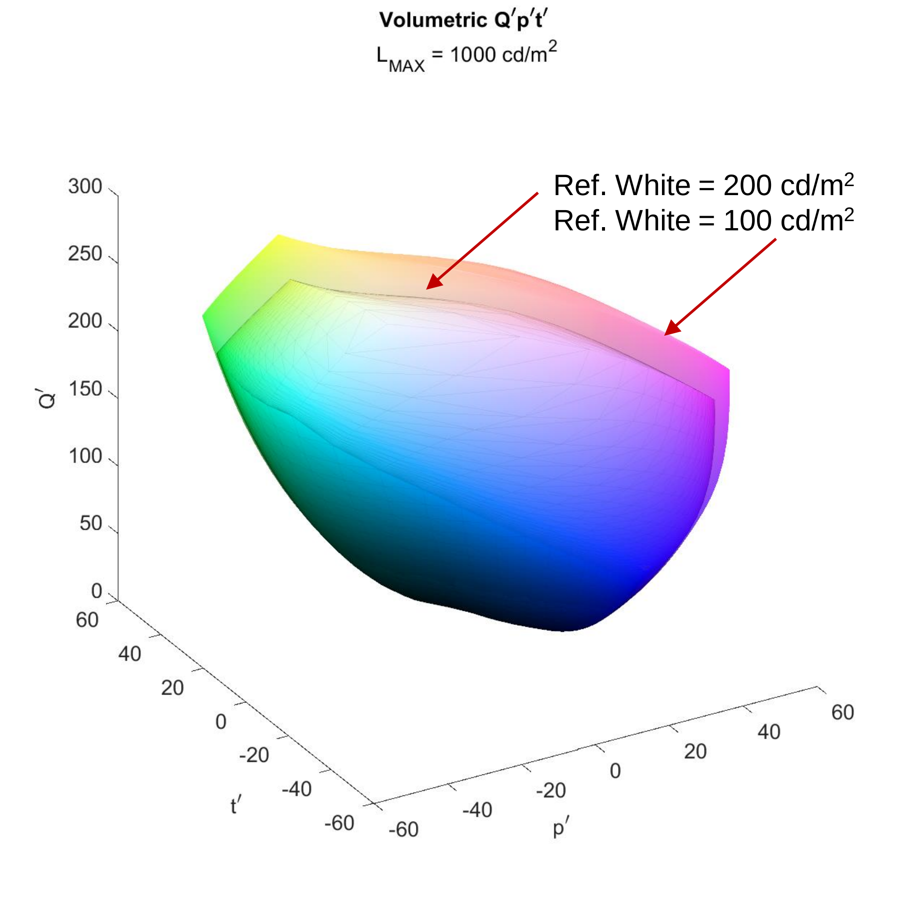
CAM16-UCS Q’ p’ t’

Brightness



Underlying formulae

- **Volumetric lightness and brightness**

$$J' = \frac{1.7J}{1+0.007J} \qquad Q' = 0.86\frac{1.7Q}{1+0.007J}$$

$$p' = M' \cos h;\ t' = M' \sin h$$

- **Use tools for their intended application**

“The characteristic nonlinearities in [J’ and Q’] warp the uniform perceptual attribute scales of CIECAM16. The resulting uniform color spaces are thus uniform only in their prediction of color differences, not in their prediction of perceptual attributes.”

– Hellwig, Fairchild Revising CAM16-UCS (2022)

Take-aways from volumetric discussion

- **CIELAB is not appropriate for HDR displays**
  - Not designed to model Hunt, Stevens or H-K Effect
- **IC_TC_P also has issues but does show what an HDR display is capable of rendering, <u>even if the observer cannot see the all colors all the time</u>**
- **CAM16-UCS is quite uniform, a good color space**
  - Great job modeling more complex color effects with added modeling parameters
  - Also designed for color difference
  - Warping of the space leads to perceptual inaccuracy – not intended for absolute color counting

Conclusions

- **Reviewed**
  - CIELAB
  - modCAM16 and XCR
  - IC_TC_P
  - CAM16-UCS
- **HDR modeling needs to be taken seriously**
  - Perceptual testing is a requirement, using a wide variety of chromatic stimuli
  - Industry should question whether volumetric analysis provides “the answer”
- **Color scales, like XCR can tell us a lot about HDR displays**
- **Watch CIE developments, for example:**
  - TC1-99 (revitalized) Modelling Two-Dimensional Colour Appearance Scales
  - TC1-100 To recommend CAM16-UCS as the CIE Uniform Colour Space

Thank you

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