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

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

- 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 and associated color transforms.

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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.

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

- 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:

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

- What are \( cy \), \( cgr \), and \( cby \)?
  - They are column vectors in XYZ space.
  - \( cgr \) is a vector which has no luminance component.
  - \( cby \) is a vector which has no luminance component.
  - They are orthogonal to the vectors \( vy \), \( vgr \), and \( vby \).
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

\[
\begin{bmatrix}
O_1 \\
O_2 \\
O_3
\end{bmatrix}
= 
\begin{bmatrix}
v_y \\
v_{gr} \\
v_{by}
\end{bmatrix}
\begin{bmatrix}
cby
\end{bmatrix}
\]

\[
= 
\begin{bmatrix}
0.2430 & 0.8560 & -0.0440 \\
-0.4574 & 0.4279 & 0.0280 \\
-0.0303 & -0.4266 & 0.5290
\end{bmatrix}
\begin{bmatrix}
0.1677 \\
0.0522 \\
1.9422
\end{bmatrix}
\]

- 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.