ECE 418: Introduction to Image & Video Processing

Human Visual Perception

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Overview

1. Color vision
   1.1 Color matching
Color vision
Light spectrum

Light is characterized by a spectrum spanning a range of wavelength.

Figure 1: Various wavelengths of electromagnetic (EM) radiation.
There is a close relationship between spectral content of light and color.

Light can be measured, color is a subjective perception.

What is color?

Color is the spectral energy distribution $C(\lambda)$ of visible light, where $\lambda$ is the wavelength.

Figure 2: Visible light approximately spans from 380 nm to 780 nm.
Spectral sensitivity

The spectral sensitivity of HVS is characterized by the *relative luminous efficiency function* $V(\lambda)$ for photopic vision.

![Spectral sensitivity with respect to the wavelength.](image)

Figure 3: Spectral sensitivity with respect to the wavelength.
When designing a color imaging system,

- What artifacts are visible.
- How objectionable these artifacts are.
Light contrast

For each pair of images, the center blocks appear to have the same color, but in reality they do not.
Spectral sensitivity

The spectral luminous efficiency function $V(\lambda)$ for photopic vision and $V'(\lambda)$ for scotopic vision are different.

Figure 4: A comparison of $V(\lambda)$ and $V'(\lambda)$. 
Perceptual attributes

<table>
<thead>
<tr>
<th>Brightness</th>
<th>Brightness is a perceptual effect of intensity.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hue</td>
<td>Hue is the dominant wavelength in a mixture of wavelengths.</td>
</tr>
<tr>
<td>Saturation</td>
<td>Saturation is the spectral purity of a color.</td>
</tr>
</tbody>
</table>

'icon' Hue and saturation are referred to as chromaticity.
Perceptual attributes

- Brightness varies along the vertical axis.
- Hue viewed as an angle, varies along the circumference.
- Saturation varies radially. Any color on the circumference is fully saturated.
Saturation

The brightness increases the colorfulness, but their saturations are the same.
The cones are of three kinds. Each has a different sensitivity to wavelengths and produces a spectral response:

\[ \alpha_i(C) = \int S_i(\lambda)C(\lambda)d\lambda, \quad i = 1, 2, 3 \]  \hspace{1cm} (2)

The sensitivity is determined by the absorption spectra \( S_i(\lambda) \).
Color vision model

Human spectral sensitivity to color

Three cone types ($\rho$, $\gamma$, $\beta$) correspond roughly to R, G, B.

The $S_i(\lambda)$, $i = 1, 2, 3$, correspond roughly to R, G, B.
The perceived color is determined by the three coefficients $\alpha_1, \alpha_2, \alpha_3$. 
Color blindness is caused by the **imbalance** among the three sets of cones.

Figure 5: The distribution of cone cells in the fovea: normal vision (left) and color blindness (right).
Color blindness

- Approximately 8% male and 1% female have color blindness.
- Red-green color blindness is the most common form, followed by blue-yellow color blindness and total color blindness.

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Condition</th>
<th>Color Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td>92%</td>
<td>Normal Vision</td>
<td><img src="image" alt="Normal Vision Chart" /></td>
</tr>
<tr>
<td>2.7%</td>
<td>Deuteranomaly</td>
<td><img src="image" alt="Deuteranomaly Chart" /></td>
</tr>
<tr>
<td>0.66%</td>
<td>Protanomaly</td>
<td><img src="image" alt="Protanomaly Chart" /></td>
</tr>
<tr>
<td>0.59%</td>
<td>Protanopia</td>
<td><img src="image" alt="Protanopia Chart" /></td>
</tr>
<tr>
<td>0.56%</td>
<td>Deuteranopia</td>
<td><img src="image" alt="Deuteranopia Chart" /></td>
</tr>
<tr>
<td>0.016%</td>
<td>Tritanopia</td>
<td><img src="image" alt="Tritanopia Chart" /></td>
</tr>
<tr>
<td>0.01%</td>
<td>Tritanomaly</td>
<td><img src="image" alt="Tritanomaly Chart" /></td>
</tr>
<tr>
<td>&lt;0.0001%</td>
<td>Achromatopsia</td>
<td><img src="image" alt="Achromatopsia Chart" /></td>
</tr>
</tbody>
</table>
Color vision model

Figure 7: A modern color vision model.

- $B_1$ corresponds to the luminance. $B_2$ and $B_3$ correspond to chromatic responses.
- $H_1$ is the modulation transfer function (MTF).
The spatial resolution for the chrominance component is not as good as the spatial resolution for the luminance.
Color matching

Color is a perception by the human brain.

- It is not necessary to reproduce exactly the original color $C(\lambda)$.
- Produce the same cone response $\alpha_1, \alpha_2, \alpha_3$.

If two colors $C(\lambda)$ and $\hat{C}(\lambda)$ have the same set of spectral response, they can not be distinguished by the human eye.
Color matching

CIE color standards use **Red**, **Green**, **Blue** monochromatic color as the primary sources.

\[
P_1(\lambda) = \delta(\lambda - \lambda_1), \quad \lambda_1 = 700.0\text{nm (Red)} \tag{3}
\]

\[
P_2(\lambda) = \delta(\lambda - \lambda_2), \quad \lambda_2 = 546.1\text{nm (Green)} \tag{4}
\]

\[
P_3(\lambda) = \delta(\lambda - \lambda_1), \quad \lambda_3 = 435.8\text{nm (Blue)} \tag{5}
\]

We can produce a color \(\widehat{C}(\lambda)\) by

\[
\widehat{C}(\lambda) = \sum_{k=1}^{3} \beta_k P_k(\lambda) \tag{6}
\]
Color matching

In order for $C(\lambda)$ and $\hat{C}(\lambda)$ to look identical to the eye, we need

$$\alpha_i(C) = \alpha_i(\hat{C})$$  \hspace{1cm} (7)

$$= \int S_i(\lambda)\hat{C}(\lambda) \, d\lambda$$  \hspace{1cm} (8)

$$= \int S_i(\lambda) \sum_{k=1}^{3} \beta_k P_k(\lambda) \, d\lambda$$  \hspace{1cm} (9)

$$= \sum_{k=1}^{3} \beta_k \int S_i(\lambda)P_k(\lambda) \, d\lambda$$  \hspace{1cm} (10)

$$= \sum_{k=1}^{3} \beta_k A_{i,k}$$  \hspace{1cm} (11)
Color matching

We can write in a matrix form

\[
\begin{bmatrix}
\alpha_1(C) \\
\alpha_2(C) \\
\alpha_3(C)
\end{bmatrix} = A \begin{bmatrix}
\beta_1 \\
\beta_2 \\
\beta_3
\end{bmatrix}
\]  

(12)

If the matrix \( A \) is invertible, then the coefficients \( \beta_k \) can be obtained:

\[
\begin{bmatrix}
\beta_1 \\
\beta_2 \\
\beta_3
\end{bmatrix} = A^{-1} \begin{bmatrix}
\alpha_1(C) \\
\alpha_2(C) \\
\alpha_3(C)
\end{bmatrix}
\]  

(13)
What happens if $\beta_k$ is negative?

- $\beta_k P_k(\lambda)$ is an energy spectrum, it cannot be negative.
- We need a new set of primary monochromatic sources.

We should note:

- No single, universal set of 3 primaries can match all colors.
- But any color can be matched using 3 appropriate primaries.
Tristimulus values

We would often prefer to normalize the coefficients $\beta_1, \beta_2, \beta_3$. Let $w_1, w_2, w_3$ be the coefficients that match a reference white light $W(\lambda)$,

\[
\begin{bmatrix}
  w_1 \\
  w_2 \\
  w_3
\end{bmatrix} = A^{-1}
\begin{bmatrix}
  \alpha_1(W) \\
  \alpha_2(W) \\
  \alpha_3(W)
\end{bmatrix}
\] (14)
Tristimulus values

\[ T_k(C) = \frac{\beta_k}{w_k}, \quad k = 1, 2, 3 \]  \hspace{1cm} (15)

\[ t_k = \frac{T_k}{T_1 + T_2 + T_3}, \quad k = 1, 2, 3 \]  \hspace{1cm} (16)

Since \( t_1 + t_2 + t_3 = 1 \), we can use two coordinates to specify a color.
Gamut

- Gamut is a complete subset of colors.
- The colors in the triangle $t_1 \geq 0$, $t_2 \geq 0$, $t_1 + t_2 \leq 1$ are reproducible by the RGB primaries.

Figure 8: The color gamut represented by the $t_1$-$t_2$ coordinate.
Suppose there are some “virtual” primary sources that are unrealizable, since $P_k(\lambda)$ could be negative:

- We can make the corresponding trichromatic coefficients $x, y, z$ all positive.
Macadam ellipses

Any color lying just outside the ellipse is **just noticeably** different from the color at the center of the ellipse.

![MacAdam Ellipses on CIE 1931](image-url)
Acknowledgment: The slides are based on the lecture notes by Prof. Pierre Moulin, UIUC.