Color Appearance Models: CIECAM02 and Beyond

IS&T/SID 12th Color Imaging Conference

Tutorial T1A, 11/9/04, 8:00-10:00AM

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Outline

- Color Appearance Phenomena
- Chromatic Adaptation
- Structure of Color Appearance Models
- CIECAM02
- Image Appearance: iCAM

Color PDF of notes at <www.cis.rit.edu/fairchild/PDFs/CIC2004.pdf>

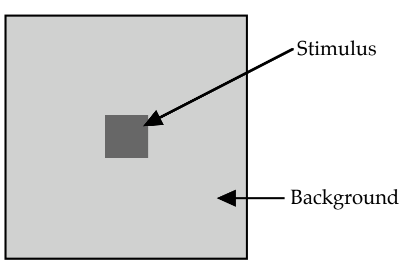
Color Appearance Phenomena

If two stimuli do not match in color appearance when $(XYZ)_1 = (XYZ)_2$, then some aspect of the viewing conditions differs.

Various **color-appearance phenomena** describe relationships between changes in viewing conditions and changes in appearance.

- Bezold-Brücke Hue Shift
- Abney Effect
- Helmholtz-Kohlrausch Effect
- Hunt Effect
- Simultaneous Contrast
- Crispening
- Helson-Judd Effect
- Stevens Effect
- Bartleson-Breneman Equations
- Chromatic Adaptation
- Color Constancy
- Memory Color
- Object Recognition

Simultaneous Contrast

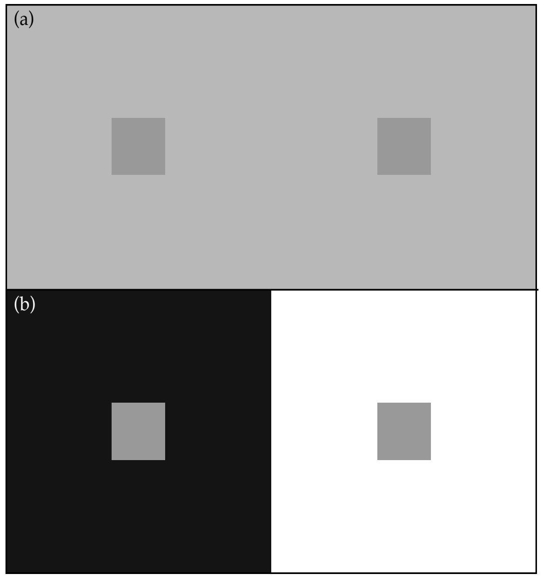


The background in which a stimulus is presented influences the apparent color of the stimulus.

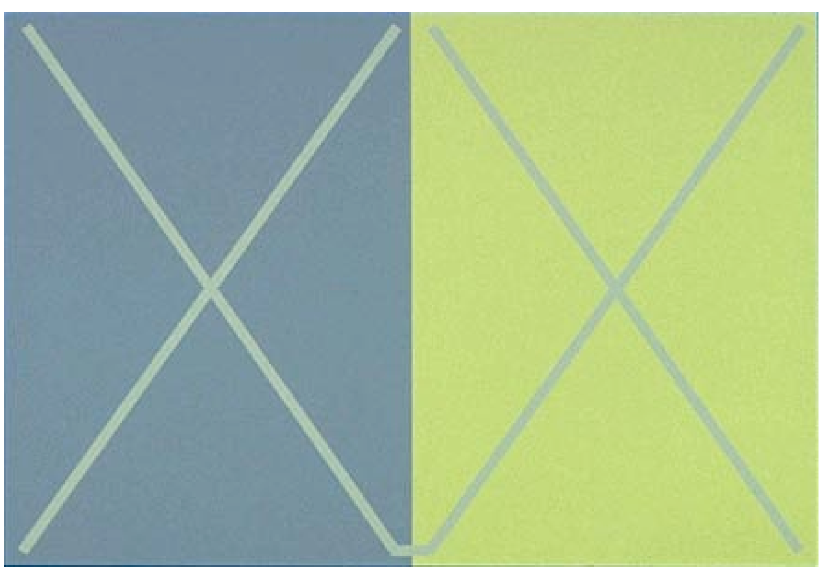
Indicates lateral interactions and adaptation.

Background Change	***Stimulus Color-Appearance Change***
Darker	Lighter
Lighter	Darker
Red	Green
Green	Red
Yellow	Blue
Blue	Yellow

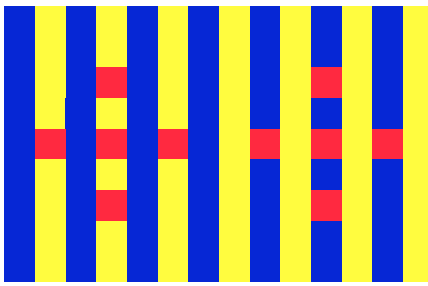
Simultaneous Contrast Example

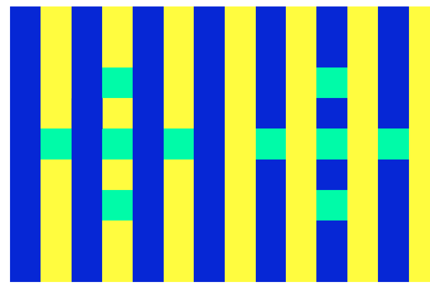


Josef Albers

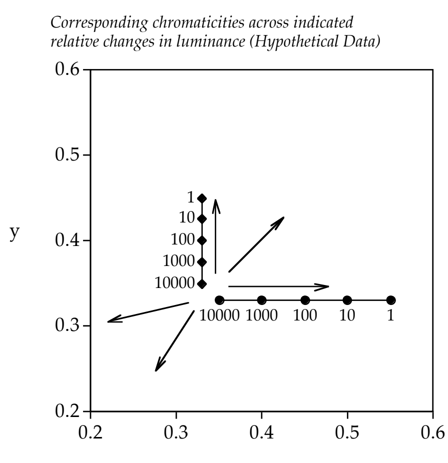


Complex Spatial Interactions





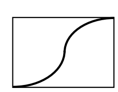
Hunt Effect



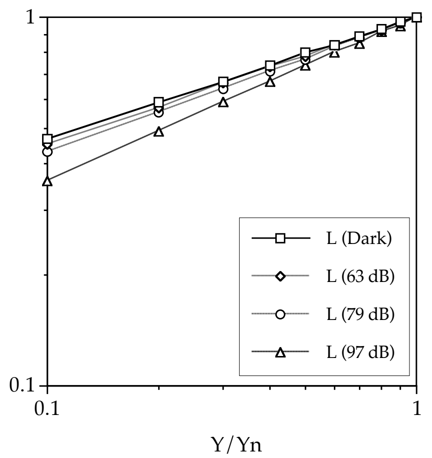
For a constant chromaticity, perceived colorfulness increases with luminance.

As luminance increases, stimuli of lower colorimetric purity are required to match a given reference stimulus.

Indicates nonlinearities in visual processing.



Stevens Effect



Perceived lightness contrast increases with increasing adapting luminance.

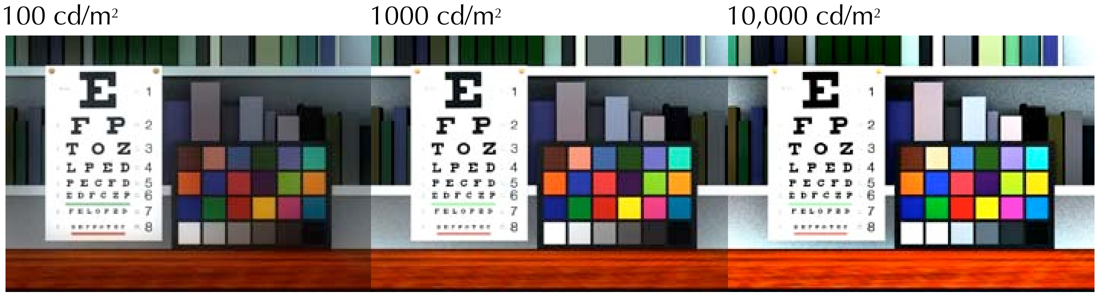
As adapting luminance increases:
dark colors look darker and
light colors look lighter.

Indicates luminance-dependent nonlinearities.

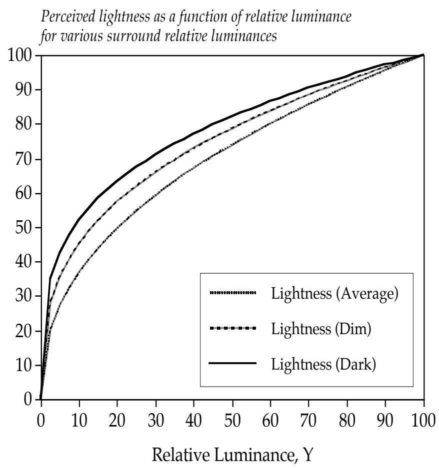
Stevens & Hunt Effects

0.1 cd/m² 1.0 cd/m² 10 cd/m²

100 cd/m² 1000 cd/m² 10,000 cd/m²



Bartleson-Breneman

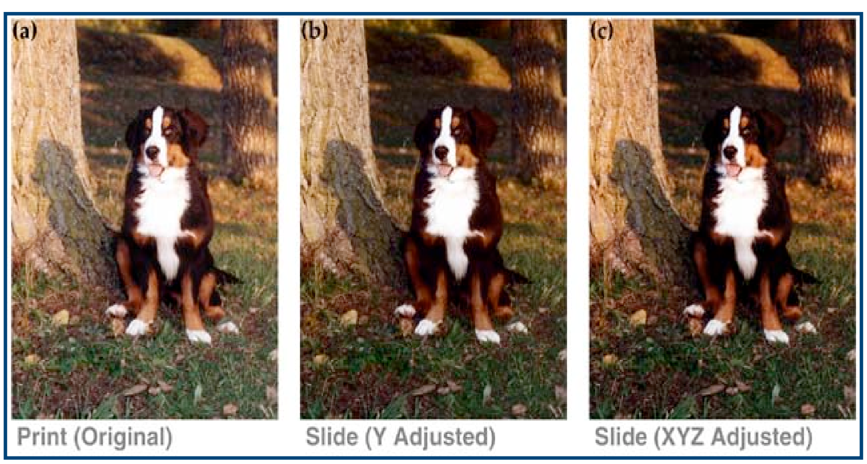


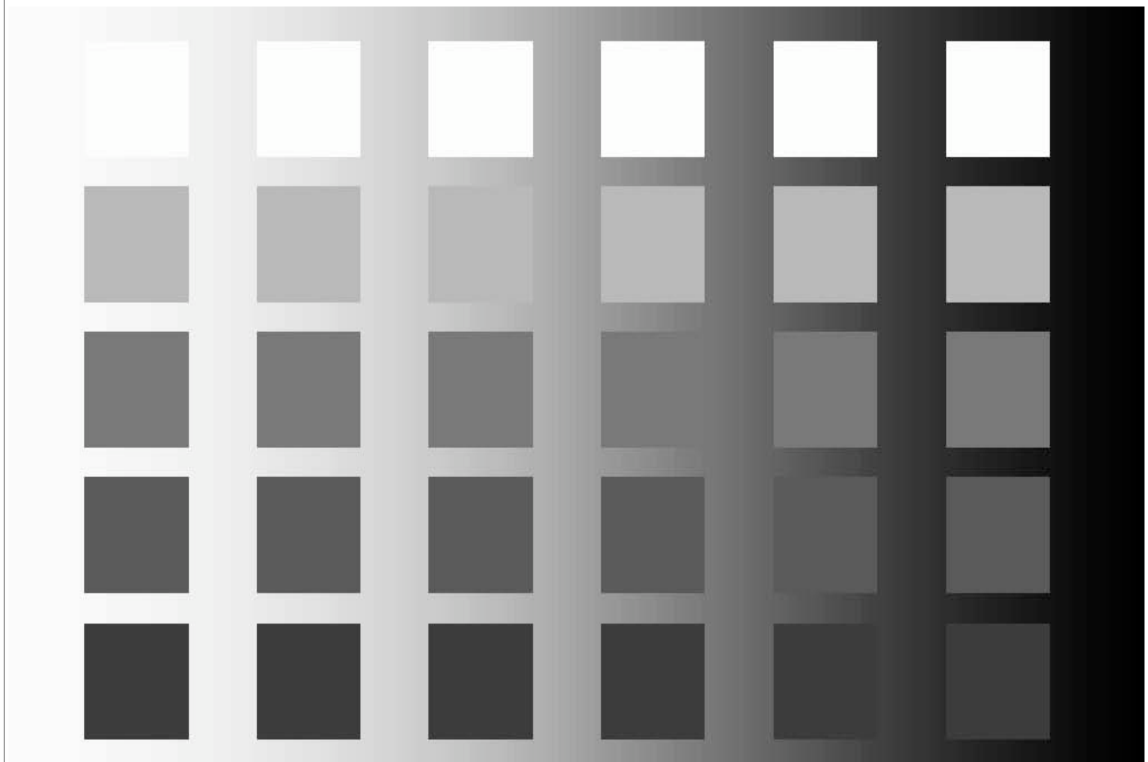
Apparent contrast in complex stimuli (i.e. images) increases with increasing surround luminance.

Decreased surround luminance increases the brightness of all image colors, but the effect is greater for dark colors.

Indicates a differential contrast effect (white-point resetting).

Surround Effect Demo





Adaptation

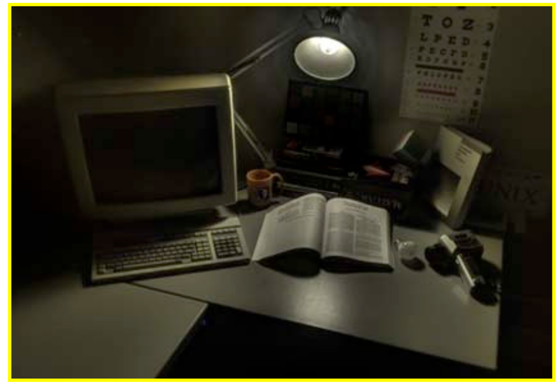
Light Adaptation:
Decrease in visual sensitivity with increases in luminance.
(Automatic Exposure Control)

Dark Adaptation:
Increase in visual sensitivity with decreases in luminance.
(Automatic Exposure Control)

Chromatic Adaptation:
Independent sensitivity regulation of the mechanisms of color vision.
(Automatic Color Balance)

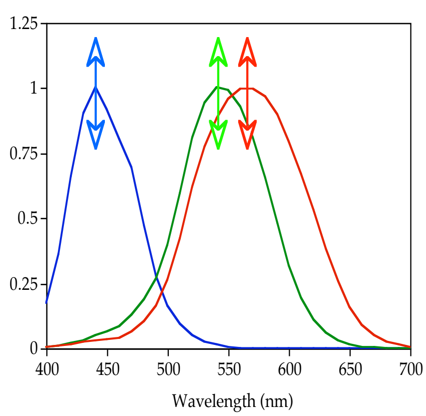
Local Adaptation

Linear Mapping



Perceptual Mapping

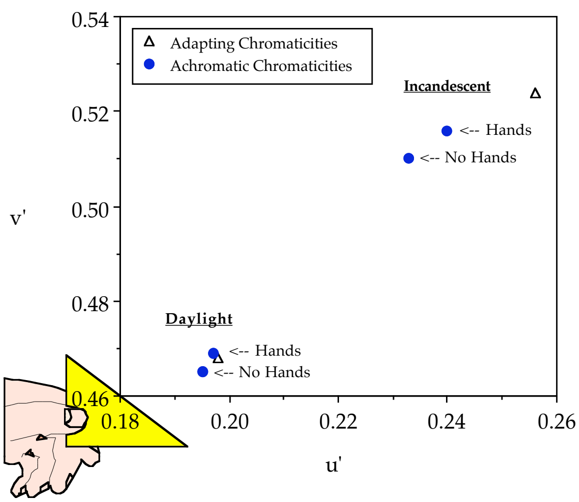
Chromatic Adaptation



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.

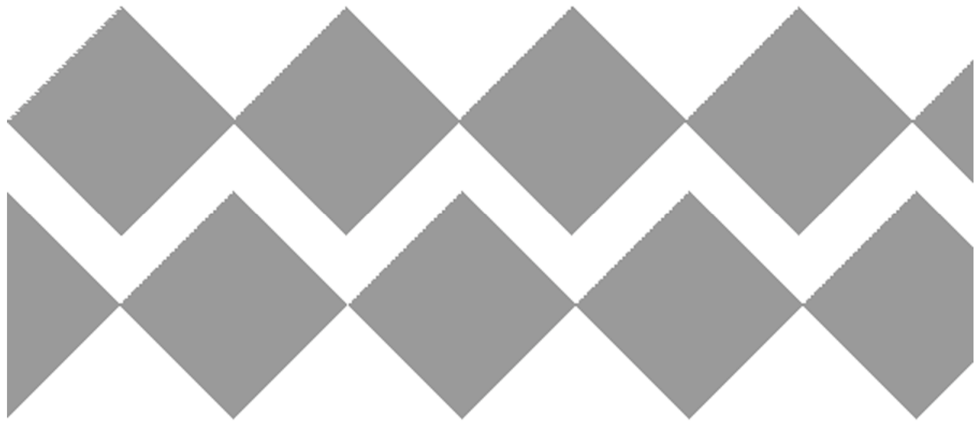
Color Constancy (Discounting)



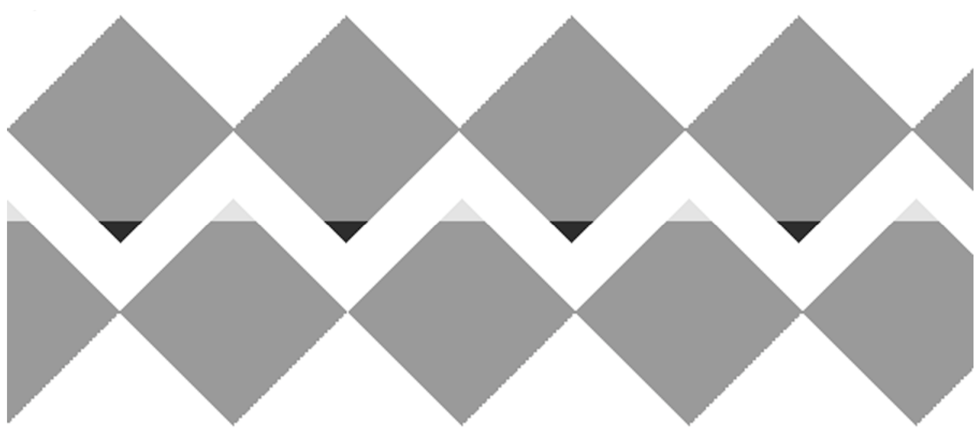
We perceive the colors of objects to remain unchanged across large changes in illumination color.

- Not True
- Chromatic Adaptation
- Poor Color Memory
- Cognitive Discounting-the-Illuminant

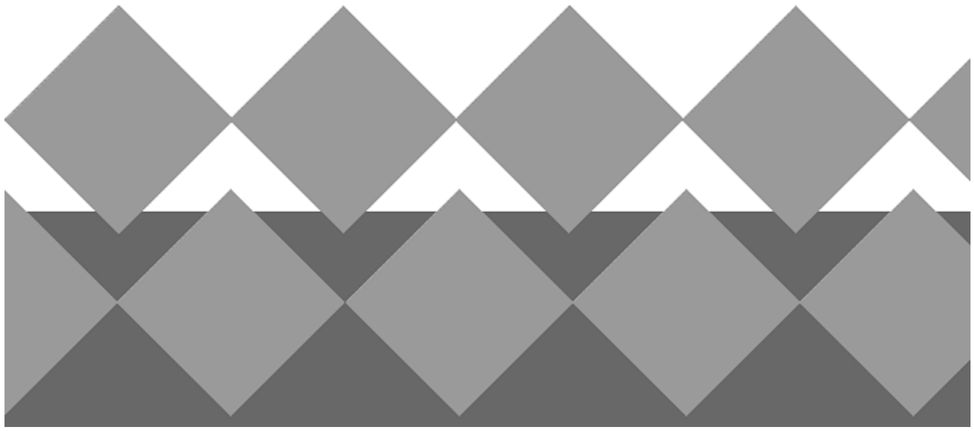
Diamonds



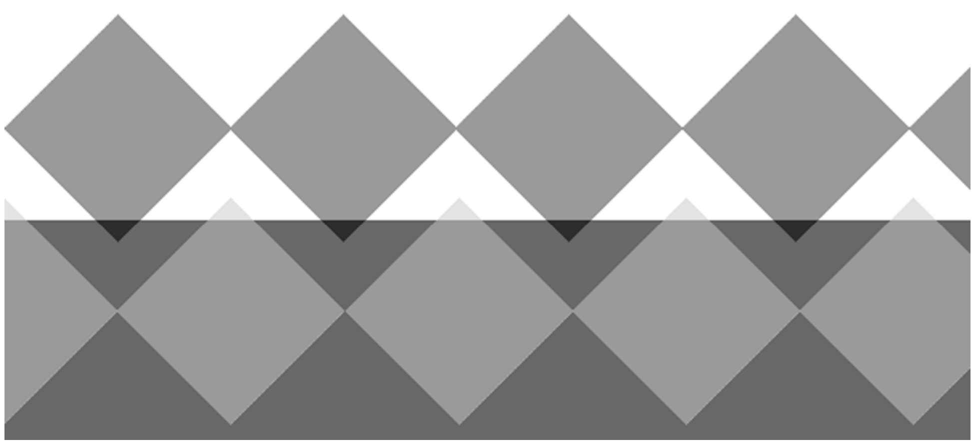
With Tips



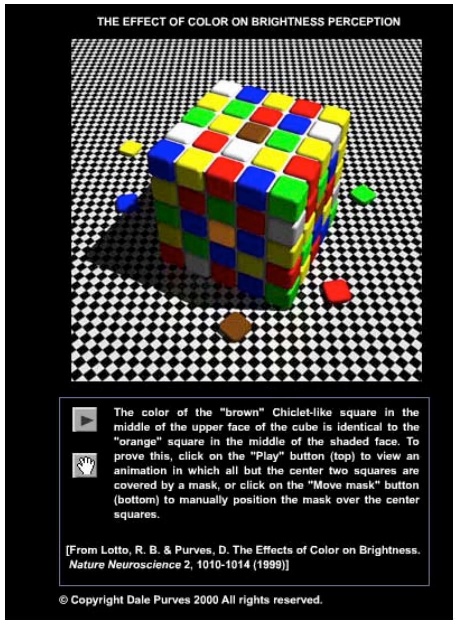
On Backgrounds



Both Tips & Backgrounds!



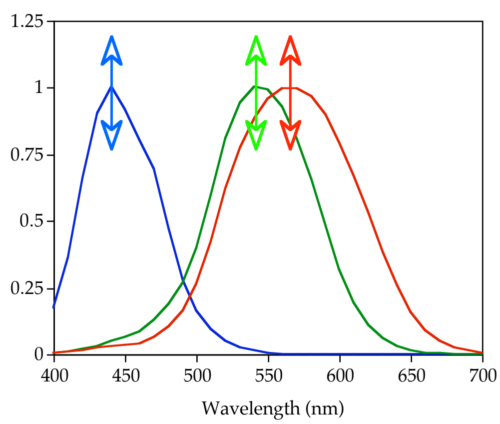
Purves "Brown"



Chromatic Adaptation Modeling

Chromatic Adaptation:

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



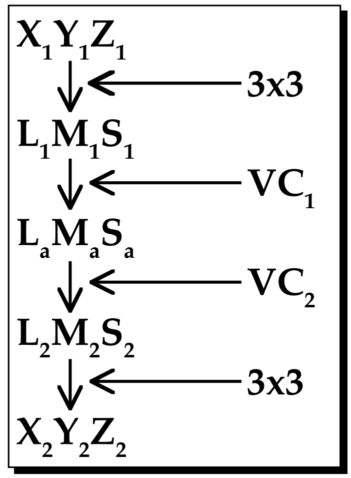
Chromatic Adaptation Models

Model:

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

Transform (CAT):

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



Chromatic Adaptation Model Output

Raw “Radiance” Images

Adapted “Perceptual” Images

Chromatic Adaptation Transform Output

Raw D65 "Radiance" Image

Raw A "Radiance" Image

A Image Transformed to Corresponding D65 Appearance

Analysis of Chromatic Adaptation Models

ADVANTAGES:

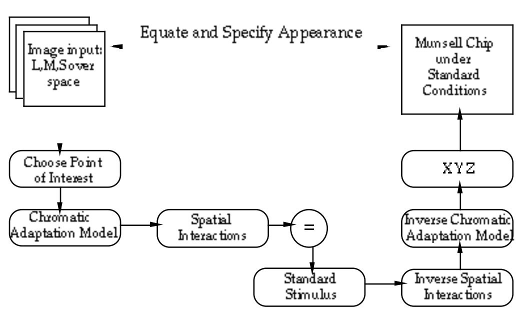
- Corresponding Colors
- Thus, Color Reproductions
- Simpler

DISADVANTAGES:

- No Appearance Attributes (*e.g.*, Lightness, Chroma, Hue)
- Can't Edit, Gamut Map, *etc*.

Since chromatic adaptation models provide only nominal scales, one could take all viewing conditions into account properly and never know what color a stimulus is.

But, a chromatic adaptation transform could be used as input to index into a color-order system to specify appearance.



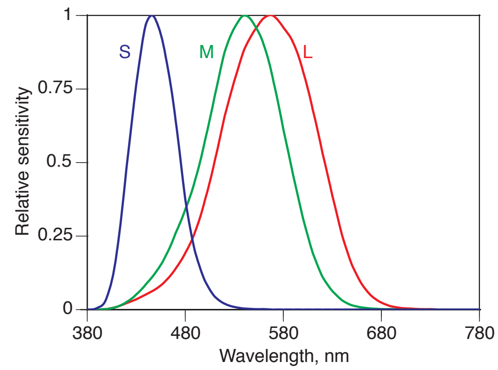
Cone Excitations

How are they found?

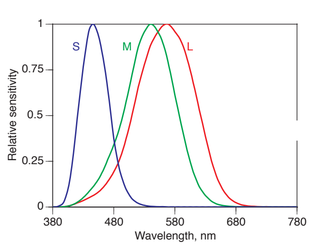
- Copunctal Points of Dichromats w/CMFs
- Chromatic Adaptation w/Model
- Selective Retinal Conditioning/Thresholds
- Retinal Pigment Absorption Measurements
- Genetics

Why are they important?

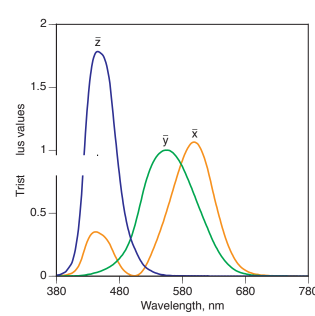
- Produce the 1st-Stage Color Signals
- Subjected to Actions of Adaptation Mechanisms



XYZ-to-LMS

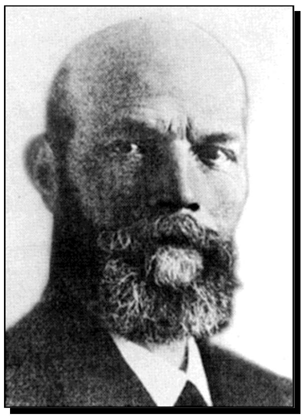


$$\begin{vmatrix} L \\ M \\ S \end{vmatrix} = \begin{vmatrix} 0.400 & 0.708 & -0.081 \\ -0.226 & 1.165 & 0.046 \\ 0.000 & 0.000 & 0.918 \end{vmatrix} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}$$



Johannes von Kries

Johannes von Kries
"Father of Chromatic-Adaptation Models"



"If some day it becomes possible to recognize and to distinguish in an objective way the various effects of light by direct observation of the retina, people will perhaps recall with pitying smiles the efforts of previous decades which undertook to seek an understanding of the same phenomena by such lengthy detours."

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):

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

The Next Line...

"But if the real physiological equipment is considered, on which the processes are based, it is permissible to doubt whether things are so simple."

-von Kries, 1902

Some Evolution of CATs

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

Back to von Kries

- Fairchild (2001)
  - Linear CATs can Perform Like Bradford
  - Optimization on Matrix (not LMS)
  - Relationship to “Spectral Sharpening”
- Calabria and Fairchild (2001)
  - Herding CATs
  - Insignificant Differences
- CAT02 in CIECAM02
  - Simple von Kies (100 years later!) non-LMS Matrix

Linear CATs

- Simple von Kries Model
- "Optimized" XYZ-to-RGB Transform

$$\begin{vmatrix} X_2 \\ Y_2 \\ Z_2 \end{vmatrix} = \mathbf{M}_{CAT}^{-1} \begin{vmatrix} R_{w2} & 0 & 0 \\ 0 & G_{w2} & 0 \\ 0 & 0 & B_{w2} \end{vmatrix} \begin{vmatrix} 1/R_{w1} & 0 & 0 \\ 0 & 1/G_{w1} & 0 \\ 0 & 0 & 1/B_{w1} \end{vmatrix} \mathbf{M}_{CAT} \begin{vmatrix} X_1 \\ Y_1 \\ Z_1 \end{vmatrix}$$

- $\mathbf{M}_{\text{CAT}}$ Defines the Transform

Picking a CAT

- Various Techniques used to Derive $\mathbf{M}_{\text{CAT}}$
- Calabria & Fairchild (2001)
  - "Herding CATs"
  - Only LMS Significantly Different
- TC8-01 Compromised on $\mathbf{M}_{\text{CAT02}}$
- Basis of CIECAM02

$$\mathbf{M}_{CAT02} = \begin{vmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{vmatrix}$$

What About Appearance?

Chromatic-adaptation models provide nominal scales for color appearance.

Two stimuli in their relative viewing conditions match each other.

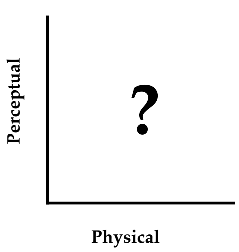
BUT **what color are they**??

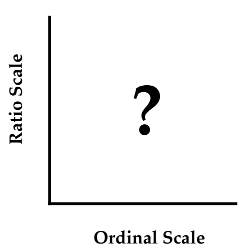
We need color-appearance models to get interval and ratio scales of:

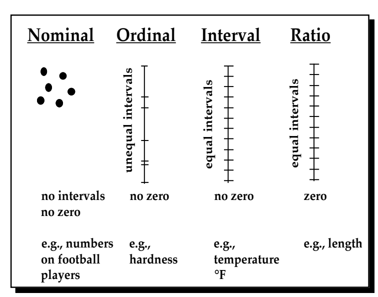
Lightness,
Brightness,
Hue,
Chroma, and
Colorfulness.

Color Appearance Models

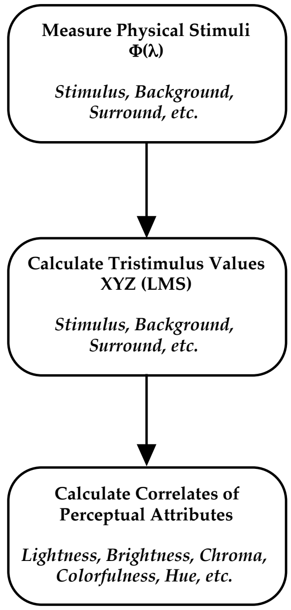
A **Color Appearance Model** provides mathematical formulae to transform physical measurements of the stimulus and viewing environment into correlates of perceptual attributes of color (*e.g.*, lightness, chroma, hue, *etc.*).



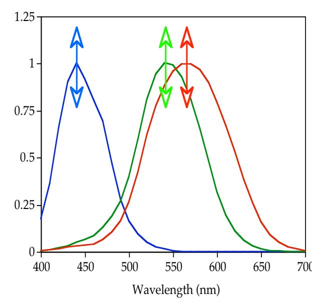




Flow Chart

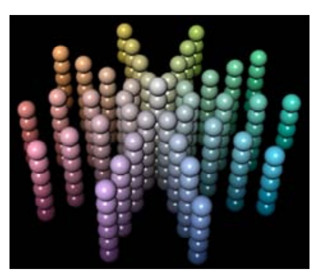


Structure of CAMs



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

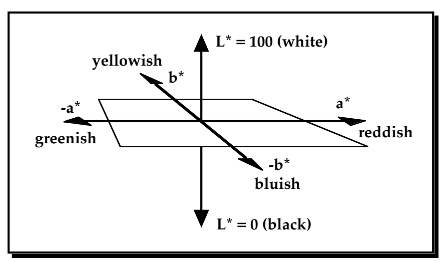
X/X_n, Y/Y_n, Z/Z_n

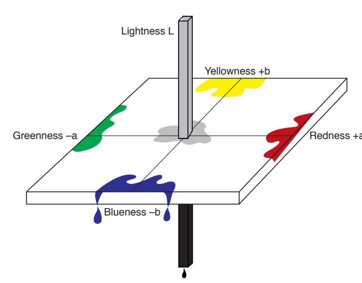
Opponent Processes

X-Y
Y-Z

Uniform Spacing

Constants 116, 500, 200
Cube Root





CIELAB Equations

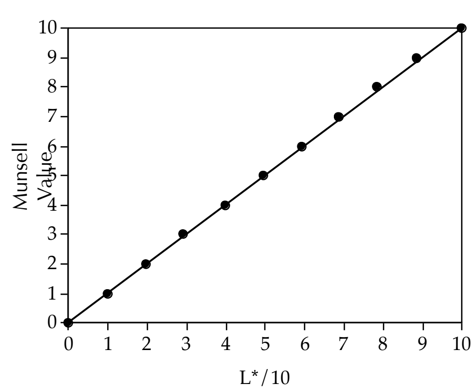
$$L^* = 116f(Y/Y_n) - 16$$
$$a^* = 500\left[f(X/X_n) - f(Y/Y_n)\right]$$
$$b^* = 200\left[f(Y/Y_n) - f(Z/Z_n)\right]$$

$$f(\omega) = (\omega)^{1/3} \qquad \omega > 0.008856$$
$$f(\omega) = 7.787(\omega) + 16/116 \qquad \omega \le 0.008856$$

CIELAB Lightness

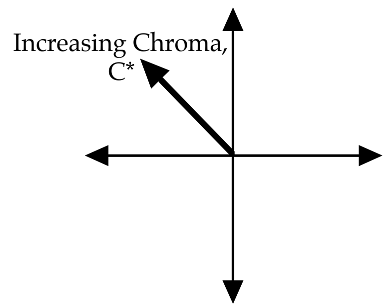
$$L^* = 116f(Y/Y_n) - 16$$

$$f(\omega) = (\omega)^{1/3} \qquad \omega > 0.008856$$
$$f(\omega) = 7.787(\omega) + 16/116 \qquad \omega \le 0.008856$$



CIELAB Chroma

$$C^* = \left(a^{*2} + b^{*2}\right)^{1/2}$$



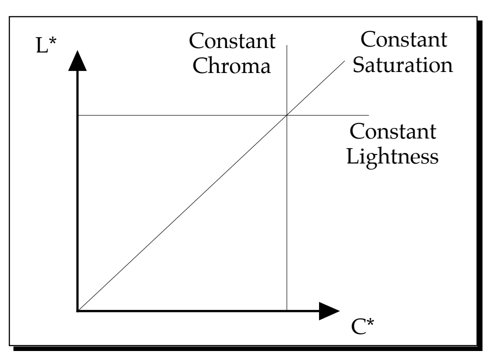
Neutrals Have Zero Chroma, C* = 0.0

Saturation in CIELAB

Due to the lack of a related chromaticity diagram, saturation is not officially defined in CIELAB.

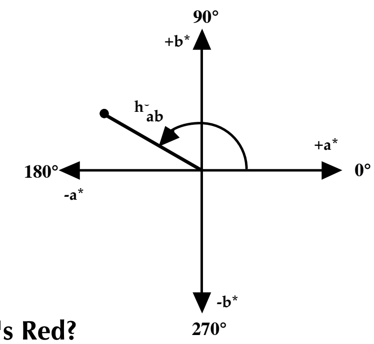
However recalling the definitions of chroma (colorfulness/ brightness of white), lightness (brightness/brightness of white), and saturation (colorfulness/brightness).

Saturation = C*/L*



CIELAB Hue

$$h_{ab} = \tan^{-1}\left(\frac{b^*}{a^*}\right)$$



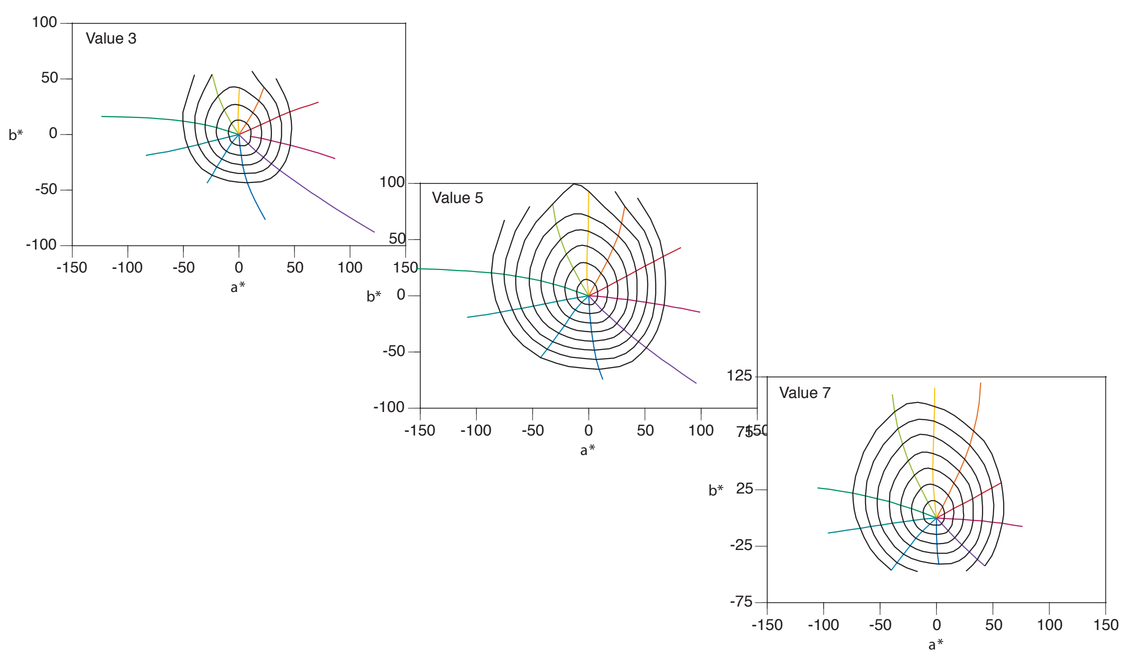
Relative Hue Scale — Where's Red?

Approximate Hue Angles of NCS Unique Hues

R — 24°
Y — 90°
G — 162°
B — 246°

Note: The number of discriminable hue steps is not equal between each of the unique hues.

CIELAB Performance



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

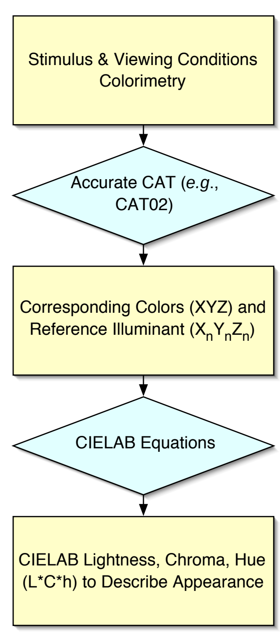
- More Accurate Adaptation Transform
- Luminance Dependencies
- Surround Dependencies
- Brightness & Colorfulness
- Hue Linearity

(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



CIELAB plus CAT Example

Step 1: Obtain colorimetric data for stimulus and viewing conditions.

Step 2: Use CAT02 to compute corresponding colors for CIE Illuminant D65 (and 1000 lux).

Step 3: Compute CIELAB coordinates using corresponding colors from step 2 and D65 white.

Step 4: Use CIELAB L*C*h as appearance correlates.

CIECAM02

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)

CIECAM97s & CIECAM97c

- Comprehensive version that includes a wide range of visual phenomena.
- Simplified version (fully compatible) that is adequate for practical applications.
- CIECAM97s Exists (May, 1997)
- CIECAM97c Does Not (No Apparent Demand?)

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)

<www.cis.rit.edu/fairchild/PDFs/CIECAM97sRev.pdf>

CIECAM02

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

Inputs

L_A:	Adapting Field Luminance in cd/m^2 (often 20% of the luminance of white)
XYZ:	Relative Tristimulus Values of the Sample
$X_wY_wZ_w$:	Relative Tristimulus Values of the White
Y_b:	Relative Luminance of the Background
D:	Specifies the Degree of Adaptation: D = 1.0, (Complete Adaptation or Discounting) D = 0.0, (No Adaptation) D in Between, (Various Degrees of Incomplete Adaptation)

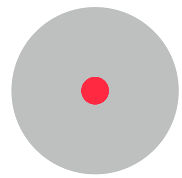
Changes from CIECAM97s:
None

Stimulus

- Uniform Patch of About 2° Angular Subtense
- Single Pixel in an Image?
- Required Measurements
  Relative XYZ (CIE 2°)

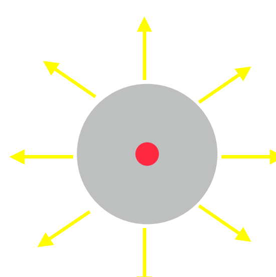
Background

- Area Immediately Adjacent to Stimulus Out to About 10°
- Average for Images? (20% Gray)
- Required Measurements
  Relative Y (called Y_b)



Surround

- Remainder of Visual Field Outside Background
- Required Measurements
  Often Categorical
  Average (>20%)
  Dim (0-20%)
  Dark (0%)



Changes from CIECAM97s:
Continuous Surround Compensation

Adapting Stimulus

- Stimulus that Sets the State of Adaptation
  - 0.2xWhite (Gray)
  - Scene Average (Spatially Weighted?)

- Required Measurements

  Absolute XYZ (CIE 2°, cd/m²)

  or

  Relative XYZ and L_A (cd/m²)

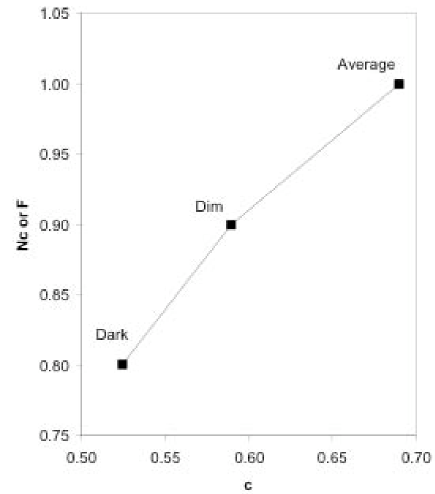
Parameter Decision Table

c: Impact of Surround
N_c: Chromatic Induction Factor
F: Factor for Degree of Adaptation

Viewing Condition	c	N_c	F
Average Surround	0.69	1.0	1.0
Dim Surround	0.59	0.9	0.9
Dark Surround	0.525	0.8	0.8

Changes from CIECAM97s:
Removal of 2 Conditions (Large Samples & Cut-Sheet)
F_{LL} Removed (Always 1.0)
Correction of N_c (Now Monotonic)
Change in F & N_c for Dark (from 0.9)

Continuously-Variable Surround



Changes from CIECAM97s:
New Feature

Discounting

- Is the stimulus viewed as an illuminated object (Discounting) or as self-luminous (No Discounting)?
- Required Measurements
  - **Yes: D=1.0**
  - **No: Use Equation**
  - **No Adaptation: D=0.0**

$$D = F\left[1 - \left(\frac{1}{3.6}\right)e^{\left(\frac{-La-42}{92}\right)}\right]$$

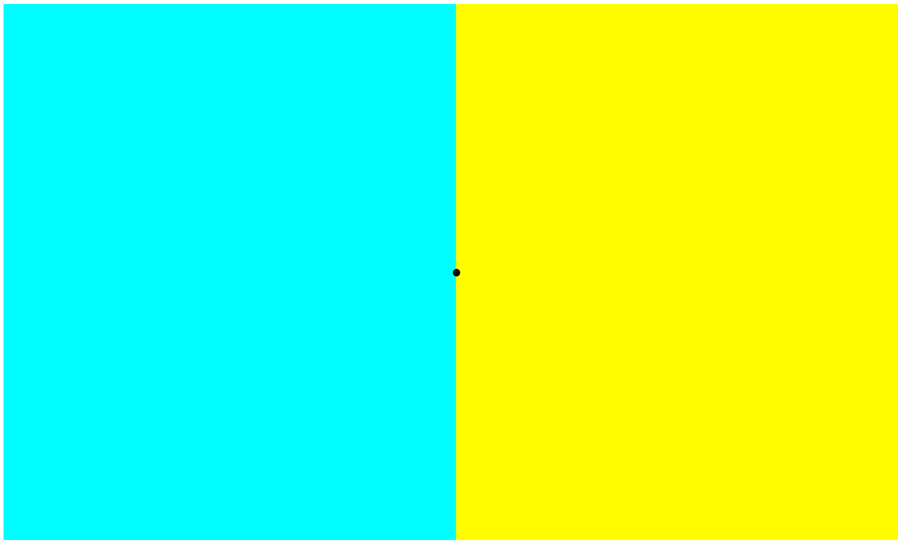
Changes from CIECAM97s:
Simplified Equation

Real-World Discounting

Outline of Model Structure

- **Chromatic Adaptation Transform**
  - (to Implicit Ill. E Reference Conditions)
  - Corresponding Colors
- **Color Space Construction**
  - Cone Responses
  - Opponent Responses
  - Appearance Correlates

Chromatic Adaptation



Chromatic Adaptation Transform: CAT02

- von Kries Normalization
- Now Linear (normal von Kries)
- "Sharpened" "Cone" Reponses (Optimized)
- Generally Good Performance

(Not Different from CIECAM97s)

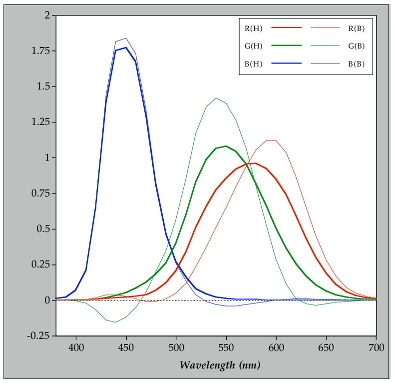
Transform to RGB Responses

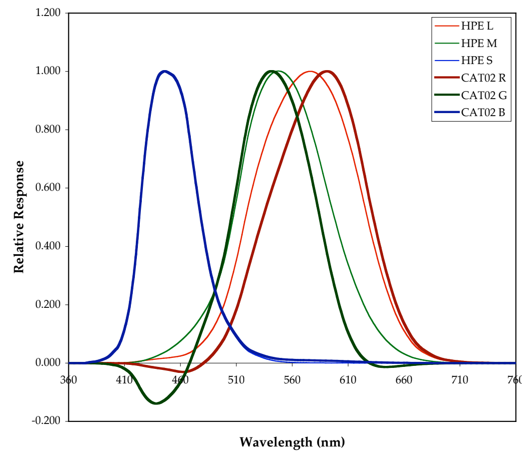
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M}_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\mathbf{M}_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \qquad \mathbf{M}_{B}^{-1} = \begin{bmatrix} 1.0961 & -0.2789 & 0.1827 \\ 0.4544 & 0.4735 & 0.0721 \\ -0.0096 & -0.0057 & 1.0153 \end{bmatrix}$$

Changes from CIECAM97s:
Simplified Transform (No /Y)
New Optimized Matrix

"Sharpened" "Cone" Responses





Changes from CIECAM97s:
RGB(CAT02) Slightly Different from RGB(B)

Adaptation Transform

$$R_c = \left[Y_W\left(D/R_w\right) + (1-D)\right]R$$

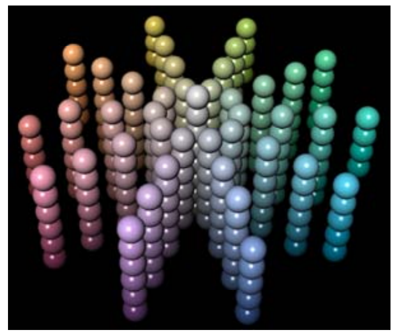
$$G_c = \left[Y_W\left(D/G_w\right) + (1-D)\right]G$$

$$B_c = \left[Y_W\left(D/B_w\right) + (1-D)\right]B$$

Changes from CIECAM97s:
Y_W Added (for cases it is not 100)
Nonlinearity on B Removed

Color Space

- Based on Structure within Hunt Model & CIECAM97s
- Enhancements Based on Various Tests, *etc*.
- Hyperbolic Nonlinearity
- Color Difference Signals
- Appearance Correlates



Intermediate Parameters

Some numbers for further computations...

F_L:	Luminance Level Adaptation Factor
n:	Background Induction Factor
N_{bb} and N_{cb}:	Brightness and Chromatic Background Factors
z:	Base Exponential Nonlinearity

$$k = 1/(5L_A + 1)$$

$$F_L = 0.2k^4(5L_A) + 0.1(1 - k^4)^2(5L_A)^{1/3}$$

$$n = Y_b / Y_w$$

$$N_{bb} = N_{cb} = 0.725(1/n)^{0.2}$$

$$z = 1.48 + n^{1/2}$$

Changes from CIECAM97s:
Slight Change in z Equation

Adapted Cone Responses

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \mathbf{M}_H \mathbf{M}_{CAT02}^{-1} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix}$$

$$\mathbf{M}_H = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00 & 0.00 & 1.00 \end{bmatrix} \quad \mathbf{M}_H^{-1} = \begin{bmatrix} 1.9102 & -1.1121 & 0.2019 \\ 0.3710 & 0.6291 & 0.00 \\ 0.00 & 0.00 & 1.00 \end{bmatrix}$$

$$R'_a = \frac{400(F_L R'/100)^{0.42}}{\left[(F_L R'/100)^{0.42} + 27.13\right]} + 0.1$$

$$G'_a = \frac{400(F_L G'/100)^{0.42}}{\left[(F_L G'/100)^{0.42} + 27.13\right]} + 0.1$$

$$B'_a = \frac{400(F_L B'/100)^{0.42}}{\left[(F_L B'/100)^{0.42} + 27.13\right]} + 0.1$$

Changes from CIECAM97s:
No Y Multiplication Required Before Transform
Modified Nonlinearity (Square-Root Behavior over Larger Range)

Opponent Responses

$$A = \left[2R'_a + G'_a + (1/20)B'_a - 0.305\right]N_{bb}$$

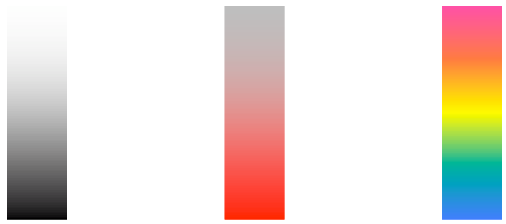
$$a = R'_a - 12G'_a/11 + B'_a/11$$

$$b = (1/9)(R'_a + G'_a - 2B'_a)$$

Changes from CIECAM97s:
Adjusted Constant in A (Perfect Black)

Appearance Correlates

- Brightness, Lightness
- Colorfulness, Chroma, Saturation
- Hue



- Built Up to Fit Experimental Data
- Need 5 of 6 to Fully Describe Appearance

Hue

The degree to which a stimulus can be described as similar to or different from stimuli that are described as red, green, blue, and yellow.

$$h = \tan^{-1}(b / a)$$

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

Red:	h = 20.14,	e = 0.8,	H = 0 or 400,
Yellow:	h = 90.00,	e = 0.7,	H = 100,
Green:	h = 164.25,	e = 1.0,	H = 200,
Blue:	h = 237.53,	e = 1.2.	H = 300

Changes from CIECAM97s:
e Now Defined Analytically

Lightness

The brightness of a stimulus relative to the brightness of a stimulus that appears white under similar viewing situations.

$$J = 100\left(A / A_w\right)^{cz}$$

Changes from CIECAM97s:
None

Brightness

The perceived quantity of light emanating from a stimulus.

$$Q = (4/c)(J/100)^{0.5}(A_w + 4)F_L^{0.25}$$

Changes from CIECAM97s:
New Constants, F_L Added, Simplified

Chroma

The colorfulness of a stimulus relative to the brightness of a stimulus that appears white under similar viewing conditions.

$$t = \frac{(50000/13) N_c N_{cb} e \left(a^2 + b^2\right)^{1/2}}{R'_a + G'_a + (21/20) B'_a}$$

$$C = t^{0.9} (J/100)^{0.5} \left(1.64 - 0.29^n\right)^{0.73}$$

Changes from CIECAM97s:
t simplified form of former s (constants in new e formula)
C Simplified and Modified (Munsell, Low Chromas)

Colorfulness

The perceived quantity of hue content (difference from gray) in a stimulus.

Colorfulness increases with luminance.

$$M = C F_L^{0.25}$$

Changes from CIECAM97s:
0.25 instead of 0.15

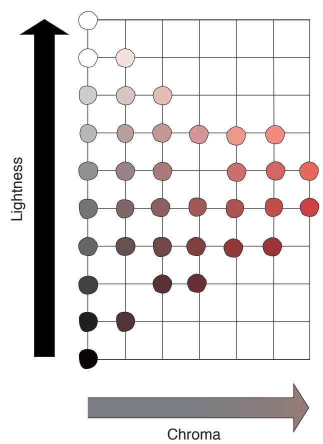
Saturation

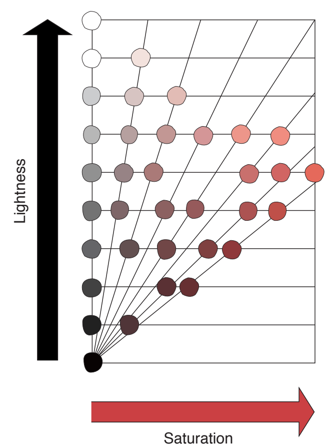
The colorfulness of a stimulus relative to its own brightness.

$$s = 100\sqrt{M/Q}$$

Changes from CIECAM97s:
Simple, Logical Definition
Data Now Available

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)

How Many Terms?

Any color perception can be described completely by its:

- Brightness
- Lightness
- Colorfulness
- Chroma
- 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
- Chroma
- Hue

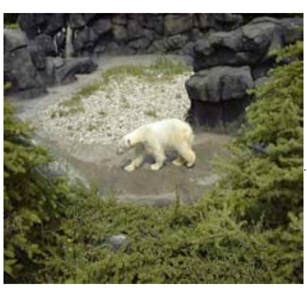
Saturation is often redundant.

Lightness/Chroma vs. Brightness/Colorfulness

When predicting color matches across different viewing conditions, Lightness-Chroma matches are not identical to Brightness-Colorfulness matches. See Nayatani *et al*. (1990).

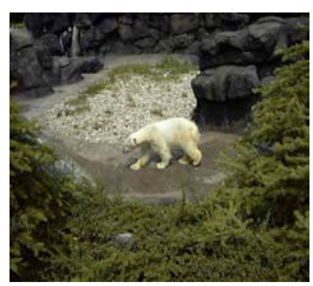
For related colors, and typical conditions, Lightness-Chroma matching (and therefore reproduction) is the only practical choice.

Reproduction at Higher Luminance



Original (50 cd/m^2)

Lightness/Chroma



Brightness/Colorfulness

Reproductions (5000 cd/m^2)

Reproduction at Lower Luminance

Original (5000 cd/m²)

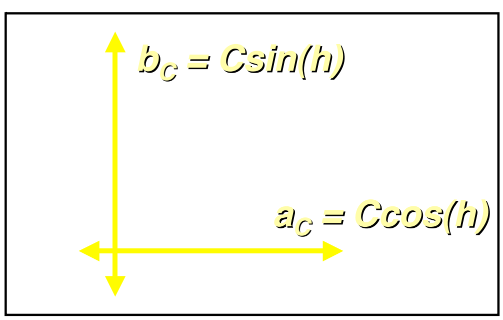
Lightness/Chroma

Brightness/Colorfulness

Reproductions (50 cd/m²)

Color Space (Rectangular)

- CIECAM02 is Expressed in Cylindrical Coordinates, JCh
- Coordinate Transformation Required for Rectangular Plots

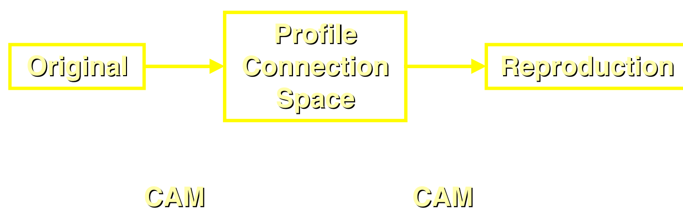


- Alternative Combinations (QMh, Qsh, Jsh)

Changes from CIECAM97s:
Now Explicitly Defined

Inverse Model

- Necessary to Reproduce Colors
- Application / ICC Flow Chart



Inversion

- CIECAM97s is Not Quite Analytically Invertible
  15 Steps with 1 Approximation
- CIECAM02 is Invertible
  Linear CAT Fixes It!

Eqs. in CIE Report; See <www.colour.org/tc8-01/>.

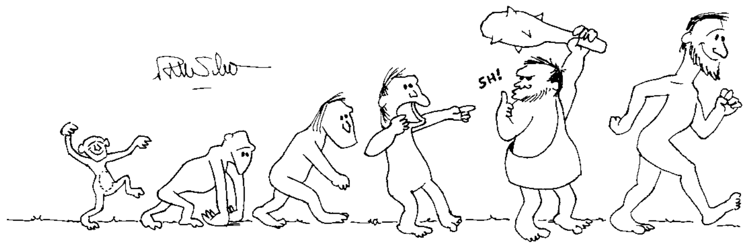
Image Appearance Modeling

What is an Image Appearance Model?

- Image appearance models extend color appearance models to include spatial vision, temporal vision, and image difference/quality properties.
-
- They account for more complex changes in visual response in a more automated manner.

What are Some of the Missing Links?

- Spatial Vision (Filtering & Adaptation)
- Scene Interpretation
- Computational Surround Effects
- Color/Image Difference Metrics
- Image Processing Efficiencies



Other Spatial Models

- S-CIELAB (Zhang & Wandell)
- CVDM (Feng et al.)
- Sarnoff Model (Lubin et al.)
- Spatial ATD (Granger)
- MOM (Pattanaik et al.)
- Modular Image Difference (Johnson et al.)

Meet iCAM

iCAM — image Color Appearance Model

A simple framework for color appearance, spatial vision effects, image difference (quality), image processing, and temporal effects (eventually).

Image Appearance & Quality

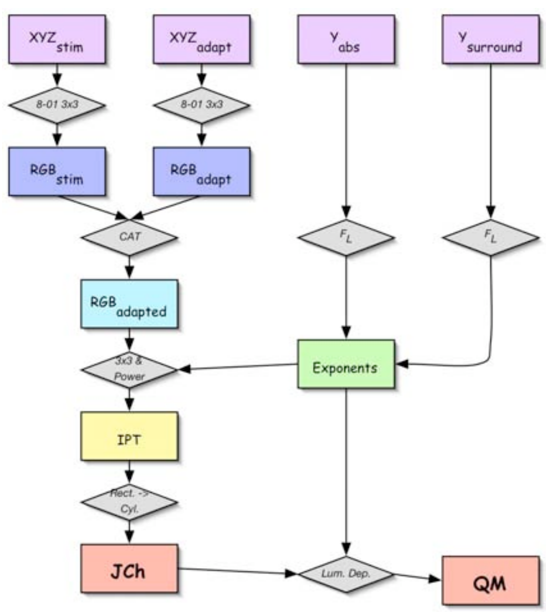
- IQ (Thresholds & Magnitudes)
- Combine with Color Appearance

- Get “Image Appearance”

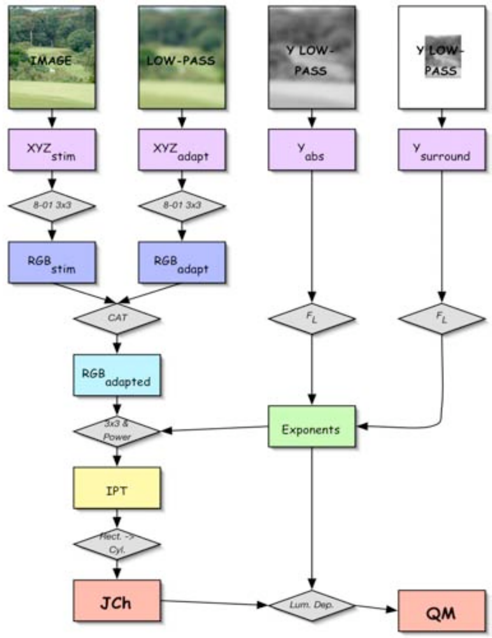
Moving Image Appearance & Quality

- Temporal Adaptation & Filtering

Pointwise iCAM



Spatial iCAM



iCAM Performance Examples

- Color Appearance Scales
- Constant Hue Lines
- Simultaneous Contrast
- Chroma Crispening
- Hue Spreading

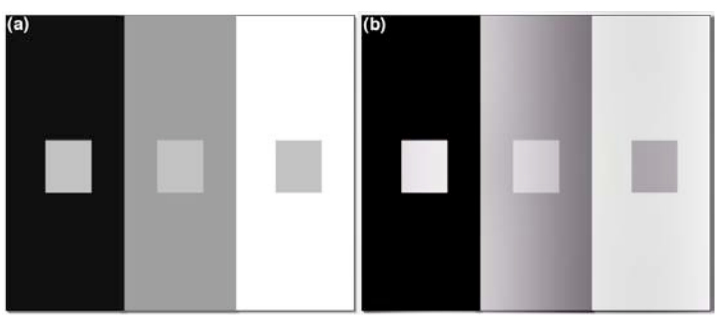
Basic Appearance Attributes

Chromatic Adaptation Transform (CAT)
Identical to CIECAM02

Color Appearance Scales
Similar to Munsell / CIECAM02 (limited)

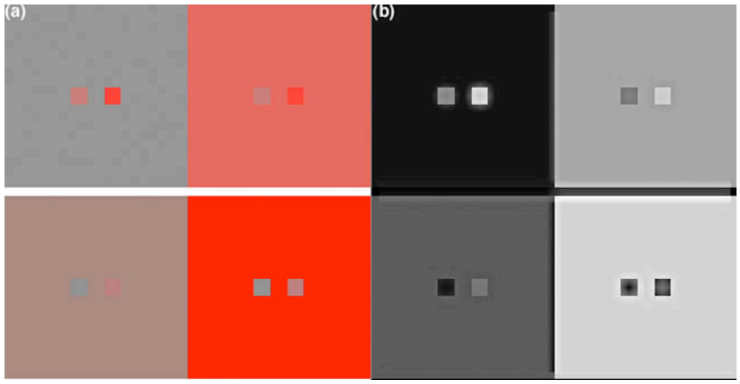
Constant Hue Lines
Best Available (IPT)
Facilitates Gamut Mapping

iCAM Simultaneous Contrast



Original Image iCAM Lightness

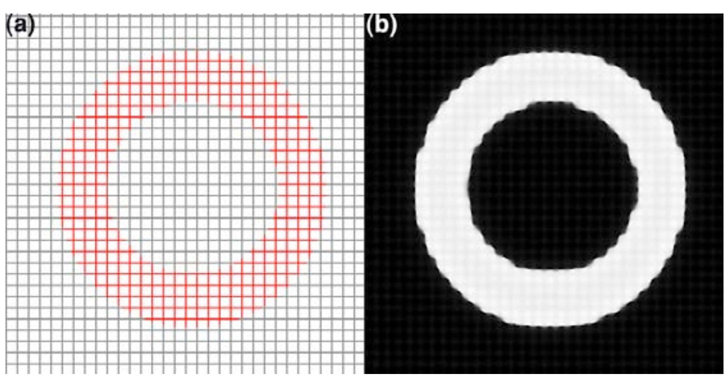
iCAM Chroma Crispening



Original Image iCAM Chroma

http://www.hpl.hp.com/personal/Nathan_Moroney/

iCAM Spreading



Original Image iCAM Hue

iCAM High-Dynamic-Range Tone Mapping

<www.debevec.org>

Earlier-Model Results

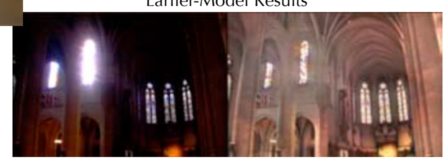
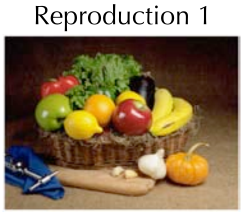
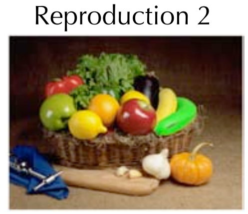


Image Difference Process

Reproduction 1



Reproduction 2



~~Mean ΔE^*_{ab} 2.5~~ ~~Mean ΔE^*_{ab} 1.25~~

Mean ΔIm 0.5 Mean ΔIm 1.5

Spatial Filtering, Local Attention, Local & Global Contrast, CIE Color Difference

iCAM Image Difference (Image Quality)

ΔIm

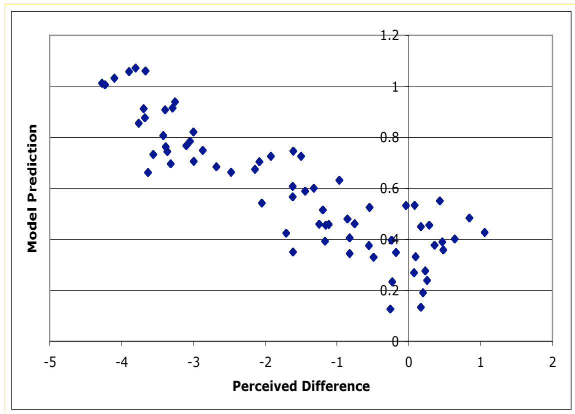


Image Difference Prediction (Sharpness Data)

iCAM Image Difference (Image Quality)

ΔIm

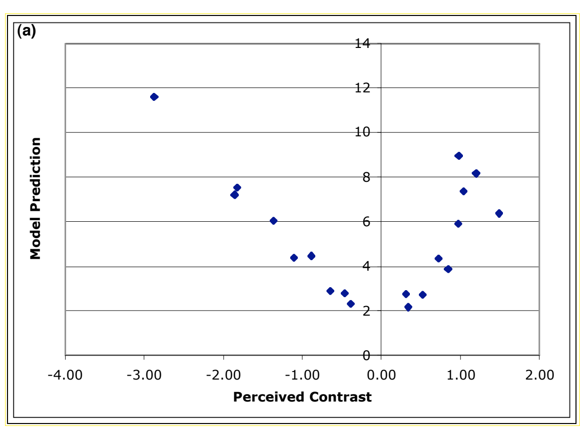


Image Difference Prediction (Contrast Data)

Spatial iCAM

Detailed references to each step and coded examples on the internet.

Open-Source Science

<www.cis.rit.edu/mcsl/iCAM>

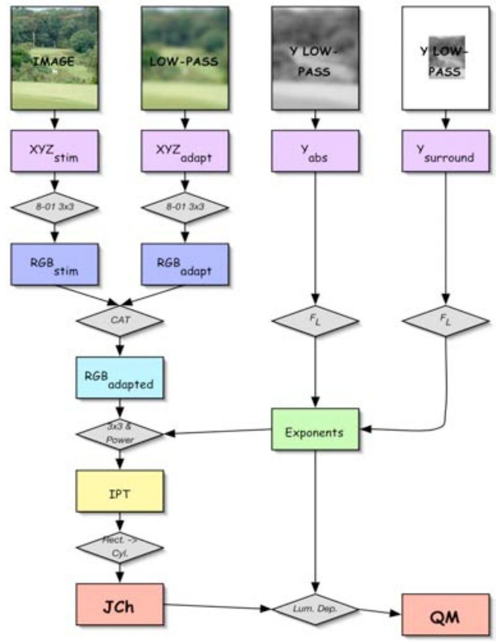
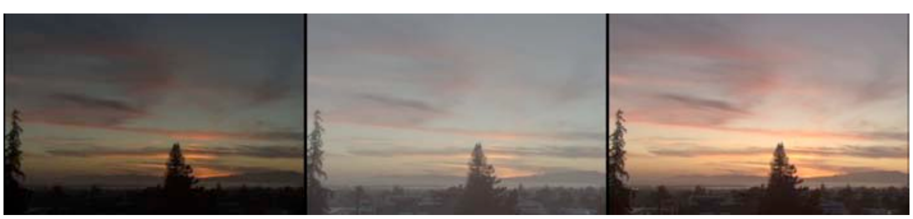


Image Rendering Examples

<www.debevec.org>



Conclusions

- **Ingredients**
  - Color Appearance Model
  - Spatial Adaptation & Filtering Models
  - Temporal Adaptation & Filtering Models
  - Image Difference Metrics
- **Results**
  - Still & Video Rendering Algorithms
  - Still & Video Quality Metrics

Free Code

<www.cis.rit.edu/mcsl/iCAM/>

Mathematica, Matlab, IDL, C++, etc.

Updates.

Summary

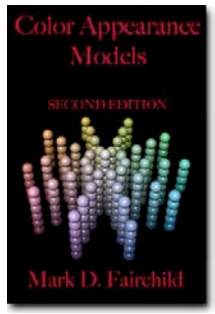
- Color Appearance Phenomena
- Chromatic Adaptation
- Structure of Color Appearance Models
- CIECAM02
- Image Appearance: iCAM

Reading List & Errata Sheet

M.D. Fairchild, Color Appearance Models, Addison-Wesley, Reading, Mass. (1998)

Watch for the 2nd Ed. in late 2004.

Reading List from SIMC 703, Color Appearance, attached.



<www.cis.rit.edu/fairchild/CAM.html>

ROCHESTER INSTITUTE OF TECHNOLOGY
Munsell Color Science Laboratory

SIMC 703 Color Appearance

READING LIST:

Course Text

M.D. Fairchild, *Color Appearance Models*, Addison-Wesley, Reading, MA (1998).

Basic and Advanced Colorimetry

W.D. Wright, 50 years of the 1931 CIE standard observer for colorimetry, *AIC Color 81*, Paper A3 (1981).

G. Wyszecki, Current developments in colorimetry, *AIC Colour 73*, 21-51 (1973).

Color Appearance Terminology

A. Hard and L. Sivik, NCS—Natural Color System: A Swedish standard for color notation, *Color Res. Appl.* **6**, 129-138 (1981).

S.M. Newhall, Preliminary report of the O.S.A. subcommittee on the spacing of the Munsell colors, *J. Opt. Soc. Am.* **30**, 617-645 (1940).

C.J. Bartleson, Brown, *Color Res. Appl.* **1**, 181-191 (1976).

Color Appearance Phenomena

D.M. Purdy, Spectral hue as a function of intensity, *Am. J. Psych*, **43**, 541-559 (1931).

M.D. Fairchild and E. Pirrotta, Predicting the lightness of chromatic object colors using CIELAB, *Color Res. Appl.* **16**, 385-393 (1991).

R.W.G. Hunt, Light and dark adaptation and the perception of color, *J. Opt. Soc. Am.* **42**, 190-199 (1952).

H. Helson, Fundamental problems in color vision. I. The principle governing changes in hue, saturation, and lightness of non-selective samples in chromatic illumination, *J. Exp. Psych.* **23**, 439-477(1938).

J.C. Stevens and S.S. Stevens, Brightness functions: Effects of adaptation, *J. Opt. Soc. Am.* **53**, 375-385 (1963).

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