TRICHOMACY, MUNSELL SYSTEM, NORMAL COLOUR VISION

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THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Evidence for trichromacy
- Molecular genetics of cone photopigments
- Colour labels
- Munsell colour appearance system
- Normal colour perception

EVIDENCE FOR TRICHROMACY

Scientific research using a variety of methods have established that the normal human retina contains three types of cones, and the characteristic absorption spectra for the photopigments contained in each has been identified. This is the basis for trichromatic colour perception. Experimental techniques used to investigate colour vision include:

- Psychophysical colour matching studies
- Retinal densitometry
- Single cell micro-spectrophotometry
- Electrophysiological recordings to measure the spectral sensitivity of individual photoreceptors
- Adaptive optics high-resolution ophthalmoscopy

A scientist named Rushton developed **retinal densitometry** in the 1960s to study retinal photopigments. To study the absorption spectrum of the M cones, you must find a colour anomalous person who has only M cones in his/her fovea. The *S cones are normally absent from the fovea*, so a person who is missing L cones will have only M cones in the fovea.

Start by shining a monochromatic (single wavelength) light, with known radiance, onto the fovea, and then measure the amount of light reflected back out. The radiance of the reflected light will be less than that of the incident light due to absorption by the photopigment. You can therefore compute the relative absorption for that wavelength. By repeating the procedure for many wavelengths you can determine the absorption spectrum for the M cones.

To find the absorption spectrum for the L cones, you must repeat the procedure with a colour anomalous person who is missing the M cones. Retinal densitometry helps determine the absorption spectrum for the L and M cones across the center of the visible spectrum, but this technique loses accuracy in the short and long wavelength range.

EVIDENCE FOR TRICHROMACY (CONT.)

In **microspectrophotometry**, a single cone is isolated and illuminated by a single wavelength of light of known radiance. The transmitted light is measured and the difference between the incident and transmitted light is attributed to photopigment absorption. By repeating for many wavelengths, you can determine the absorption spectrum for one type of cone. (Refer to Schwartz Fig. 5-8.)

Electrophysiologic recordings of individual cones cells can also be used to determine their absorption spectra. In this technique, a microelectrode measures the electrical response of an isolated cone cell when illuminated by monochromatic light. By measuring the minimum radiance needed to elicit a response, you determine the threshold for that wavelength. Repeat for many wavelengths to determine the threshold spectrum; the inverse of this gives the relative sensitivity spectrum of the cone.

Dr. Austin Roorda, of the University of California at Berkeley, used **adaptive optics** to measure and neutralize the optical aberrations of the eye, and then took ultra-high resolution photographs of living human photoreceptors. Prior to this, the only way to photograph individual photoreceptors was to excise the eye and perform electron microscopy on histological sections. He combined the high-resolution images with retinal densitometry and identified the cone type among an array of retinal photoreceptors. Figure 22-1 (left), copied from his website, shows the spatial arrangement of the three cones types in one subject's retina. Dr. Roorda has been able to image and photograph individual photoreceptors in the living human eye, and has used selective bleaching techniques to isolate different photopigments in the living human eye.

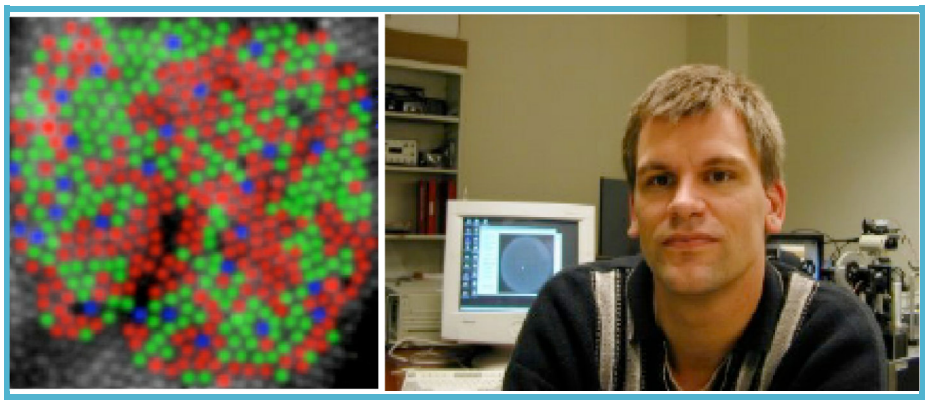

Figure 22-1 *Using a high resolution adaptive optics fundus cameras and retinal densitometry, Dr. Austin Roorda (above) was able to identify individual S, M and L cones in a living retina.*

MOLECULAR GENETICS OF CONE PHOTOPIGMENTS

(Read Schwartz, 2004 p. 98-101)

COLOUR LABELS

Although wavelength is usually associated with a particular colour, light produced by one wavelength does not always appear the same colour. For example, depending on the brightness of a monochromatic light, it could have a different appearance. You could have 555 nm bright green, or 555 nm dark green. It's more correct to describe the attribute of colour most closely associated with the wavelength as the 'hue'. For example, the hue associated with a wavelength of about 400 nm is violet; 525 green; 570 yellow; 630 red, etc. Colour is a common, generic term, but to be more specific in describing a colour, we should describe it in terms of its three basic attributes:

- Hue
- Saturation
- Brightness

COLOUR LABELS (CONT.)

A given hue may also differ in terms of its **saturation**. Saturation describes how pure or rich a certain colour is. For example, highly saturated red (pure red) can be **desaturated** by mixing in white, making it pink. In this example, the pure red and pink would have the same hue, but different saturation. Note that in this example, red and pink are different colours even but they have the same *hue*.

The relative saturation of a test colour can be specified by its **colourimetric purity (p)**.

L_λ – luminance of a pure spectrally wavelength

L_w – luminance of a white light added to L_λ to match the test colour.

In the example in Figure 22-2, the left test colour is matched to a mixture of 90 parts pure red + 10 parts pure white. It has a colourimetric purity of 0.9. The colour being tested in the right test patch matches a mixture of 90 parts pure red + 210 parts pure white for a colourimetric purity of 0.3.

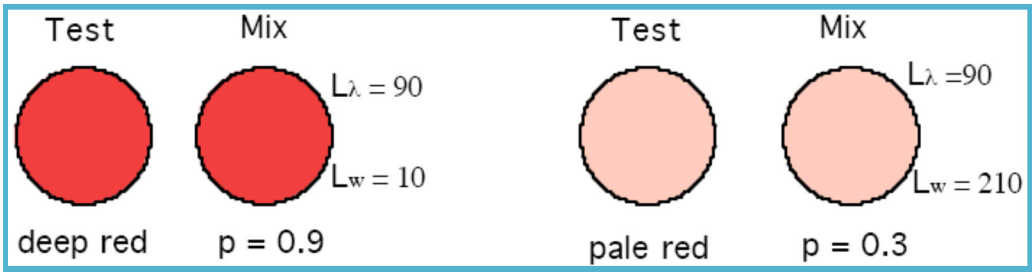

Figure 22-2: *Two examples of how colourimetric purity, or saturation of a particular hue can be measured*

Excitation purity is given by the formula:

$$\text{Excitation purity (p)} = \frac{a}{a+b}$$

Brightness was mentioned previously. It is also a basic parameter used to describe a particular colour. Perceived brightness is closely related to the V(λ) function. Brightness information is encoded based on input from both the M and L cones. Note that brightness does not exactly equal luminance, though they are closely related. Because of neural processing, two lights of the same luminance can sometimes have different perceived brightnesses.

MUNSELL COLOUR APPEARANCE SYSTEM

Several systems have been developed to specify colours. One is the CIE colour specification system. Another well-known system used in art and for the paint industry is the Munsell colour-order system. You can read a technical description of the Munsell system at the following web site:

http://www.coloursystem.com/?page_id=860&lang=en

Wikipedia has a nice plain-language summary of the Munsell system:

(http://en.wikipedia.org/wiki/Munsell_color_system).

In 1905, artist A.H. Munsell organized a large number of colour samples according to their hue, saturation and brightness. This became the Munsell colour appearance system.

> *The Munsell colour-order system is a way of precisely specifying colours and showing the relationships among colours. Every colour has three qualities or attributes: hue, value and chroma. Munsell established numerical scales with visually uniform steps for each of these attributes. The Munsell Book of Colour displays a collection of coloured chips arranged according to these scales. Each chip is identified numerically using these scales. The colour of any surface can be identified by comparing it to the chips, under proper illumination and viewing conditions. The colour is then identified by its* ***hue****,* ***value*** *and* ***chroma****. These attributes are given the symbols H, V, and C and are written in a form H V/C, which is called the Munsell notation. (from: http://www.munsell.com/munsell1.htm)*

MUNSELL COLOUR APPEARANCE SYSTEM

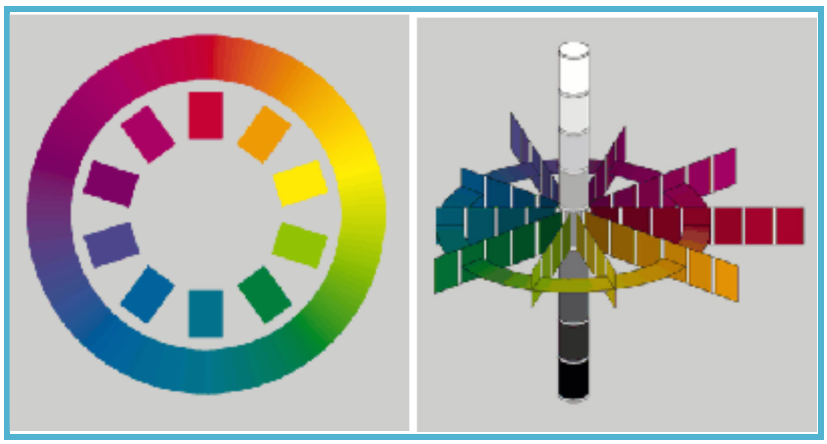

Figure 22-3: *The left figure shows the progression of hues when the Munsell cylinder is viewed from above. The right shows that colours also vary from center to periphery (chroma or saturation) and from top to bottom (value or brightness)*

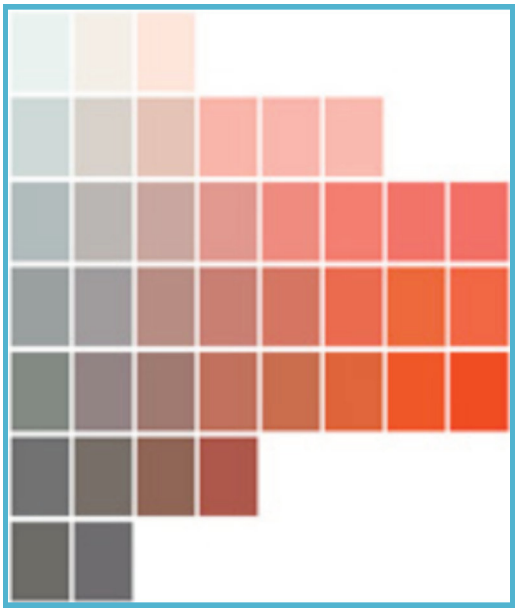

Figure 22-4: *The Munsell system*

In the Munsell system, the highly saturated colours are further out from the center. Figure 22-4 shows one leaf of the Munsell tree. All samples in this leaf have the same hue, but differ in their brightness (Munsell value) and saturation (Munsell chroma)

In the Munsell system, all the colours are arranged in a cylinder-like volume in which hues change around the circumference of the cylinder. Figure 22-3 left shows the arrangement if viewed from above. The **hues** are divided into ten broad sectors, each of which has ten smaller hue steps. Altogether there are 100 hues in this system. The major hues are abbreviated R, YR, Y, GY, G, BG, B, PB, P and RP, and the steps within each major hue are given a number. For example, the hue in the middle of the red sector is designated 5R. **Value** is related to brightness and varies from 0 (black) at the bottom, to 10 (white) at the top.

MUNSELL COLOUR APPEARANCE SYSTEM (CONT.)

Chroma corresponds to saturation (colourimetric purity or excitation purity). The neutral colours (white-gray-black) have a chroma of zero, but all the other colours can have a chroma of 1 or greater. Higher numbers are more saturated. Some natural colours can have a chroma as high as 20, while some fluorescent colours can have a chroma as high as 30. Schwartz says that chroma varies from a value of 1 to 14, with 1 at the center and 14 at the edge. See Fig. 5-19 in Schwartz, 2004.

Taking into account all these parameters, any single colour in the Munsell system is specified by the following format (Fig. 24-4): hue value/chroma. For example, a vivid red, with a value (brightness) of 6 and chroma (saturation) of 14, is designated 5R 6/14. Finer divisions can be specified using decimals. For example: 5.3R 6.1/13.5.

NORMAL COLOUR PERCEPTION

RELATIVE SATURATION OF PURE SPECTRAL HUES

Some wavelengths appear to be more saturated than others, even if they all have a colourimetric purity or excitation purity of 1.0. Described differently, some colours appear to be stronger than others. The least saturated wavelength is 570 nm, which has a yellow hue.

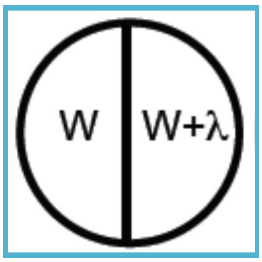

Figure 22-5: *Bipartite field to test relative saturation of different hues*

Using a stimulus such as that shown in Figure 22-5, you can test the relative saturation of one wavelength by adding a small amount of that wavelength (fully saturated) to white light. Continue to add light of that wavelength until it no longer looks white compared to the pure white half of the stimulus. (Note that the total luminance on both sides is kept constant.) Using the luminance values for the white and test hue, you can compute a relative spectral saturation according to the formula below.

$$\text{relative saturation} = \left[\frac{(L_\lambda + L_w)}{L_\lambda}\right]$$

You must add very little of strongly saturated hues, such as blue or red, but much of desaturated hues, such as 570 nm yellow, to make the test portion appear different from white. Table 22.1 gives hypothetical values in an experiment to compare saturation of three wavelengths. Figure 5-11 of Schwartz, 2004 plots the results of this kind of experiment for many spectral hues. Note that the least saturated hue is associated with 570 nm light.

Table 22-1: *Comparing relative saturation of different wavelengths*

Λ	HUE	WHITE INTENSITY	Λ INTENSITY	(Λ+W)/Λ	LOG(Λ+W)/Λ
470	blue	95	5	20	1.3
570	yellow	70	30	3.33	0.5
630	red	94	6	16.7	1.2

NORMAL COLOUR PERCEPTION (CONT.)

WAVELENGTH DISCRIMINATION

How small of a difference in two wavelengths can be discriminated? This varies depending on the wavelength, as shown in Schwartz, 2004 Fig. 5-12. The stimulus used to test wavelength discrimination is shown in Fig. 5-12 top.

A fixed test wavelength is compared to another wavelength that is only slightly different. Test the minimum difference in wavelengths that the subject can distinguish as different.

Wavelength discrimination as a function of wavelength is plotted as a W-shaped curve that shows the best discrimination at 495 and 590 nm. Maximum wavelength discrimination is seen at the wavelengths where slopes of the photopigment absorption spectral functions have the greatest change relative to each other (Fig.22-6 below).

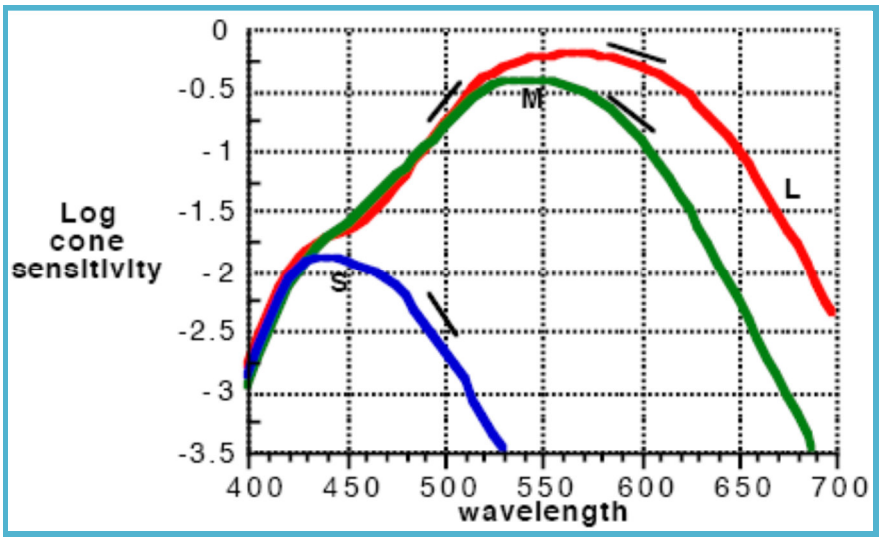

Figure 22-6: *S, M & L cones sensitivity functions*

BEZOLD-BRÜCKE PHENOMENON

The hues of most wavelengths change slightly with different levels of luminance. See (Schwartz, 2004 Fig. 5-13). The bipartite stimulus shown in Fig 22-7, below, is used to measure this effect, known as the **Bezold-Brücke phenomenon**. λv represents a test wavelength that can be varied; λc represents a light that maintains a constant wavelength and luminance. Initially λv and λc have the same wavelength and luminance. The luminance of λv is then gradually increased, and for most wavelengths its hue gradually shifts. The subject must adjust the wavelength of λv so that it remains the same hue as λc; that is, he/she tries to keep it at a constant hue, the hue of λc.

For example, λv = 550 nm (green), with increasing intensity it begins to look more yellow, like 580 nm. To compensate, the subject adjusts it to a shorter wavelength. Therefore the plot shows the line originating at 550 nm leaning to the left (Fig. 22-7).

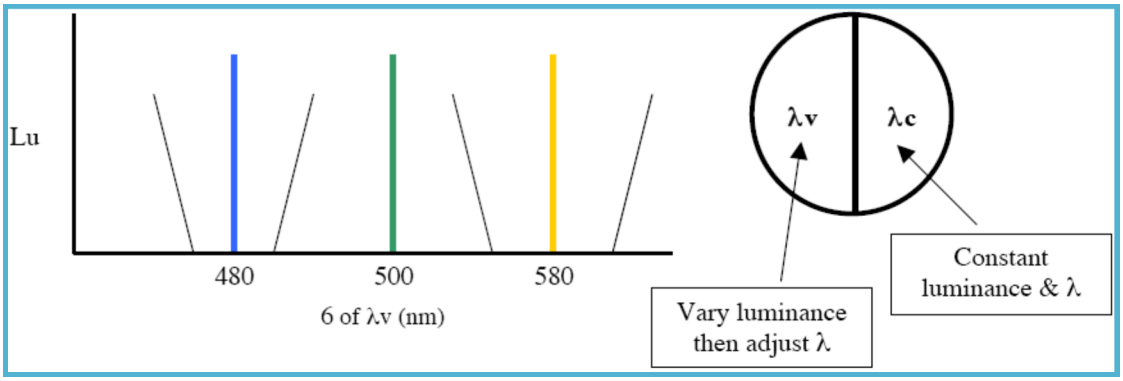

Figure 22-7: *The three invariant wavelengths are ~480, ~500 and ~580.*
Tilted lines are hue contour lines that indicate the wavelengths that keep a constant hue with increasing luminance

NORMAL COLOUR PERCEPTION (CONT.)

The lines in the plot represent the wavelengths that appear to have the same hue with increasing intensity. They are called **hue contour lines**. At three wavelengths (478, 503, 578 nm), there is no change in perceived hue with increasing intensity. These are called the **invariant wavelengths, invariant points or unique hues**.

To summarize the Bezold-Brücke phenomenon, remember that with increasing intensity, wavelengths below ~500 nm shift in appearance more toward blue (~480), and above ~500 nm, hues shift in appearance more toward yellow (~580).

For example, 490 nm (blue-green) gets bluer (closer to 480 nm), and to compensate λv is changed to longer wavelengths, making the colour contour line tilt to the right.

A stimulus with 450 nm (violet) becomes bluer (closer to 480 nm), therefore λv must be changed to shorter wavelengths to compensate, and so the hue contour line leans to the left.

A stimulus of 525 nm (green-blue) becomes yellower (closer to 580 nm) and λv must be adjusted to lower wavelengths to compensate (hue contour line leans left).

A stimulus of 590 nm (yellow-orange) becomes yellower (closer to 580 nm) and λv must be adjusted to longer wavelengths to compensate (hue contour line leans right).

Abney's phenomenon describes a slight change in hue that accompanies a change in saturation for some wavelengths. Wavelength lights near 488 nm (blue-green) become more different from the hue of 488 nm with increasing saturation. Wavelength lights near 577 nm (yellow) become more like the hue of 577 nm with increasing saturation.

COLOUR CONSTANCY

When lights of slightly different colours illuminate an object, there is a change in the spectral content of the reflected light. Despite this, it often looks the same colour. This is referred to as **colour constancy**.

SELECTED READING/REFERENCES

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