Luminance & Lightness

SS 2008 – Image Processing
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Chapters 20

Figures are mostly taken from that book
Definitions

• Visible light: in the range of 400nm to 700nm

• Luminance $Y := \text{linear-light quantity}; \text{direct proportional to physical intensity weighted by the spectral sensitivity of human vision}$ ➔ Can be computed as weighted sum of linear-light red (R), green (G), and blue (B) tri-stimulus components.

• Lightness $L^* := \text{defined by CIE as a nonlinear transfer function of luminance that approximates the perception of brightness}$

• Luma $Y' := \text{approximates } L^* \text{ by a weighted sum of nonlinear (gamma-corrected) R', G', B' components.}$

• Brightness $:= \text{fuzzy term; can denote luminance, lightness or something related.}$
Radiometry, Photometry

:= measures radiant power of electromagnetic waves (e.g., in the range of 1 mm to 1 nm)

Flux := radiant power; in [W]
Irradiance := flux per unit area, in [W / m²]
Radiant intensity := flux in a certain direction, in [W / sr] (steradian)
Radiance := flux in a certain direction, per unit area [W * m⁻² * sr⁻¹]

:= measures radiant power of electromagnetic waves in the range of 360 nm to 830 nm weighted by the spectral response of human vision

≡ luminous flux
≡ illuminance
≡ luminous intensity
≡ luminance, in [cd * m⁻²]
More Definitions

• CIE = International Commission on Illumination

• *Brightness* := attribute of visual sensation according to which an area appears to exhibit more or less light
  ➔ subjective, cannot be measured.

Thus, CIE defines the sensitivity of a standard observer to power at different wavelengths \( Y(\lambda) \)

➔ Luminance becomes the \( Y(\lambda) \)-weighted average of the spectral power distribution (SPD)
Luminous efficiency function
= color-matching function (CMF)
= $Y(\lambda)$

Figure 20.1 Luminous efficiency functions. The solid line indicates the luminance response of the cone photoreceptors – that is, the CIE photopic response. A monochrome scanner or camera must have this spectral response in order to correctly reproduce lightness. The peak occurs at about 555 nm, the wavelength of the brightest possible monochromatic 1 mW source. (The lightly shaded curve shows the scotopic response of the rod cells – loosely, the response of night vision. The increased relative luminance of blue wavelengths in scotopic vision is called the Purkinje shift.)
Relative Luminance

• In reproduction we rarely, if ever, reproduce the absolute, but the relative luminance!

• Luminance is usually normalized to 1 or 100 units relative to a specified or implied reference white.
Luminance $709Y$

- The 3 primaries (red, green, blue) of contemporary CRT displays are standardized in Rec. ITU-R BT.709

$$709Y = 0.2126R + 0.7152G + 0.0722B$$
Lightness (CIE L*)

- CIE $L^*$ approximates the lightness response of human vision
- $L^*$ has a range of 0 to 100.
- $Y_n$ is the luminance of reference white
- $Y$ is CIE luminance

$$L^* = \begin{cases} 
903.3 \frac{Y}{Y_n} & Y \leq 0.008856 \\
116 \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - 16 & 0.008856 < \frac{Y}{Y_n} \\
\approx 100 \left( \frac{Y}{Y_n} \right)^{0.4} & \end{cases}$$

Figure 20.2 Luminance and lightness. The dependence of lightness ($L^*$) or value ($V$) upon relative luminance ($Y$) has been modeled by polynomials, power functions, and logarithms. In all of these systems, 18% "mid-gray" has lightness about halfway up the perceptual scale. For details, see Fig. 2 (6.3) in Wyszecki and Stiles, Color Science (cited on page 231).
\( \Delta L^* \)

- \( \Delta L^* \) is a measure of perceptual distance
- \( \Delta L^* < 1 \) is generally imperceptible
- \( \Delta L^* = 1 \) lies at the threshold of discrimination

\( \rightarrow \) \( L^* \) is one component of a uniform color space
Reference

Slides are taken from

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Agenda

• What are digital colors?
• What are color spaces?
• Why do we have different color spaces?
What are Colors?

• Colors that humans perceive are determined by the nature of the light reflected from an object! Green objects reflect “green” light!

• **Achromatic**: Only *intensities* (amount of light)
  – Gray levels as seen on black/white TV
  – Ranges from black to white

• **Chromatic**: Light waves; Visual range: 400nm-700nm
Red, Green, Blue

• R,G,B are called **Primary Colors**
• R,G,B where chosen due to the structure of the human eye
• R,G,B are used in cameras
Receptivity of the Eye Cells

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R+G+B=White? Really?!?

- So why don’t we get white, when we use paint? *Subtractive Color!*
- But why does it work for the TV? *Additive Color!*

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Additive/Subtractive Color

- **Additive Color**: Sum of light of different wave lengths. That light reaches our eye directly.
  - Examples: TV, Multimedia Projector

- **Subtractive Color**: White Color is emitted by the sun and is only partly reflected from an object!
  - Red paint filters all light, except red!
  - Yellow paint absorbs blue, but reflects red and green
  - Examples: Paint
RGB Color Space

• The “classical” Computer Color space
• 3 different colors: Red, Green, Blue
• Similar to the human visual system!
• If R,G,B have the same energy, we perceive a shade of white (grey, black).
A single pixel consists of three components: [0,255]. Each pixel is a Vector.

\[
\begin{bmatrix}
128 \\
251 \\
60
\end{bmatrix}
\]

Pixel-Vector in the computer memory

= Final pixel in the image

Caution! Sometimes pixels are not stored as vectors. Instead, first is stored the complete red component, then the complete green, then blue.
Example RGB

Original Image

R-Component

G-Component

B-Component
Convert color to grayscale

\[ I = \frac{R + G + B}{3} \]
Another way of separating color and intensity: HSI

- **H**=Hue  **S**=Saturation  **I**=intensity
- H and S may characterize a color: Chromaticities
- **Hue**: associated with the dominant wavelength in the mixture of light waves, as perceived by an observer.
  - Hue is color attribute that describes a pure color
- **Saturation**: relative purity; amount of white light mixed with hue
  - **Example**: Pure colors are fully saturated. Not saturated are for example pink (red+white)
• Perhaps the most intuitive color representation!
• Used in Computer Graphics (and computer vision)
A single pixel consists of three components. Each pixel is a **Vector**.

Pixel-Vector in the computer memory:

| 128 | 251 | 60 |

Final pixel in the image:

Caution! Sometimes pixels are not stored as vectors. Instead, first is stored the complete hue component, then the complete sat., then the intensity.
Example HSI

Original Image

Hue

Saturation

Intensity
YUV Color Space

• YUV: used in commercial color TV broadcasting and video signals
• We need a format that decouples grayscale and color: HSI
• “Poor-man’s” HSI
  – Much easier to compute from RGB, than HSI
YUV Color Space

A single pixel consists of three components.
Each pixel is a **Vector**

\[
\begin{bmatrix}
128 \\
251 \\
60
\end{bmatrix}
\]

Pixel-Vector in the computer memory

= Final pixel in the image

Same Caution as before applies here!
Example YUV

Original Image

Intensity

U-Component

V-Component
Full Color / Pseudo Color

• **Full Color**: acquired by a TV camera/scanner

• **Pseudo Color**: Assigning a shade of color to a monochrome intensity or range of intensities
Mapping of Gray Values into Pseudo Color Images
FIGURE 6.22 (a) Gray-scale image in which intensity (in the lighter horizontal band shown) corresponds to average monthly rainfall. (b) Colors assigned to intensity values. (c) Color-coded image. (d) Zoom of the South America region. (Courtesy of NASA.)

Chapters 21

Figures are mostly taken from that book
• The CIE system of colormetry maps a spectral power distribution (SPD) into a triple of numeric values

        CIE XYZ tri-stimulus

for a hypothetical standard observer

• Note: No single coordinate system fills all of the needs of user

⇒ we have many different color spaces!
Figure 21.2 Spectral and tristimulus color reproduction. A color can be represented as a spectral power distribution (SPD), perhaps in 31 components representing power in 10 nm bands over the range 400 nm to 700 nm. However, owing to the trichromatic nature of human vision, if appropriate spectral weighting functions are used, three components suffice to represent color. The SPD shown here is the CIE D_65 daylight illuminant.
Determined by means of extensive color matching experiments throughout the 1920s.

Figure 21.4 CIE 1931, 2° color-matching functions. A camera with 3 sensors must have these spectral response curves, or linear combinations of them, in order to capture all colors. However, practical considerations make this difficult. These analysis functions are not comparable to spectral power distributions!
CIE XYZ Tri-Stimulus

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.0143 & 0.0004 & 0.0679 \\ 0.0435 & 0.0012 & 0.2074 \\ 0.1344 & 0.0040 & 0.6456 \\ 0.2839 & 0.0116 & 1.3856 \\ 0.3483 & 0.0230 & 1.7471 \\ 0.3362 & 0.0380 & 1.7721 \\ 0.2908 & 0.0600 & 1.6692 \\ 0.1954 & 0.0910 & 1.2876 \\ 0.0956 & 0.1390 & 0.8130 \\ 0.0320 & 0.2080 & 0.4652 \\ 0.0049 & 0.3230 & 0.2720 \\ 0.0093 & 0.5030 & 0.1582 \\ 0.0633 & 0.7100 & 0.0782 \\ 0.1655 & 0.8620 & 0.0422 \\ 0.2904 & 0.9540 & 0.0203 \\ 0.4334 & 0.9950 & 0.0087 \\ 0.5945 & 0.9950 & 0.0039 \\ 0.7621 & 0.9520 & 0.0021 \\ 0.9163 & 0.8700 & 0.0017 \\ 1.0263 & 0.7570 & 0.0011 \end{bmatrix}^T \begin{bmatrix} 82.75 \\ 91.49 \\ 93.43 \\ 86.68 \\ 104.86 \\ 117.01 \\ 117.81 \\ 114.86 \\ 115.92 \\ 108.81 \\ 109.35 \\ 107.80 \\ 104.79 \\ 107.69 \\ 104.41 \\ 104.05 \\ 100.00 \\ 96.33 \\ 95.79 \\ 88.69 \end{bmatrix}$$

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>X Value</th>
<th>Y Value</th>
<th>Z Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 nm</td>
<td>1.0622</td>
<td>0.6310</td>
<td>0.0008</td>
</tr>
<tr>
<td>450 nm</td>
<td>1.0026</td>
<td>0.5030</td>
<td>0.0003</td>
</tr>
<tr>
<td>500 nm</td>
<td>0.8544</td>
<td>0.3810</td>
<td>0.0002</td>
</tr>
<tr>
<td>550 nm</td>
<td>0.6424</td>
<td>0.2650</td>
<td>0.0000</td>
</tr>
<tr>
<td>600 nm</td>
<td>0.4479</td>
<td>0.1750</td>
<td>0.0000</td>
</tr>
<tr>
<td>650 nm</td>
<td>0.2835</td>
<td>0.1070</td>
<td>0.0000</td>
</tr>
<tr>
<td>700 nm</td>
<td>0.1649</td>
<td>0.0610</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>0.0874</td>
<td>0.0320</td>
<td>0.0000</td>
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<td>0.0227</td>
<td>0.0082</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>0.0114</td>
<td>0.0041</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Figure 21.5 Calculation of tristimulus values by matrix multiplication starts with a column vector representing the SPD. The 31-element column vector in this example is a discrete version of CIE Illuminant $D_65$, at 10 nm intervals. The SPD is matrix-multiplied by a discrete version of the CIE X(λ), Y(λ), and Z(λ) color-matching functions of Figure 21.4, here in a 31×3 matrix. The superscript $^T$ denotes the matrix transpose operation. The result of the matrix multiplication is a set of XYZ tristimulus components.
Grassmann’s Third Law

• The tri-stimulus values computed from the sum of a set of SPDs is identical to the sum of the tri-stimulus values of each SPD

⇒ linear system

⇒ Any set of three components that is a nontrivial linear combination of X, Y, and Z – such as R, G, B – is also a set of tri-stimulus values.
Perceptually Uniform Color Spaces

- **Perceptual uniform**: if a small perturbation to a component value is approximately equally perceptible across the range of that value.

- 1 unit of Euclidean distance corresponds to a just-noticeable difference (JND) of color.

- Even after working for a decade on this, no single system could be agreed upon.

- In 1976, two CIE systems were standardized:
  - L*u*v* and
  - L*a*b*
CIE L*u*v*

\[ u' = \frac{4X}{X + 15Y + 3Z} \; ; \; \; v' = \frac{9Y}{X + 15Y + 3Z} \]

\[ u^* = 13L^*(u' - u'_n) \; ; \; \; v^* = 13L^*(v' - v'_n) \]
If \( X/X_n, Y/Y_n, \) and \( Z/Z_n \) \( \geq 0.008856 \)

\[
a^* = 500 \left[ \left( \frac{X}{X_n} \right)^{\frac{1}{3}} - \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} \right] ; \quad b^* = 200 \left[ \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - \left( \frac{Z}{Z_n} \right)^{\frac{1}{3}} \right]
\]

else use for any quantity \( X/X_n, Y/Y_n, \) or \( Z/Z_n \) that is below 0.008856 and denoted by \( t \) instead of the cube root the following quantity:

\[
7.787t + \frac{16}{116}
\]
Figure 21.11 **Color systems** are classified into four groups that are related by different kinds of transformations. Tristimulus systems, and perceptually uniform systems, are useful for image coding. (I flag HSB, HSI, HSL, HSV, and IHS with a question mark: These systems lack objective definition of color.)