Color in Advanced Displays: HDR, OLED, AR & VR

Michael J. Murdoch
Munsell Color Science Laboratory
Rochester Institute of Technology

GENERATIONS
SIGGRAPH2018

R·I·T

SIGGRAPH '18 Courses , August 12-16, 2018, Vancouver, BC, Canada
ACM 978-1-4503-5809-5/18/08.
10.1145/3214834.3214840

PoCS
MCSL

Color in Advanced Displays: HDR, OLED, AR & VR

Michael J. Murdoch
Munsell Color Science Laboratory
Rochester Institute of Technology

GENERATIONS
SIGGRAPH2018

R·I·T

PoCS
MCSL

Introduction: Mike Murdoch

- Assistant Professor in Color Science @ RIT since 2015

- Research Topics: Visual adaptation, color and material appearance, AR display applications, dynamic lighting

- Philips Research (Eindhoven, NL) 2008-2015
- Kodak Research (Rochester, NY) 1997-2008

- Chemical Engineering / Computer Science / Human-Technology Interaction (PhD: Human-Centered Display Design)

- Photography, snowboarding, xc skiing, kayaking, maker stuff

Munsell Color Science Laboratory http://mcsl.rit.edu

Program of Color Science

RIT's Program of Color Science and Munsell Color Science Laboratory unite to form one of the world's foremost color science research and educational organizations.

Color science is a fundamental field of science dedicated to understanding the creation of colored stimuli, sources of illumination, and ultimately the human perception of color. It builds upon, and crosses the disciplinary boundaries of, chemistry, physics, life sciences, mathematics, and psychology. Color science is used in the design and production of most man-made materials including textiles, paints, plastics, ceramics, and imaging systems and to specify the properties of diverse natural materials such as skin, plants, animals, and soil. The applications of color science are truly ubiquitous.

MS degree

The M.S. degree requires 30

Ph.D. degree

The Ph.D. degree

Munsell Laboratory

RIT's Munsell Color

In the News

RIT color scientist explains why the NFL's 'Color Rush' debut lacked luster

Ph.D. in color science-Yuta Asano '15, Motorola Mobility

Follow the adventures of a recent alumnus in Antarctica.

CIE publishes Research Strategy with strong correlation to RIT PoCS/MCSL Research

Outline & Schedule

10 min	Idealized display concepts
20 min	Tone reproduction, EOTF, dynamic range
30 min	Color primaries, gamut, calibration & characterization
20 min	Viewing environment, adaptive displays, observer differences
10 min	Wrap-up & discussion

Please ask questions as we go! I'll try to stay on schedule

Idealized Display Concepts

GENERATIONS
SIGGRAPH2018

R·I·T

PoCS
MCSL

All displays have…

- Image input specifications / encodings
- Tone characteristics: Electro-optical transfer function (EOTF)
- Color characteristics (primaries, gamut, additivity)
- Calibration state
- Dynamic behavior / algorithms
- Viewing environment effects (physical and perceptual)

Not the Structure of the Course

	LCD	HDR-LCD	OLED	LED Wall	DLP Proj	LCD Proj
Encoding						
Tone/EOTF						
Color						
Calibration						
Dynamic behavior						
Viewing env.						

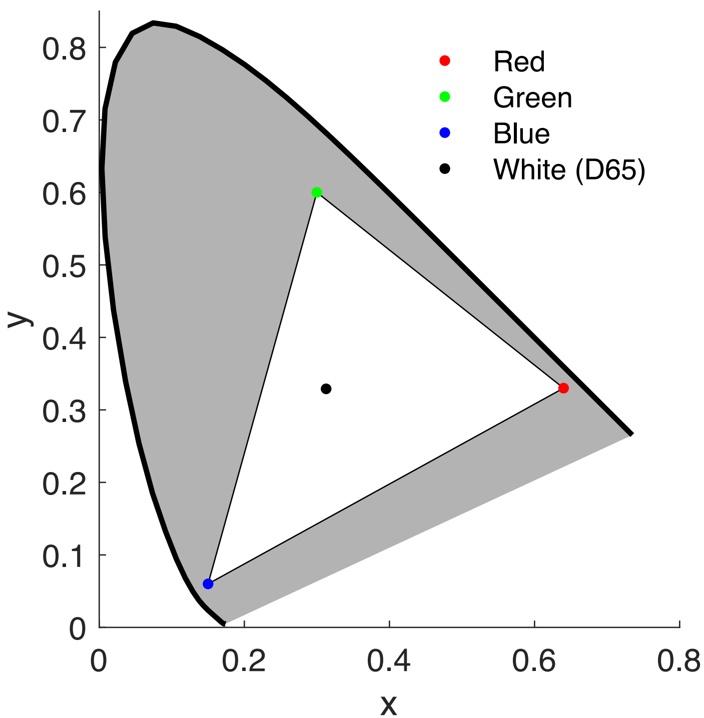
An Idealized Display: sRGB

- sRGB "Standard" RGB
- Defined in 1999 by International Electrotechnical Commission (IEC 61966-2-1) & previously (1996) by the W3C
- Defines:
  - Display white point: D65, CIE x,y (0.3127, 0.3290), 80 cd/m^2
  - Color primaries: RGB CIE x,y (0.64, 0.33), (0.30, 0.60); (0.15, 0.06)
  - EOTF: piecewise function approximating $y = x^{2.2}$
  - Viewing conditions: 4 cd/m^2 D50 surround

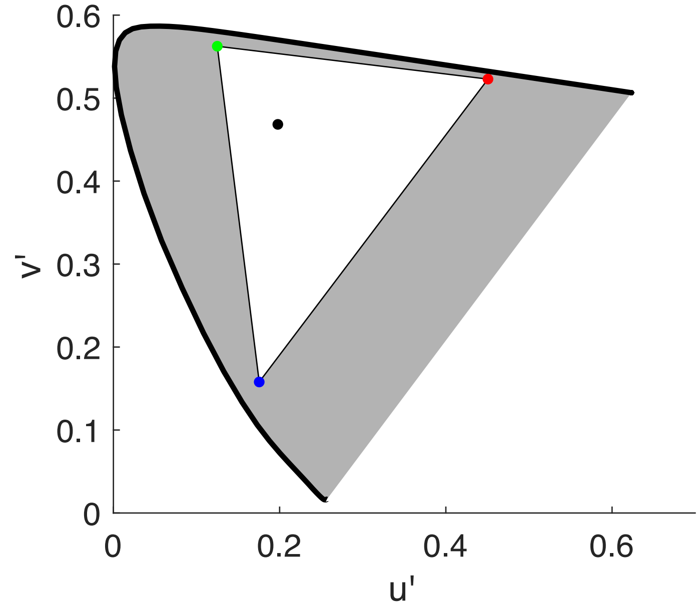
W3C sRGB: https://www.w3.org/Graphics/Color/sRGB.html
IEC 61966-2-1: https://webstore.iec.ch/publication/6169

An Idealized Display: sRGB Primaries

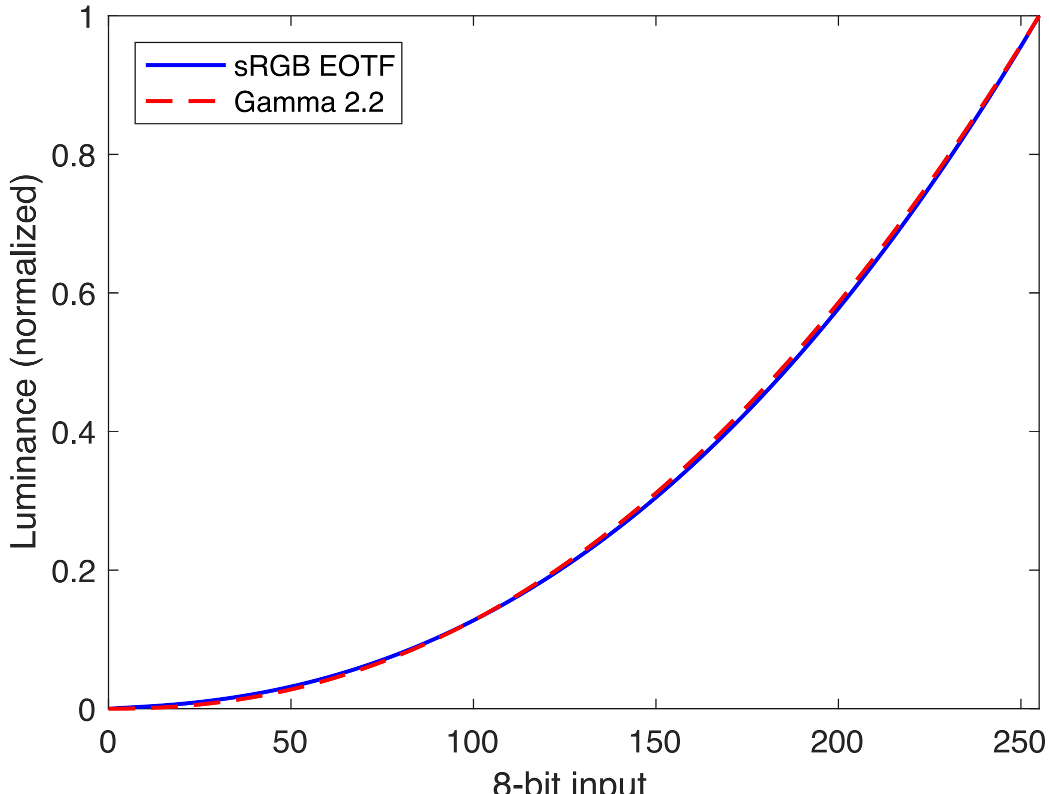
CIE 1931 xy (nonuniform!)



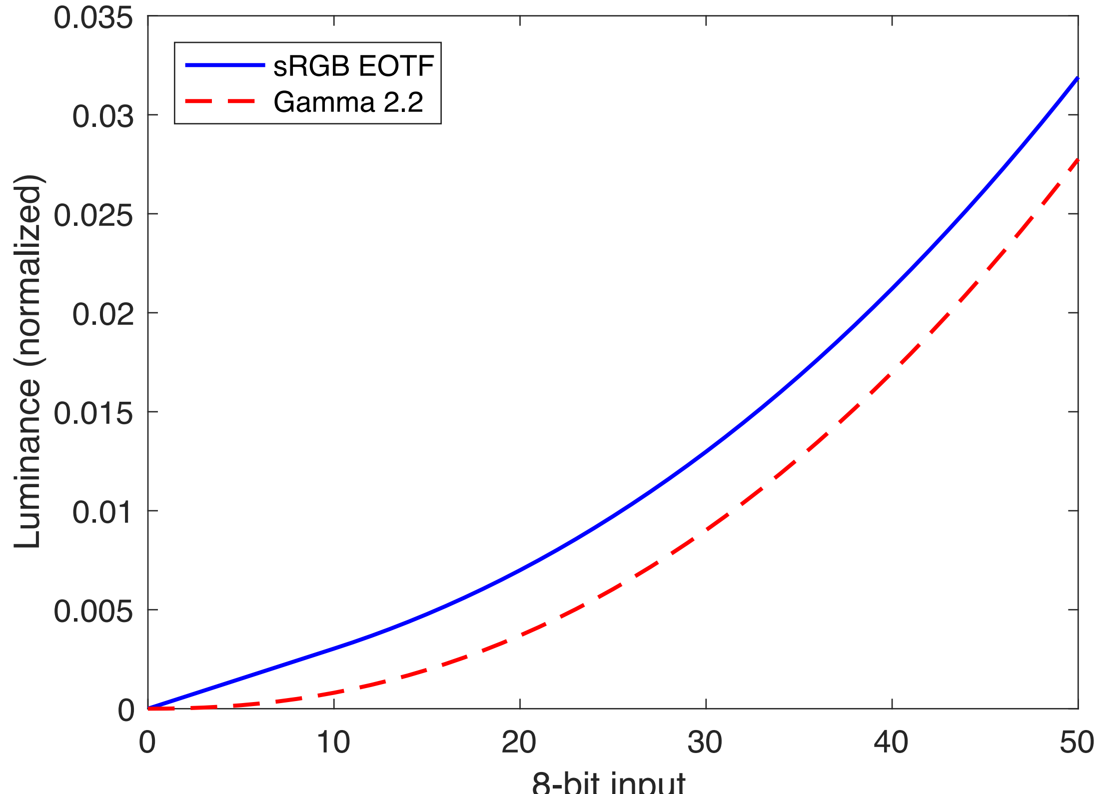
CIE 1976 u'v' (better!!)



An Idealized Display: sRGB EOTF

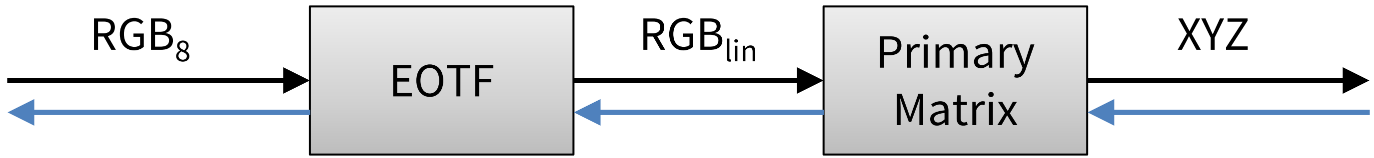


An Idealized Display: sRGB EOTF



An Idealized Display: sRGB

- Deterministic colorimetric output (CIE XYZ) for any RGB input



- Color gamut is well-defined (additive)
- And also: black = ZERO

- sRGB is ubiquitously used as a color image encoding: JPG, www

Real-World sRGB

- Much higher white point (200-300 cd/m^2 instead of 80)
- Decent consumer monitors match primaries and relative EOTF
- BUT black is not zero!
- Viewing conditions??

Tone Reproduction & Dynamic Range

Luminance Dynamic Range

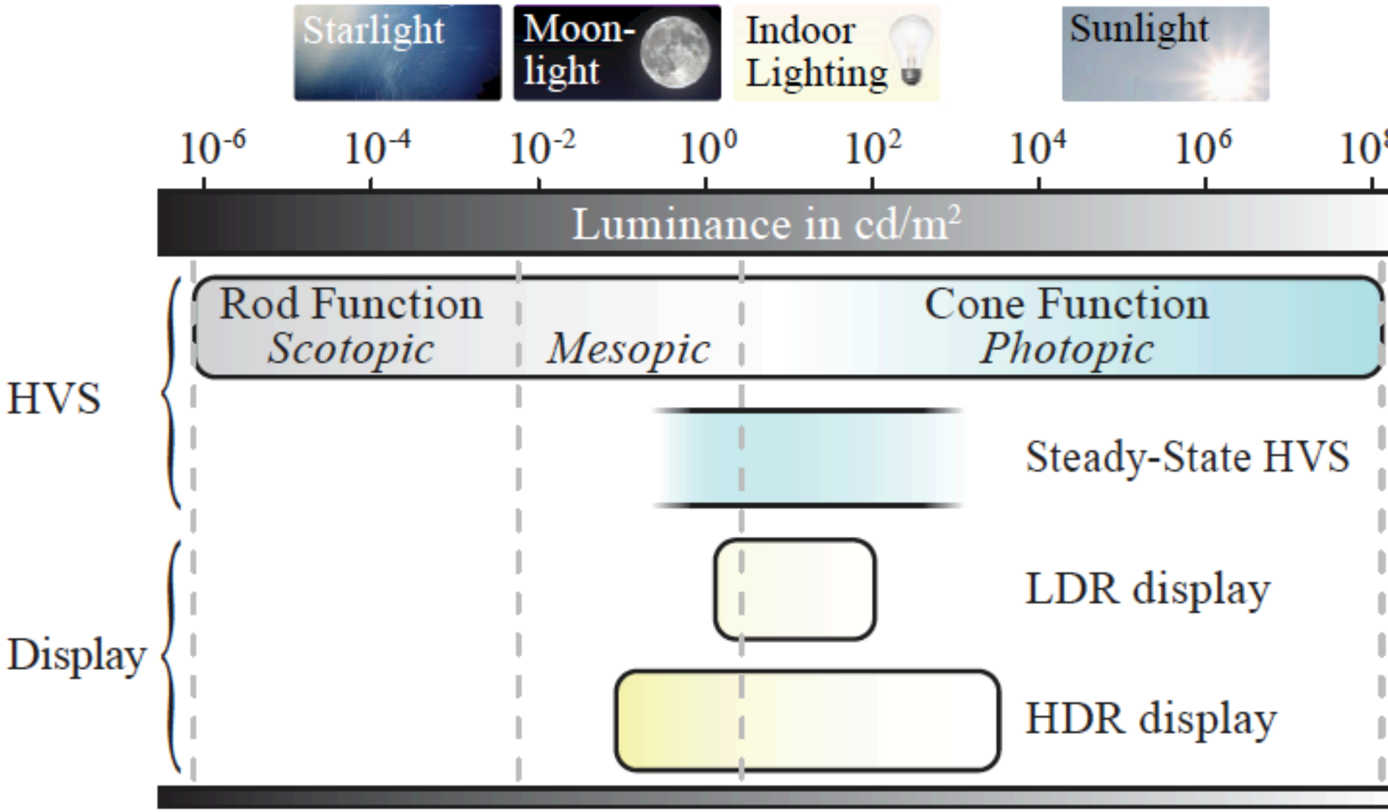


Figure 1 from Kunkel & Daly, A Reassessment of the Simultaneous Dynamic Range of the Human Visual System, ACM APGV 2010: https://doi.org/10.1145/1836248.1836251

Display Types and Dynamic Range

Emissive displays:

- (CRT, Plasma)
- OLED, LED-walls

- Light is generated at each pixel as needed

- Typically limited at high end

Light-filtering displays:

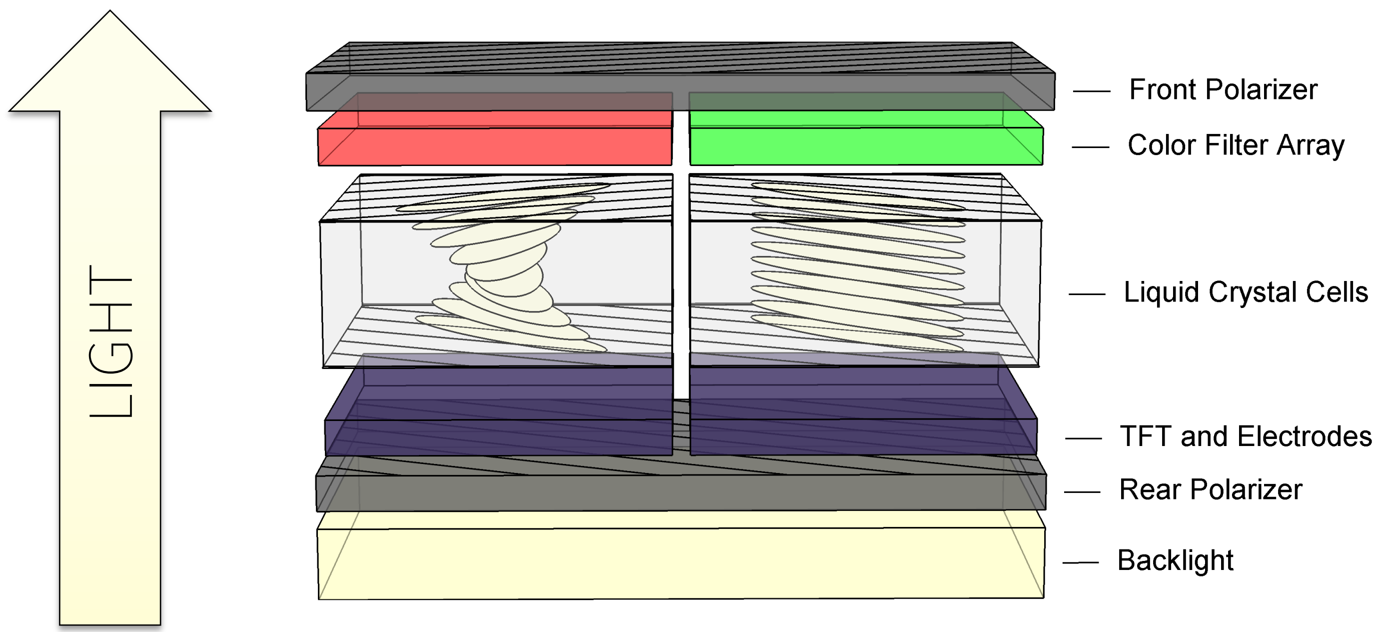
- LCD flat panels
- LCD & DLP projection

- White light source is attenuated by pixels

- Typically limited at low end

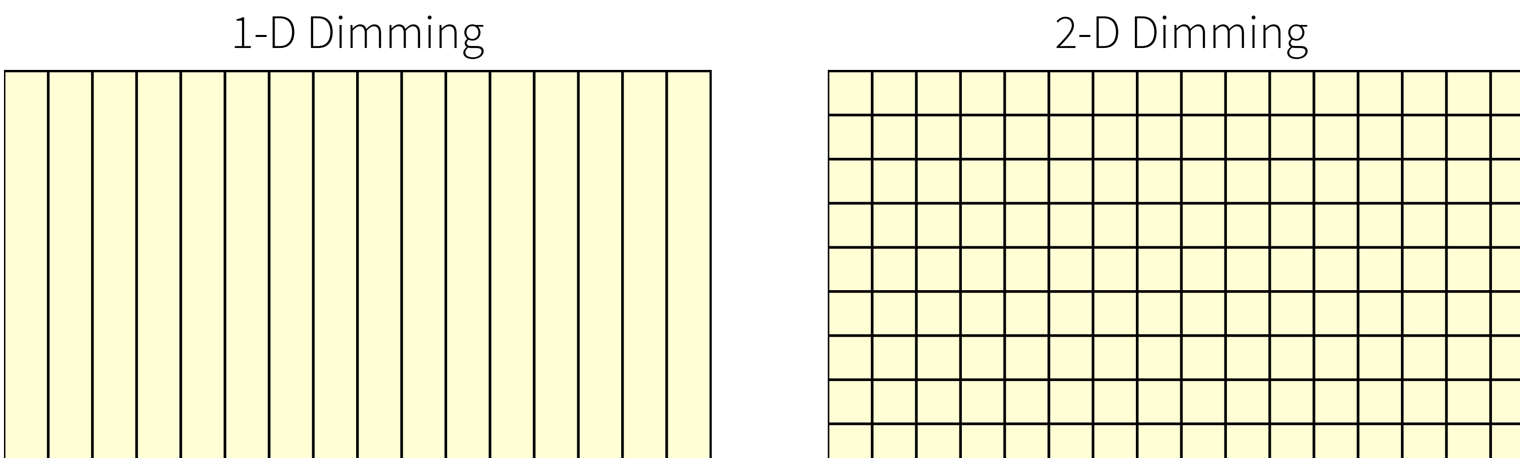
LCD: Liquid Crystal Display

- A light valve at each pixel, max attenuation ~1000:1

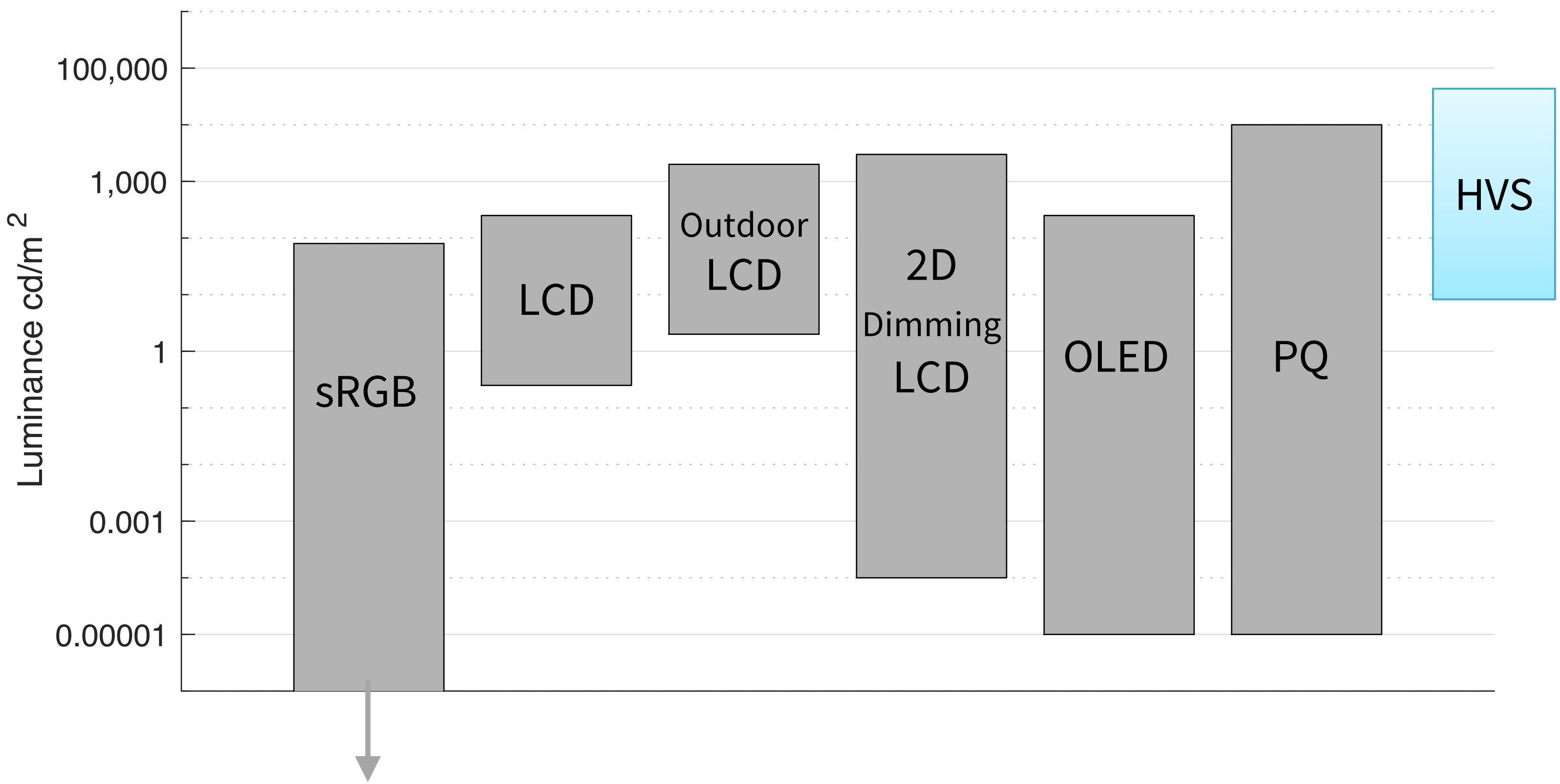


HDR LCDs

- Getting past the 1000:1 limitation
- Spatially-addressable backlight, much lower than pixel resolution (i.e. 16 columns or 16x9 blocks):



Luminance Dynamic Range



Display Dynamic Range: How Much is Enough?

Two extreme answers:

- Kunkel & Daly: 3.7 log units simultaneously visible
- But, HVS can handle ~12 log units with adaptation

Philosophical considerations:

- Do we want a Full-DR display?
- Assume adaptation
- Rendering high-key & low-key scenes

Dynamic Range is a Physical Property

- Dynamic range *of a scene* or *of a display*
- Luminance dynamic range: Contrast ratio: max Y / min Y; or "log units" or for real photo geeks "stops" ($\log_2$ units)

  100:1 (2 log units) for a good photo print

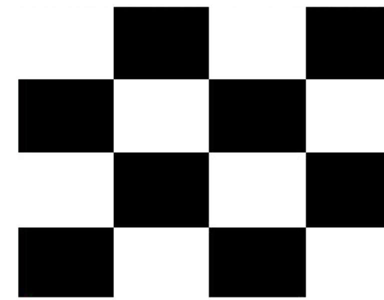
  1,000:1 (3 log units) for typical LCD

  10,000,000:1 (7 log units) for HDR displays (?)

  "Infinite contrast" marketing language

Practical Limitations to Dynamic Range

- Flare/reflections from the viewing environment[1]
- Intra-ocular glare[2]



- Specifications vs. Measurements[3]
  - Simultaneous vs. sequential dynamic range
  - ANSI “checkerboard” contrast, dynamic contrast, …

1: Helt, HDR Perception Challenges and Measurements in Cinema Environments, SMPTE Motion Imaging Journal (2017): https://doi.org/10.5594/JMI.2016.2643800
2: Murdoch & Heynderickx, Veiling glare and perceived black in high dynamic range displays, JOSA A 29(4), 2012: https://doi.org/10.1364/JOSAA.29.000559
3: SID Information Display Measurement Standards https://www.icdm-sid.org/downloads/index.html

Tone Reproduction is a Luminance Relationship

OETF EETF EOTF

- Depends on camera, image processing, display

  Scene luminance → reproduction luminance

- If you are "gamma" minded:

  scene log luminance → reproduction log luminance

- If you are "old school photo" minded:

  scene log exposure → reproduction density

Why Tone Reproduction?

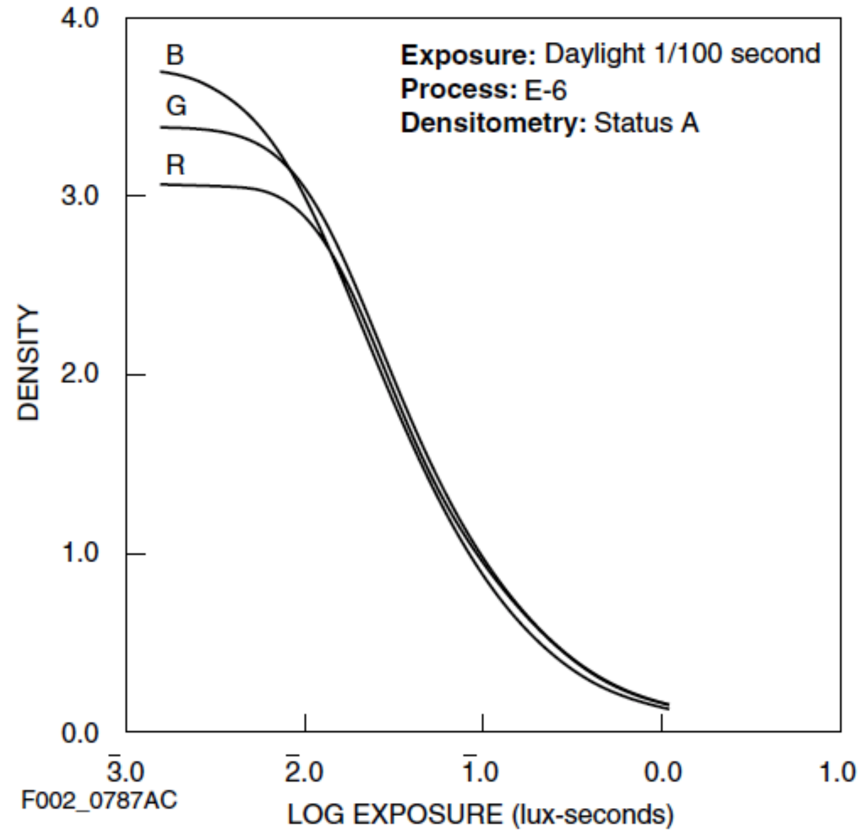
- 1:1 tone reproduction would mean the repro equals the world

  An amazing display this would be!
- Generally speaking, lower display peak white requires steeper tone reproduction curve:
  - Stevens effect: perceived **contrast** increases with luminance
  - Hunt effect: perceived **colorfulness** increases with luminance
  - Bartleson-Breneman effect: **contrast** increases with **surround** lum.
- Thus tone reproduction ← display characteristics

Background:
Fairchild, Color Appearance Models, Wiley (2013): http://doi.org/10.1002/9781118653128
Giorgianni & Madden, Digital Color Management, Wiley (2009): http://doi.org/10.1002/9780470994375
Miller, A Perceptual EOTF for Extended Dynamic Range Imagery (2014)
https://www.smpte.org/sites/default/files/2014-05-06-EOTF-Miller-1-2-handout.pdf

Tone Reproduction Examples

- Photographic system OOTF "Characteristic Curve" for Kodak Ektachrome 100 (circa 2007)
- Density vs. Log Exposure
  - Straight line in log-log would be a "gamma curve"
  - Steep curve for Stevens & Hunt
  - Curve gets steeper to compensate for flare
- Dynamic range ~1,000:1

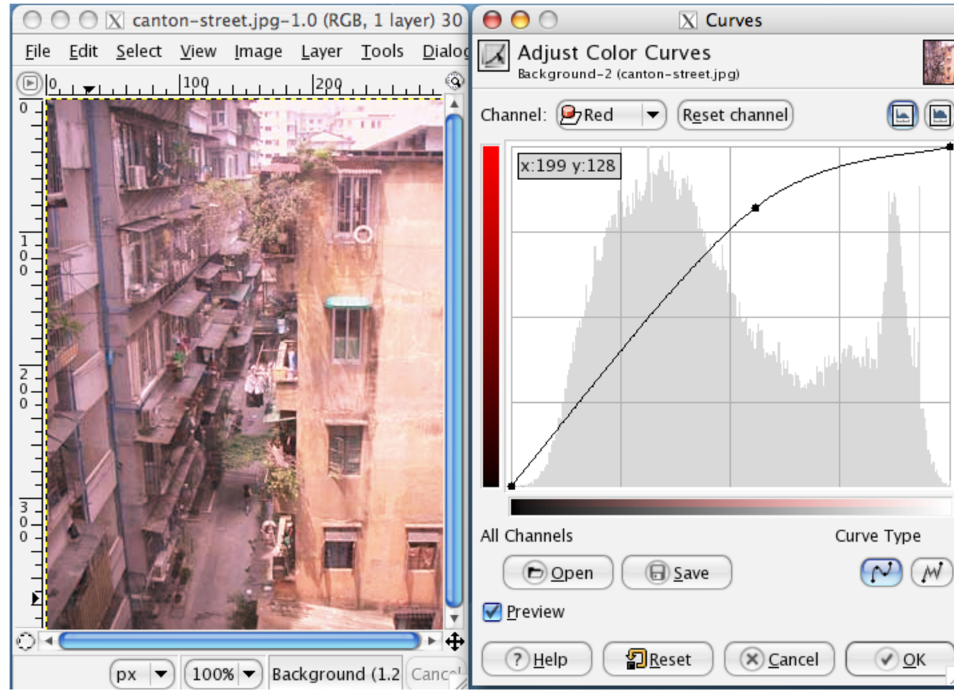


Kodak Technical Data Sheet E-27 (2007)
http://wwwuk.kodak.com/global/en/professional/support/techPubs/e27/e27.pdf

Tone Reproduction Examples

- "Curves" tool in GIMP or Photoshop: EETF adjustment
- Camera modes, display modes…

- Note that steeper RGB curves increase luminance *and* increase color saturation



Magnus Lewan, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=1446146

HDR Tone Reproduction & Tone Mapping

- Compress HDR scene/image to LDR

- Global tone mapping operators (TMOs)
- Local TMOs

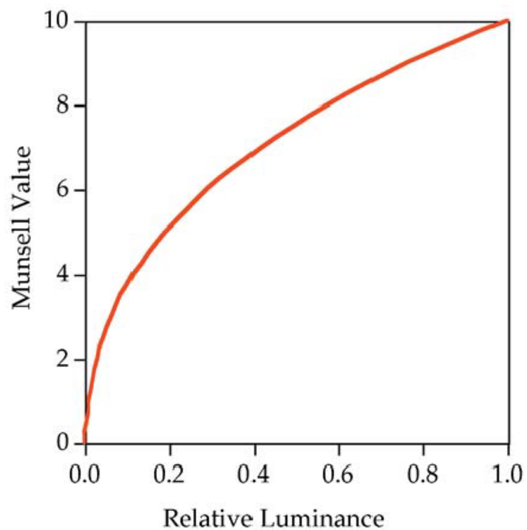
- TMOs for HDR display?
- Luminance of diffuse white?

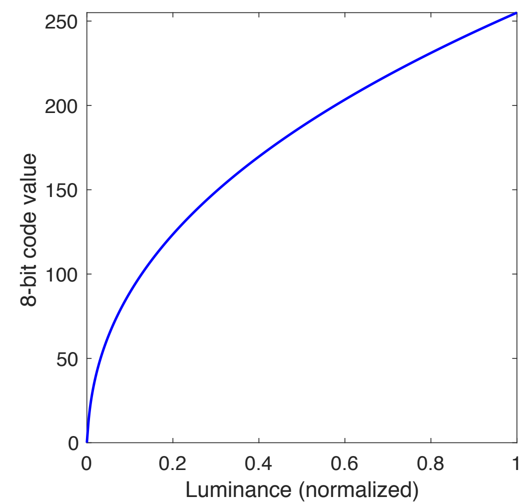
Kevin McCoy, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=7798262

Background:
Reinhard et al., Color Imaging: Fundamentals and Applications, CRC (2008)
Reinhard et al., High Dynamic Range Imaging, Morgan Kaufmann (2010)

EOTF & EOTF^{-1} for Encoding

- EOTF allows perceptually-efficient use of bit depth
- This is a lucky coincidence: lightness perception nearly matches a CRT's EOTF^{-1}





Left: Fairchild, Color Appearance Models 3ed, Wiley (2013): http://doi.org/10.1002/9781118653128

EOTF & EOTF^{-1} for Encoding

- DICOM[1]: 10-bit EOTF for monochrome radiographic displays
- HDR EOTFs:
  - Perceptual Quantizer (PQ)[2]: "stacked" JNDs from 10,000 cd/m^2 down, over 10 or 12 bits (HDR10, Dolby Vision)
  - Hybrid Log-Gamma (HLG)[3]: piecewise function extending SDR "gamma" curve with logarithmic compression

1: DICOM PS 3.14-2011 Part 14: Grayscale Standard Display Function: http://dicom.nema.org/Dicom/2011/11_14pu.pdf
2: ST 2084:2014 - SMPTE Standard - High Dynamic Range Electro-Optical Transfer Function of Mastering Reference Displays: http://doi.org/10.5594/SMPTE.ST2084.2014
3: ARIB STD-B67, Essential Parameter Values For The Extended Image Dynamic Range Television (EIDRTV) System For Programme Production (2015): https://www.arib.or.jp/english/html/overview/doc/2-STD-B67v1_0.pdf
See Also: SMPTE Report: https://www.smpte.org/sites/default/files/Study%20Group%20On%20High-Dynamic-Range-HDR-Ecosystem.pdf

Comparison of EOTFs

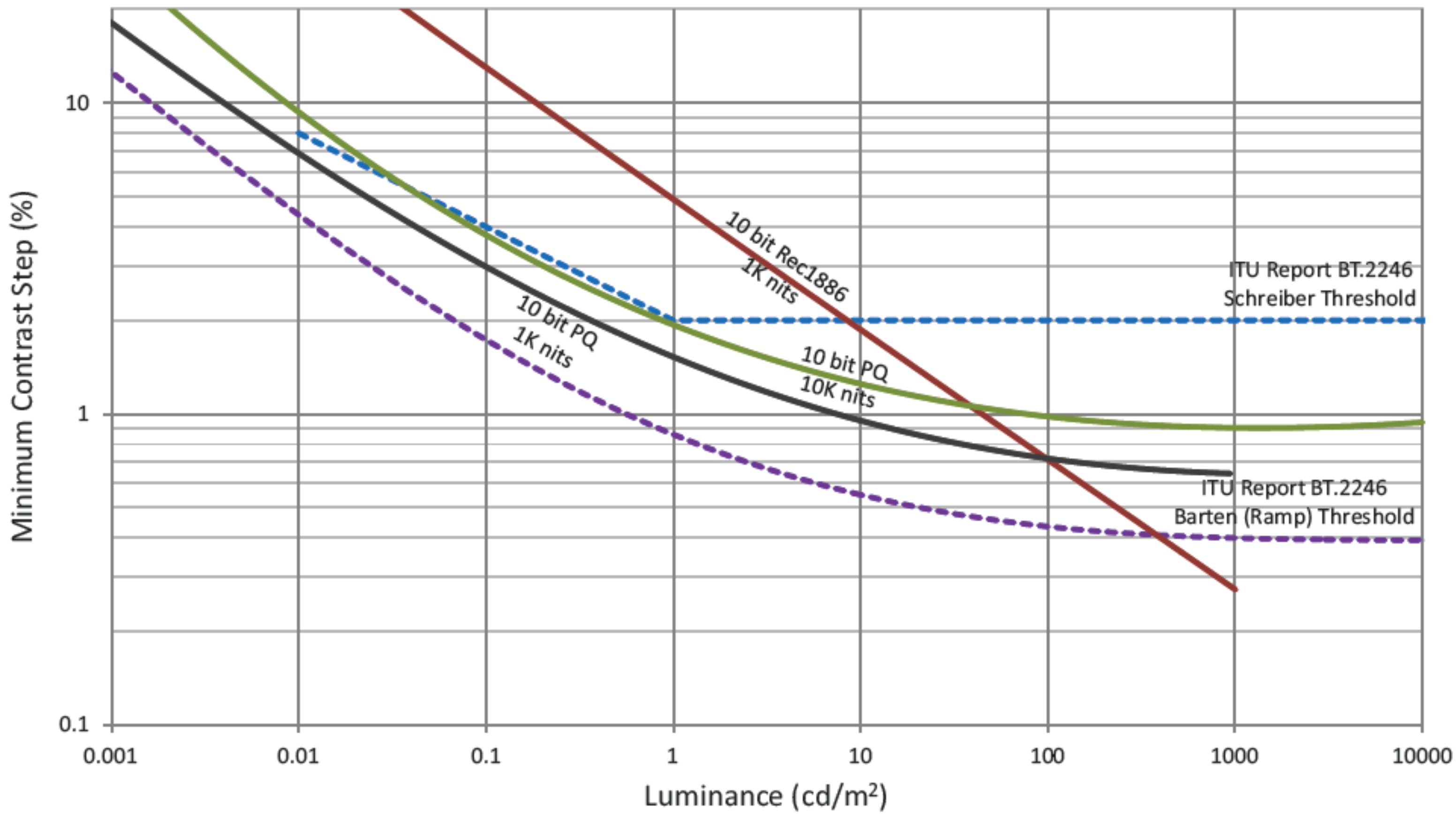


Figure 5 from: Miller et al., Perceptual Signal Coding for More Efficient Usage of Bit Codes, SMPTE Motion Imaging Journal, 2013: https://doi.org/10.5594/j18290

Color Display Characteristics

GENERATIONS
SIGGRAPH2018

R·I·T

PoCS
MCSL

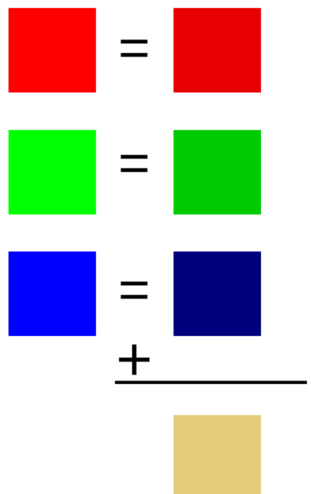
Additive RGB

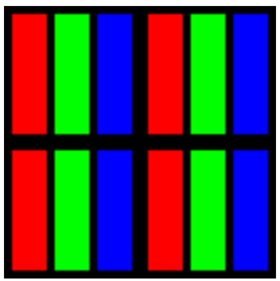
- Primaries: Red, Green, and Blue
- A display is an additive system, meaning colors may be synthesized using linear combinations of the primaries.
- Example: 0.8 * =

0.6 * =

0.2 * =

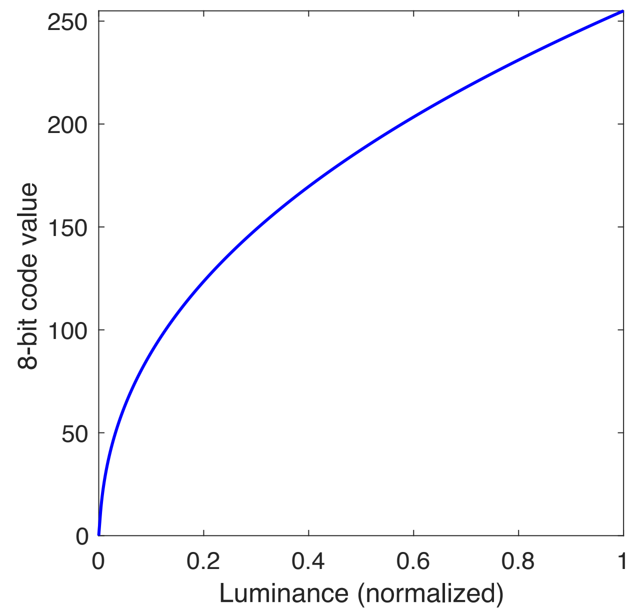
+



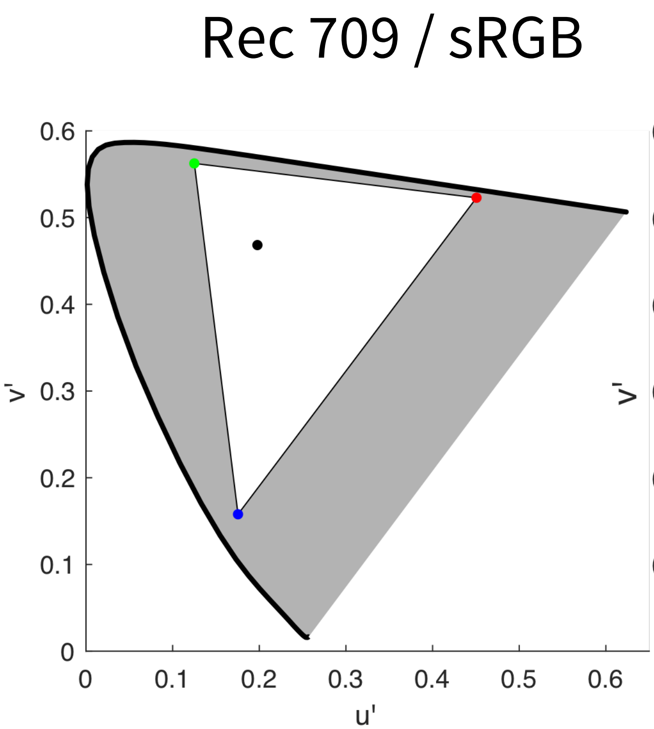


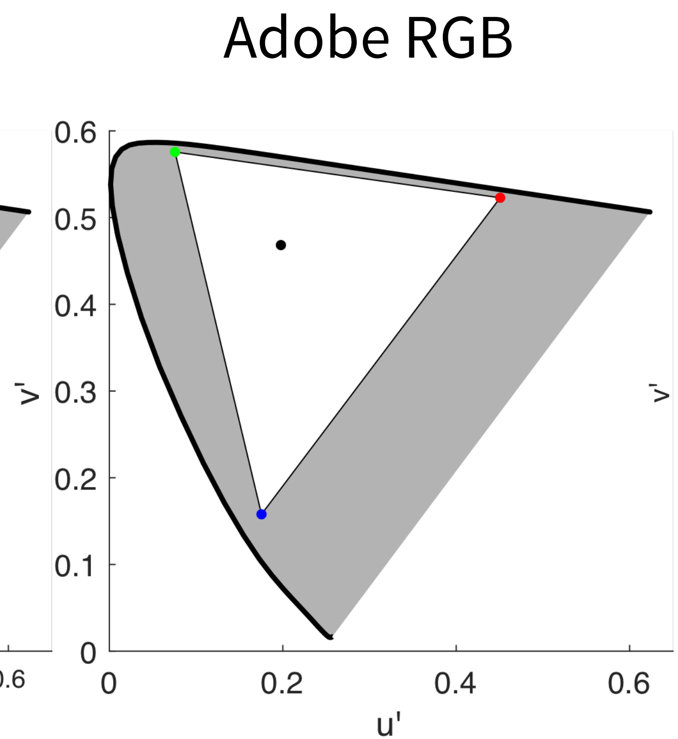
Additive *Nonlinear* RGB

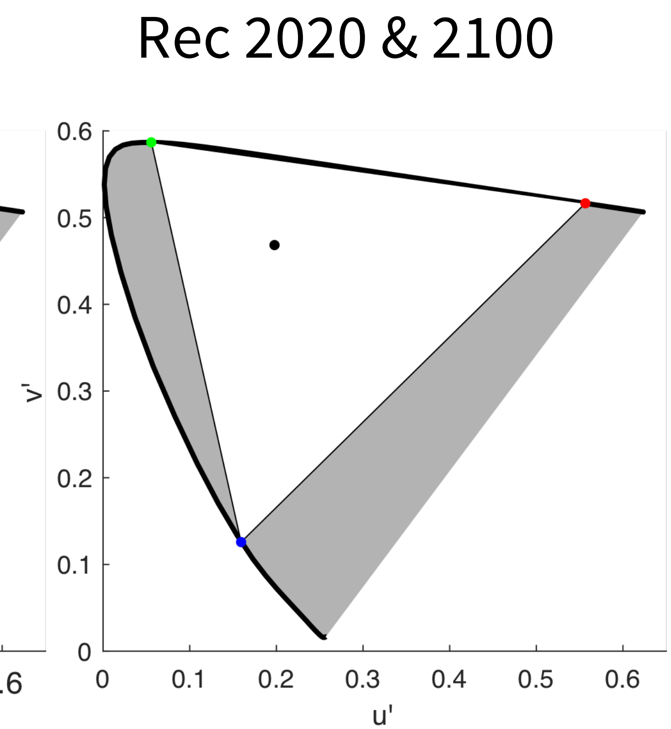
- Thanks to EOTF: RGB Code Values are nonlinear
- Using an sRGB monitor, linear intensity values (0.8, 0.6, 0.2) correspond to 8-bit nonlinear code values (231, 203, 124).



But *Which* RGB?



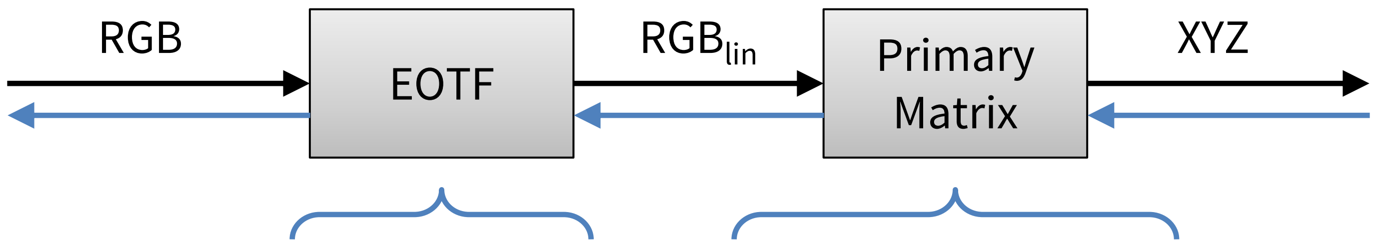




http://www.itu.int/rec/R-REC-BT.709
https://www.adobe.com/digitalimag/pdfs/AdobeRGB1998.pdf

https://www.itu.int/rec/R-REC-BT.2020
https://www.itu.int/rec/R-REC-BT.2100

General Additive Colorimetric RGB Model



LUT or function

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare}$$

- Primary matrix $\mathbf{M}$: XYZ of individual R, G, B channels
- 3x3 matrix $\mathbf{M}$ is invertible
- Model assumes: Channel independence & additivity

RGB Primary Selection

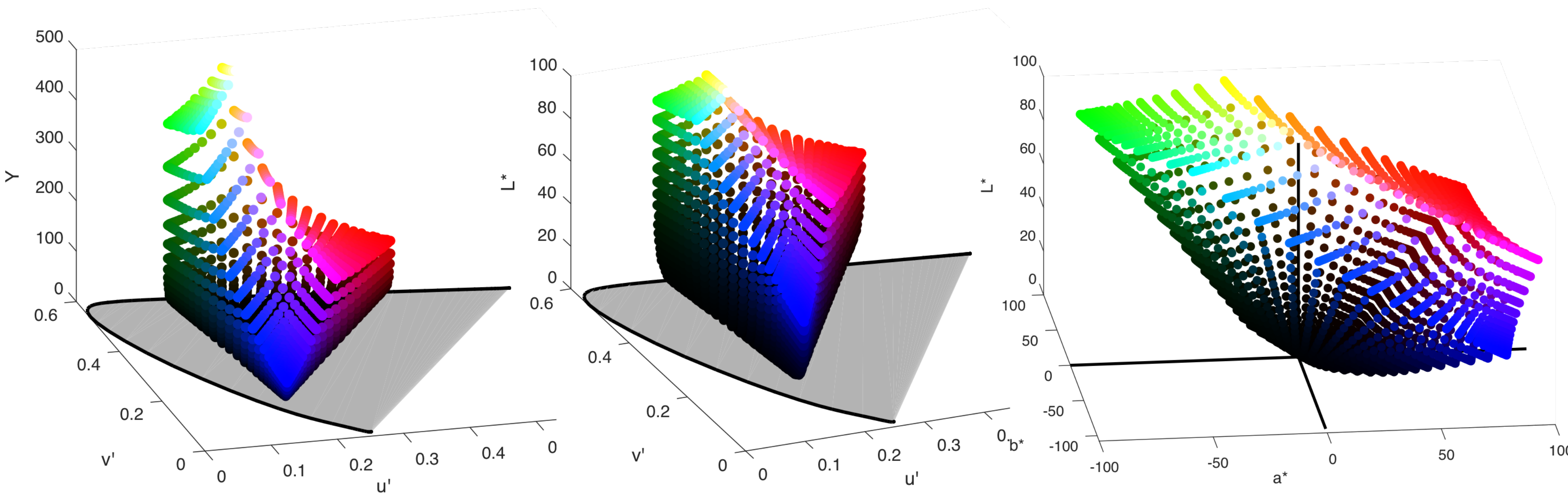
“Wider Gamut” RGB →

- Larger chromaticity gamut (triangle)
- Larger gamut volume?
- Different luminance distribution (G higher, B/R lower)
- Higher quantization potential (bit depth dependence)
- More inter-observer variation (observer metamerism)

Color Gamut is 3D

However, no real agreement on Z-axis; thus no volume measure

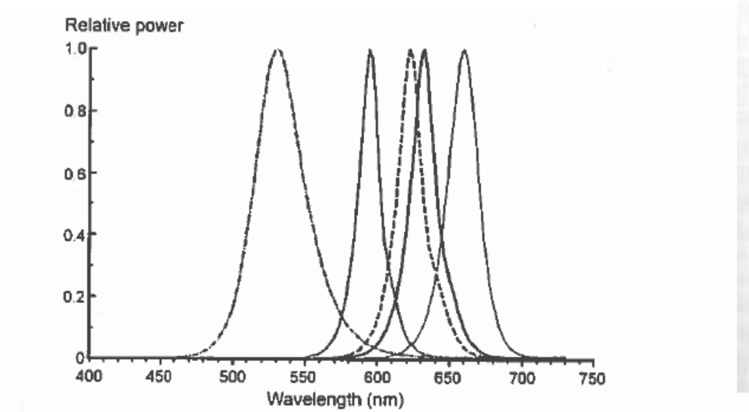
Below: u’v’Y,   u’v’L*,   a*b*L*:

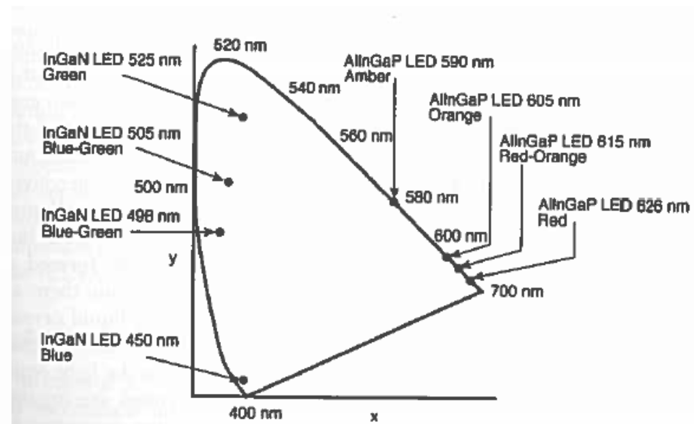


Mechanisms for Color

Emissive displays:

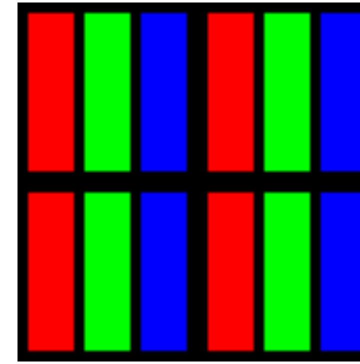
- LED & OLED electroluminescence (electron → photon): chemical structure / dopants tune the energy of the band gap (bluer is higher energy, redder lower energy)





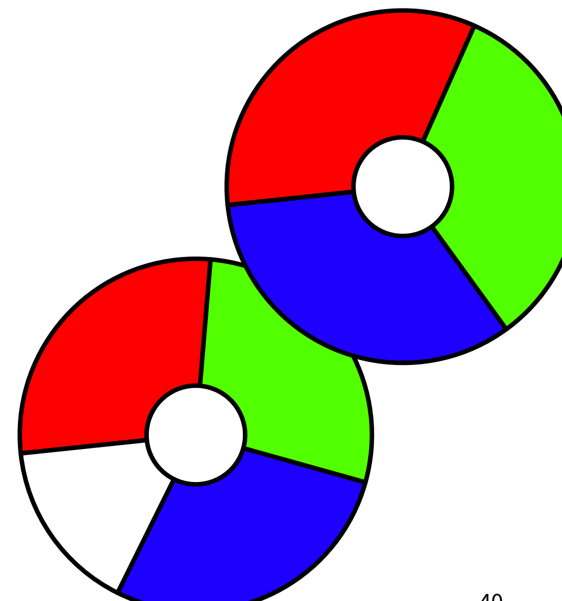
Boyce, Peter Human Factors in Lighting, Taylor & Francis (2003): https://www.taylorfrancis.com/books/9780203426340

Mechanisms for Color



Light-filtering displays:

- “White” light source: CCFL, LED (RGB or PC) + Color filter array
- RGB LEDs, sequential color



Projection:

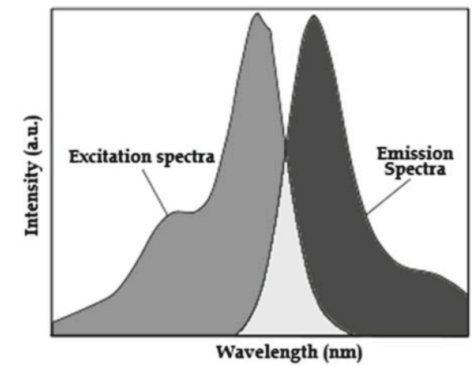
- Halogen, Xenon, Laser (RGB or PC) + Color filters (separate imagers) OR color filter wheel (sequential color)
- RGB LEDs, sequential color

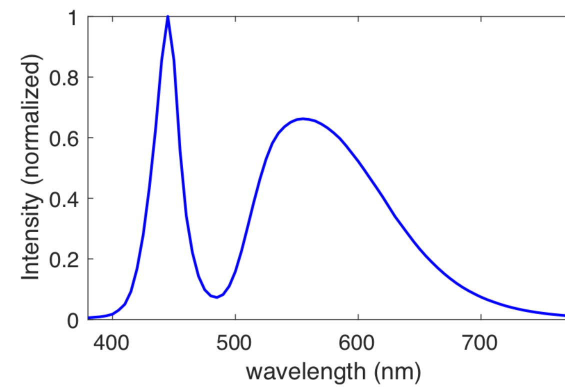
Mechanisms for Color

Phosphors:

- Fluorescent materials: absorb photons, emit lower-energy photons
- Phosphor-converted (PC) white LEDs: blue LED + yellow phosphor

- Quantum Dots: narrow emission bandwidth determined by size of nano-sphere of shells of ZnS, CdSe, PbS, etc.



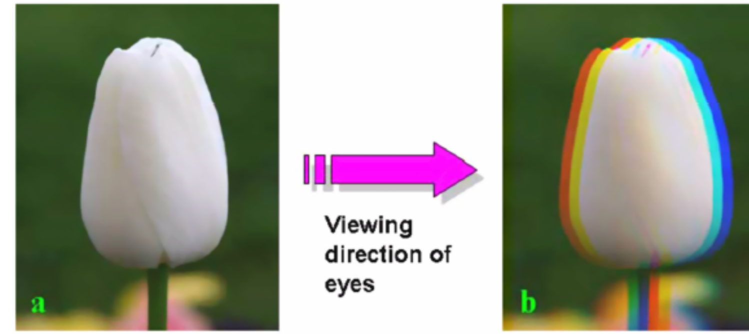


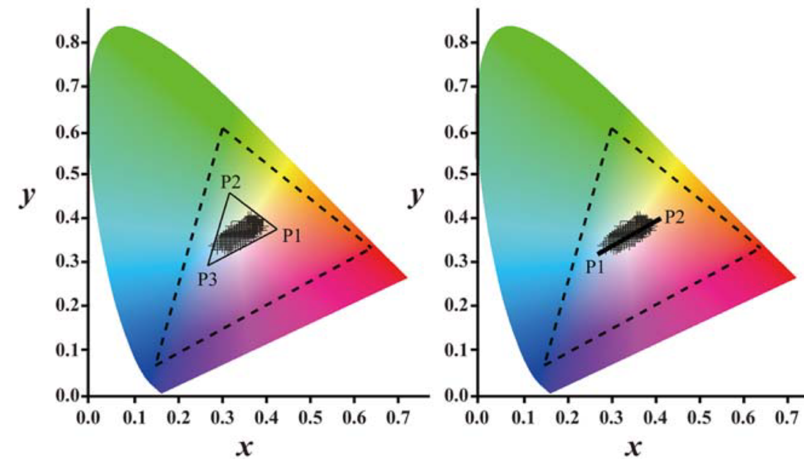
Shinde et al., Phosphate Phosphors for Solid-State Lighting, Springer (2013): http://doi.org/10.1007/978-3-642-34312-4

Mechanisms for Color

Sequential color:

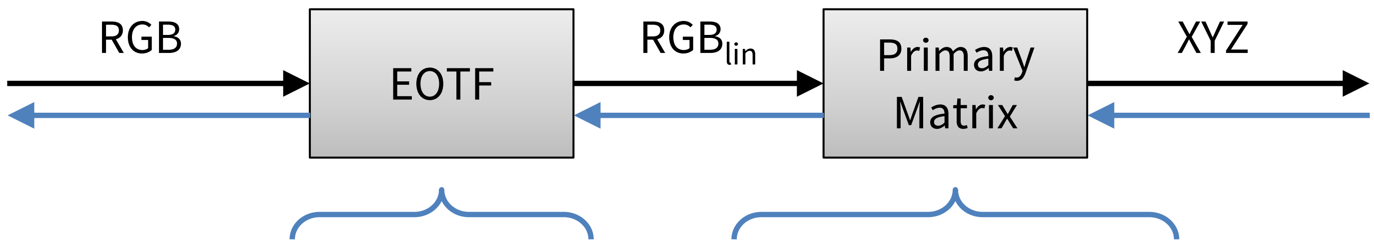
- Very high efficiency (no color filters)
- Color break-up, especially with moving content or moving eyes
- RGB or RGBW (default)
- Optimized 2+ frame subfields via mixes of RGB primaries





Wang et al., Color breakup visibility thresholds for 2-field sequential colors, CR&A, 2017: http://doi.org/10.1002/col.22125
Huang et al., Suppressing color breakup in LCDs, SPIE Newsroom, 2008: http://doi.org/10.1117/2.1200808.1254
See also: Mineo et al., Mechanism of color breakup in field-sequential-color projectors, JSID, 7(4), 1999.

Breaking the General RGB Model



LUT or function

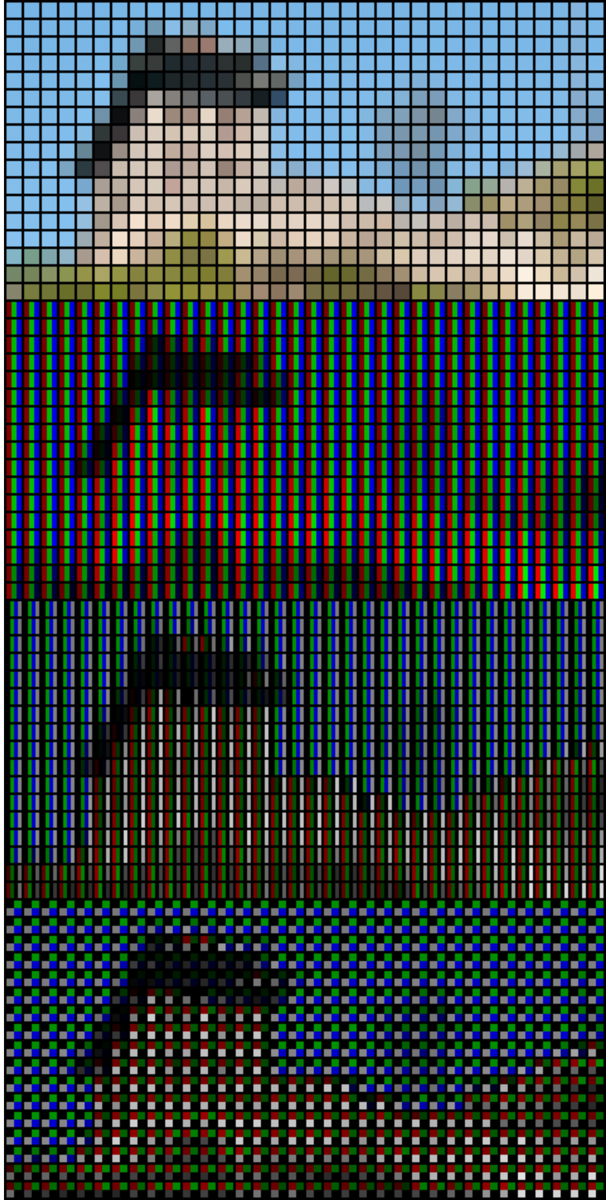
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{lin} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{flare}$$

- Extra primaries (W, C, Y, etc.): $\mathbf{M}$ is not invertible
- Power limiting: non-additivity
- 1D or 2D dimming backlight: ~ per-pixel gain adjustment
- Display color processing: PFAs

RGBW: good or evil?

Two options:

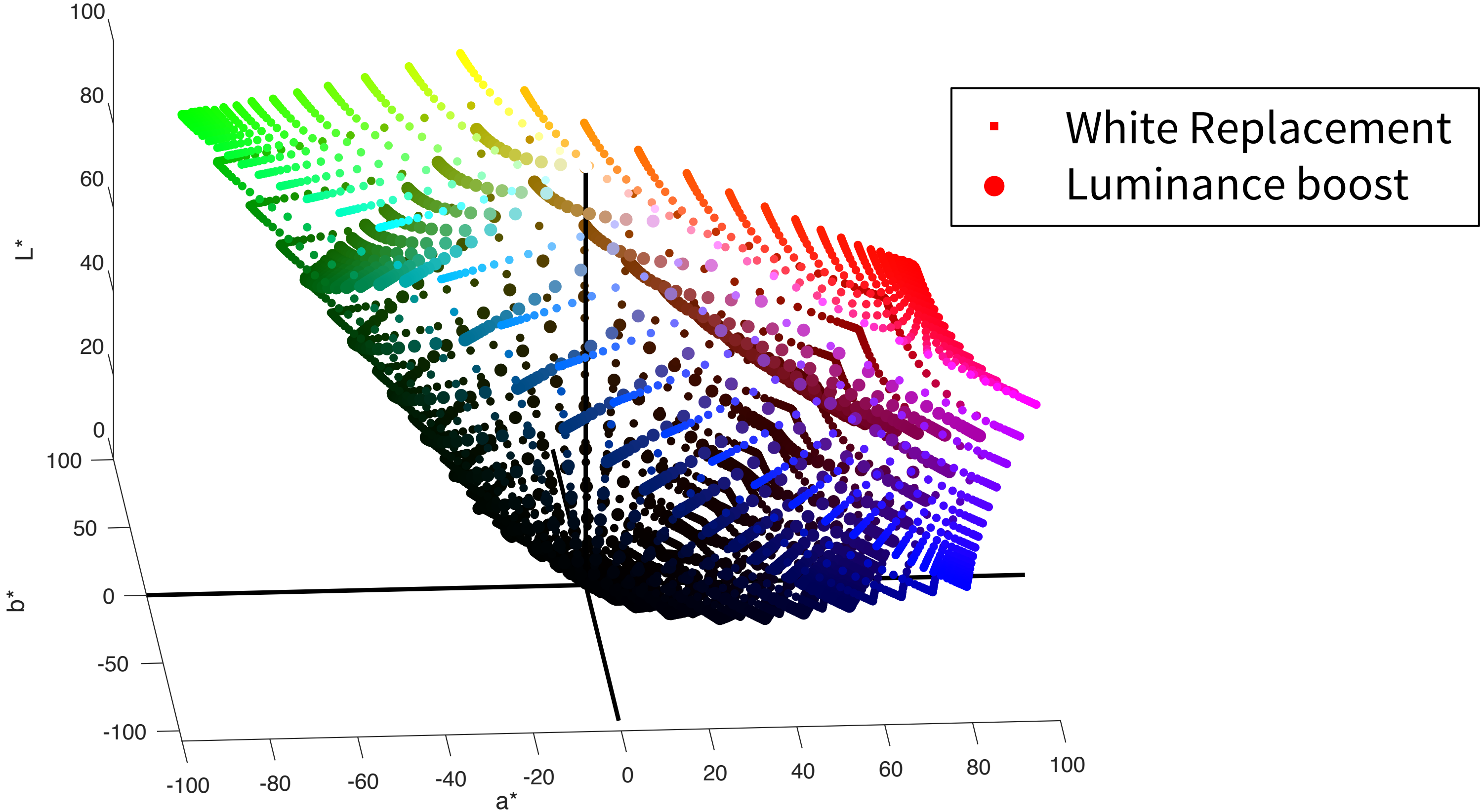
- Add W for luminance boost (trade away color gamut and color fidelity, common in projectors)
- Use W in place of RGB (improve power efficiency, especially in OLED)



Murdoch et al., Perfecting the color reproduction of RGBW OLED, ICIS 06.
Miller & Murdoch, RGB-to-RGBW conversion with current limiting for OLED displays, JSID 2009: https://doi.org/10.1889/JSID17.3.19

RGBW: Breaking the General RGB Model

- Gamut volume changes shape…

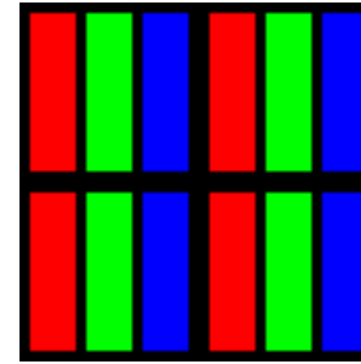


Multi-primary Color

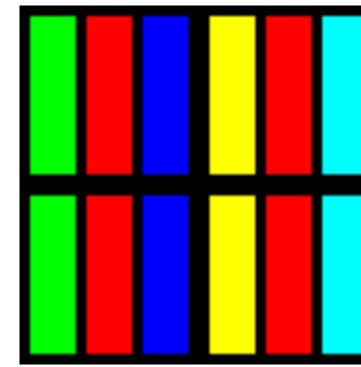
- Chromaticity gamut increase
- Primaries beyond RGB give extra degrees of freedom

- Spatial layout can reduce resolution
- Sub-pixel interpolation even more important than with RGB: smart spatial luminance distribution

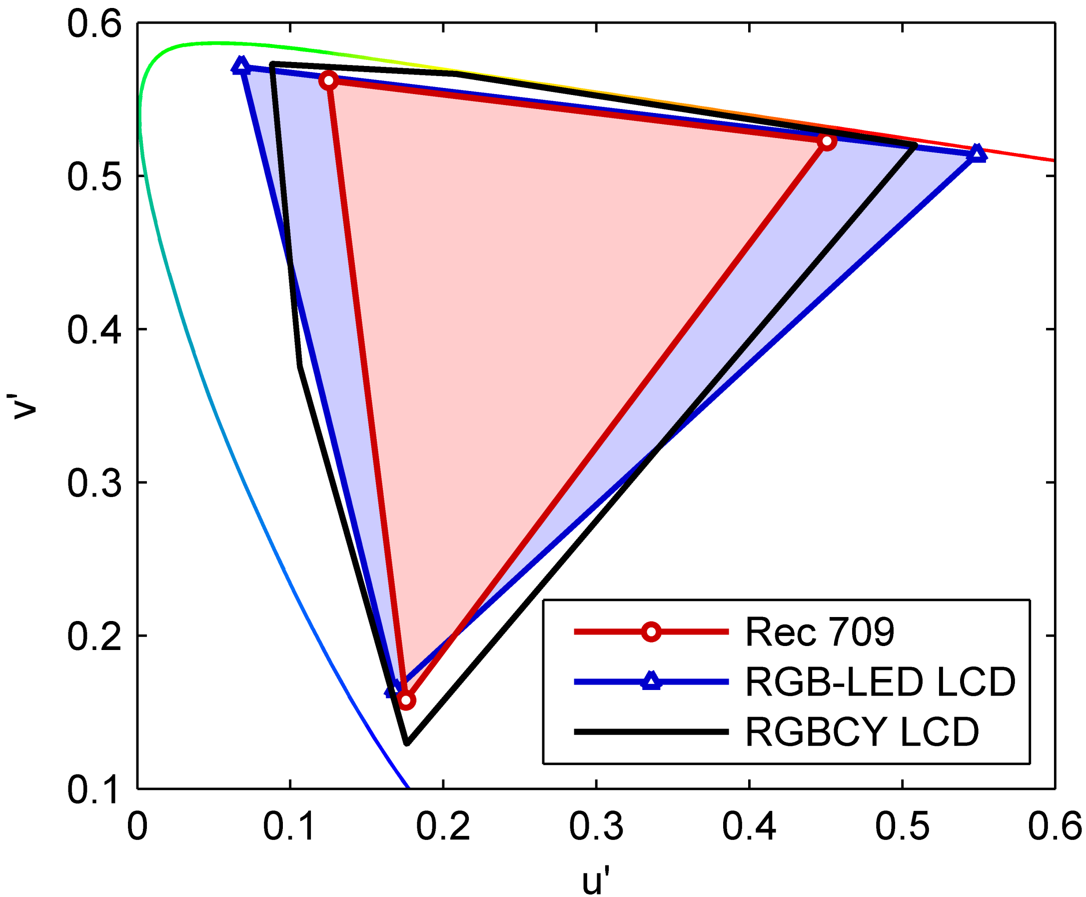
RGB
4 logical pixels



RGBCY
2(?) logical pixels



Multi-primary Chromaticity Gamut



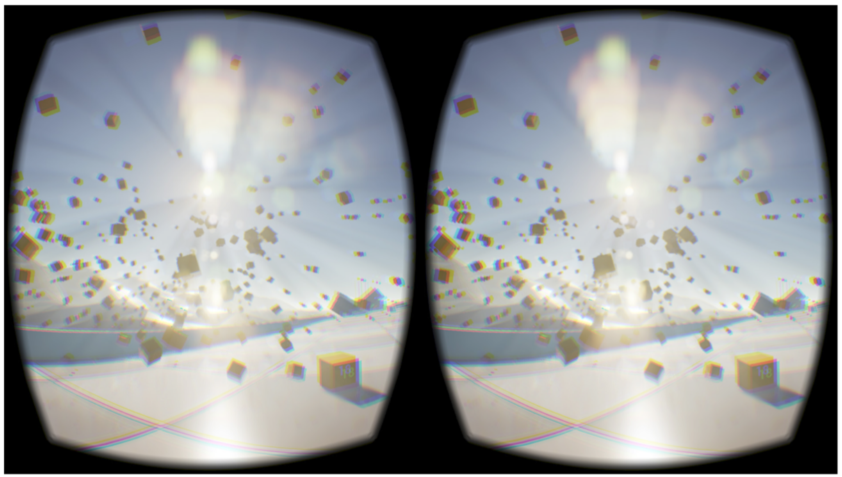
VR Displays

- LCD or OLED + optics
- Displays similar limitations as in bigger LCD or OLED
- Lenses → chromatic aberration, distortion, resolution

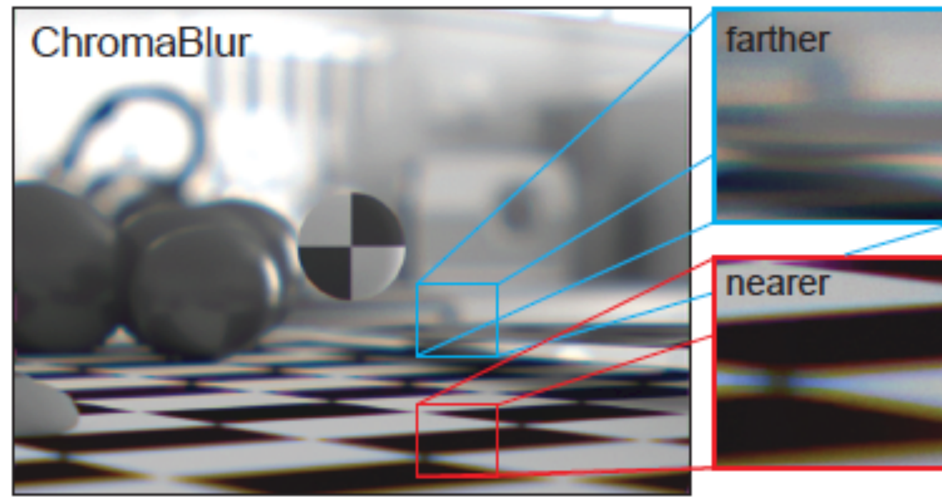
https://homido.com/mini/

Chromatic Aberration in VR

Compensation for CA in lenses[1]



Intentional CA for natural retinal focus cues[2]



1: Ats Kurvet, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=35920265
2: Cholewiak et al., Chromablur: rendering chromatic eye aberration improves accommodation and realism, https://doi.org/10.1145/3130800.3130815

Measurement, Characterization, Calibration

- **Measurement**: spectral or colorimetric measurement from perspective of viewer[1]
- **Characterization**: measure & build a model (e.g. LUT, M, flare), allowing predictable behavior via device-dependent RGB[2,3]
- **Calibration**: adjust display behavior to match a standard, to allow direct use of device-independent RGB
  - Calibration pucks
  - Self-calibrating displays

1: SID Information Display Measurement Standards https://www.icdm-sid.org/downloads/index.html
2: Fairchild & Wyble, Colorimetric characterization of the Apple studio display (Flat panel LCD), RIT 1998: http://scholarworks.rit.edu/article/920/
3: Berns, Methods for Characterizing CRT Displays, Displays (1996): https://doi.org/10.1016/0141-9382(96)01011-6

Viewing Environment Effects

GENERATIONS
SIGGRAPH2018

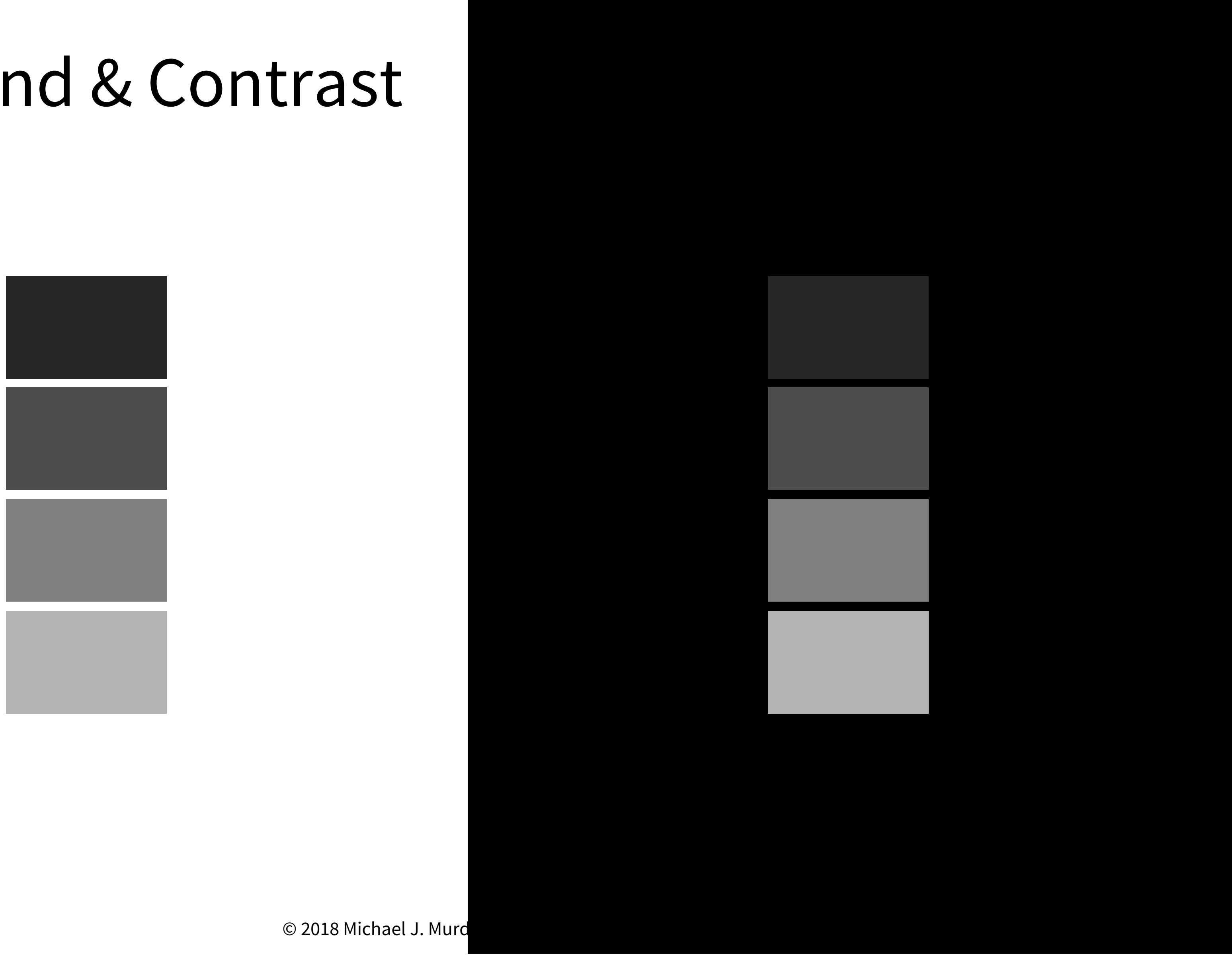
R·I·T

PoCS
MCSL

Reflections, Flare, and Glare

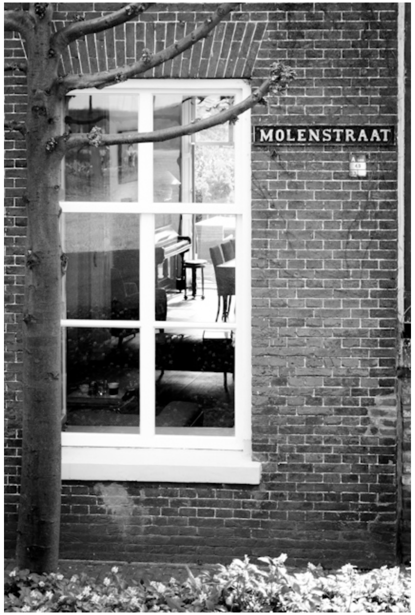
- Matte vs. Glossy
- Moth-eye coatings
- Circular polarizer on OLED
- Curved Displays

Surround & Contrast



Surround & Contrast

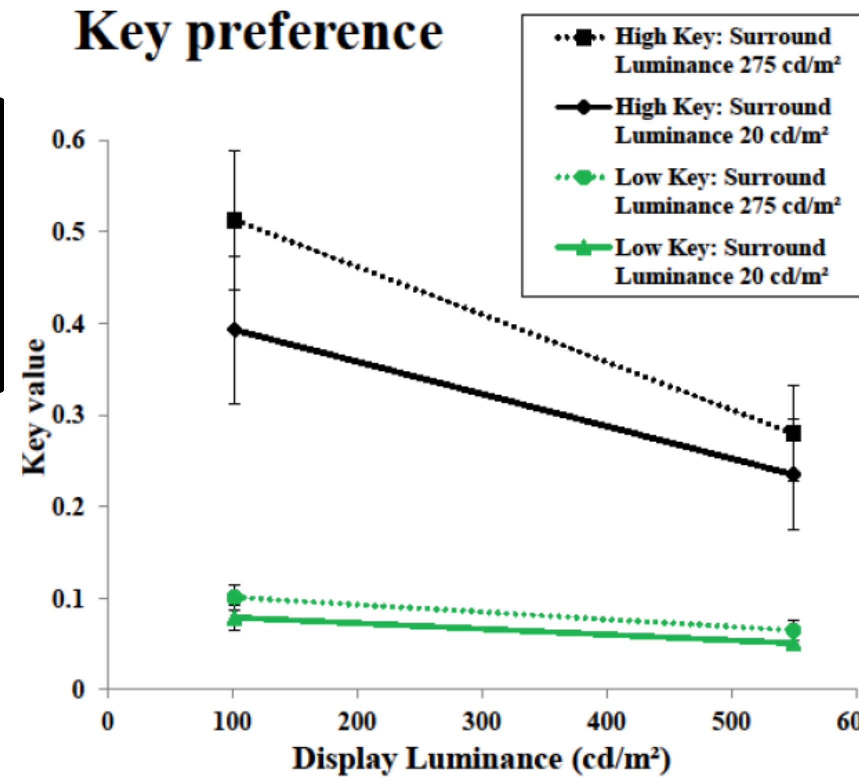
Surround & Contrast



Luminance & Interpretation

Luminance & Interpretation

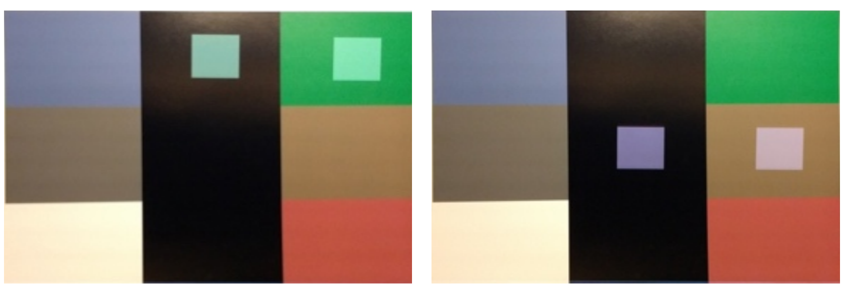
Scene, Display & Surround affect TMO

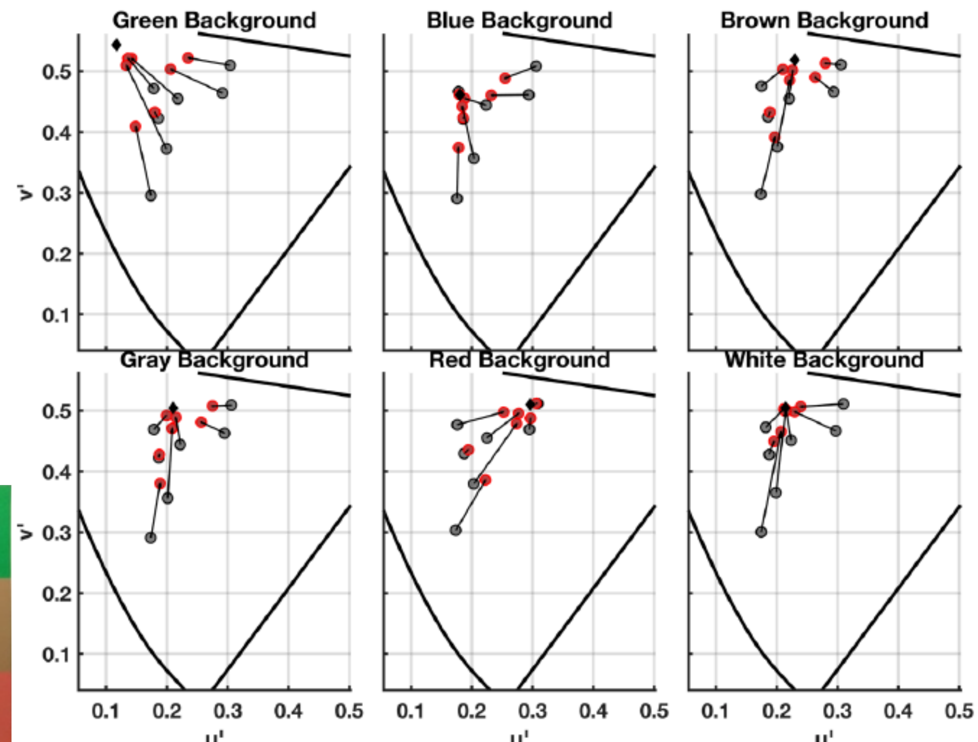


Stokkermans, Murdoch, Engelke: Experiencing Light 2012: https://pure.tue.nl/ws/portalfiles/portal/4024703
“Key” refers Reinhard et al, Photographic Tone Reproduction for Digital Images, SIGGRAPH 2002: https://doi.org/10.1145/566570.566575

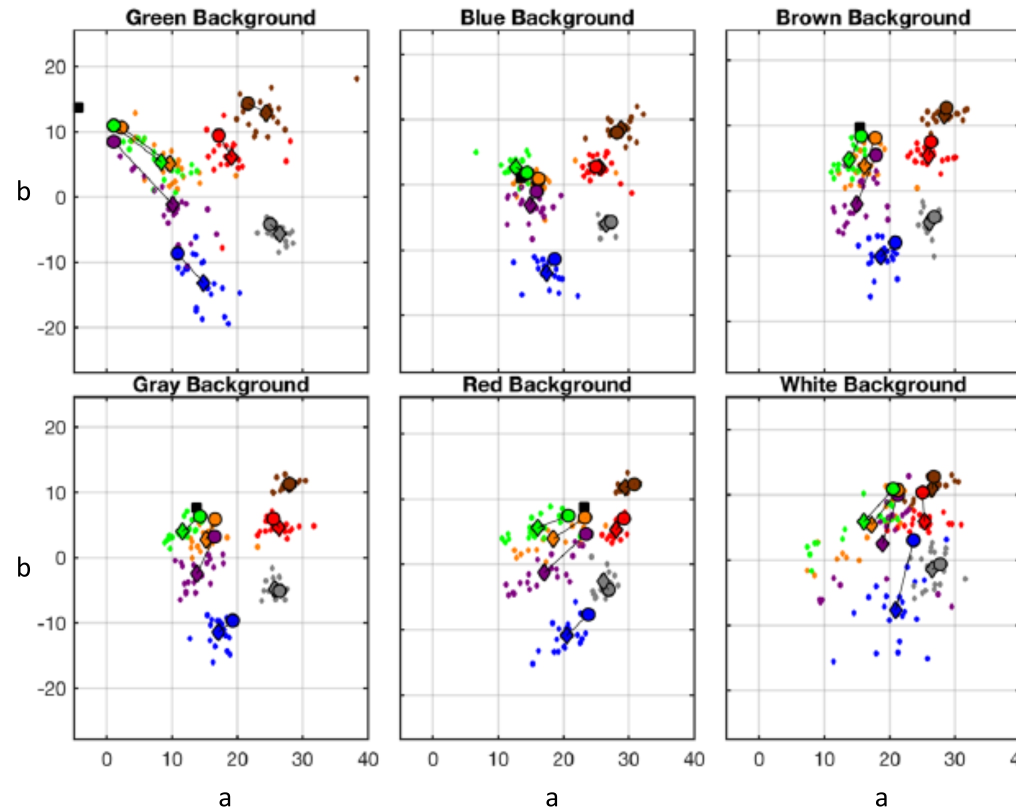
[Optical See-Through] Augmented Reality

- Real background + virtual foreground
- Background colors bleed through transparent display, distorting virtual colors
- Display model: flare++





[Optical See-Through] Augmented Reality



Hassani & Murdoch, *in preparation*, see also:
Hassani & Murdoch, Color appearance modeling in augmented reality, ACM SAP 2016: https://doi.org/10.1145/2931002.2948719

Adaptive Displays

GENERATIONS
SIGGRAPH2018

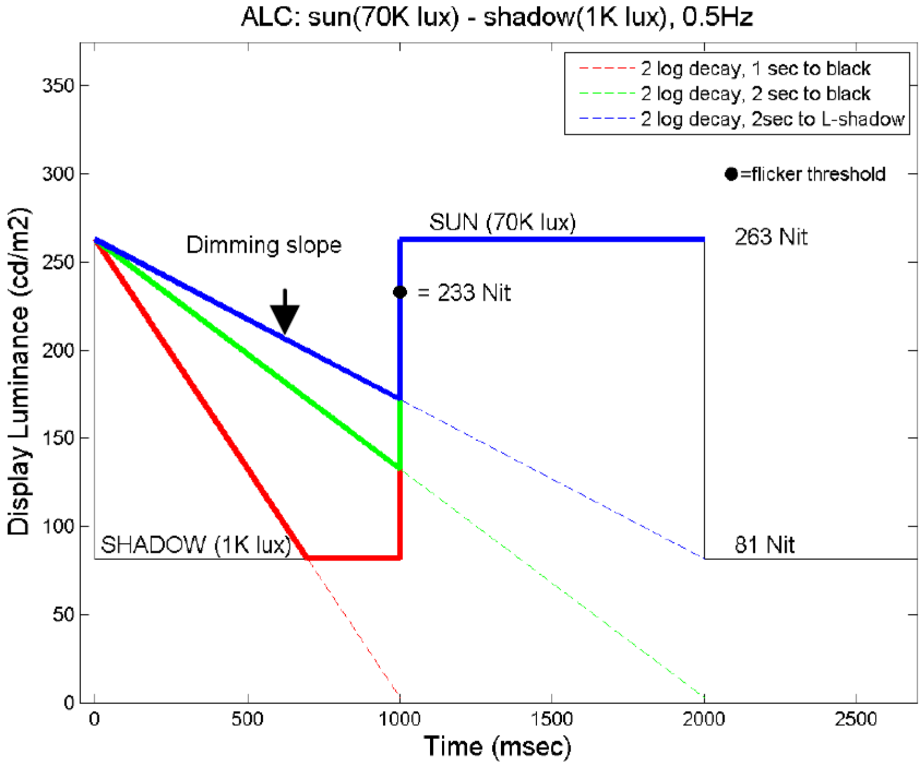
R·I·T

PoCS
MCSL

Adaptive Displays: Automatic Brightness Control

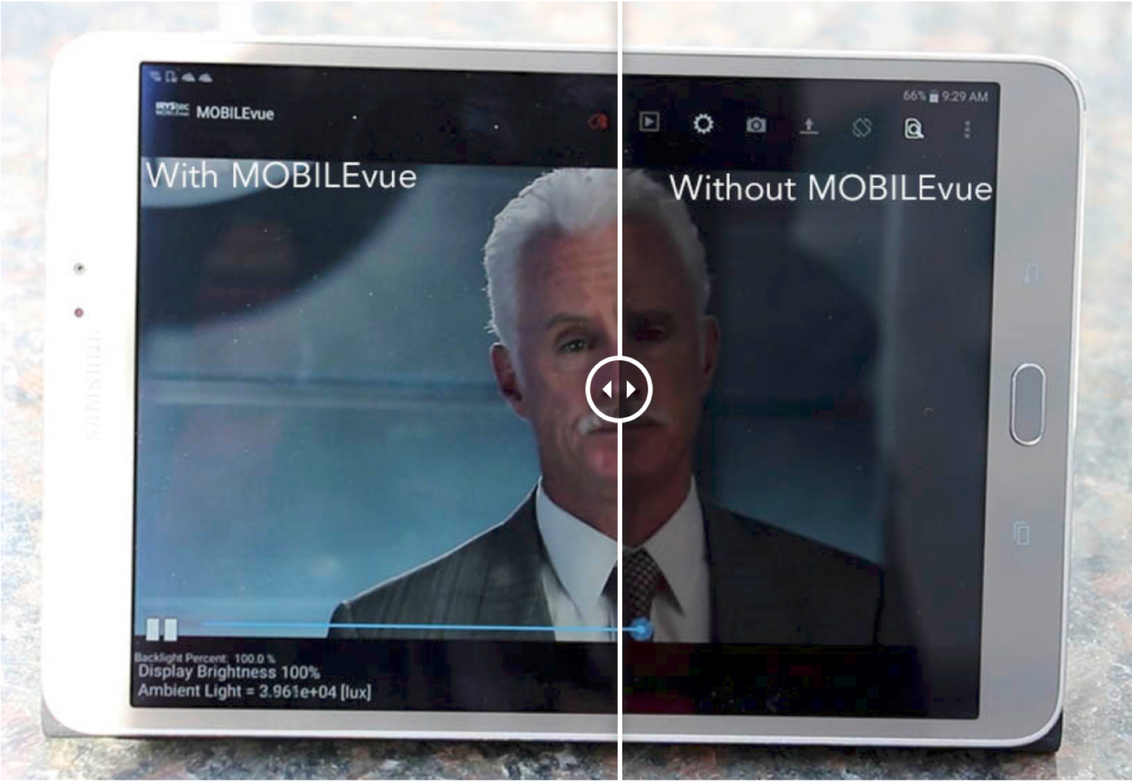
- Display white changes with ambient illumination
- Power savings
- 80:20 rule…

- Related to HVS luminance adaptation and camera auto-iris



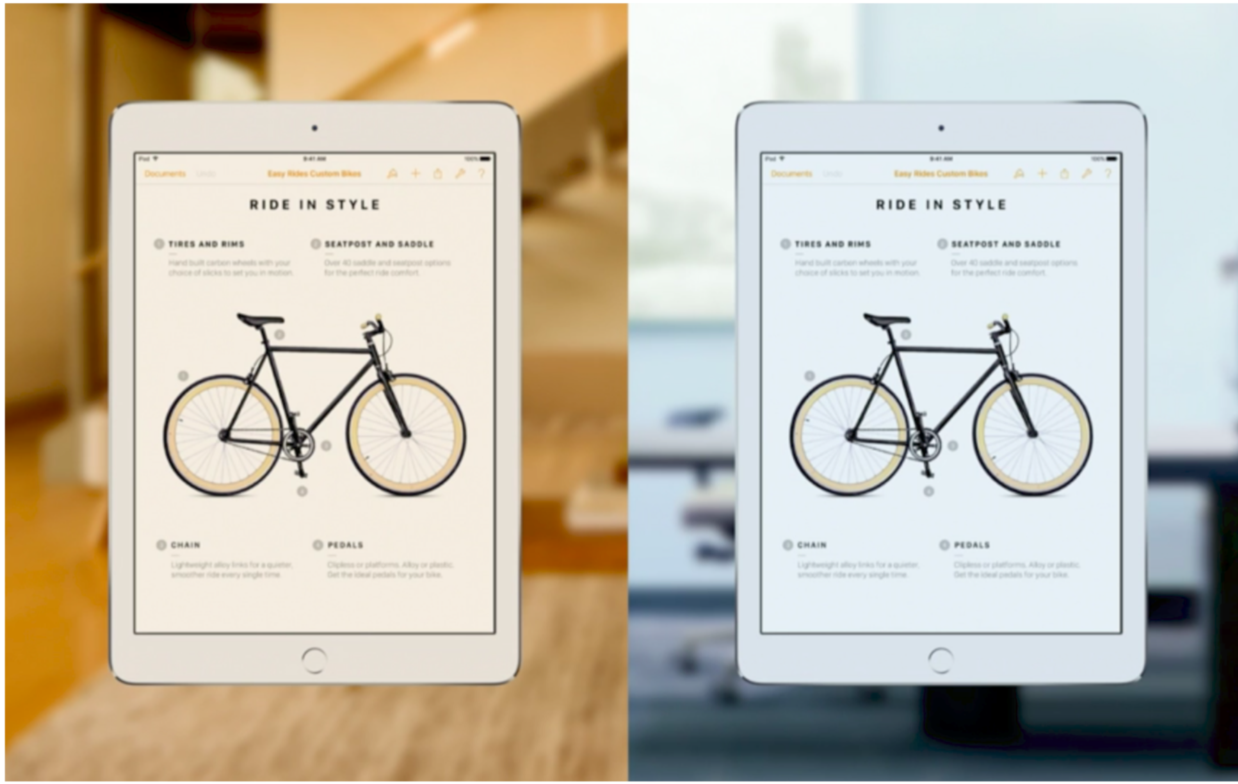
Swinkels et al., Ambient Light Control for Mobile Displays, SID, 2008: https://doi.org/10.1889/1.3069301
See also: Merrifield and Silverstein, The ABC's of automatic brightness control, SID, 1988.

Adaptive Displays: Brightness and Tonescale



Apple iPhone X via TechCrunch: https://techcrunch.com/gallery/12-neat-hidden-features-in-iphone-x/
IRYStec's Perceptual Display Platform (PDP): http://www.irystec.com/

Adaptive Displays: White Point



Apple TrueTone example, MacWorld: https://www.macworld.com/article/3055407/ios/how-to-make-night-shift-act-more-like-true-tone.html

Adaptive Displays: White Point

Apple TrueTone example, MacWorld: https://www.macworld.com/article/3055407/ios/how-to-make-night-shift-act-more-like-true-tone.html

Missing blue?

f.lux and Night Shift

When melatonin

is more important

than color

Inter-Observer Differences

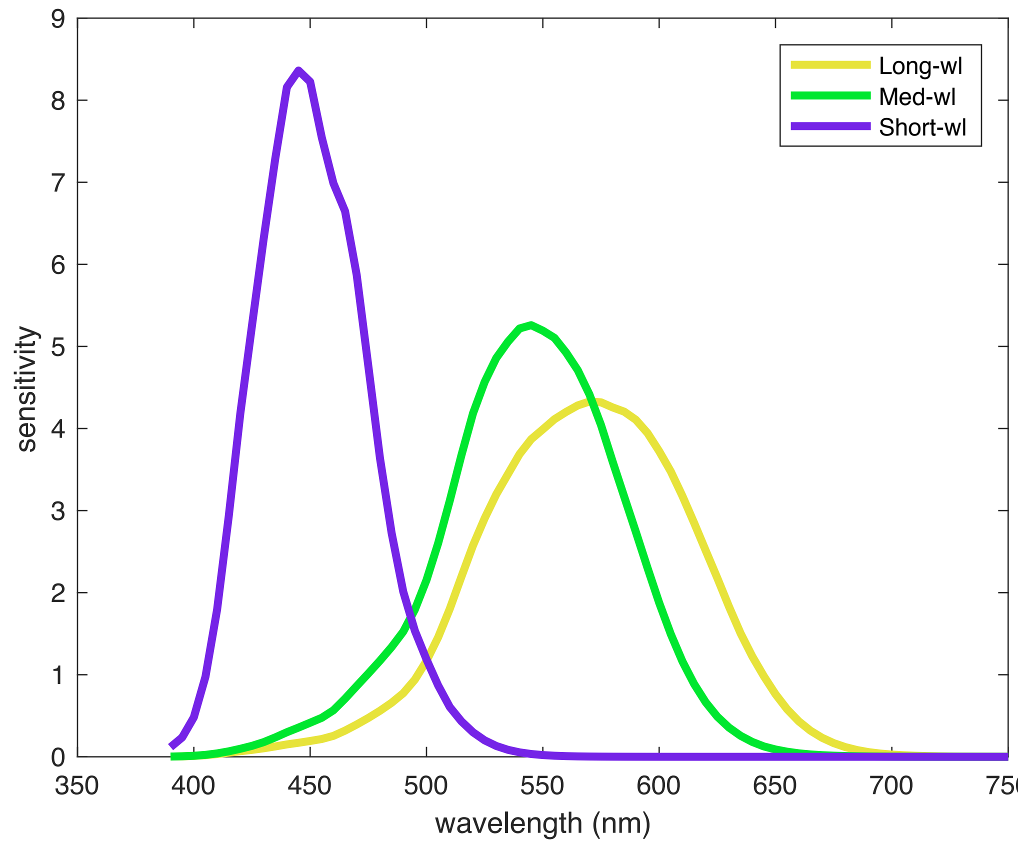
GENERATIONS
SIGGRAPH2018

R·I·T

PoCS
MCSL

LMS Cone Sensitivities

- Visible light ~400-700nm
- Peak sensitivities:
  445, 545, 570 nm
- Line colors approximate the hues of these peak wavelengths



LMS Variations: “Color blindness”

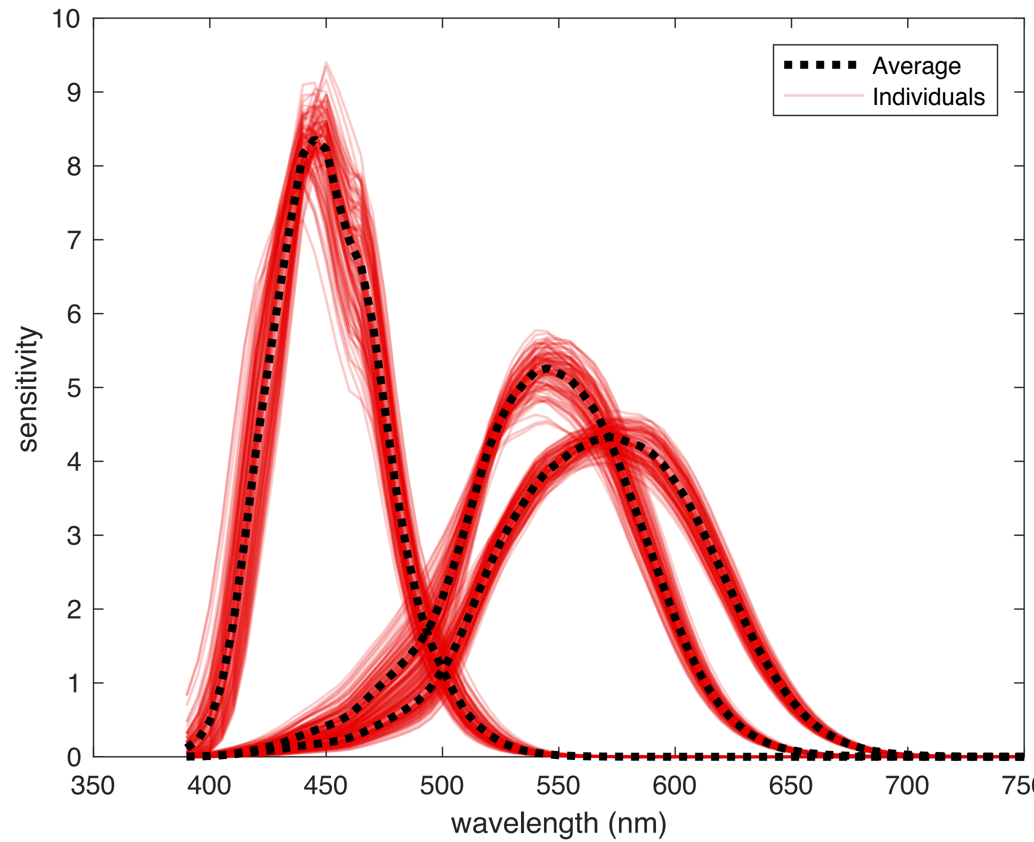
- Color vision deficiency: missing one or more cone types
  - Protanopia: missing L cone: red/green colorblindness
  - Deuteranopia: missing M cone: "
  - Tritanopia: missing S cone: yellow/blue colorblindness
  - Monochromatism: only a single cone type
- Anomalous color vision: cones are shifted slightly left or right (usually L or M, often with more overlap)

LMS Variations: Normal color vision

Natural variation in:

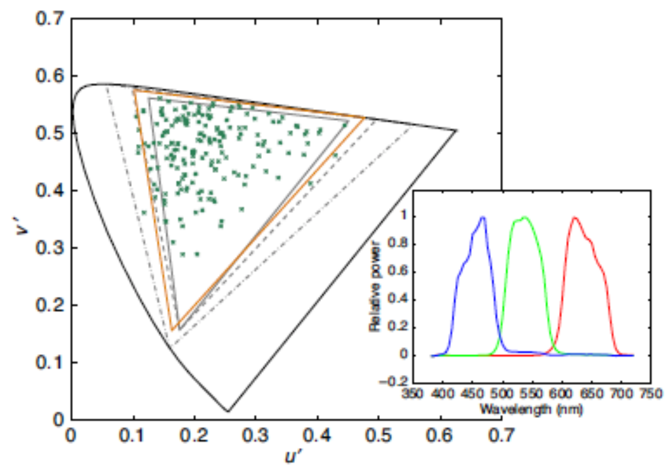
- Ocular media
- Lens
- Macula
- Peak wavelength

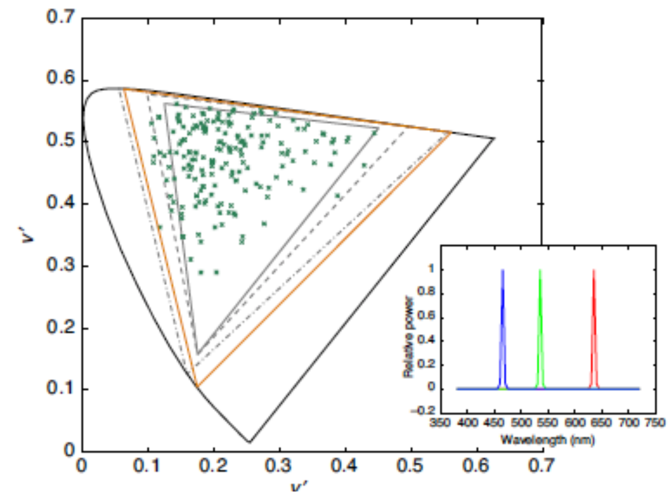
Plot: Example cone sensitivities for normal color vision individuals

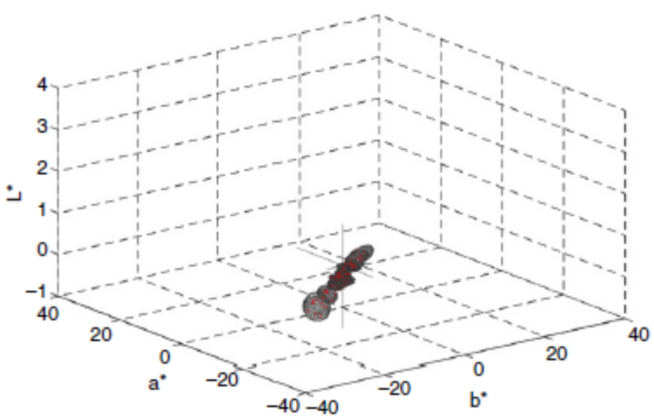


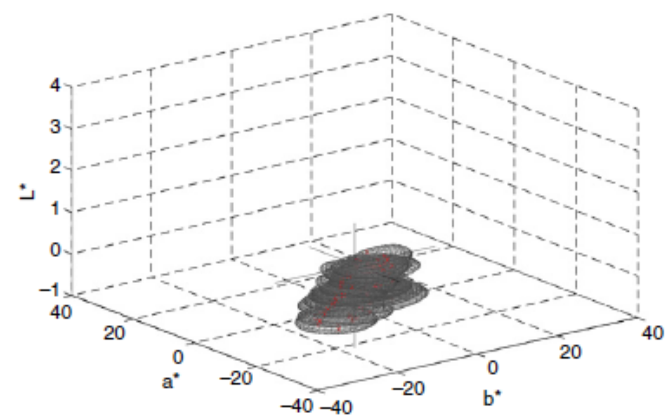
See also: Asano et al., Individual Colorimetric Observer Model, PLOS One, 2016: https://doi.org/10.1371/journal.pone.0145671

Observer Metamerism due to Narrow Spectra









Long & Fairchild, Modeling observer variability and metamerism failure in electronic color displays, JIST 2014: http://doi.org/10.2352/J.ImagingSci.Technol.2014.58.3.030402

Thank you!

Questions and Discussion?

Michael J. Murdoch

mmpocs@rit.edu

GENERATIONS
SIGGRAPH2018

R·I·T

PoCS
MCSL