Vision Science II - Monocular Sensory Aspects of Vision

Lecture 27 - Introduction to Color Vision

INTRODUCTION TO COLOR VISION

So far we have studied aspects of vision such as visual adaptation, spatial vision, temporal vision and motion perception. With today's lecture we will begin an important new topical area—color vision. We will closely follow the material presented in Schwartz Chapters 5 and 6. The major sub-topics are:

- The trichromatic theory of color vision
- Phenomena associated with color vision
- Color specification systems
- Color vision anomalies
- Testing color vision

Why should we study color vision?

- It is one of the most important aspects of our sense of vision.
- Sometimes we evaluate the color vision of patients to see if they meet occupational requirements.
- We need a basic knowledge of color vision to diagnose color vision anomalies (color blindness, etc.).
- Color vision testing helps diagnose certain diseases, such as optic neuritis or Plaquenil toxicity.
- National boards

THE TRICHROMATIC THEORY OF COLOR VISION

You already know that color is closely related to the wavelength of light. A basic issue in color perception is, How does our visual system discriminate one wavelength from another?

Long ago, people theorized that we perceive different colors because there is a photoreceptor for each color. For example, if a person were looking at fall foliage, the retinal image of red leaves would stimulate red receptors, yellow leaves stimulate yellow receptors, orange leaves stimulate orange receptors, green leaves stimulate green receptors, and so on for every color.

Q: What is the problem with this theory?

The famous vision scientist, Thomas Young, in 1802, proposed a theory of color perception that required only three kinds of color receptors. This is known as the **trichromatic theory** of color vision. Page 90 in Schwartz quotes from Young:

> *As it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation, it becomes necessary to suppose the number limited; for instance, to three principal colors ... And that each of the particles is capable of being put in motion more or less forcibly by undulations differing less or more from perfect unison. Each sensitive filament of the nerves may consist of three portions, one for each principal color.*

Monochromacy

To understand trichromatic color vision, we begin by considering what wavelength discrimination would be like if there were only one class of retinal photoreceptors, such as just rods. This is the case for persons with a hereditary color anomaly called a **rod monochromacy**. If presented with two stimuli that differ in wavelength, could a rod monochromat tell them apart, based wavelength alone?

Photopigments have an absorption spectrum, such as that show in Fig. 5-2 of Schwartz. Different pigments are absorbed differently, so how could a person with only one photopigment (in one type of photoreceptor cell) discriminate between two different wavelengths (λ_a, λ_b)?

Referring to Fig. 5-2, you can see that, if the two stimuli (λ_a, λ_b) had the same radiance, the relative brightness of the two lights would differ based on the differing wavelength-dependent absorption. If both lights emitted 100 quanta, the receptor would absorb 25 quanta in the case of λ_a, but 50 quanta for λ_b. The two lights would appear different, but only because of differences in their perceived brightness.

Note that the photoreceptor does not transmit any specific information on the wavelength itself. It simply absorbs light and sends an electrical signal. Although the probability of absorbing light varies as a function of wavelength, once light is absorbed, there is only one response—neural excitation. This is known as the **principle of univariance**.

Now, if you doubled the radiance of λ_a, it would appear to be the same brightness as λ_b (Fig. 5-2). In that case, the neural excitations for both lights would become equal, and the visual cortex would receive the same signal from both, in spite of the fact that they have different wavelengths.

For a monochromat, it will always be possible to match two lights of different wavelengths by adjusting their relative intensities. In other words, it is possible to fool a monochromat into thinking that two different wavelengths are the same color by adjusting their relative radiances.

This means that the monochromat cannot distinguish between two wavelengths based on differences in wavelength alone. Monochromats are therefore color blind, in the sense that they have no wavelength discrimination

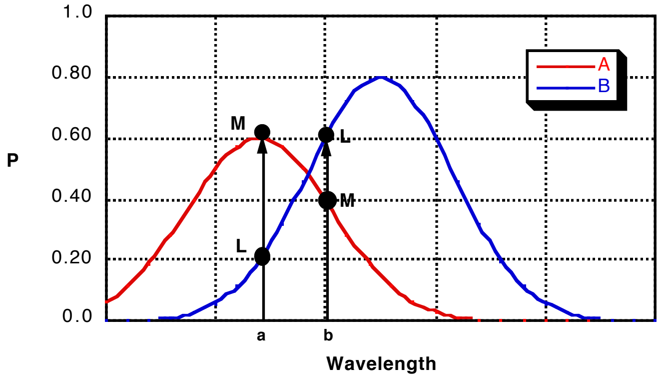

Figure 1. Color matching for a dichromat who has two photoreceptors.

Dichromacy

If the retina had two different photopigments (M and L in Figure 1 above; Schwartz Fig. 5-5), each of which had slightly different absorption spectra, would such a color system be able to distinguish two different wavelengths based on wavelength alone?

Show the subject two patches of light, one with λ_a, and another with λ_b. To test whether he can distinguish the two wavelengths, you ask him to try to adjust the relative intensities of the two patches to make them match. If he can achieve a match, then he cannot discriminate between the wavelengths based on wavelength information alone. If he cannot match them, then we know that no matter what the relative intensities, they will always look different. This indicates that he *can* discriminate between these two wavelengths based on their wavelength alone.

In the example presented in Schwartz Fig. 5-5, the spectral absorption spectra of the two example photopigments are different but have overlapping distributions. Refer to the table in Fig. 5-5. If the luminance of both patches is set to 100, the signal output by the retina for the two lights will be different. For λ_a the neural response would be based on 60 quantal absorptions from the M receptor + 20 quantal absorptions from the L receptor (60M + 20L). For λ_b the response would be 40M + 60L. This is illustrated in Schwartz Fig. 5-5.

Q. Is it possible to adjust the luminances of the two lights so that the signal from the M and L cones is the same for the two patches of light?

A.

No matter how you attempt to adjust the intensities of the two patches, the combined L and M output signals will always be different for the two test wavelengths.

- For λ_a, the M response will always be larger and the L response will always be smaller.
- For λ_b, the M response will always be smaller and the L response will always be larger.

Using *two* wavelengths, divided between *two* patches of light, a dichromat can never make them match. You cannot fool them into thinking that the two wavelengths are the same, therefore they have superior wavelength discrimination to a monochromat, due to the presence of an additional photopigment.

Adding another wavelength
To further investigate wavelength discrimination in a dichromat, consider the experiment illustrated in Schwartz Fig. 5-6. Present two patches of light, but this time the left patch consists of a mixture of two wavelengths (λ_a and λ_c). By varying the mix of these two wavelengths, is it possible to make them match a third wavelength (λ_b)?

Note that λ_a normally stimulates the M cones strongly and the L cones weakly. λ_c stimulates the L cones very strongly and the M cones less. By carefully adjusting the combination of λ_a plus λ_c you can make the M and L cone outputs match the M and L outputs for λ_b alone. To the subject, the light containing λ_a plus λ_c will appear identical to λ_b. Two stimuli that contain different wavelengths, yet appear to be identical are called **metamers**.

Dichromats therefore have some wavelength discrimination, but it is not perfect. They can be fooled into thinking that a particular mix of two wavelengths is the same as a third wavelength. In other words, two patches of light can be matched with the correct mix of three wavelengths.

Trichromacy
A trichromat has superior wavelength discrimination to a dichromat because he will have three photopigments (in three kinds of cone photoreceptors). Figure 2 shows the absorption spectra for the photopigments contained in the three human cones. The cones are labeled S, M and L because of their peak sensitivities in the short, middle and long wavelength ranges, respectively. Table 1 summarizes some characteristics of the three photopigments.

Table 1 Three human cone types and characteristics of their photopigments.

Cone type	Photopigment	Peak sensitivity (nm)	Range (nm)
S	cyanolabe	426	~400-530+
M	chlorolabe	530	~400-680+
L	erythrolabe	552 or 557	~400-700+

In the past, the three photopigments have been referred to as the blue, green and red photopigments, but this can give the incorrect impression that each absorbs only a single wavelength. *Note that each of the photopigments absorbs light over a broad range of wavelengths, and there is considerable overlap*. All three photopigments have overlapping absorption spectra over a certain range of wavelengths (below about 545 nm).

Q. How many types of cone photoreceptors are available to absorb wavelengths above 545?

A.

The metameric match that fooled the dichromat will not fool the trichromat. Given two patches of light, and using three wavelengths, they will never be fooled into matching them. They will always be able to tell that the patch containing the two wavelengths is different from the other patch.

However, if you mix in a fourth wavelength (λ_d), it is possible to achieve a metameric match for a trichromat. That is, given four wavelengths divided between two patches, you can mix them in such a way that, although they are actually different, they appear to be identical.

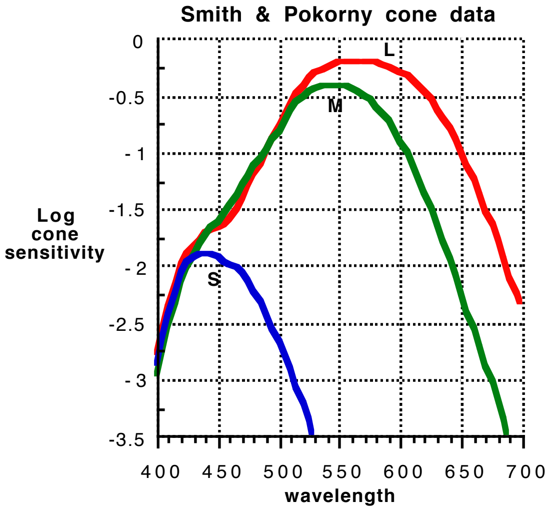

Figure 2. Absorption spectra of S, M, and L cones.

Tetrachromacy

Some researchers have suggested that rods may also contribute to color perception. If that were true, then we would have a tetrachromatic system. As summarized in Table 2, if a person received input from four different photoreceptors (a tetrachromat), he would have superior wavelength discrimination to a trichromat. He would always be able to discriminate between two patches of light that had any combination of four wavelengths. However, he could achieve a metameric match using five different wavelengths.

Table 2 Principles of color matching

Condition	Number of Photopigments	Minimum number of λs for metamerism
monochromat	1	2
dichromat	2	3
trichromat	3	4
tetrachromat	4	5

METAMERS AND GRASSMAN'S LAWS

Color matching experiments have been used to study color perception, and it is generally accepted that humans have a trichromatic color system based on the S, M and L cones. Recall that **metamers** are pairs of stimuli that can be color matched in spite of the fact that they are composed of different wavelengths. **Grassman's laws** summarize some basic principles of metameric color matching.

- **Additivity property** of metamers. If the same wavelength is added to two metamers, they remain metamers (Schwartz Fig. 5-8 top).
- **Scalar property** of metamers. If you multiply (or scale) the intensity of two metamers by the same factor, they remain metamers (Fig. 5-8 middle).
- **Associative property** of metamers. Metamers can be substituted into other mixtures, and the color perception will remain the same (Fig. 5-8 bottom).