Opponent Color Spaces

- Perception of color is usually not best represented in RGB.
- A better model of HVS is the so-call opponent color model.
- Opponent color space has three components:
  - $O_1$ is luminance component
  - $O_2$ is the red-green channel
    \[ O_2 = G - R \]
  - $O_3$ is the blue-yellow channel
    \[ O_3 = B - Y = B - (R + G) \]
- Comments:
  - People don’t perceive redish-greens, or bluish-yellows.
  - As we discussed, $O_1$ has a bandpass CSF.
  - $O_2$ and $O_3$ have low pass CSF’s with lower frequency cut-off.
Opponent Channel Contrast Sensitivity Functions (CSF)

- Typical CSF functions looks like the following.
Consequences of Opponent Channel CSF

- Luminance channel is
  - Bandpass function
  - Wide band width $\Rightarrow$ high spatial resolution.
  - Low frequency cut-off $\Rightarrow$ insensitive to average luminance level.

- Chrominance channels are
  - Lowpass function
  - Lower band width $\Rightarrow$ low spatial resolution.
  - Low pass $\Rightarrow$ sensitive to absolute chromaticity (hue and saturation).
Some Practical Consequences of Opponent Color Spaces

- Analog video has less bandwidth in $I$ and $Q$ channels.
- Chrominance components are typically subsampled 2-to-1 in image compression applications.
- Black text on white paper is easy to read. (couples to $O_1$)
- Yellow text on white paper is difficult to read. (couples to $O_3$)
- Blue text on black background is difficult to read. (couples to $O_3$)
- Color variations that do not change $O_1$ are called “isoluminant”.
- Hue refers to angle of color vector in $(O_2, O_3)$ space.
- Saturation refers to magnitude of color vector in $(O_2, O_3)$ space.
Opponent Color Space of Wandell

- First define the LMS color system which is approximately given by

\[
\begin{bmatrix}
  L \\
  M \\
  S
\end{bmatrix}
= 
\begin{bmatrix}
  0.2430 & 0.8560 & -0.0440 \\
  -0.3910 & 1.1650 & 0.0870 \\
  0.0100 & -0.0080 & 0.5630
\end{bmatrix}
\begin{bmatrix}
  X \\
  Y \\
  Z
\end{bmatrix}
\]

- The opponent color space transform is then\(^1\)

\[
\begin{bmatrix}
  O_1 \\
  O_2 \\
  O_3
\end{bmatrix}
= 
\begin{bmatrix}
  1 & 0 & 0 \\
  -0.59 & 0.80 & -0.12 \\
  -0.34 & -0.11 & 0.93
\end{bmatrix}
\begin{bmatrix}
  L \\
  M \\
  S
\end{bmatrix}
\]

- We may use these two transforms together with the transform from sRGB to XYZ to compute the following transform.

\[
\begin{bmatrix}
  O_1 \\
  O_2 \\
  O_3
\end{bmatrix}
= 
\begin{bmatrix}
  0.2814 & 0.6938 & 0.0638 \\
  -0.0971 & 0.1458 & -0.0250 \\
  -0.0930 & -0.2529 & 0.4665
\end{bmatrix}
\begin{bmatrix}
  sR \\
  sG \\
  sB
\end{bmatrix}
\]

- Comments:
  - \(O_1\) is luminance component
  - \(O_2\) is referred to as the red-green channel (G-R)
  - \(O_3\) is referred to as the blue-yellow channel (B-Y)
  - Also see the work of Mullen ’85\(^2\) and associated color transforms\(^3\)

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Paradox?

• Why is blue text on yellow paper easy to read??

• Shouldn’t this be hard to read since it stimulates the yellow-blue color channel?
Better Understanding Opponent Color Spaces

• The XYZ to opponent color transformation is:

\[
\begin{bmatrix}
O_1 \\
O_2 \\
O_3
\end{bmatrix}
= \begin{bmatrix}
0.2430 & 0.8560 & -0.0440 \\
-0.4574 & 0.4279 & 0.0280 \\
-0.0303 & -0.4266 & 0.5290
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

\[
= \begin{bmatrix}
v_y \\
v_{gr} \\
v_{by}
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

• What are \( v_y, v_{gr}, \) and \( v_{by} \)?

  – They are row vectors in the XYZ color space.
  – \( v_{gr} \) is a vector point from red to green
  – \( v_{by} \) is a vector point from yellow to blue
  – They are not orthogonal!
Plots of $v_y$, $v_{gr}$, and $v_{by}$

Opponent Color Directions of Color Matching Functions
Answer to Paradox

• Since $v_y$, $v_{gr}$, and $v_{by}$ are not orthogonal

$$
\begin{bmatrix}
  v_y \\
v_{gr} \\
v_{by}
\end{bmatrix}
\begin{bmatrix}
  v_y^t \\
v_{gr}^t \\
v_{by}^t
\end{bmatrix} \neq \text{identity matrix}
$$

• Blue text on yellow background produces and stimulus in the $v_{by}$ space.

$$
\begin{bmatrix}
  O_1 \\
  O_2 \\
  O_3
\end{bmatrix} =
\begin{bmatrix}
  v_y \\
v_{gr} \\
v_{by}
\end{bmatrix} v_{by}^t =
\begin{bmatrix}
  -0.3958 \\
  -0.1539 \\
  0.4627
\end{bmatrix}
$$

• This stimulus is not isoluminant!

• Blue is much darker than yellow.
Basis Vectors for Opponent Color Spaces

• The transformation from opponent color space to XYZ is:

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
0.9341 & -1.7013 & 0.1677 \\
0.9450 & 0.4986 & 0.0522 \\
0.8157 & 0.3047 & 1.9422
\end{bmatrix}
\begin{bmatrix}
O_1 \\
O_2 \\
O_3
\end{bmatrix}
\]

\[
= \begin{bmatrix} c_y & c_{gr} & c_{by} \end{bmatrix}
\begin{bmatrix}
O_1 \\
O_2 \\
O_3
\end{bmatrix}
\]

• What are \(c_y\), \(c_{gr}\), and \(c_{by}\)?

  – They are column vectors in XYZ space.
  – \(c_{gr}\) is a vector which has no luminance component.
  – \(c_{by}\) is a vector which has no luminance component.
  – They are orthogonal to the vectors \(v_y\), \(v_{gr}\), and \(v_{by}\).
Plots of $c_y$, $c_{gr}$, and $c_{by}$

Opponent Color Directions of Color Matching Functions
Interpretation of Basis Vectors

- Since $c_y$, $c_{gr}$, and $c_{by}$ are orthogonal to $v_y$, $v_{gr}$, and $v_{by}$, we have

$$
\begin{bmatrix}
  v_y \\
  v_{gr} \\
  v_{by}
\end{bmatrix}
\begin{bmatrix}
  c_y \\
  c_{gr} \\
  c_{by}
\end{bmatrix}
= 
\begin{bmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & 1
\end{bmatrix}
$$

- Therefore, we have that

$$
\begin{bmatrix}
  O_1 \\
  O_2 \\
  O_3
\end{bmatrix}
= 
\begin{bmatrix}
  v_y \\
  v_{gr} \\
  v_{by}
\end{bmatrix}
\begin{bmatrix}
  c_{by}
\end{bmatrix}
= 
\begin{bmatrix}
  0.2430 & 0.8560 & -0.0440 \\
  -0.4574 & 0.4279 & 0.0280 \\
  -0.0303 & -0.4266 & 0.5290
\end{bmatrix}
\begin{bmatrix}
  0.1677 \\
  0.0522 \\
  1.9422
\end{bmatrix}
= 
\begin{bmatrix}
  0 \\
  0 \\
  1
\end{bmatrix}
$$

- So, $c_{by}$ is an isoluminant color variation.

- Something like a bright saturated blue on a dark red.
Solution to Paradox

• Why is blue text on yellow paper is easy to read??

• Solution:
  – The blue-yellow combination generates the input $v_{by}$.
  – This input vector stimulates all three opponent channels because it is not orthogonal to $c_y$, $c_{gr}$, and $c_{by}$.
  – In particular, it strongly stimulates $c_y$ because it is not iso-luminant.