Berkeley Lecture

11/17/2020

MDF-RIT

Some Thoughts on Color Appearance (Modeling)

Mark Fairchild
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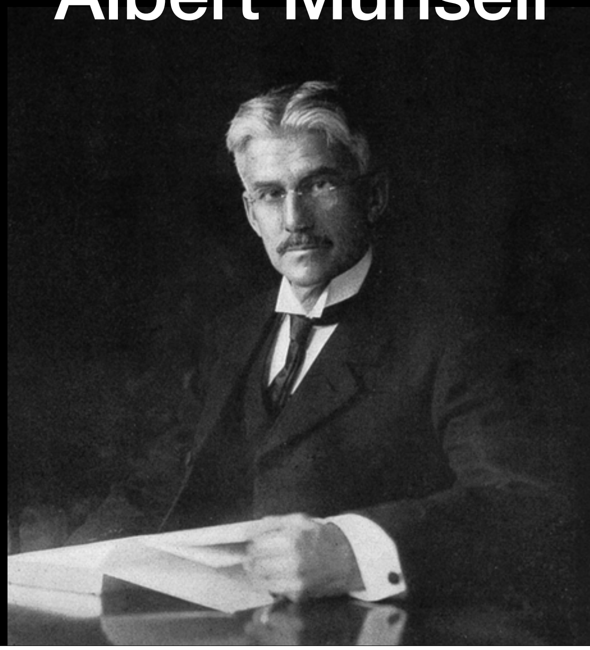
Integrated Sciences Academy
Program of Color Science / Munsell Color Science Laboratory

Albert Munsell



Munsell Color Foundation, Inc.

Guided Munsell Color Company

Supported "Academic" Projects & Students

Cleveland State University: Surround Influence on Lightness
Harvard University: Color in Art
Illuminating Eng. Research Institute: Surface Color Variation with Adaptation
Library of Congress: Color in Graphic Arts
National Bureau of Standards: Methods of Specifying Color
Rensselaer Polytechnic Institute: Step Size in Munsell System
University of California at Los Angeles: Dyestuffs in Ancient Textiles

Dissolved …

Dissolution:
Proposals for Endowments

RIT vs. Berkeley

Munsell Color Science Laboratory

Objectives: Current (Rev. 2002)

1) To provide undergraduate and graduate education in color science,

2) To carry on applied and fundamental research,

3) To facilitate spectral, colorimetric, photometric, spatial, and geometric measurements at the state of the art, and

4) To sustain an essential ingredient for the success of the first three — namely, liaison with industry, academia, and government.

MCSL Students

Programs & Numbers

Color Science M.S. & Ph.D.
Imaging Science M.S. & Ph.D.
Several Other RIT Undergraduate and Graduate Programs

130+ MCSL Alumni
From 15+ Countries
Working in Industry, Government, & Academia Worldwide

About 1000 Publications under MCSL

A few historical research topics …

Chromatic Adaptation Models

Color Appearance Models/Dimensions

Color Difference Modeling

Color Display Characterization/Calibration

Color Psychophysics

Cultural Heritage Imaging

Image Quality

High-Dynamic-Range (HDR) Perception & Imaging

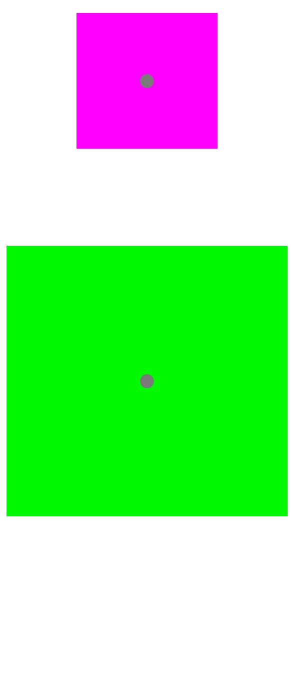
Measurement Services

Spectral Imaging/Reproduction

Color is in us — not outside.

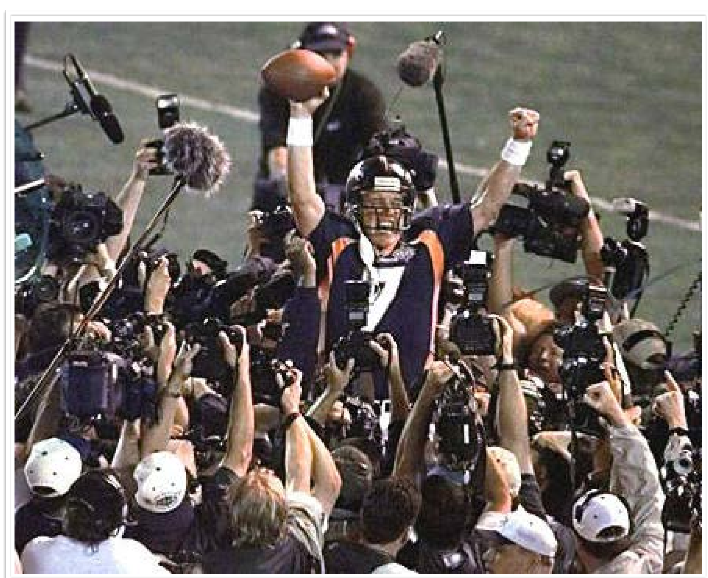
-A. Munsell

Supersaturated Grass

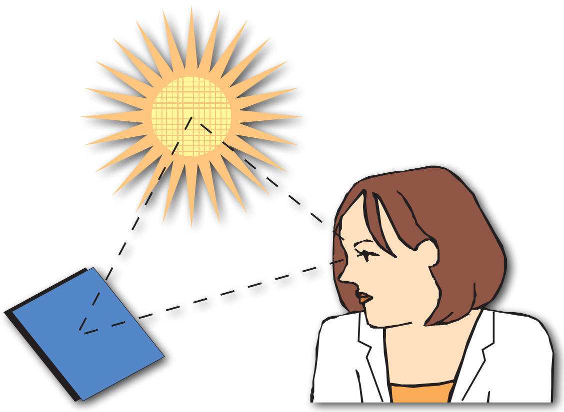


What or Why is Color?

Color is the Process of Observing



Why is Color?



Color Science

Sources of Optical Radiation: PHYSICS
Characterization of Objects: PHYSICS, CHEMISTRY
Perception: ANATOMY, PHYSIOLOGY, PSYCHOLOGY

Terminology

CIE International Lighting Vocabulary

EILV - http://cie.co.at/eilv

"When I use a word it means just what I choose it to mean — neither more nor less"

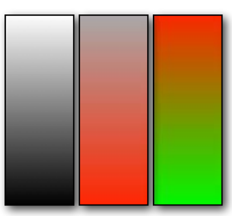
-Humpty-Dumpty
(in Wonderland, as quoted by Hunt, 1978)

CIE
Commission Internationale de L'Éclairage
(International Commission on Illumination)

CIE Publication 17.4, International Lighting Vocabulary*
Approximately 950 terms and their definitions "to promote international standardization in the use of quantities, units, symbols and terminology."

**New Edition Recently Published*

Color



Attribute of visual perception consisting of any combination of chromatic and achromatic content. This attribute can be described by chromatic color names such as yellow, orange, brown, red, pink, green, blue, purple, *etc*., or by achromatic color names such as white, grey, black, etc., and qualified by bright, dim, light, dark, *etc*., or by combinations of such names.

Note. — Perceived color depends on the spectral distribution of the colour stimulus, on the size, shape, structure and surround of the stimulus area, on the state of adaptation of the observer's visual system, and on the observer's experience of the prevailing and similar situations of observations.

Unrelated & Related Colors

Unrelated Color
Color perceived to belong to an area or object seen in isolation from other stimuli.

Related Color
Color perceived to belong to an area or object seen in relation to other colors.

"Brown" and "Gray" are only perceived as related colors.

Brightness

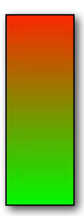
Attribute of a visual sensation according to which an area appears to emit more or less light.

Lightness

The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

Note. — Only related colours exhibit lightness.

Hue



Attribute of a visual sensation according to which an area appears to be similar to one of the perceived colors, red, yellow, green, and blue, or to a combination of two of them.

Achromatic Color: Perceived color devoid of hue.

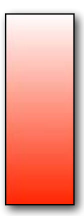
Chromatic Color: Perceived color possessing a hue.

Colorfulness

Attribute of a visual sensation according to which the perceived color of an area appears to be more or less chromatic.

Notes 1. — For a color stimulus of a given chromaticity and, in the case of related colors, of a given luminance factor, this attribute usually increases as the luminance is raised except when the brightness is very high.

Saturation



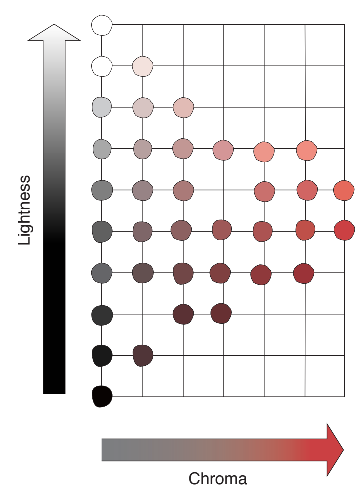
Colorfulness, chromaticness, of an area judged in proportion to its brightness.

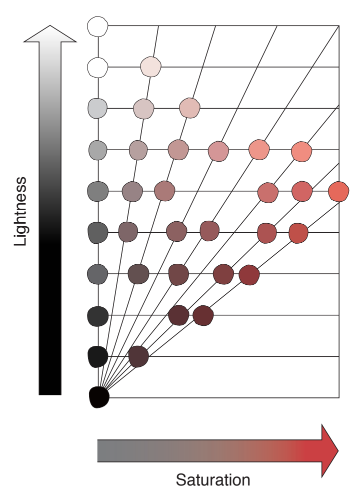
Note* — For given viewing conditions and at luminance levels within the range of photopic vision, a color stimulus of a given chromaticity exhibits approximately constant saturation for all luminance levels, except when the brightness is very high.

Chroma

Colorfulness, of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting.

Chroma/Saturation





Definitions in “Equations”

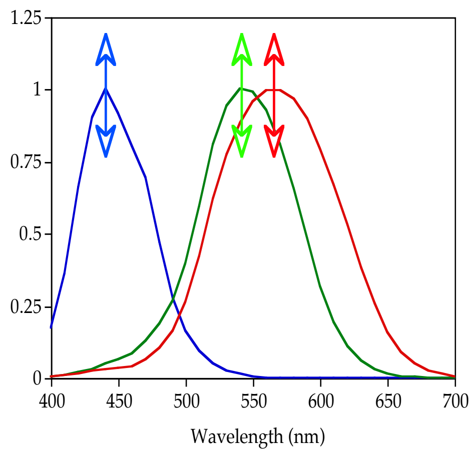
Chroma = (Colorfulness)/(Brightness of White)

Saturation = (Colorfulness)/(Brightness)

Lightness = (Brightness)/(Brightness of White)

Saturation = (Chroma)/(Lightness)
= [(Colorfulness)/(Brightness of White)][(Brightness of White)/(Brightness)]
=(Colorfulness)/(Brightness)

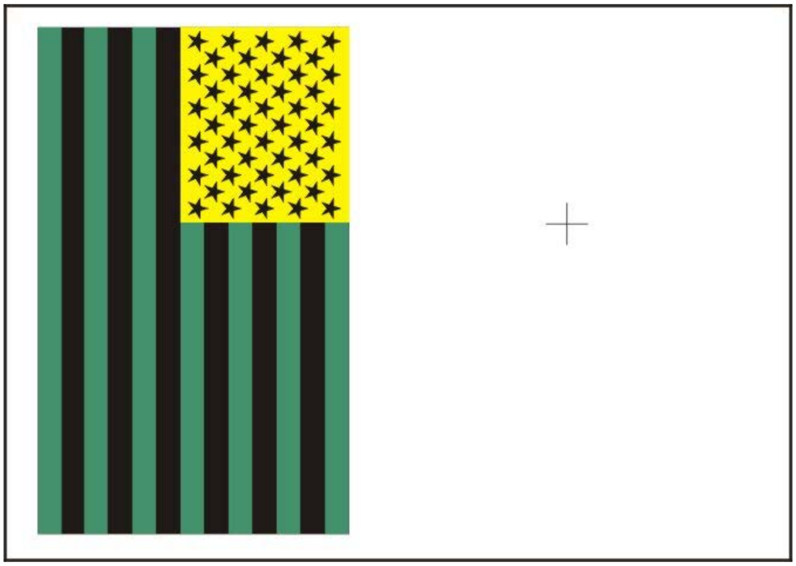
Chromatic Adaptation



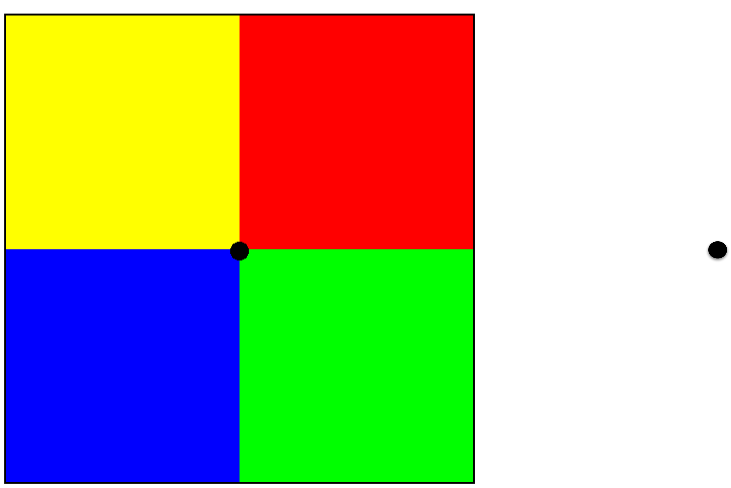
The three cone types, LMS, are capable of independent sensitivity regulation. (Adaptation occurs in higher-level mechanisms as well.)

Magnitudes of chromatic responses are dependent on the state of adaptation (local, spatial, temporal). Afterimages provide evidence.

Afterimages



Afterimages



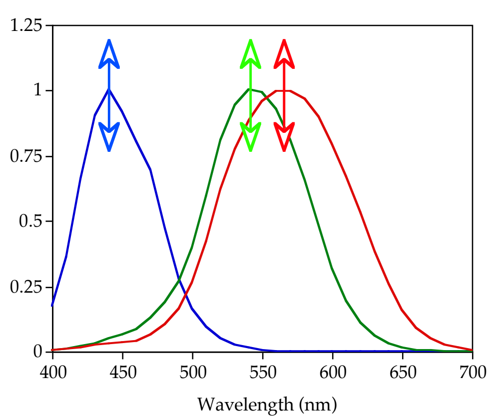
Banana Adaptation

A Cyan Filter

Chromatic Adaptation Modeling

Chromatic Adaptation:

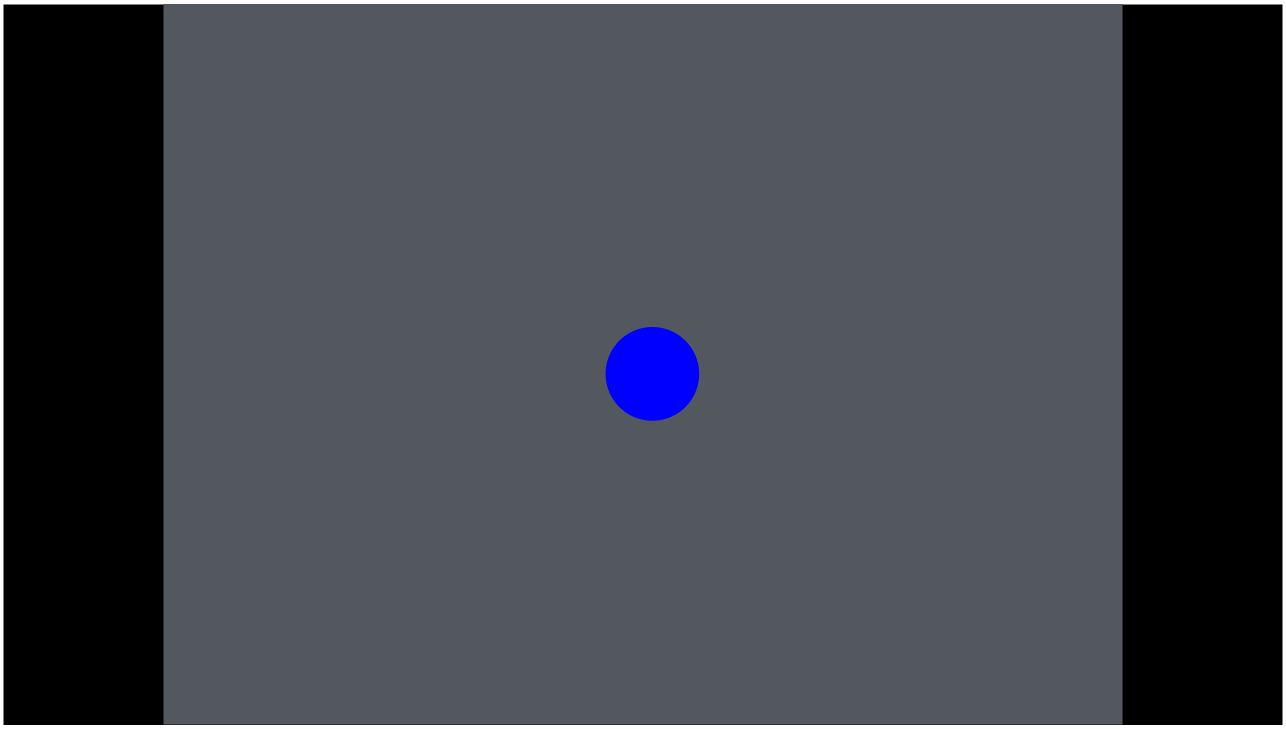
Largely independent sensitivity regulation of the (three) mechanisms of color vision.



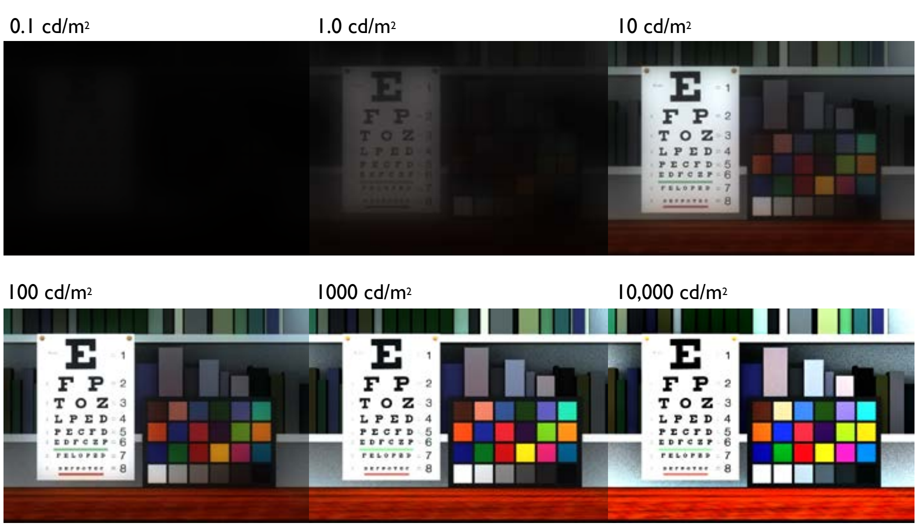
Appearance Phenomena

Brightness-Luminance

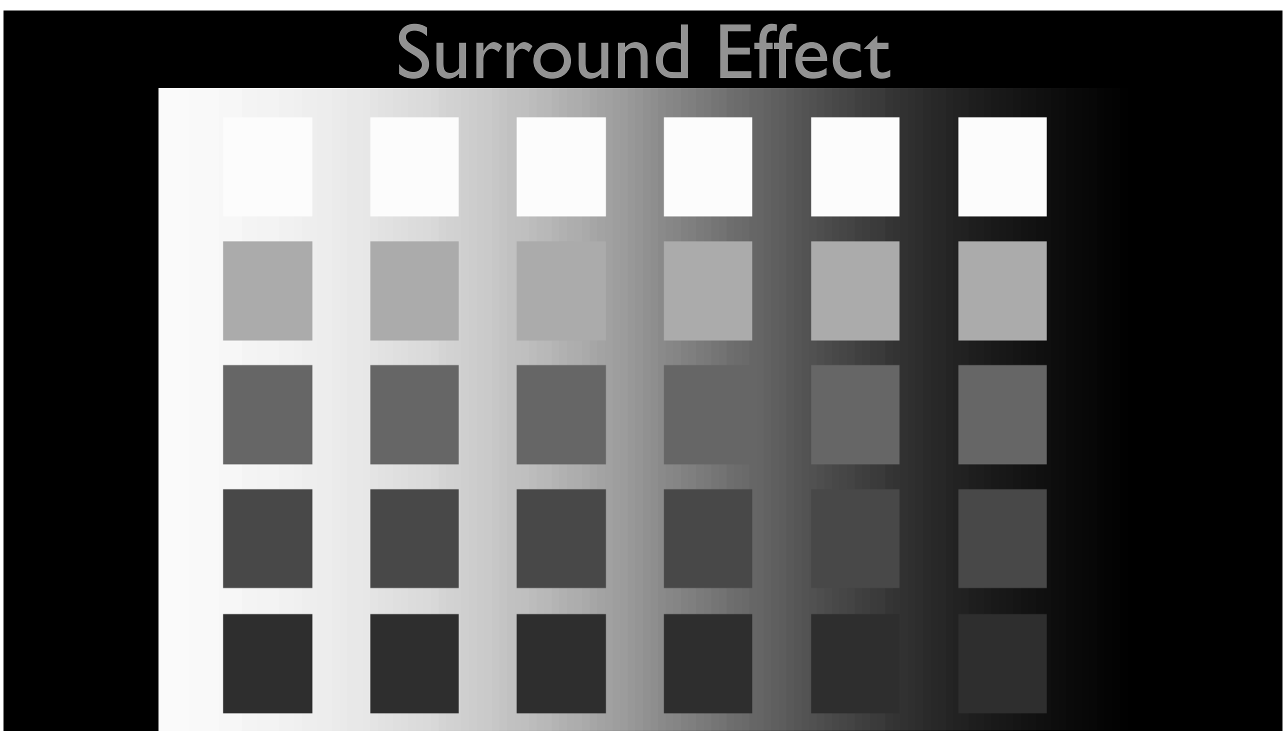
Helmholtz-Kohlrausch Effect



Stevens & Hunt Effects



Hunt & Stevens



How Many Terms?

Any color perception can be described completely by its:

- •Brightness
- •Lightness
- •Colorfulness
- •Saturation
- •Hue

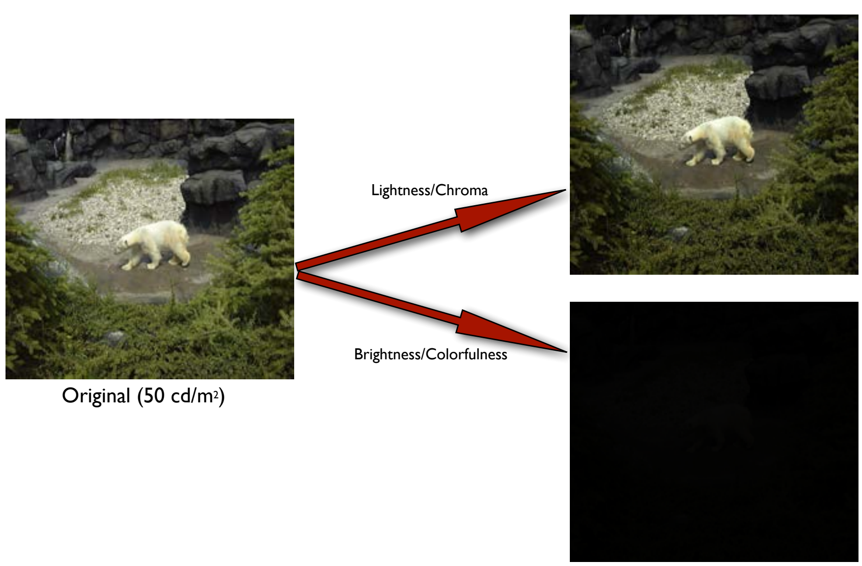
and only one of brightness or colorfulness is required to derive the others.

In general, the relative appearance attributes are adequate for object colors in typical viewing environments:

- •Lightness
- •Saturation
- •Hue

Chroma is often redundant.

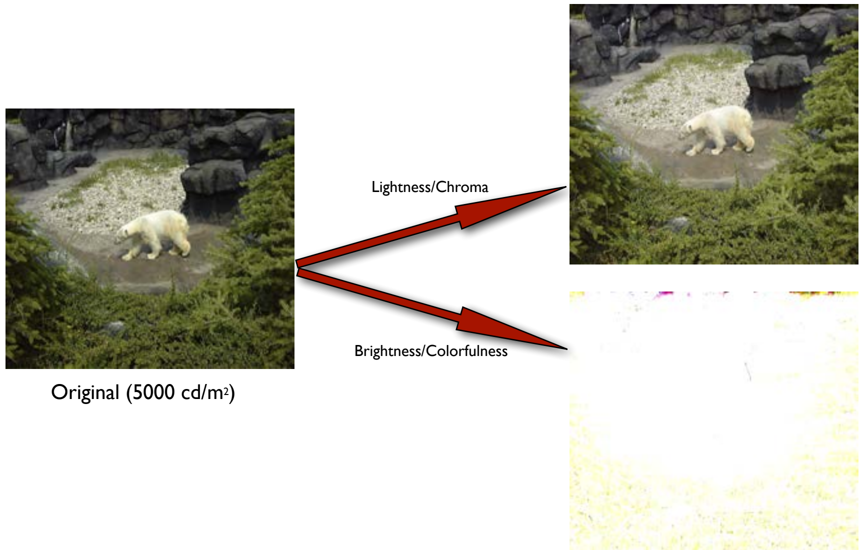
Reproduction at Higher Luminance



Original (50 cd/m^2)

Reproductions (5000 cd/m^2)

Reproduction at Lower Luminance



Original (5000 cd/m^2)

Reproductions (50 cd/m^2)

Individual Differences & Color Appearance Models (CAMs)

Color Matching Functions
CMFs

INDIVIDUALS

- Stiles & Burch (1959)

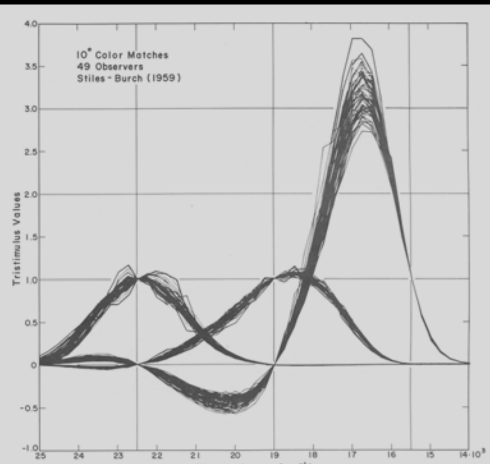


Fig. 3(5.5.6). 10° color-matching functions of 49 observers participating in the Stiles–Burch (1959) experiment. All functions refer to primary stimuli at $m_R = 15{,}500$, $m_G = 19{,}000$, and $m_B = 22{,}500\ \mathrm{cm}^{-1}$.

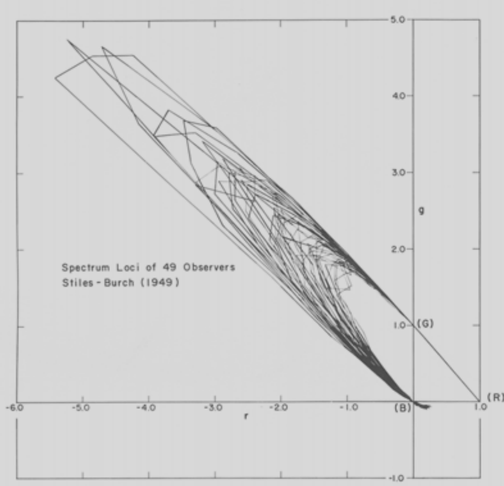
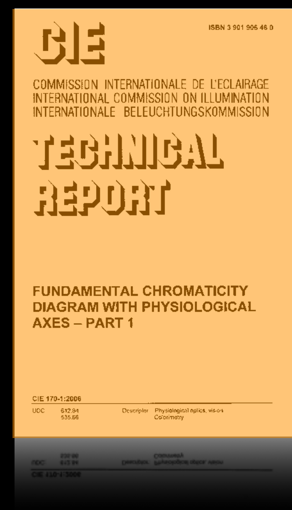


Fig. 4(5.5.6). (r, g)-chromaticity diagram of Stiles–Burch (1959) 10° color-matching investigation showing the spectrum loci of 49 observers.

CIE 2006 APPROACH

- TC1-36
- Fundamental Chromaticity Diagram with Physiological Axes
- CIE 170-1 (2006)
- Compute cone responsivities (LMS) as a function of age and field size



CIE 2006

Cone Absorptivity Spectra

f(field size)

Ocular Media Density

f(age)

$$\bar{l}(\lambda) = \alpha_{i,l}(\lambda)\cdot 10^{\left[-D_{\tau,\max,macula}\cdot D_{macula,relative}(\lambda)-D_{\tau,ocul}(\lambda)\right]}$$

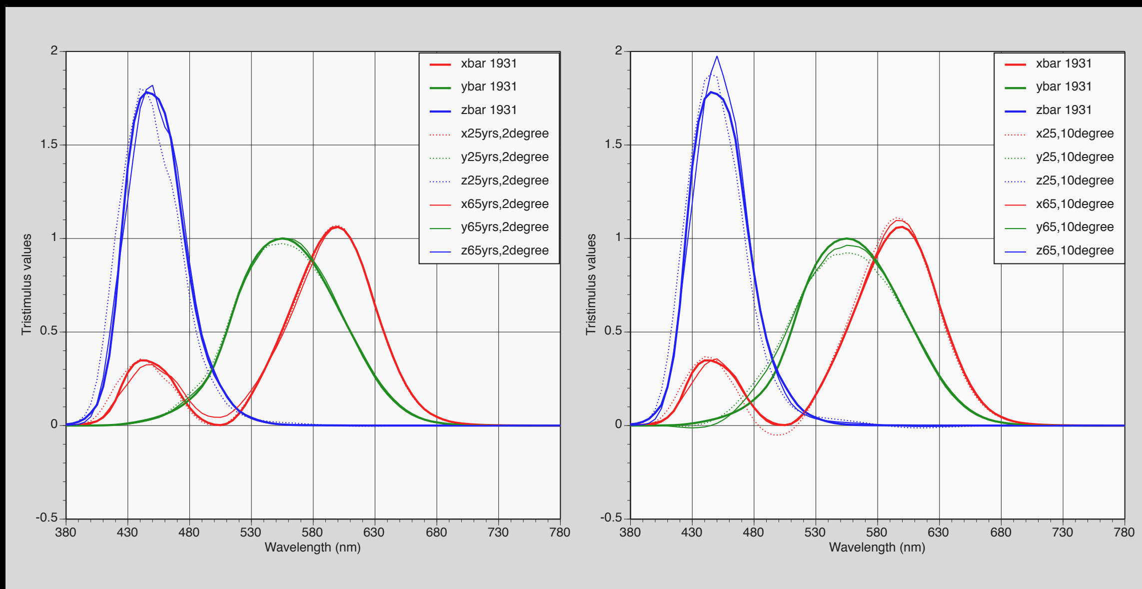
$$\bar{m}(\lambda) = \alpha_{i,m}(\lambda)\cdot 10^{\left[-D_{\tau,\max,macula}\cdot D_{macula,relative}(\lambda)-D_{\tau,ocul}(\lambda)\right]}$$

$$\bar{s}(\lambda) = \alpha_{i,s}(\lambda)\cdot 10^{\left[-D_{\tau,\max,macula}\cdot D_{macula,relative}(\lambda)-D_{\tau,ocul}(\lambda)\right]}$$

Macular Density

f(field size)

EXAMPLES:



MEANS, NOT INDIVIDUALS...

ASANO (2016) MODEL

- Start with CIE 2006 mean observers
- Perturb with individual variations in physiological components
- Create individual color matching functions
- Monte Carlo or measurement driven

CIE 2006 + INDIVIDUALS

- Stiles & Burch 49 Observers

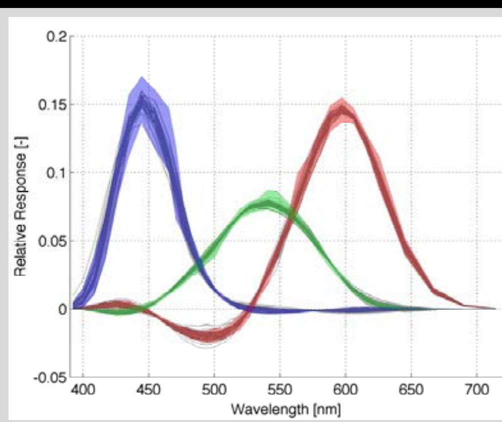
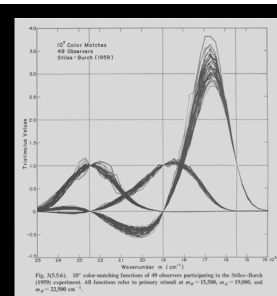
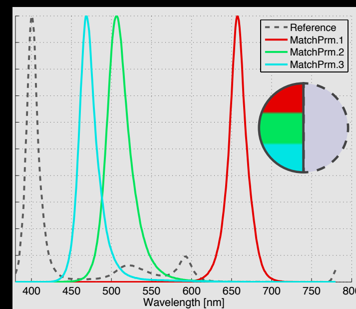


Fig. 3.12 – 49 sets of rgb-CMFs generated by the proposed observer model (gray lines) aiming to predict the Stiles and Burch's experiment results. The maxima and minima of 49 sets of CMFs for the Stiles and Burch's experiment participants are superimposed as color-shaded areas. All the CMFs are normalized to equal area.



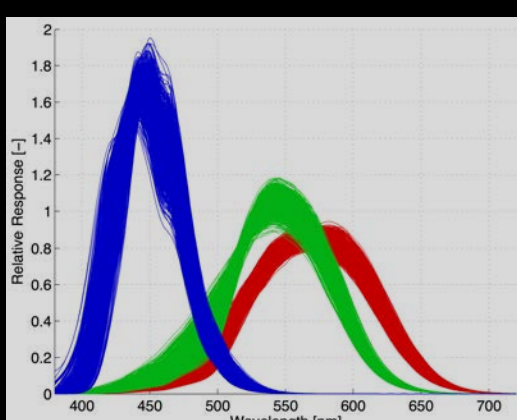
INDIVIDUALIZED COLORIMETRY

- Observer Calibrator (5 Matches)
- Individual Parameters
- Asano Model
- Individual (Customized) Color Matching Functions

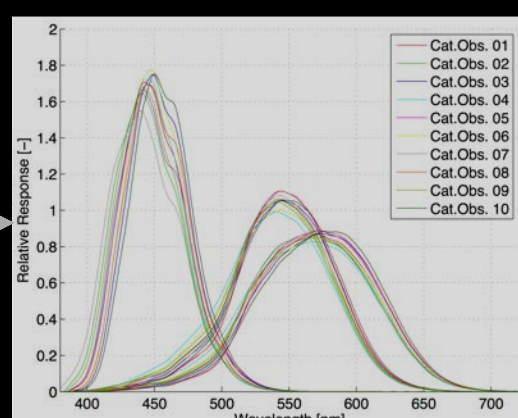


CATEGORICAL OBSERVERS

STEP 1: GENERATE 10,000 CMFS BY INDIVIDUAL OBSERVER MODEL + MONTE CARLO SIMULATION



STEP 2: CLUSTER ANALYSIS



CATEGORIES

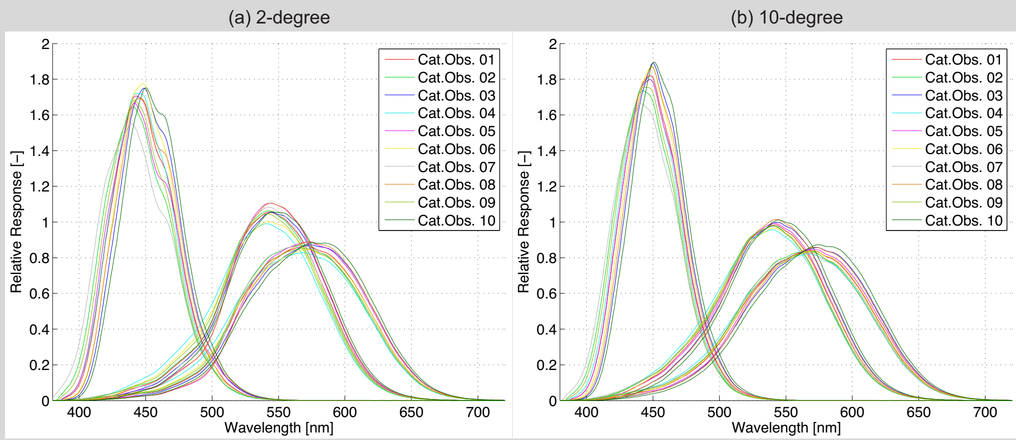
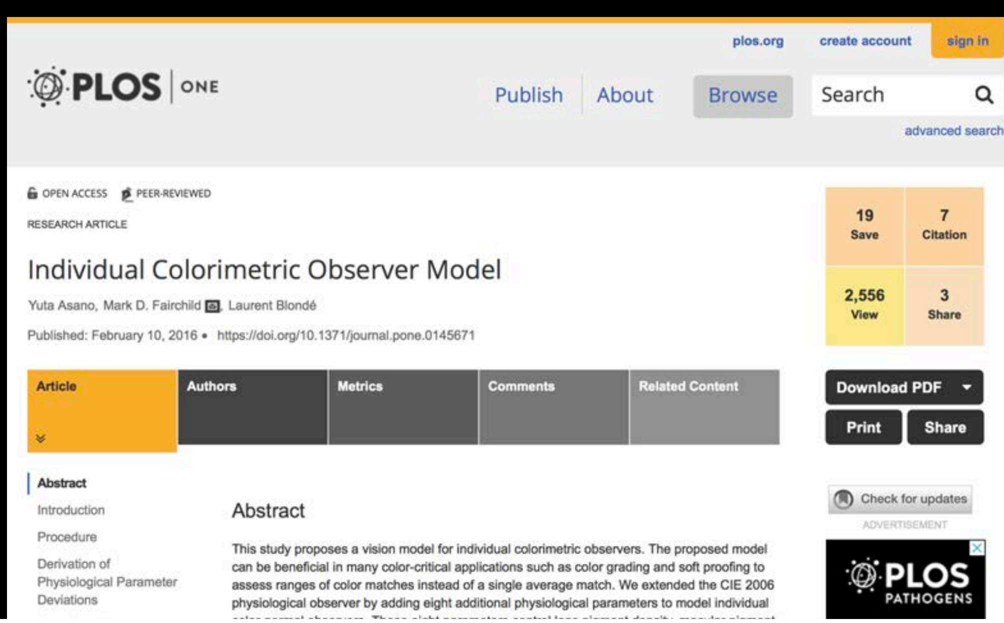


Fig. 3.16 – lms-CMFs (cone fundamentals) of the first ten categorical observers for a field size of 2° (a) and 10° (b). Each function is area-normalized.

PLOS ONE PAPER



Chromatic Adaptation Transforms (CATs)

Chromatic Adaptation Models

Model:

$$L_a = f(L, L_{white}, \ldots)$$
$$M_a = f(M, M_{white}, \ldots)$$
$$S_a = f(S, S_{white}, \ldots)$$

Transform (CAT):

$$XYZ_2 = f(XYZ_1, XYZ_{white}, \ldots)$$

$$\begin{array}{ll}
X_1Y_1Z_1 & \\
\downarrow \longleftarrow & 3x3 \\
L_1M_1S_1 & \\
\downarrow \longleftarrow & VC_1 \\
L_aM_aS_a & \\
\downarrow \longleftarrow & VC_2 \\
L_2M_2S_2 & \\
\downarrow \longleftarrow & 3x3 \\
X_2Y_2Z_2 &
\end{array}$$

Chromatic Adaptation Model Output

Raw "Radiance" Images

Adapted "Perceptual" Images

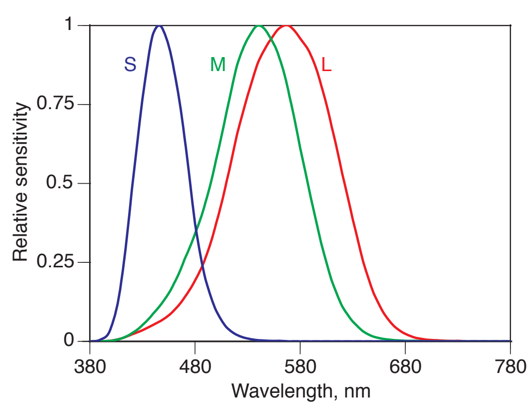
Cone Excitations

How are they found?

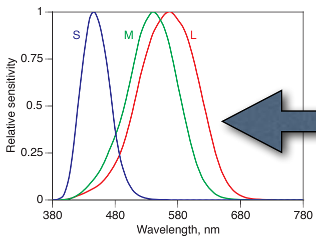
•Copunctal Points of Dichromats w/CMFs
•Chromatic Adaptation w/Model
•Selective Retinal Conditioning/Thresholds
•Retinal Pigment Absorption Measurements
•Molecular Genetics

Why are they important?

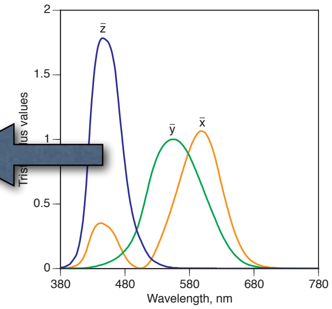
•Produce the 1st-Stage Color Signals
•Subjected to Actions of Adaptation Mechanisms



XYZ-to-LMS

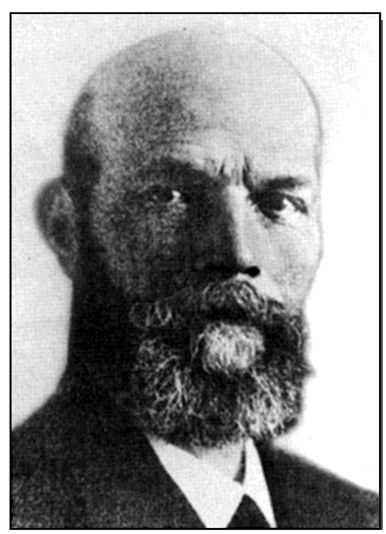


$$\begin{vmatrix} L \\ M \\ S \end{vmatrix} = \begin{vmatrix} 0.400 & 0.708 & -0.081 \\ -0.226 & 1.165 & 0.046 \\ 0.000 & 0.000 & 0.918 \end{vmatrix} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}$$



Johannes von Kries

Johannes von Kries
"Father of Chromatic-Adaptation Models"



von Kries Hypothesis

"This can be conceived in the sense that the individual components present in the organ of vision are completely independent of one another and each is fatigued or adapted exclusively according to its own function."

-von Kries, 1902

$$L_a = k_L L$$
$$M_a = k_M M$$
$$S_a = k_S S$$

Von Kries thought of this "proportionality law" as an extension of Grassmann's Laws to span two viewing conditions.

Modern "von Kries" Model

$$k_L = 1/L_{max} \quad \text{or} \quad 1/L_{white}$$
$$k_M = 1/M_{max} \quad \text{or} \quad 1/M_{white}$$
$$k_S = 1/S_{max} \quad \text{or} \quad 1/S_{white}$$

$$L_a = L/L_{max} \quad M_a = M/M_{max} \quad S_a = S/S_{max}$$

Corresponding Colors (CAT):

$$L_2 = \left(L_1/L_{max_1}\right)L_{max_2} \quad M_2 = \left(M_1/M_{max_1}\right)M_{max_2} \quad S_2 = \left(S_1/S_{max_1}\right)S_{max_2}$$

Matrix Form:

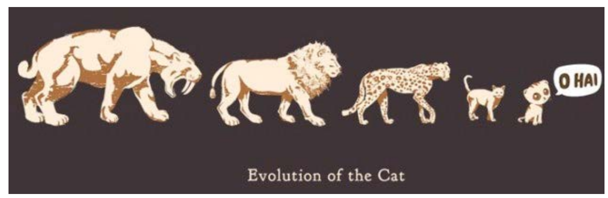
$$\begin{vmatrix} L_a \\ M_a \\ S_a \end{vmatrix} = \begin{vmatrix} 1/L_{max} & 0 & 0 \\ 0 & 1/M_{max} & 0 \\ 0 & 0 & 1/S_{max} \end{vmatrix} \begin{vmatrix} L \\ M \\ S \end{vmatrix}$$

XYZ Corresponding Colors (CAT):

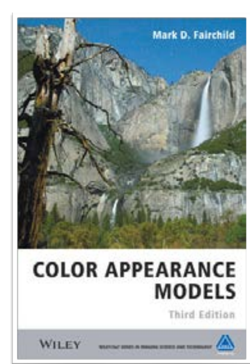
$$\begin{vmatrix} X_2 \\ Y_2 \\ Z_2 \end{vmatrix} = M^{-1} \begin{vmatrix} L_{max_2} & 0 & 0 \\ 0 & M_{max_2} & 0 \\ 0 & 0 & S_{max_2} \end{vmatrix} \begin{vmatrix} 1/L_{max_1} & 0 & 0 \\ 0 & 1/M_{max_1} & 0 \\ 0 & 0 & 1/S_{max_1} \end{vmatrix} M \begin{vmatrix} X_1 \\ Y_1 \\ Z_1 \end{vmatrix}$$

Some Evolution of CATs

- Nayatani et al. Nonlinear Model
- Fairchild (1991) & (1994) Models
- Bradford Model
- CIELAB & CIELUV
- CAT02



Color Appearance Models (CAMs)



What About Appearance?

Chromatic-adaptation models provide nominal scales for color appearance.

Two stimuli in their relative viewing conditions match each other.

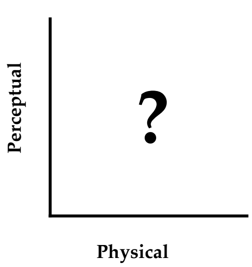
BUT **what color are they**??

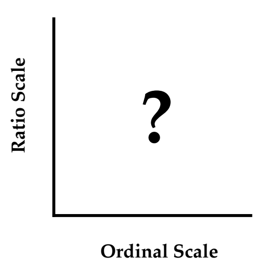
We need color-appearance models to get interval and ratio scales of:

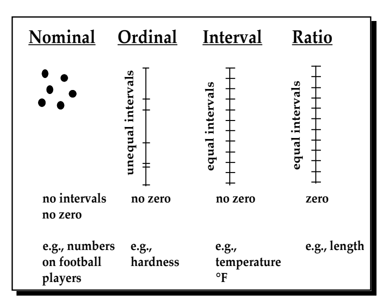
Lightness,
Brightness,
Hue,
Chroma, and
Colorfulness.

Color Appearance Models

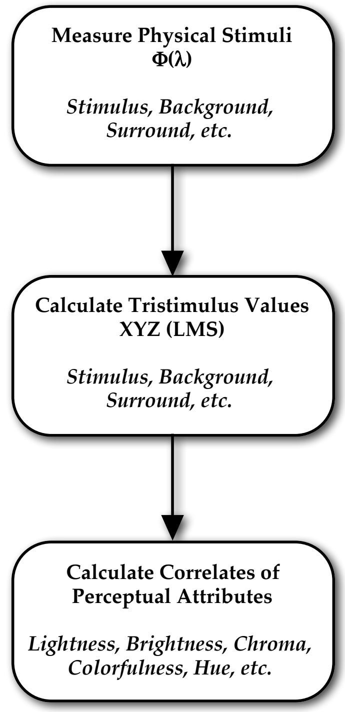
A **Color Appearance Model** provides mathematical formulae to transform physical measurements of the stimulus and viewing environment into correlates of perceptual attributes of color (*e.g.*, lightness, chroma, hue, *etc.*).







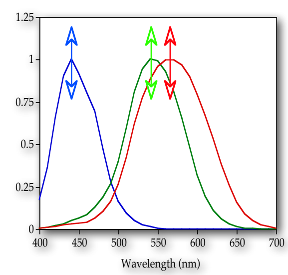
Flow Chart



Structure of CAMs

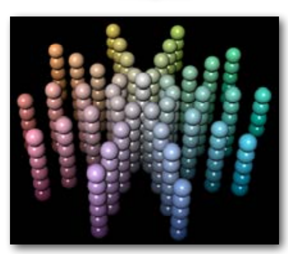
Chromatic Adaptation Transform

(to Implicit or Explicit Reference Conditions)
Corresponding Colors



Color Space Construction

Cone Responses
Opponent Responses
Appearance Correlates



CIELAB as an Example

CIELAB Does:

- Model Chromatic Adaptation
- Model Response Compression
- Include Correlates for Lightness, Chroma, Hue
- Include Useful Color Difference Measure

CIELAB Doesn't:

- Predict Luminance Dependent Effects
- Predict Background or Surround Effects
- Have an Accurate Adaptation Transform

CIELAB as a CAM

Chromatic Adaptation

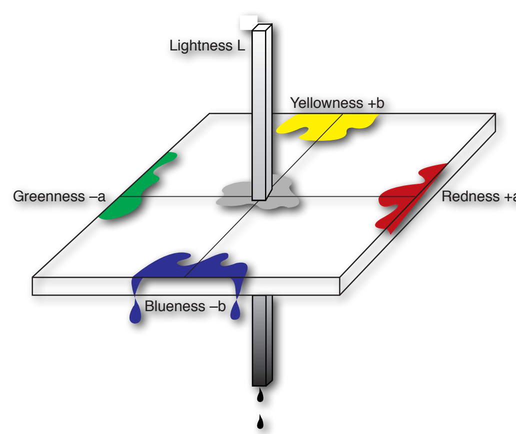
$X/X_n, Y/Y_n, Z/Z_n$

Opponent Processes

X-Y
Y-Z

Uniform Spacing

Constants 116, 500, 200
Cube Root



Why Not Just CIELAB?

Positive Aspects:

- •Accounts for Chromatic Adaptation
- •Works Well for Near-Daylight Illuminants
  - (also Medium Gray Background & Surround and Moderate Luminance Levels)
- •

Negative Aspects:

- •Does Not Account for Changes in:
  - Background
  - Surround
  - Luminance
  - Cognition
- •Cannot Predict Brightness & Colorfulness
- •"Wrong" von Kries Transform Works Poorly for Large Changes From Daylight
- •Constant-Hue Predictions could be Improved
  - (especially Blue)

CIELAB Makes a Good, Simple Baseline for Comparison

Beyond CIELAB

• More Accurate Adaptation Transform

• Luminance Dependencies

• Surround Dependencies

• Brightness & Colorfulness

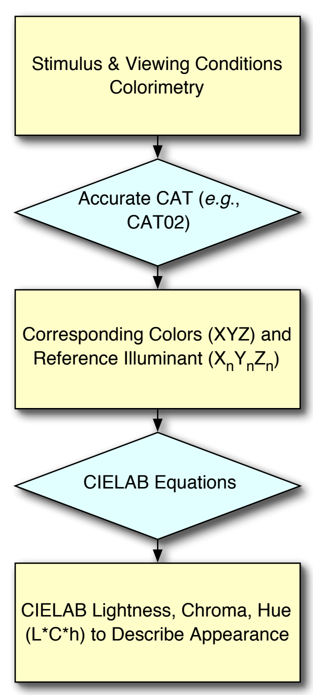
• Hue Linearity

(Hunt, Nayatani, RLAB, LLAB, CIECAM97s, CIECAM02)

Extending CIELAB

- Main Limitation is "Wrong" von Kries
- Can be Replaced with More Accurate CAT
- CIELAB Under Daylight a Very Good Color Space

CIELAB plus CAT Concept



Need for CIECAM02

- Vienna Experts Symposium (1996)
- Industrial Demand
- Uniformity of Practice (like CIELAB)

History

- Task Assigned to TC1-34 (1996)
- CIECAM97s Completed May 1997 !!
- Several Suggestions for Improvements
- TC8-01 Tasked with Suggesting Revisions (1998)
- CIECAM02 Published Nov. 2002

Where Did CIECAM97s Come From?

Examples of Model Pedigree Include:

•Bradford Chromatic-Adaptation Transform (Lam, 1985; Luo, 1997)
•Different Exponent on Short-Wavelength (Nayatani et al., 1982)
•Partial Adaptation Factors (Fairchild, 1996; Nayatani, 1997)
•Cone Responsivities (Estevez; see Hunt and Pointer, 1985)
•Hyperbolic Response Function (Seim and Valberg, 1986)
•R-G and Y-B Scales (Hunt, 1994; Nayatani, 1995)
•Surround Effects (Bartleson and Breneman, 1967)
•No Negative Lightness Predictions (Nayatani, 1995, Fairchild, 1996)
•Chroma Scale (Hunt, 1994)

Changes Considered *(TC8-01)*

- Correction of Surround Anomaly in N_c
- Adjustment of J for Zero Luminance
- Linear Adaptation Transform (Simple Inversion)
- Continuously Variable Surround Compensation
- Reduce Expansion of Chroma Scale for Near Neutrals
- Define Rectangular Coordinates
- References and Summary (submitted to CR&A/TC8-01)

<http://www.rit-mcsl.org/fairchild/PDFs/PAP10.pdf>

CIECAM02

- Revision of CIECAM97s
- Simplified and Improved
- Published in 2004 (CIC10, 2002 … CIE Pub. 159:2004)
- No "s" since there is no CIECAM02c

By no means perfect, but still holding up quite well...

Thoughts on Direct Cone Stimulation

Objective A: Minimize Individual Differences
(e.g. identical quantal stimulations of cone types)

Objective B: Match Appearance
(e.g. somehow figure out differential stimulations needed to produce similar perceptions given different internal calibration and adaptation)

Thank you …

Feel free to contact me any time with questions …

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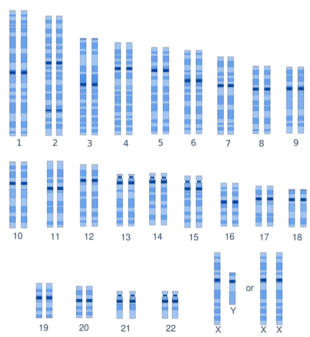
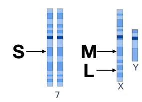
Bonus Material …

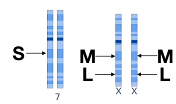
Tetrachromatic Females

Karyotype (Chromosomes)

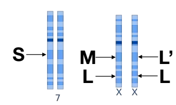




Male (L M S)



Female (L M S)



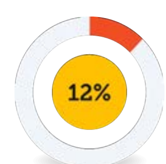
Carrier: Deuteranomaly (L L' M S)

Look for the mothers of deuteranomalous (L L' S) sons as likely tetrachromats. Certain tetrachromats if they also have a son with "normal" color vision.

Prevalence

~12% of Females Carry Anomalous Trichromacy

Random X-Chromasome Inactivation



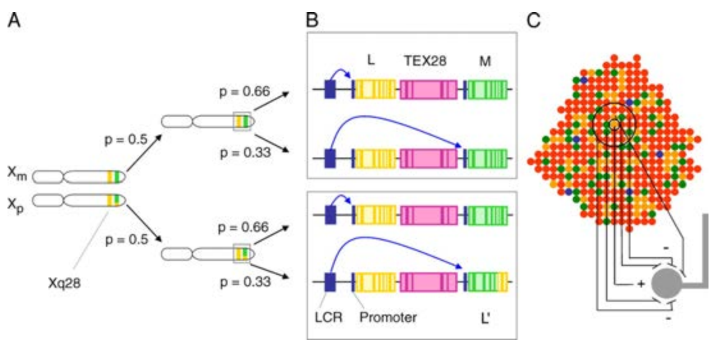
Therefore, They Must Have 4 Cone Types!

But … Not Necessarily Tetrachromatic

Deuteranomaly : 5% of Men ***(These women are not difficult to find!)***

*****We all have at least 6 sensitivities … LMS inside and outside the Macula (plus rods and ipRGCs). But we don't seem to consciously use them.***

Gene Expression



Gabriele Jordan; Samir S. Deeb; Jenny M. Bosten; J. D. Mollon; The dimensionality of color vision in carriers of anomalous trichromacy, *Journal of Vision* **10**:8, doi.org/10.1167/10.8.12 (2010).

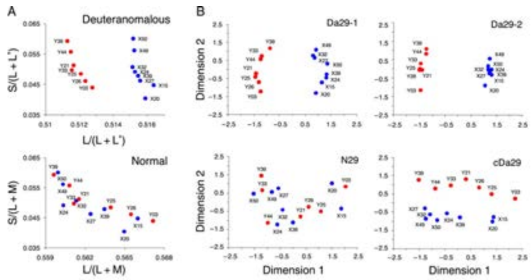
Weak vs. Strong

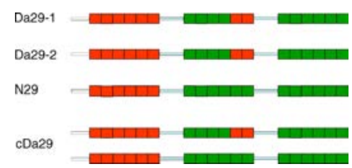
Weak Tetrachromacy: Possessing 4 Cone Types (12% Females)

Strong Tetrachromacy: Using Them; 4D Color Space (Perhaps nonexistent … certainly not 12%)

None have been proven. One might show improved discrimination (Jordan *et al.* 2010)

Jordan *et al.* 2010

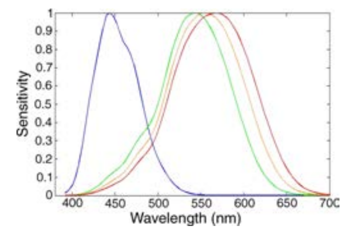




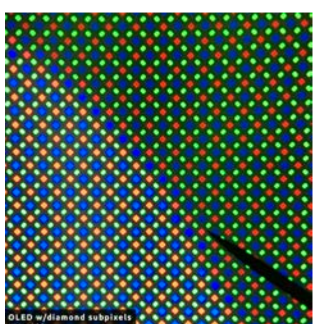
Stimuli created that deuteranomalous can discriminate, but normals not.
Two deuteranomalous sons can discriminate (Da29-1, Da29-1)
Normal son cannot (N29)
Carrier mother (cDa29) can.

This shows a different discrimination than normals, but IT DOES NOT show strong tetrachromacy. ALL observers discriminate in 2 dimensions!!

Only 1 of 24 carriers could do this. No others yet found?



Trichromatic Color Reproduction



Trichromatic reproduction (*e.g.* TV, cinema, prints) would look as bad to a strong tetrachromat as a two-primary reproduction looks to a normal trichromat.

Dichromatic Color Reproduction

3D Color

2D Color

Hypotheses …

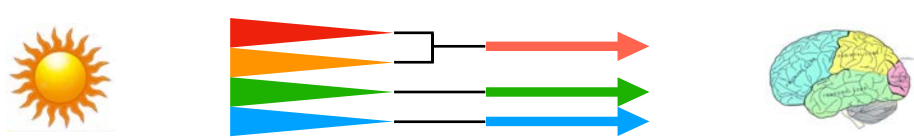
The four cone types feed into three color channels at the level of ganglion cells (or higher).

Why? Two of the four cone types are so highly correlated that they do not produce significantly different signals from one another.

The natural world is so well described with 3 color dimensions, that the 4th provides no significant additional information.

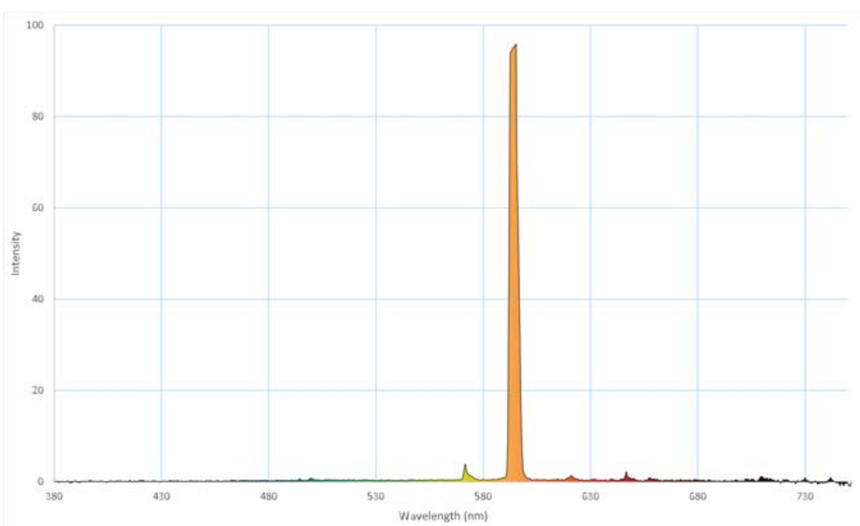
A tetrachromatic girl raised in a highly metameric world (to normal trichromats) might develop strong metamerism. Even our built environment has fairly rare metamerism (wrt importance for survival).

HOWEVER: Those 12% of women might need another category (or more) of CMFs to be fully included in trichromatic colorimetry.

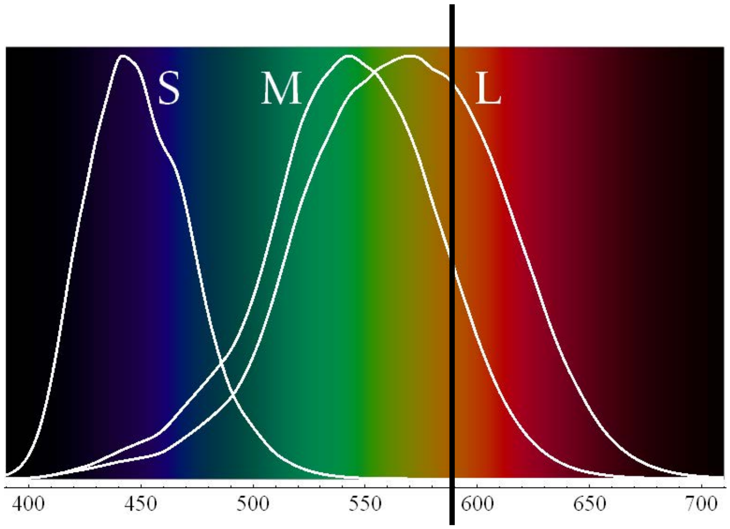


Low Pressure Na

Low Pressure Na



Low Pressure Na



Vision

Trichromatic?

Dichromatic? (like tritanope?)

Monochromatic? (but with a hue?)

What about adaptation?

Notes

Imagine you have one cone type and it responds to only a single wavelength.
What would the world look like?

Lamp is emission from sodium vapor.

Wavelengths are sodium doublet.
- Fraunhofer D1 and D2
- 589.592 and 588.995 nm
- Essentially monochromatic (less than 0.6 nm apart)

High-pressure sodium has a much wider emission spectrum.

With the LP Na lamp, two types of cone (L & M) are stimulated in equal proportions. The S-cone might also have a small, and proportional, response.

Do you expect a gray world or a single-hued world? If a hue, which one?

If you see a single hue, it tells us that the color vision system is linear and additive up to the point of hue determination?

Do we see that? Would we expect to for other wavelengths?

Strictly no. The Bezhold-Brücke hue shift and Helson-Judd effects tell us there should be changes.

Does the hue of the environment become less saturated over time? Why?
Chromatic adaptation, just like to an incandescent light.

This is seriously strong illuminant metamerism!

Can we bring full color perception back … the “Color Cannon”!!
This is a strictly physical effect. The full spectral stimulus was missing and then it returns.