Encoding Color Difference Signals for High Dynamic Range and Wide Gamut Imagery

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Outline

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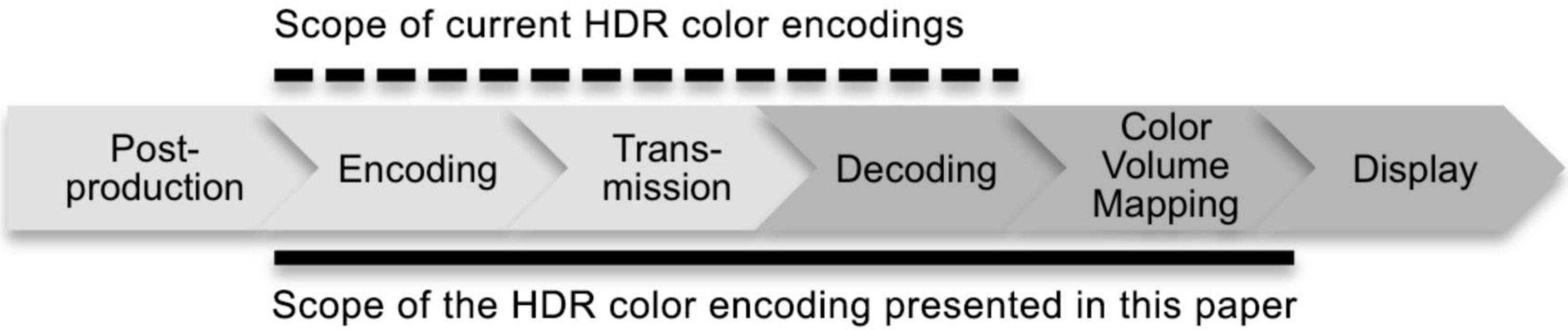
2) Requirements & Related work
3) Model
    1) Data sets
    2) Cost functions
4) Results
5) Further Work & Conclusion

Introduction

Find a **most efficient encoding for HDR color imagery** co-optimized for

- Efficient Color Encoding &
- Color Volume Mapping (Tone- and Gamut-Mapping)



Why color volume mapping?

Example HDR Mastering Display

- Rec.2020
- 0.005-4000cd/m^2
- Dark environment

Example Tablet

- Rec.709
- 0.1-400cd/m^2
- Bright environment

Example HDR-TV

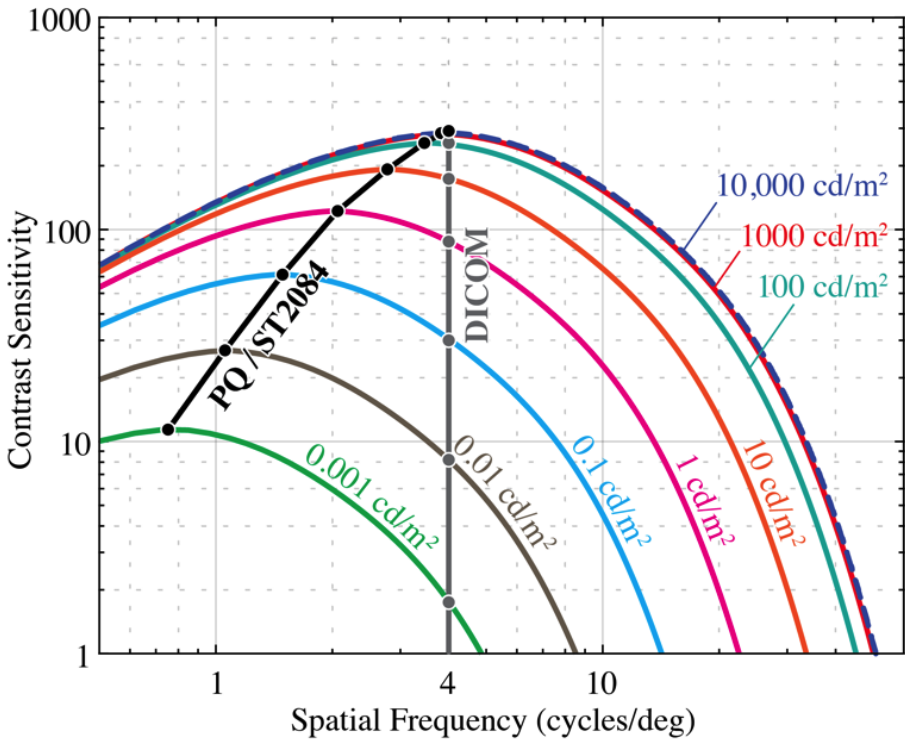
- ~P3
- 0.01-1000cd/m^2
- Dark environment

Requirements to an HDR color encoding

- 0.005 – 10,000 cd/m^2 dynamic range
- Minimum Rec.2020 gamut – better be able to encode all colors
- Efficient quantization – ‘JND-uniformity’
- Static encoding (not content or viewer dependent)
- Low computational complexity (mobile devices)
- Decorrelate the achromatic axis (for color subsampling)
- Hue-linear (for gamut mapping)

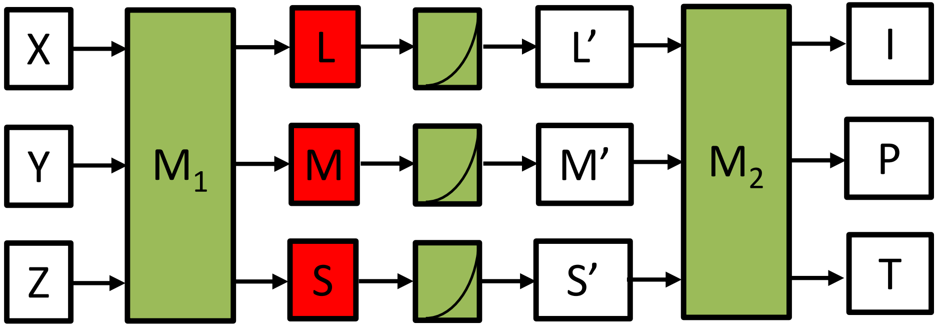
Related work

- “PQ” / SMPTE ST.2084 [1]
- PQ is a **luminance encoding scheme** that quantizes according to the minimum step beyond the visibility threshold according to the Barten’s contrast sensitivity model [2]
- It follows the peak contrast sensitivity for any adaptation state

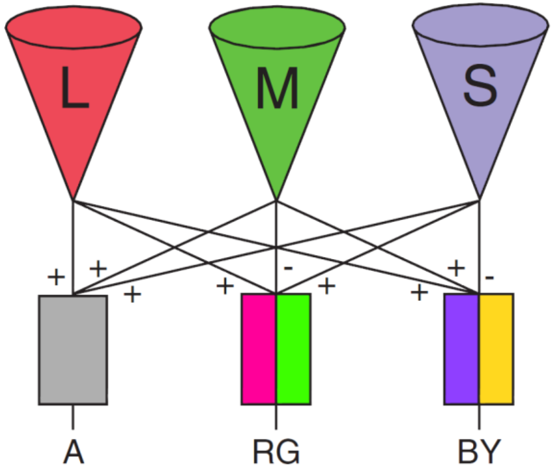


Model selection

IPT

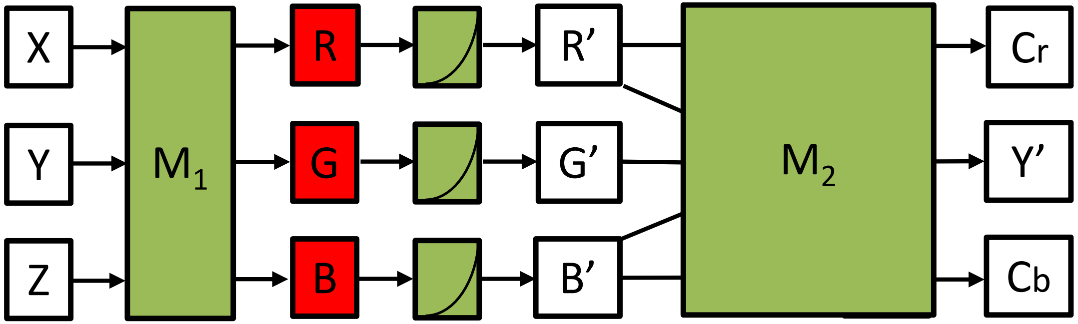


- Motivated by human perception
- Optimized for hue-linearity
- LMS – cone response

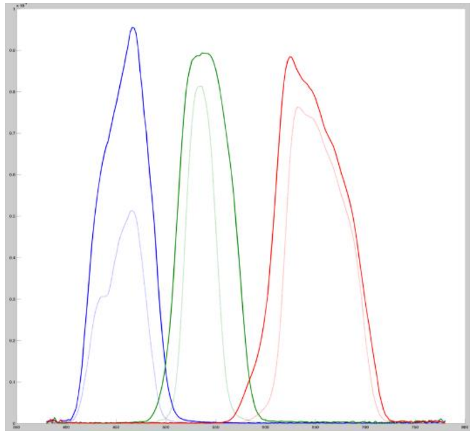


Model selection

$Y'C_bC_r$



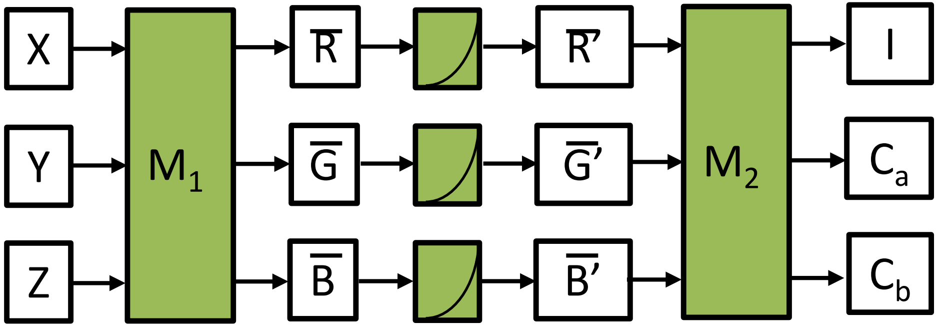
- RGB - physically realizable display primaries
- Color differencing scheme



Typical digital projector primaries (Barco DP90 & DP90KP dashed)

Selecting a Model

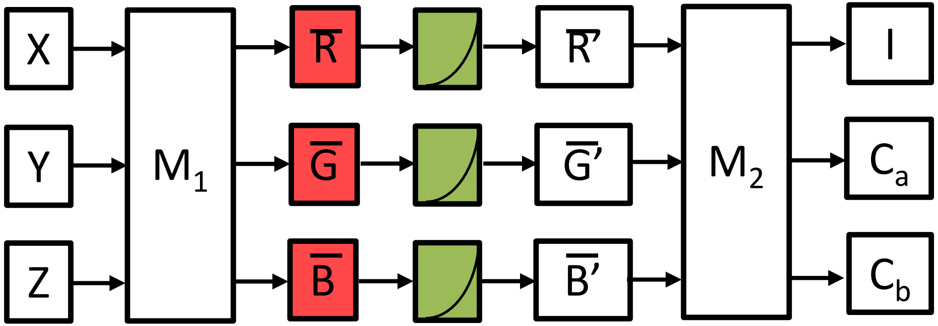
IC_aC_b



- Low computational cost
- Well known from YC_bC_r & IPT in encoding and color communities
- Already implemented in a large number of devices

Selecting a nonlinearity

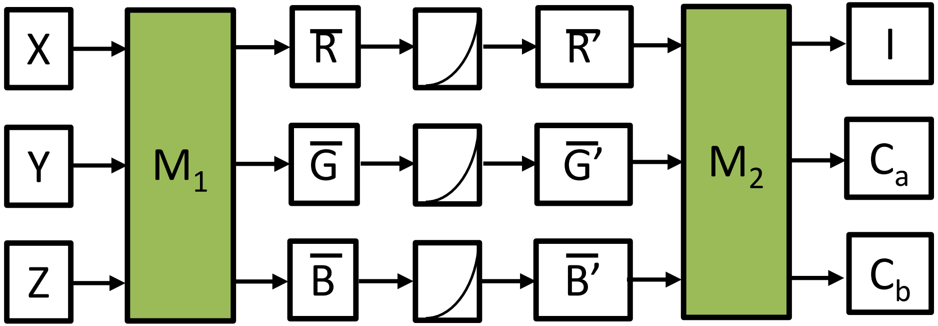
IC_aC_b



- By model definition, the achromatic case is true when $\bar{R} = \bar{G} = \bar{B}$
- In consequence the nonlinearity () must be PQ to guarantee an optimal encoding along the achromatic axis

Finding the Model Parameters

IC_aC_b



- But how to find the best matrix parameters?
- Optimization
- → Need training and test set as well as cost functions

Data sets: Isoluminance

Test set:

- Comparable to Kindlmann [3] but:
  - near Rec.2020 gamut
  - HDR (up to ~2000cd/m^2)

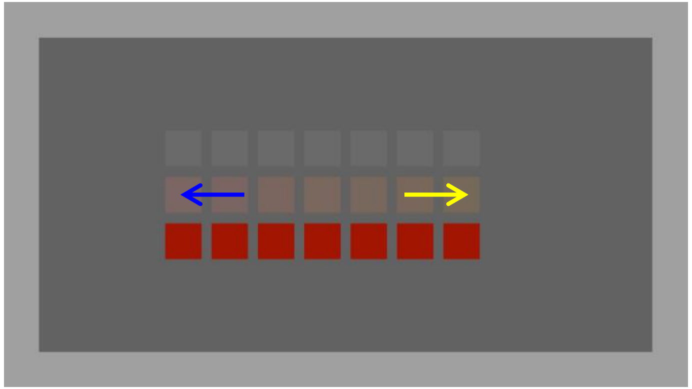
Verification set:

- Kindlmann 2002 [3]

Data sets: Hue linearity

Test set:

- Setup as Hung & Berns but:
  - near Rec.2020 gamut
  - HDR (up to ~2000cd/m^2)



Verification set:

- Hung & Berns 1995 [4]

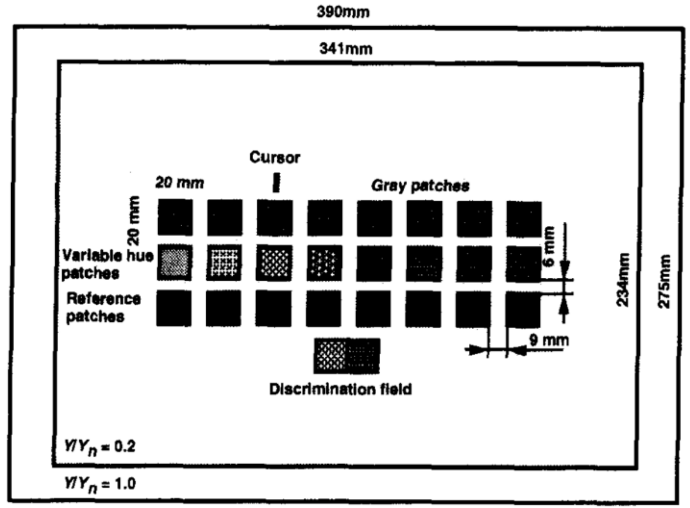
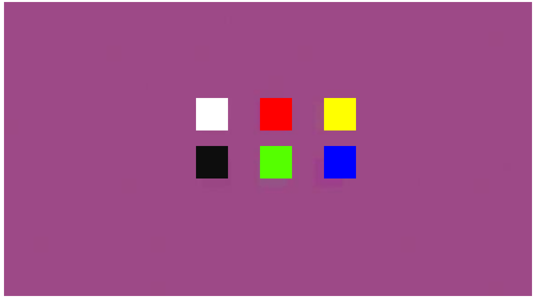


FIG. 3. Monitor layout for the experiment.

Data sets: JND uniformity

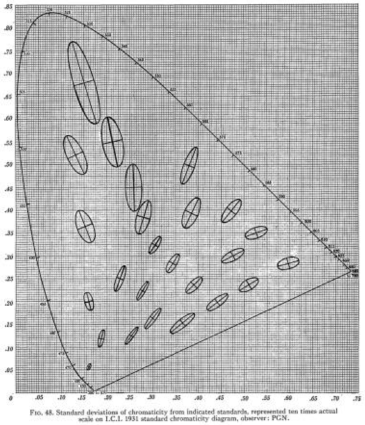
Test set:

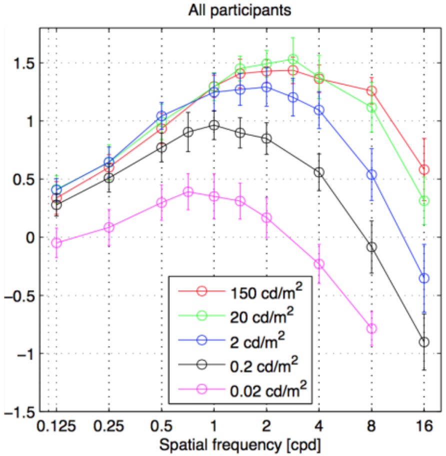
- Step edge pattern on stimuli background in dark environment using method of adjustment
  - P3 gamut
  - HDR (0.005 - 1000cd/m^2)



Verification sets:

- MacAdam 1942 [5] (Observer: PGN)
- Kim 2013 [6]





Finding the matrix parameters

Isoluminance cost function:

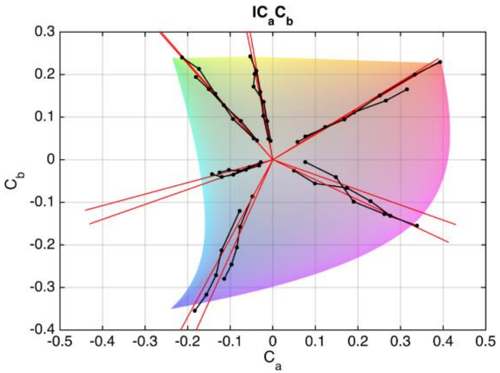
- Mean squared difference in predicted intensity between equiluminant patches

$$C_{\mathrm{il}} = \frac{1}{n}\sum_{i=1}^{n}\left(I_{i,1} - I_{i,2}\right)^2$$

where $I_{i,1}$ and $I_{i,2}$ are the intensities for n color pairs that were adjusted by human observers to have the same perceived luminance.

Finding the matrix parameters

Hue linearity cost function:



$$h_{i,j} = \text{atan2}\left(C_{a,i,j}, C_{b,i,j}\right)$$

$$s_{i,j} = \sqrt{\left(C_{a,i,j}\right)^2 + \left(C_{b,i,j}\right)^2}$$

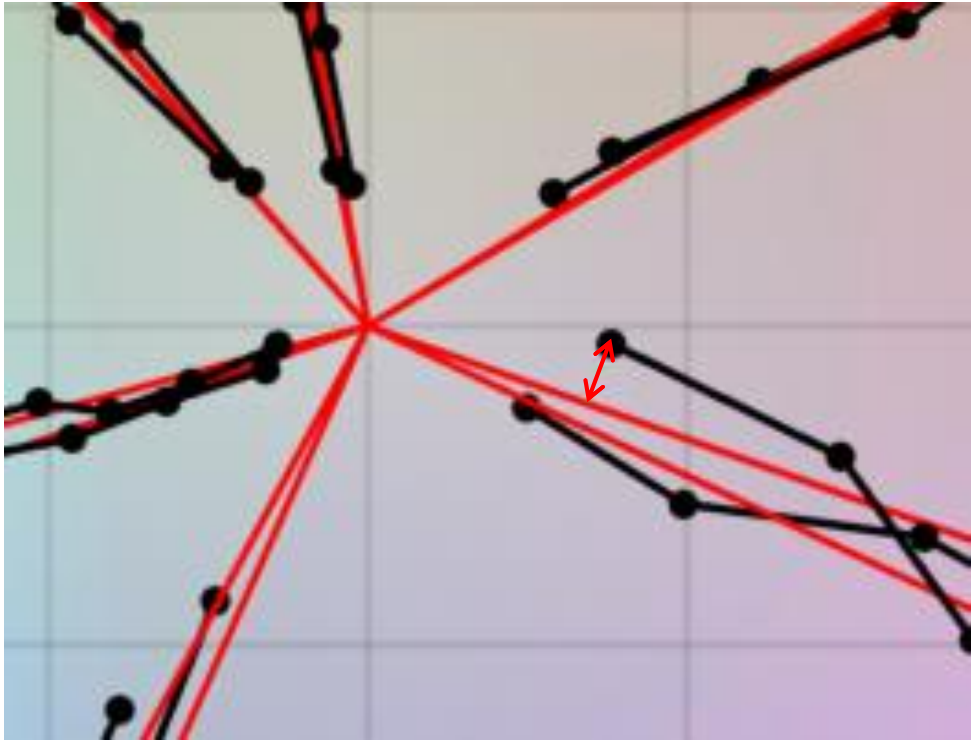
$$C_{\text{hl}} = \frac{1}{nm}\sum_{i=1}^{n}\sum_{j=1}^{m}\left(\frac{h_{i,j} - \frac{1}{m}\sum_{w=1}^{m} h_{i,w}}{\frac{1}{n\,m}\sum_{u=1}^{n}\sum_{v=1}^{m} s_{u,v}} s_{i,j}\right)^2$$

where $h_{i,j}$ and $s_{i,j}$ are the hue and saturation in the new color space for n color tuples of m elements. Human observers adjusted all m elements of each tuple to have the same perceived hue.

Finding the matrix parameters

Hue linearity cost function:

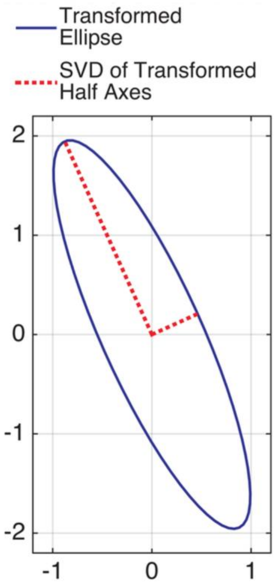
- Mean squared distance of predicted hue to the mean predicted hue. (for samples that have been adjusted to have the same hue by human observers)



Finding the matrix parameters

JND uniformity cost function:

- Variance in JND-ellipsoid half axes length after SVD



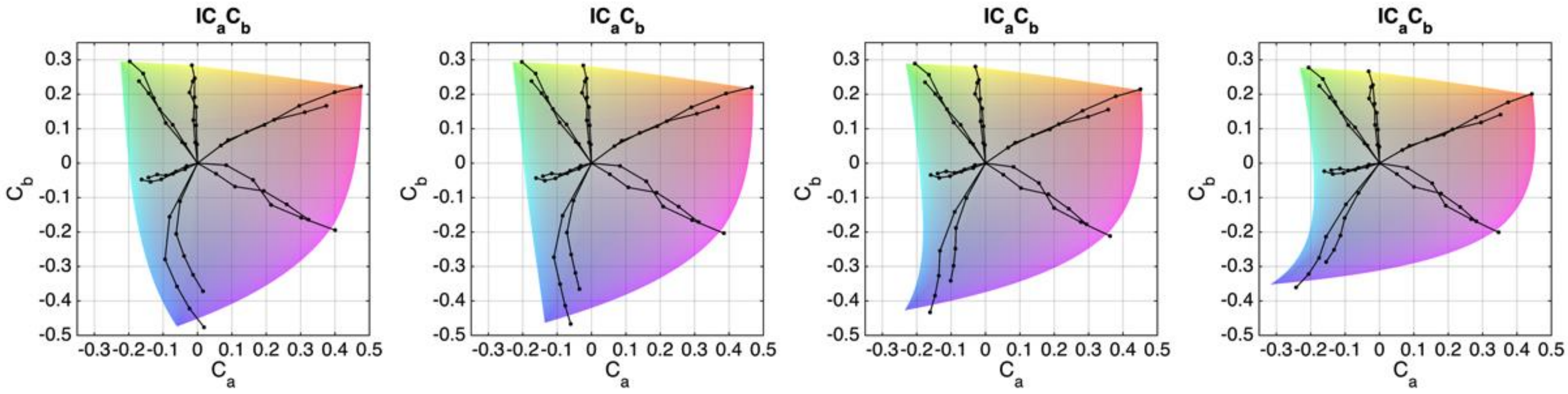
$$C_{\text{jnd}} = \frac{1}{3n} \sum_{j=1}^{3} \sum_{i=1}^{n} \left(\frac{\|q_{i,j}\|}{\frac{1}{3n} \sum_{u=1}^{n} \sum_{v=1}^{3} \|q_{u,v}\|} - 1 \right)^2$$

where $q_{i,j}$ are the three half axes of n JND ellipsoids after singular value decomposition (SVD) has been applied to the half axes of each ellipsoid.

Results

- IC_aC_b can be optimized for different purposes by weighting the cost function differently:

JND-uniformity vs. hue-linearity



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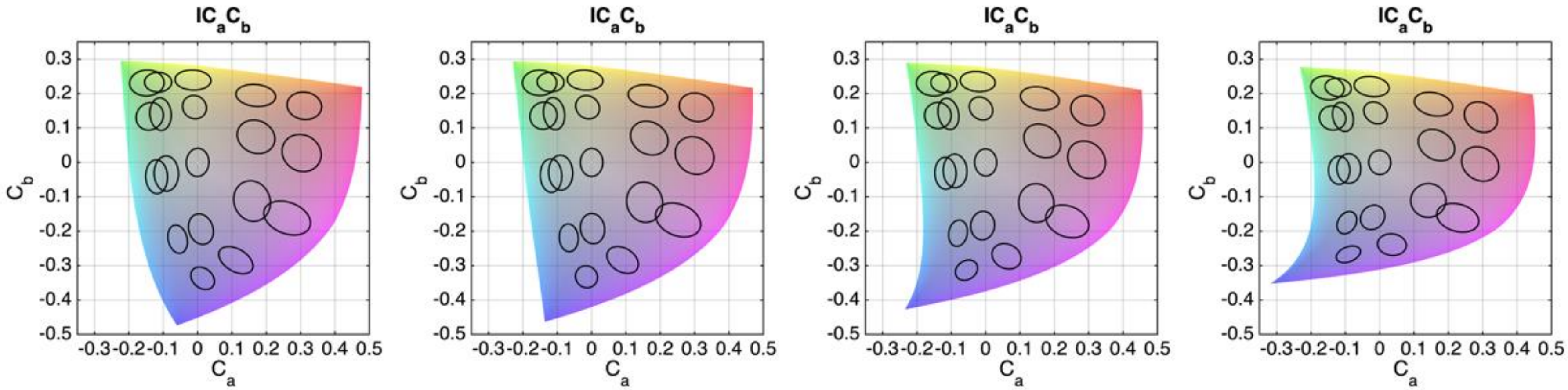
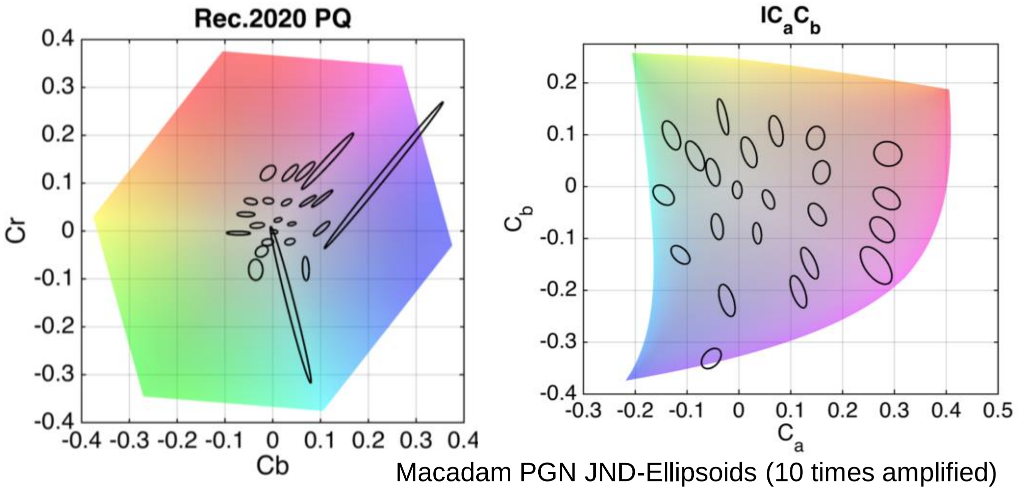


IC_aC_b compared to YC_bC_r

- Better JND uniformity / encoding efficiency (YCbCr JNDs can range from half a 10bitCV to more than one hundred 10bitCVs)

- More tonal resolution around pastels



Macadam PGN JND-Ellipsoids (10 times amplified)

IC_aC_b compared to YC_bC_r

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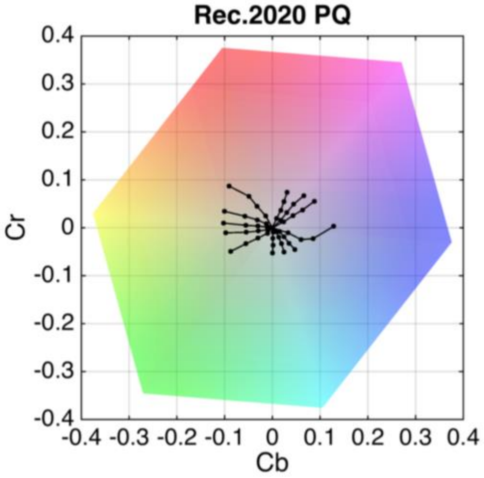

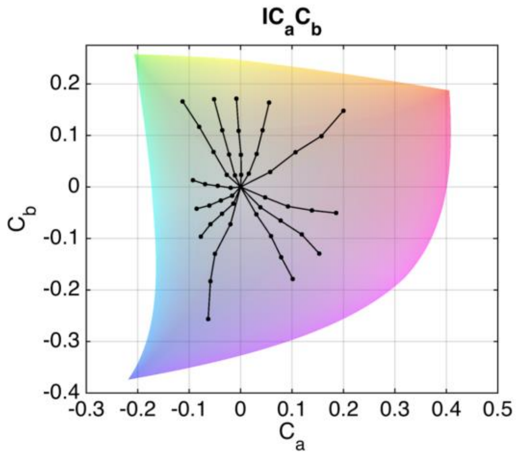

Hung & Berns Hue-Linearity (@100cd/m^2)

IC_aC_b compared to YC_bC_r

- Better JND uniformity / encoding efficiency (YCbCr JNDs can range from half a 10bitCV to more than one hundred 10bitCVs)
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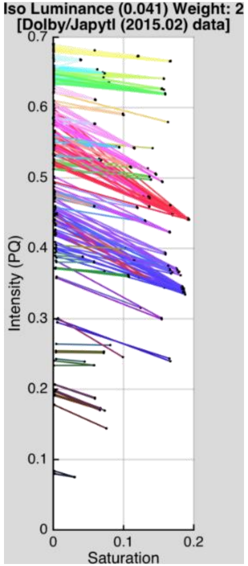
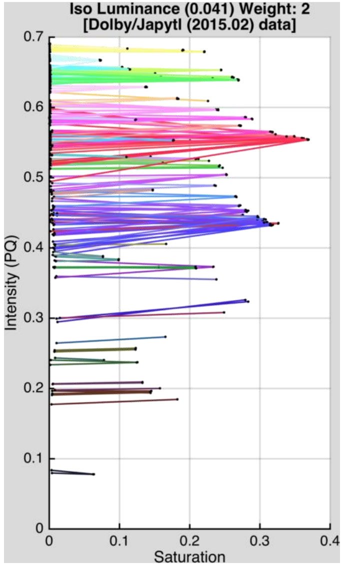
- Better hue-linearity
- Better iso-luminance



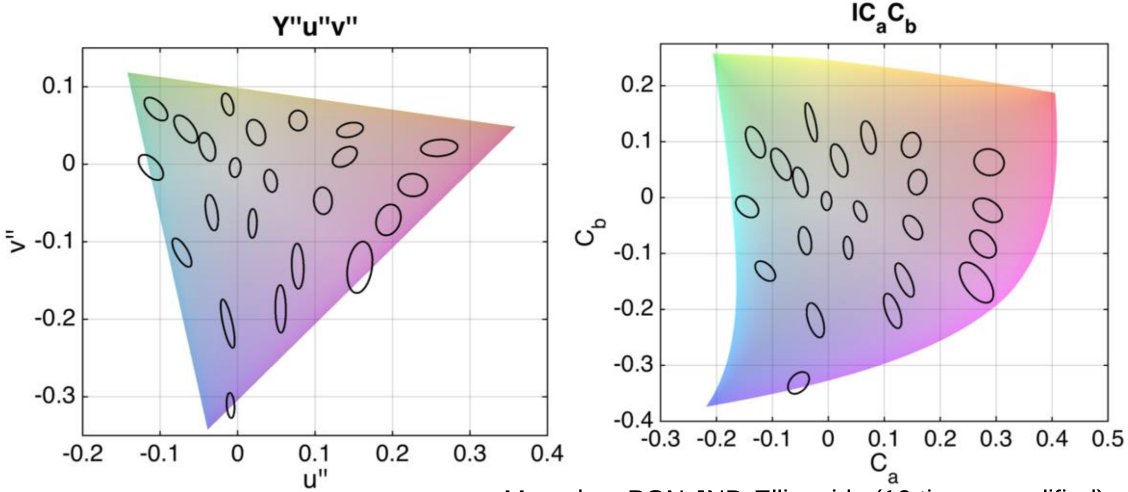
YC_bC_r



IC_aC_b

IC_aC_b compared to CIE 1976 u'v' based encodings

- More perceptually uniform
- More tonal resolution around skin tones



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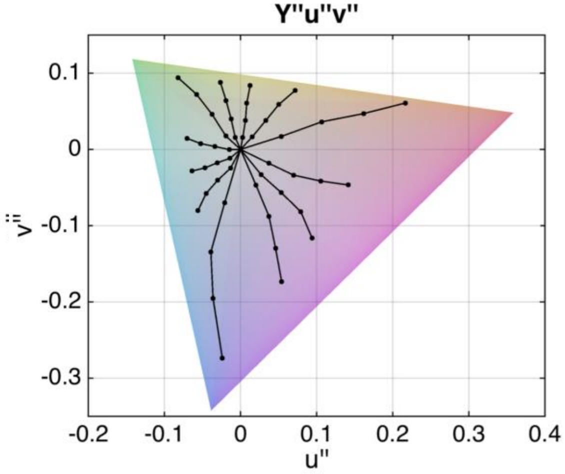
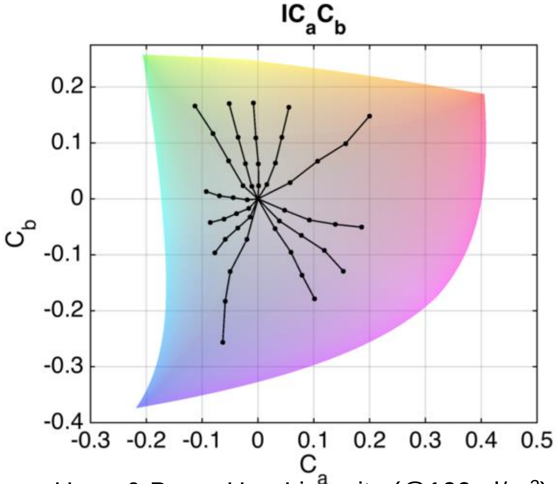
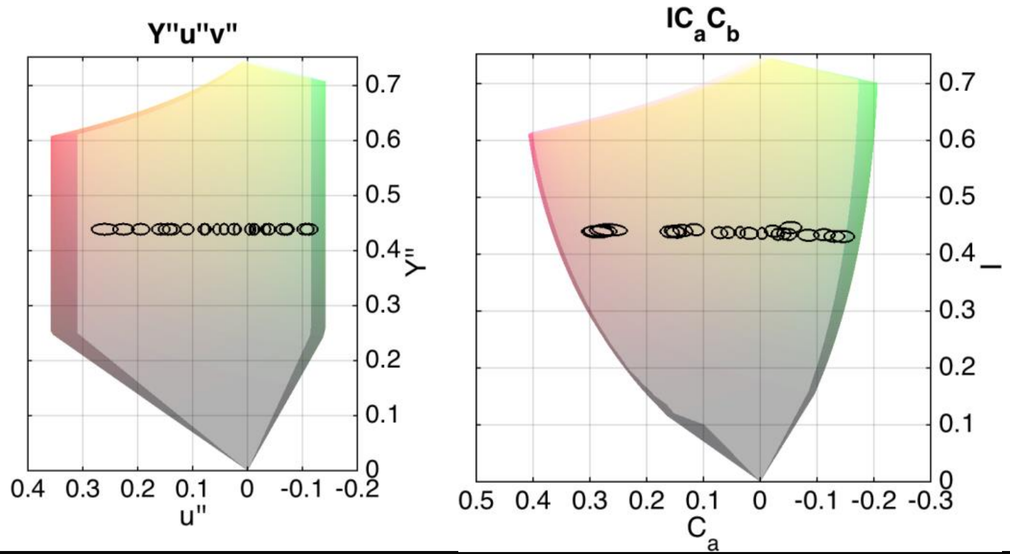




Hung & Berns Hue-Linearity (@100cd/m^2)

IC_aC_b compared to CIE 1976u'v' based encodings

- More perceptually uniform
- More tonal resolution around skin tones
- Better hue-linearity
- Smoother modeling of the Hunt effect

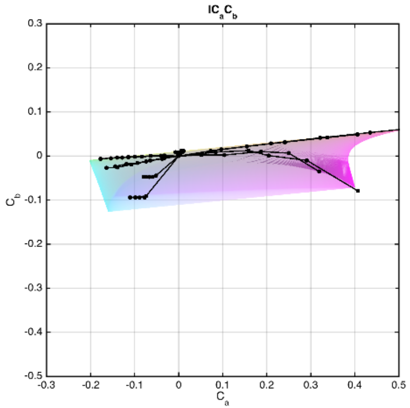


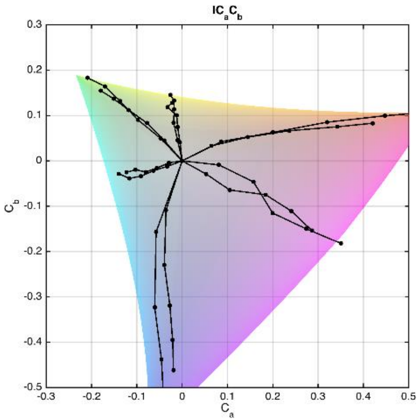
IC_aC_b compared to CIE 1976u'v' based encodings

- More perceptually uniform
- More tonal resolution around skin tones
- Better hue-linearity
- Smoother modeling of the Hunt effect
- Less computations needed (no division)

Further research

- Optimization sometimes has to be run multiple times to find global minima when initializing x0 with random values from the full range of possible values.
- Example local minima:





- Can be easily excluded by running optimization multiple times

Further research

- Test set data was small
  - N = 2 to 30 depending on the data set.
- Acquisition methods for the test sets could be enhanced
  - Method of adjustment for JNDs suboptimal
- Running the optimization on the verification set instead of the test set resulted in a stronger compression of the blue-yellow axis

Conclusion

- We present a new HDR color encoding that performs better in coding efficiency compared to current approaches:
  - $Y'C_bC_r$ PQ
  - $Y'C_bC_r$ BBC
  - Y''u''v''
- Our color space is co-optimized for encoding efficiency and color volume mapping (Tone Mapping & Gamut Mapping) and is therefore applicable for HDR and WCG color encoding in TV and cinema szenarios

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References

[1] Miller, Scott, Mahdi Nezamabadi, and Scott Daly. "Perceptual signal coding for more efficient usage of bit codes." *SMPTE Conferences*. Vol. 2012. No. 10. Society of Motion Picture and Television Engineers, 2012.

[2] Barten, Peter GJ. "Formula for the contrast sensitivity of the human eye." *Electronic Imaging 2004*. International Society for Optics and Photonics, 2003.

[3] G. Kindlmann, E. Reinhard, et al. "Face-based luminance matching for perceptual colormap generation," IEEE Conference on Visualization, Boston, MA, USA, 2002.

[4] P.C. Hung and R. S. Berns, "Determination of constant hue loci for a CRT gamut and their predictions using color appearance spaces," Color Research & Application, vol. 20, no. 5, pp. 285-295, 1995.

[5] D. L. MacAdam "Visual sensitivities to color differences in daylight." Journal of the Optical Society of America, vol. 32, no.5, pp. 247-273, 1942.

[6] K.J.Kim,R.Mantiuk,etal."Measurements of achromatic and chromatic contrast sensitivity functions for an extended range of adaptation luminance," IS&T/SPIE Electronic Imaging, Burlingame, CA, USA, 2013.