Color Appearance Models

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Today's topic

- Color Appearance Models
  CIELAB
- The Nayatani et al. Model
- The Hunt Model
- The RLAB Model

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Terminology recap

- Color
- Hue
- Brightness/Lightness
- Colorfulness/Chroma
- Saturation

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Color

- Attribute of visual perception consisting of any combination of chromatic and achromatic content.
- Chromatic name
- Achromatic name
- others

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Hue

- Attribute of a visual sensation according to which an area appears to be similar to one of the perceived colors
- Often refers red, green, blue, and yellow

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Brightness

- Attribute of a visual sensation according to which an area appears to emit more or less light.
- Absolute level of the perception

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Lightness

- The brightness of an area judged as a ratio to the brightness of a similarly illuminated area that appears to be white
- Relative amount of light reflected, or relative brightness normalized for changes in the illumination and view conditions

Colorfulness

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

Chroma

- Colorfulness of an area judged as a ratio of the brightness of a similarly illuminated area that appears white
- Relationship between colorfulness and chroma is similar to relationship between brightness and lightness

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Saturation

- Colorfulness of an area judged as a ratio to its brightness
- Chroma – ratio to white
- Saturation – ratio to its brightness

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Definition of Color Appearance Model

- so much description of color
- such as: wavelength, cone response, tristimulus values, chromaticity coordinates, color spaces, …
- it is difficult to distinguish them correctly
- We need a model which makes them straightforward

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Definition of Color Appearance Model

- CIE Technical Committee 1-34 (TC1-34) *(Comission Internationale de l'Eclairage)*
- They agreed on the following definition: A color appearance model is any model that includes predictors of at least the relative color-appearance attributes of lightness, chroma, and hue.
- CIELAB meets this criteria

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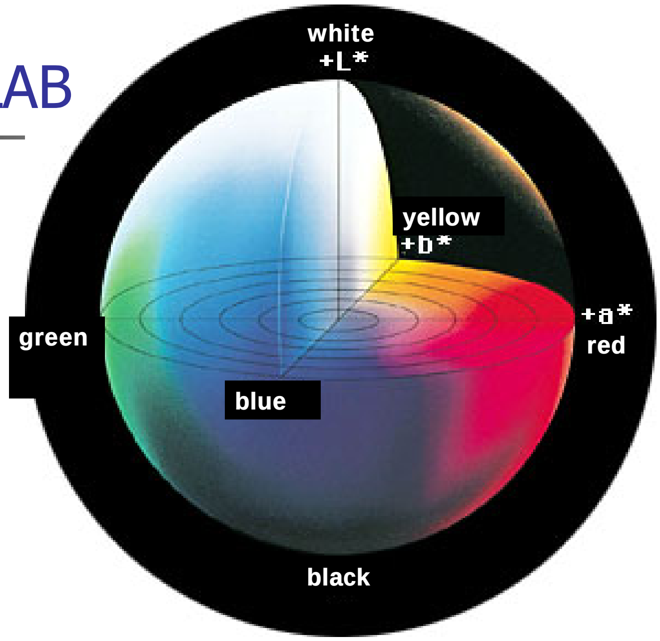
CIELAB



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Construction of Color Appearance Models

- All color appearance models start with CIE XYZ tristimulus values
- The first process is the linear transformation from CIE XYZ tristimulus values to cone responses
- so that we can more accurately model the physiological processes in the human visual system

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Calculating CIELAB Coordinate

- To calculate CIELAB coordinates, one must begin with two sets of CIE XYZ tristimulus values
- Stimulus XYZ
- reference white $X_nY_nZ_n$

  used to define the color "white"

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Calculating CIELAB Coordinate

- Then, add appropriate constants

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

  $a^* = 500[f(X/X_n) - f(Y/Y_n)]$

  $b^* = 200[f(Y/Y_n) - f(Z/Z_n)]$

- $f(w) = w^{1/3}$ (if $w > 0.008856$)

  $= 7.787(w)+16/116$ (otherwise)

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Calculating CIELAB Coordinate

- $L^* = 116f(Y/Y_n) - 16$
- L^* is perceived lightness approximately ranging from 0.0 for black to 100.0 for white

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Calculating CIELAB Coordinate

- $a^* = 500[f(X/X_n) - f(Y/Y_n)]$
- $b^* = 200[f(Y/Y_n) - f(Z/Z_n)]$
- a^* represents red-green chroma perception
- b^* represents yellow-blue chroma perception

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Calculating CIELAB Coordinate

- $a^* = 500[f(X/X_n) - f(Y/Y_n)]$
- $b^* = 200[f(Y/Y_n) - f(Z/Z_n)]$

- They can be both negative and positive value
- What does it mean if a value is 0.0?

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CIELAB color space

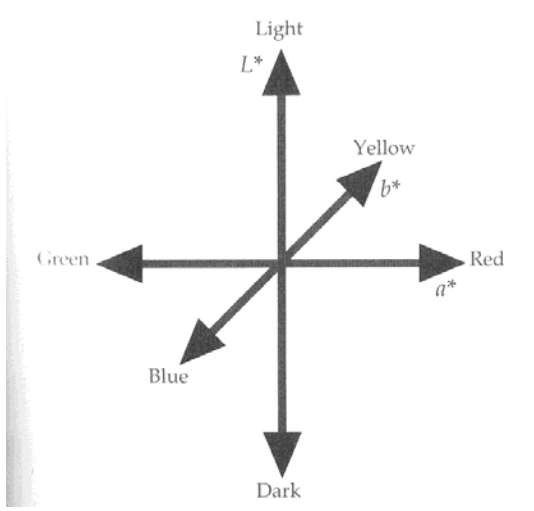

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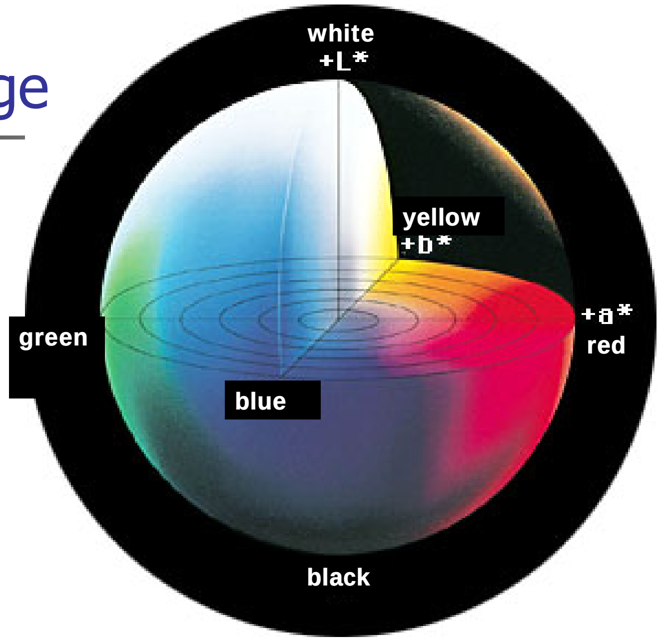
Image



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Calculating CIELAB Coordinate

- Chroma (magnitude)

  $C^*_{ab} = [a^{*2} + b^{*2}]^{1/2}$

- Hue (angle)

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

  expressed in positive degrees starting at the positive a* axis and progressing in a counterclockwise direction

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Example of CIELAB calculations

Table 10-1. Example CIELAB calculations.

Quantity	Case 1	Case 2	Case 3	Case 4
X	19.01	57.06	3.53	19.01
Y	20.00	43.06	6.56	20.00
Z	21.78	31.96	2.14	21.78
X_n	95.05	95.05	109.85	109.85
Y_n	100.00	100.00	100.00	100.00
Z_n	108.88	108.88	35.58	35.58
L^*	51.84	71.60	30.78	51.84
a^*	0.00	44.22	−42.69	−13.77
b^*	−0.01	18.11	2.30	−52.86
C^*_{ab}	0.01	47.79	42.75	54.62
h_{ab}	270.0	22.3	176.9	255.4

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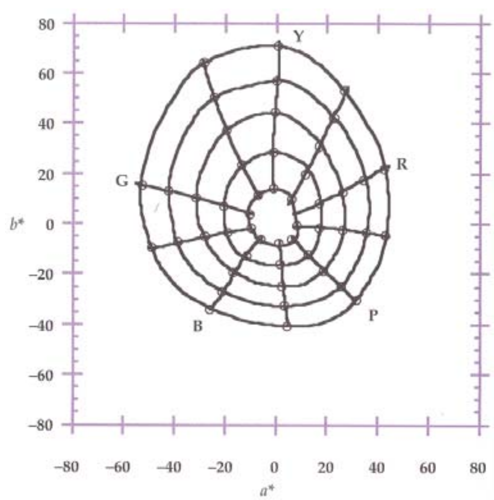
Evaluation of CIELAB space

Plots of hue and chroma from the Munsell Book of Color

Straight lines represent hue

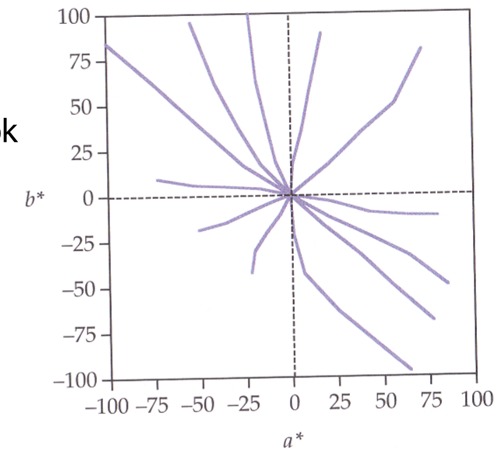
Concentric circles represent chroma



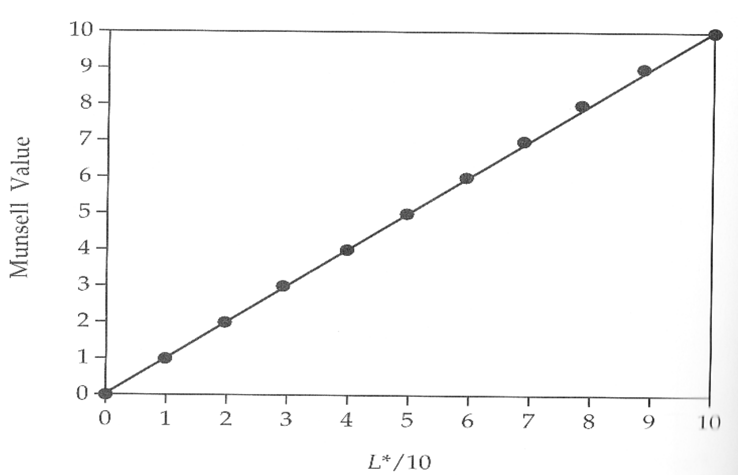
Evaluation of CIELAB space

Further examinations using a system called CRT which is capable of achieving wider chroma than the Munsell Book of Color

Illustrated differences between observed and predicted results



Evaluation of CIELAB space



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Evaluation of CIELAB space

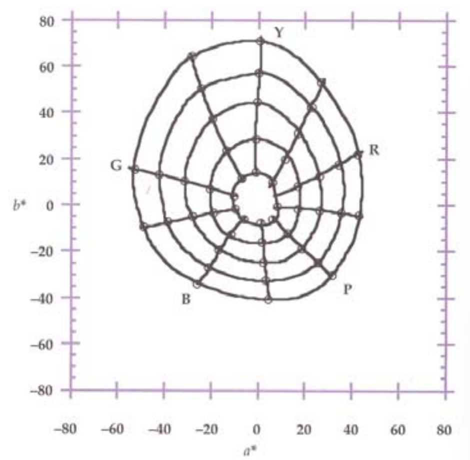
Unique hues

Red 24° (not 0°)

Yellow 90°

Green 162° (not 180°)

Blue 246° (not 270°)



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Summary of CIELAB (pros)

- well-established, de facto international-standard color space
- capable of color appearance prediction

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Summary of CIELAB (cons)

- limited ability to predict hue
- no luminance-level dependency
- no background or surround dependency
- and so on...

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Therefore...

- CIELAB is used as a benchmark to measure more sophisticated models

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The Hunt Model

- designed to predict a wide range of visual phenomena
- requires an extensive list of input data
- complete model
- complicated

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Input data

- chromaticity coordinates of the illuminant and the adapting field
- chromaticities and luminance factors of the background, proximal field, reference white, and test sample
- photopic luminance L_A and its color temparature T
- chromatic surrounding induction factors N_c
- brightness surrounding induction factors N_b
- luminance of reference white Y_w
- luminance of background Y_b
- If some of these are not available, alternative values can be used

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Adaptation Model

- In Hunt model, the cone responses are denoted ργβ rather than LMS

$$\begin{vmatrix}\rho\\ \gamma\\ \beta\end{vmatrix} = \begin{vmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.0 & 0.0 & 1.0 \end{vmatrix}\begin{vmatrix}X\\ Y\\ Z\end{vmatrix}$$

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Adaptation Model

$$\rho_a = B_\rho\left[f_n\left(F_L F_\rho \rho/\rho_W\right) + \rho_D\right] + 1$$

$$\gamma_a = B_\gamma\left[f_n\left(F_L F_\gamma \gamma/\gamma_W\right) + \gamma_D\right] + 1$$

$$\beta_a = B_\beta\left[f_n\left(F_L F_\beta \beta/\beta_W\right) + \beta_D\right] + 1$$

- There are many parameters need to be defined...

$$f_n[I] = 40\left[I^{0.75}/(I^{0.75} + 2)\right]$$

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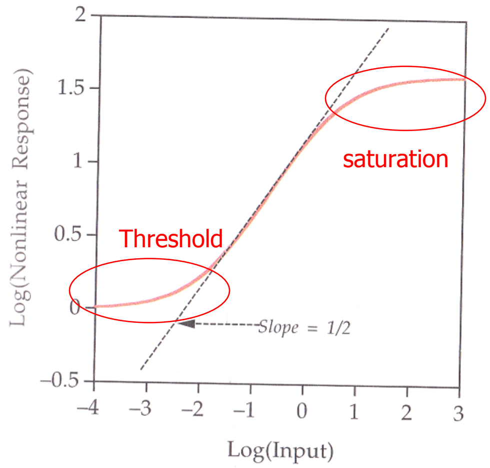
The nonlinear response function f_n



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Adaptation Model

$$\rho_a = B_\rho\left[f_n\left(F_L F_\rho \rho / \rho_W\right) + \rho_D\right] + 1$$

$$\gamma_a = B_\gamma\left[f_n\left(F_L F_\gamma \gamma / \gamma_W\right) + \gamma_D\right] + 1$$

$$\beta_a = B_\beta\left[f_n\left(F_L F_\beta \beta / \beta_W\right) + \beta_D\right] + 1$$

→

$$\rho_a = f_n\left(F_L F_\rho \rho / \rho_W\right)$$

$$\gamma_a = f_n\left(F_L F_\gamma \gamma / \gamma_W\right)$$

$$\beta_a = f_n\left(F_L F_\beta \beta / \beta_W\right)$$

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Opponent-color Dimensions

- Given the adapted cone signals, ρ_a, γ_a, and β_a, one can calculate opponent-type visual responses very simply

$$A_a = 2\rho_a + \gamma_a + (1/20)\beta_a - 3.05 + 1$$

$$C_1 = \rho_a - \gamma_a$$

$$C_2 = \gamma_a - \beta_a$$

$$C_3 = \beta_a - \rho_a$$

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Opponent-color Dimensions

$$A_a = 2\rho_a + \gamma_a + (1/20)\beta_a - 3.05 + 1$$

$$C_1 = \rho_a - \gamma_a$$

$$C_2 = \gamma_a - \beta_a$$

$$C_3 = \beta_a - \rho_a$$

- The achromatic post-adaptation signal A_a is calculated by summing the cone responses with weights that represent their relative population in the retina

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Opponent-color Dimensions

$$A_a = 2\rho_a + \gamma_a + (1/20)\beta_a - 3.05 + 1$$

$$C_1 = \rho_a - \gamma_a$$

$$C_2 = \gamma_a - \beta_a$$

$$C_3 = \beta_a - \rho_a$$

- The three color difference signals, C1, C2, and C3, represent all of the possible chromatic opponent signals that could be produced in the retina

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Others

- Hue, saturation, brightness, lightness, chroma, and colorfulness also can be calculated by solving quite complicated equations…

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Summary of the Hunt model (pros)

- seem to be able to do everything that anyone could ever want from a color appearance model
- extremely flexible
- capable of making accurate predictions for a wide range of visual experiments

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Summary of the Hunt model (cons)

- optimized parameter is required; otherwise, this model may perform extremely poorly, even worse than much simpler model
- computationally expensive
- difficult to implement
- Requires significant user knowledge to use consistently

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Color Appearance Models II

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Agenda

- Nayatani et al Model. (1986)
- RLAB Model. (1990)

Nayatani et al Model

- Illumination engineering
- Color rendering properties of light sources.
- Explanation of naturally occurring natural phenomenon.

Color Appearance Phenomenon

- Stevens Effect
  - Contrast Increase with luminance
- Hunt Effect
  - Colorfulness increases with luminance
- Helson Judd Effect
  - Change in hue depending on background

Nayatani Model - Input Data

- Background
  - Luminance Factor, Y_o
  - Chromaticity Co-ordinates, x_o and y_o.
- Stimulus
  - Luminance Factor, Y
  - Chromaticity Co-ordinates, x and y.
- Absolute luminance E_o
- Normalizing Illuminance, E_{or}

Nayatani Model - Starting Points

- Use chromaticity coordinates.

Nayatani Model - Starting Points

- Use chromaticity coordinates.
- Convert them to 3 intermediate values.

Nayatani Model - Starting Points

- Use chromaticity coordinates.
- Convert them to 3 intermediate values.

$$\xi = (0.48105x_o + 0.78841y_o - 0.08081)/y_o$$

$$\eta = (-0.27200x_o + 1.11962y_o + 0.04570)/y_o$$

$$\zeta = 0.91822(1 - x_o - y_o)/y_o$$

Adaptation Model

- Calculate the cone responses for the adapting field

$$\begin{vmatrix} R_o \\ G_o \\ B_o \end{vmatrix} = \frac{Y_o E_o}{100\pi} \begin{vmatrix} \xi \\ \eta \\ \zeta \end{vmatrix}$$

R -> L
G -> M
B -> S

Chromatic Adaptation Model

- Adapted Cone Signals
  - L_a, M_a, S_a
- Cone excitations
  - L, M, S
- Noise terms
  - L_n, M_n, S_n

$$L_a = a_L \left(\frac{L + L_n}{L_0 + L_n} \right)^{\beta_L}$$

$$M_a = a_M \left(\frac{M + M_n}{M_0 + M_n} \right)^{\beta_M}$$

$$S_a = a_S \left(\frac{S + S_n}{S_0 + S_n} \right)^{\beta_S}$$

Adaptation Model

- Compute the exponents nonlinearities used in the chromatic adaptation model

$$\beta_1(R_o) = \frac{6.469 + 6.362 R_o^{0.4495}}{6.469 + R_o^{0.4495}}$$

$$\beta_1(G_o) = \frac{6.469 + 6.362 G_o^{0.4495}}{6.469 + G_o^{0.4495}}$$

$$\beta_2(B_o) = \frac{8.414 + 8.091 B_o^{0.5128}}{8.414 + B_o^{0.5128}} \times 0.7844$$

Adaptation Model

- For the test stimulus,

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.40024 & 0.70760 & -0.08081 \\ -0.22630 & 1.16532 & 0.04570 \\ 0.0 & 0.0 & 0.91822 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Opponent Color Dimensions

- Use opponent theory to represent the cone response in achromatic and chromatic channels.
- Single achromatic channel.
- Double chromatic channels.

Achromatic Response

$$Q = \frac{41.69}{\beta_1(L_{or})}\left[\frac{2}{3}\beta_1(R_o)e(R)\log\frac{R+n}{20\xi+n} + \frac{1}{3}\beta_1(G_o)e(G)\log\frac{G+n}{20\eta+n}\right]$$

- Considers only the middle and long wavelength cone response.
- Logarithm -> model the nonlinearity of the human eye.

Chromatic Channels

- Tritanopic and Protanopic responses.
- Tritanopic
  - Red Green Response
- Protanopic
  - Blue Yellow Response

Chromatic Channels

$$t = \beta_1(R_o)\log\frac{R+n}{20\xi+n} - \frac{12}{11}\beta_1(G_o)\log\frac{G+n}{20\eta+n} + \frac{1}{11}\beta_2(B_o)\log\frac{B+n}{20\zeta+n}$$

$$p = \frac{1}{9}\beta_1(R_o)\log\frac{R+n}{20\xi+n} + \frac{1}{9}\beta_1(G_o)\log\frac{G+n}{20\eta+n} - \frac{2}{9}\beta_2(B_o)\log\frac{B+n}{20\zeta+n}$$

Hue

- Hue Angle
- Hue Quadrature
- Hue Composition

$$\theta = \tan^{-1}\left(\frac{p}{t}\right)$$

Brightness

$$B_r = Q + \frac{50}{\beta_1(L_{or})}\left[\frac{2}{3}\beta_1(R_o) + \frac{1}{3}\beta_1(G_o)\right]$$

$$\beta_1(L_{or}) = \frac{6.469 + 6.362L_{or}^{0.4495}}{6.469 + L_{or}^{0.4495}}$$

Lightness

- Calculated from the achromatic response alone.
- $L_p = Q + 50$.
  - Black => $L_p = 0$;
  - White => $L_p = 100$;

Pros and Cons

- Pros
  - 'Complete' model.
  - Relatively simple.
- Cons
  - Changes in background and surround
  - Not helpful for cross media applications.

The RLAB Model

- A color appearance model which would be suitable for most practical applications.
- simple and easy to use.
- takes the positive aspects of CIELAB and tries to overcome its drawbacks.
- application – cross media image reproduction.

Input Data

- Tristimulus values of the test stimulus.
- Tristimulus values of the white point.
- Absolute luminance of a white object.
- Relative luminance of the surround.

Adaptation Model

- Cone Response

$$\begin{vmatrix} L \\ M \\ S \end{vmatrix} = \mathbf{M} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}$$

$$\mathbf{M} = \begin{vmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{vmatrix}$$

Adaptation Model

- Chromatic Adaptation

$$\mathbf{A} = \begin{vmatrix} a_L & 0.0 & 0.0 \\ 0.0 & a_M & 0.0 \\ 0.0 & 0.0 & a_S \end{vmatrix}$$

Adaptation Model

- Mapping the X,Y,Z to a reference viewing condition.
-
- R = $M^{-1} A^{-1}$, a constant.

$$\begin{vmatrix} X_{ref} \\ Y_{ref} \\ Z_{ref} \end{vmatrix} = \mathrm{RAM} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}$$

$$R = \begin{vmatrix} 1.9569 & -1.1882 & 0.2313 \\ 0.3612 & 0.6388 & 0.0 \\ 0.0 & 0.0 & 1.0000 \end{vmatrix}$$

Opponent Color Dimensions

- A 'better' and 'simplified' CIELAB.

$$L^R = 100\left(Y_{ref}\right)^{\sigma}$$

$$a^R = 430\left[\left(X_{ref}\right)^{\sigma} - \left(Y_{ref}\right)^{\sigma}\right]$$

$$b^R = 170\left[\left(Y_{ref}\right)^{\sigma} - \left(Z_{ref}\right)^{\sigma}\right]$$

Exponents

- σ = 1/2.3, for an average surround.
- σ = 1/2.9, for a dim surround.
- σ = 1/3.5, for a dark surround.

Lightness

- The RLAB Correlate of lightness is just L^R!

Hue

- Hue Angle, $h^R = \tan^{-1}(b^R/a^R)$
- Hue Composition, H^R - same as before.

Chroma and Saturation

- $C^R = \{ (b^R)^2 + (a^R)^2 \}^{1/2}$
- $S^R = C^R / L^R$

Pros and Cons

- Pros
  - Simple.
  - Straightforward.
  - Accurate.
- Cons
  - Can't be applied to really large luminance ranges.
  - Does not explain Hunt, Stevens model.

Thanks!