INTRODUCTION TO COLOUR VISION

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THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Trichromatic theory of colour vision
- Metamers and Grassman's laws

INTRODUCTION

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—colour vision. We will closely follow the material presented in Schwartz, 2004 Chapters 5 and 6. The major sub-topics are:

- The trichromatic theory of colour vision
- Phenomena associated with colour vision
- Colour specification systems
- Colour vision anomalies
- Testing colour vision

WHY SHOULD WE STUDY COLOUR VISION?

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

TRICHROMATIC THEORY OF COLOUR VISION

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

Long ago, people theorized that we perceive different colours because there is a photoreceptor for each colour. 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 colour.

Q. What is the problem with this theory?

A. _____

The famous vision scientist, Thomas Young, in 1802, proposed a theory of colour perception that required only three kinds of colour receptors. This is known as the **trichromatic theory** of colour 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 colours ... 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 colour.*

MONOCHROMACY

To understand trichromatic colour 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 colour anomaly called rod monochromacy. If presented with two stimuli that differ in wavelength, could a **rod monochromat** tell them apart, based on wavelength alone?

Photopigments have an absorption spectrum, such as that show in Fig. 5-1 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 (λa, λb)?

Referring to Figure 5-2, you can see that, if the two stimuli (λa, λb) 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 λa, but 50 quanta for λb. 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 λa, it would appear to be the same brightness as λb (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 colour by adjusting their relative radiances.

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

TRICHROMATIC THEORY OF COLOUR VISION (CONT.)

DICHROMACY

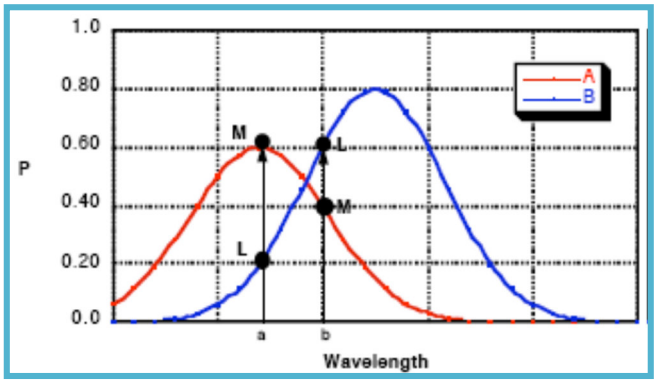

Figure 21-1: *Colour matching for a dichromat who has two photoreceptors*

If the retina had two different photo-pigments (M and L in Figure 21-1 above; Schwartz Fig. 5-4), each of which had slightly different absorption spectra, would such a colour 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/she can distinguish the two wavelengths, you ask him/her to try to adjust the relative intensities of the two patches to make them match. If he/she can achieve a match, then he/she cannot discriminate between the wavelengths based on wavelength information alone. If he/she cannot match them, then we know that no matter what the relative intensities, they will always look different. This indicates that he/she can discriminate between these two wavelengths based on their wavelength alone.

In the example presented in Fig 21-1 and Schwartz Fig. 5-4, the spectral absorption spectra of the two example photo-pigments are different but have overlapping distributions. Refer to the table in Fig. 5-4. 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. 5-4.

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. 5-5. 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.

TRICHROMATIC THEORY OF COLOUR VISION (CONT.)

TRICHROMACY

A trichromat has superior wavelength discrimination to a dichromat because he/she will have three photopigments (in three kinds of cone photoreceptors). Figure 21-2 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 21-1 summarizes some characteristics of the three photopigments.

Table 21-1: *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.

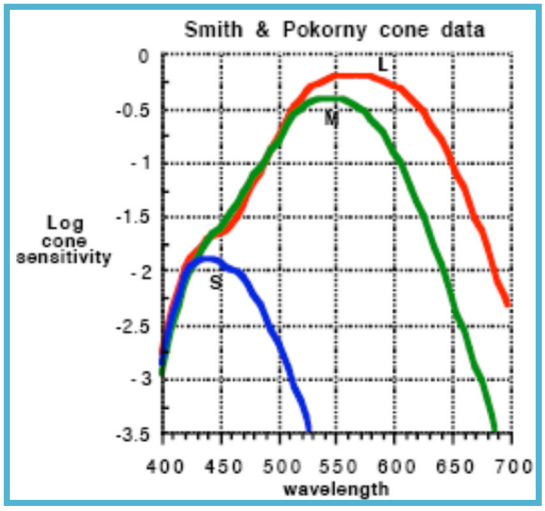

Figure 21-2: *Absorption spectra of S, M, and L cones.*

TRICHROMATIC THEORY OF COLOUR VISION (CONT.)

TETRACHROMACY

Some researchers have suggested that rods may also contribute to colour perception. If that were true, then we would have a tetrachromatic system. As summarized in Table 21-2, if a person received input from four different photoreceptors (a tetrachromat), he/she would have superior wavelength discrimination to a trichromat. He/she would always be able to discriminate between two patches of light that had any combination of four wavelengths. However, he/she could achieve a metameric match using five different wavelengths.

Table 21-2: *Principles of colour 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

Colour matching experiments have been used to study colour perception, and it is generally accepted that humans have a trichromatic colour system based on the S, M and L cones. Recall that **metamers** are pairs of stimuli that can be colour matched in spite of the fact that they are composed of different wavelengths. **Grassman's laws** summarize some basic principles of metameric colour 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 colour perception will remain the same (Fig. 5-8 bottom)

SELECTED READING/REFERENCES

- Schwartz SH. **Visual Perception - A Clinical Orientation, 3rd Edition**. Appleton & Lange, Stamford, Connecticut, 2004