

## 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

$$O_2 = G - R$$

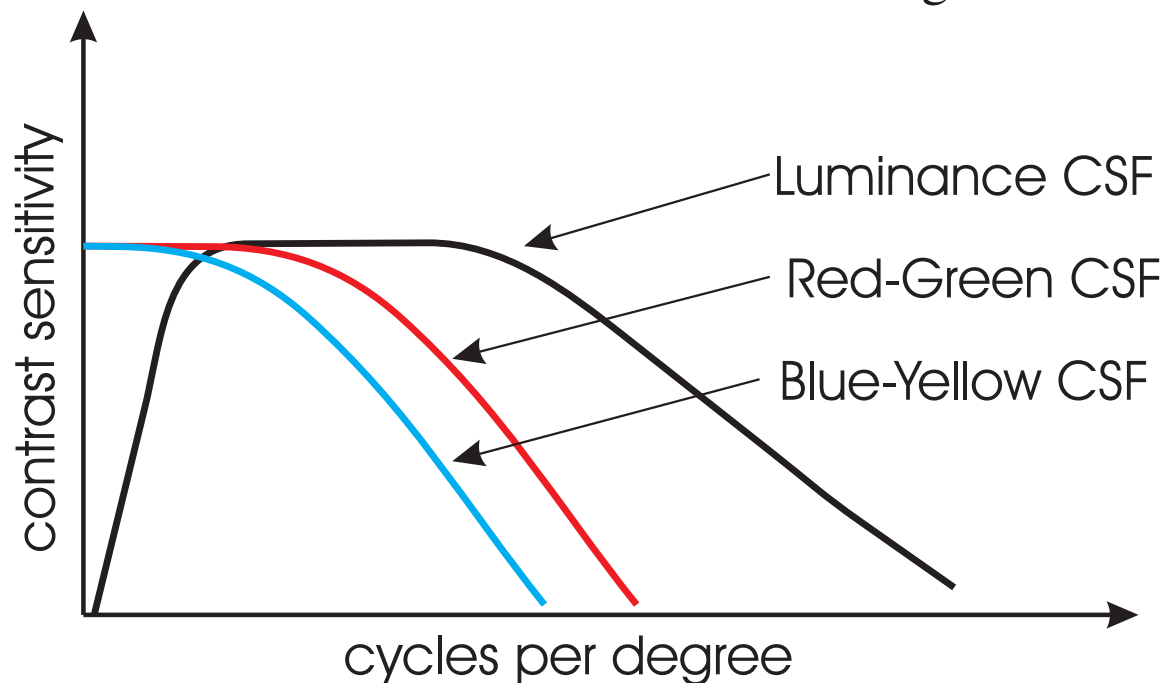
- $O_3$  is the blue-yellow channel

$$O_3 = B - Y = B - (R + G)$$

- 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<sup>1</sup>

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

- We many 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<sup>2</sup> and associated color transforms.<sup>3</sup>

<sup>1</sup> B. A. Wandell, *Foundations of Vision*, Sinauer Associates, Inc., Sunderland MA, 1995.

<sup>2</sup> K. T. Mullen, "The contrast sensitivity of human color vision to red-green and blue-yellow chromatic gratings," *J. Physiol.*, vol. 359, pp. 381-400, 1985.

<sup>3</sup> B. W. Kolpatzik and C. A. Bouman, "Optimized Error Diffusion for Image Display," *Journal of Electronic Imaging*, vol. 1, no. 3, pp. 277-292, July 1992.

## **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

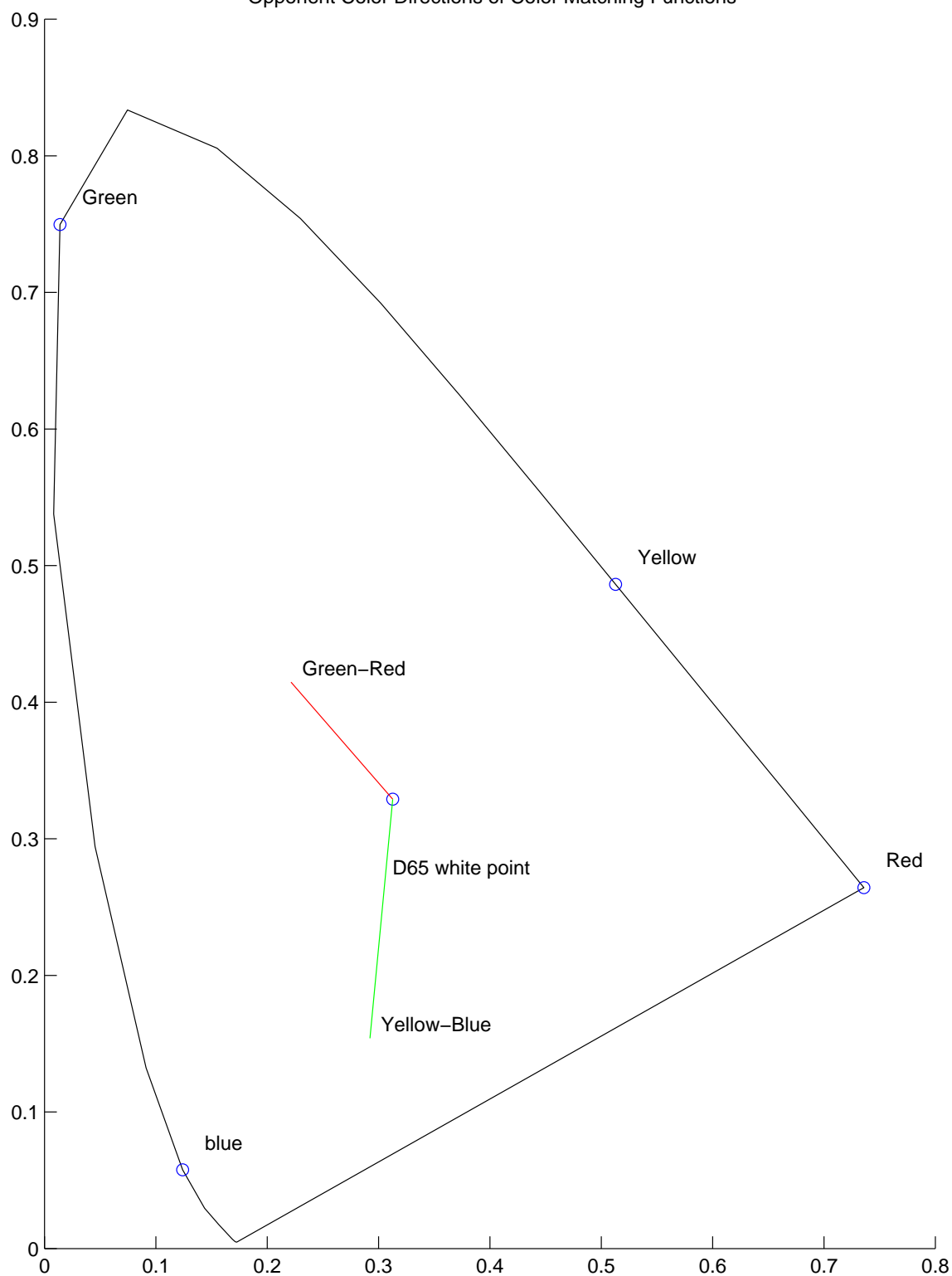
- The XYZ to opponent color transformation is:

$$\begin{aligned} \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} &= \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.4574 & 0.4279 & 0.0280 \\ -0.0303 & -0.4266 & 0.5290 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \\ &= \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \end{aligned}$$

- 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

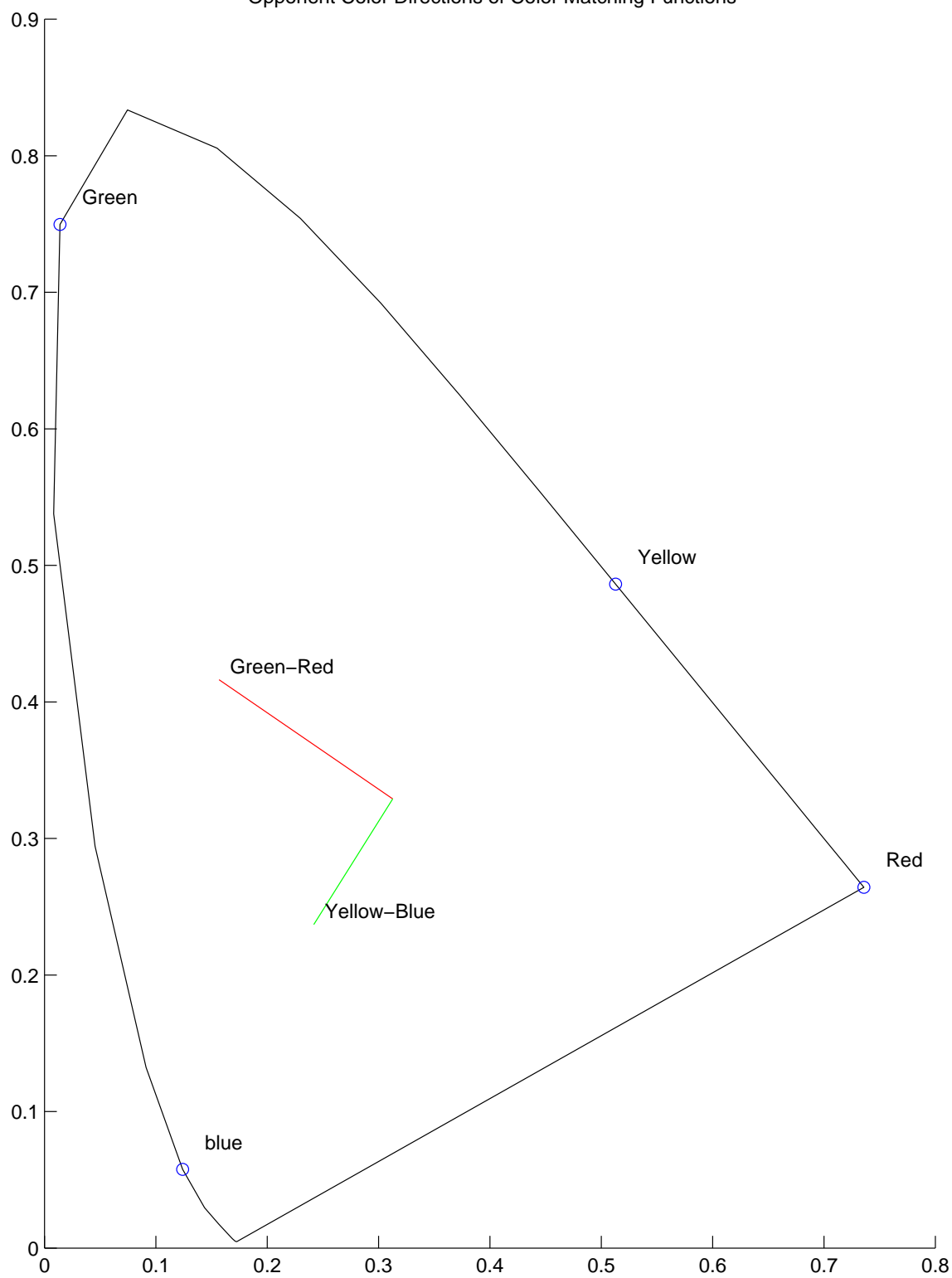
- The transformation from opponent color space to XYZ is:

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

- 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

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

- Therefore, we have that

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

- 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.