ECE 418: Introduction to Image & Video Processing

Human Visual Perception

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Overview

1. Color vision

1.1 Color matching

2. Image fidelity criterion
Color vision
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.

Figure 3: Spectral sensitivity with respect to the wavelength.
What is luminance?

The luminance of light is the integrated spectral energy $C(\lambda)$ weighted by $V(\lambda)$:

$$Y(C) := \int C(\lambda)V(\lambda)d\lambda$$

Informally referred to as light intensity $I(\theta, \phi)$ perviously.

When designing a color imaging system,

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

- Spectral energy distribution $C(\lambda)$ depends on the wavelength $\lambda$ of the light, it can be measured.
- The luminance $Y(C)$ is spectral energy $C(\lambda)$ weighted by the relative luminous efficiency function $V(\lambda)$: $Y(C) = \int C(\lambda)V(\lambda)d\lambda$. Also referred to as the light intensity $I$.
- The Brightness $B$ is a perceptual effect of light intensity $I$.

![Diagram](image)

Figure 4: A simple vision model.
Spectral sensitivity

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

Figure 5: 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>

◎ 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, the saturations are different but their hues are the same.
Chromatic adaption

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

- Human eye adapts its color response to the environment.
- The appearance of a color $C(\lambda)$ depends on the state of the visual system.
Three-color theory

The cones are of three kinds. Each has a different sensitivity to wavelengths and produces a spectral response

$$\alpha_i(C) = \int S_i(\lambda)C(\lambda)d\lambda, \quad i = 1, 2, 3$$

The sensitivity is determined by the absorption spectra $S_i(\lambda)$. 
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 6: 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>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>92%</td>
<td>Normal Vision</td>
</tr>
<tr>
<td>2.7%</td>
<td>Deuteranomaly</td>
</tr>
<tr>
<td>0.66%</td>
<td>Protanomaly</td>
</tr>
<tr>
<td>0.59%</td>
<td>Protanopia</td>
</tr>
<tr>
<td>0.56%</td>
<td>Deuteranopia</td>
</tr>
<tr>
<td>0.016%</td>
<td>Tritanopia</td>
</tr>
<tr>
<td>0.01%</td>
<td>Tritanomaly</td>
</tr>
<tr>
<td>&lt;0.0001%</td>
<td>Achromatopsia</td>
</tr>
</tbody>
</table>

![Color charts](image)
Color vision model

Figure 8: A modern color vision model.

- $B_1$ corresponds to the brightness. $B_2$ 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 \( \tilde{C}(\lambda) \) have the same set of spectral response, they cannot be distinguished by the human eye.
Color matching

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

\[
P_1(\lambda) = \delta(\lambda - \lambda_1), \quad \lambda_1 = 700.0\text{nm (Red)} \\
P_2(\lambda) = \delta(\lambda - \lambda_2), \quad \lambda_2 = 546.1\text{nm (Green)} \\
P_3(\lambda) = \delta(\lambda - \lambda_3), \quad \lambda_3 = 435.8\text{nm (Blue)}
\]

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

\[
\hat{C}(\lambda) = \sum_{k=1}^{3} \beta_k P_k(\lambda)
\]
In order for \( C(\lambda) \) and \( \hat{C}(\lambda) \) to look identical to the eye, we need

\[
\alpha_i(C) = \alpha_i(\hat{C})
\]

\[
= \int S_i(\lambda)\hat{C}(\lambda) \, d\lambda
\]

\[
= \int S_i(\lambda) \sum_{k=1}^{3} \beta_k P_k(\lambda) \, d\lambda
\]

\[
= \sum_{k=1}^{3} \beta_k \int S_i(\lambda)P_k(\lambda) \, d\lambda
\]

\[
= \sum_{k=1}^{3} \beta_k A_{i,k}
\]
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)
Color matching

What happens if $\beta_k$ is negative?

- $\beta_k P_k(\lambda)$ is an energy spectrum, it can not 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

**Tristimulus values**

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

**Tristimulus coefficients**

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

Since \( t_1 + t_2 + t_3 = 1 \), we can use two coordinates to specify a color.
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 9: 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.

Used for designing color quantization systems.
Image fidelity criterion
How do we quantify the difference between the original image $x(n_1, n_2)$ and the acquired image $\hat{x}(n_1, n_2)$?

- Define a *fidelity criterion*. 

Image fidelity criterion
Image fidelity criterion

Application-specific criterion

- TV: Mean opinion score (MOS), a number 1 ~ 5 rating quality based on extensive subject tests.
- Cable TV: percentage of customers who call in and complain about picture quality.
- Quality control: percentage of misclassified objects.

Drawback:

- Analytically untractable.
- Suitability is arguable.
Image fidelity criterion

Mean square error (MSE)

\[
MSE := \frac{1}{N_1 N_2} \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} |\hat{x}(n_1, n_2) - x(n_1, n_2)|^2
\]  

(17)

Peak signal-to-noise ratio (PSNR)

\[
PSNR := 10 \log_{10} \left( \frac{\text{Range}^2}{MSE} \right),
\]

(18)

where \text{Range} is the range of grayscale values (Range = 255 for 8-bit image)
Image fidelity criterion

Advantage:

- Easy to compute.
- Analytically tractable.
- Widely adopted. When $PSNR > 30$ dB, the quality of the image is usually acceptable.

Drawback: Sometimes not a good measure of quality.

- Viewers are sensitive to certain artifacts, but not to others, even though both may have the same $MSE$.

![Figure 11: The image corrupted by noise with the same MSE.](image)
Color image fidelity criterion

The color image is given as a set of three images $x_1(n_1, n_2)$, $x_2(n_1, n_2)$, $x_3(n_1, n_2)$.

- The coordinate system $x_1, x_2, x_3$ could denote any color coordinate systems introduced earlier, such as RGB, XYZ, etc.

Question: Why do we use 3 primary color sources instead of 4 or 5?

MSE for a color image

$$MSE := \sum_{i=1}^{3} \frac{1}{N_1 N_2} \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} |\hat{x}_i(n_1, n_2) - x_i(n_1, n_2)|^2$$  (19)
Acknowledgment: The slides are based on the lecture notes by Prof. Pierre Moulin, UIUC.