Rich visual perceptions from simple physical variations and simple biological mechanisms

Color Vision:



# Joe Lappin 9 Feb, 2004



#### Monday — from light to color:

···· Overview

- <sup>①</sup>How does light yield color?
- ② How many receptor mechanisms?
  - <sup>③</sup> How do we know the receptor characteristics?
- ④ What happens to color when illumination is reduced?
- <sup>(5)</sup> Having identified the receptor mechanisms, what issues remain?
- Wednesday neural representations, color deficiencies.
- Friday perceiving environmental colors: color constancy, contrast effects, surface colors, material substances.



- McIlwain, J.T. (1996). "Color vision" (ch. 11). An introduction to the biology of vision. Cambridge U. Press.
- 2) Tovée, M.J. (1996). "Retinal colour vision" (ch. 3), "Colour
  - constancy" (ch. 7). An introduction to the visual system. Cambridge
    U. Press.
- 3) <u>For Weds</u>: De Valois, R.L., Abramov, I., & Jacobs, G.H. (1966).
- Analysis of response patterns of LGN cells. Journal of the Optical Society of America, 56, 966-977. [This is a classic & important
  article.]
- 4) For Fri: Land, E.H. (1959). Experiments in color vision. Scientific American, May, 1959. Reprinted in R. Held & W. Richards (Eds.), Readings from Scientific American, (pp. 286-298). San Francisco:
  Freeman, 1972.



# Newton's (1666) experiment on the color composition of light:







# Newton's (1672) explanation for the colors of objects:



#### \* The Rays to speak properly are not coloured. In them there is nothing else but a certain Power and Disposition to stir up a Sensation of this or that Colour. ... So Colours in the object are nothing but a Disposition to reflect this or that sort of Rays more copiously than the rest (1672)." (Warning: The words "nothing but" now seem misleading or mistaken.)



# Colors from Material Surfaces

Retinal images usually are formed from light reflected from surfaces. Different materials absorb, reflect, and scatter light differently. Color carries visual information about the material composition of objects.



# Physical Dimensions and Visual Dimensions

- 1-D variations in the wavelength of light yield
- ⇒ 3-D visual variations in perceived color and lightness.
- This must tell us something about the visual mechanisms.





#### From lights to colors:

• Visually perceived <u>colors</u> do not correspond at all to <u>beams</u> of light. ("Beams" refers here to linear combinations of various (incoherent, additive) wavelengths.) Thus, two physically different beams, say  $\mathcal{A}$  and  $\mathcal{B}$ , may have identical colors:  $\mathcal{A} \iff \mathcal{B}$ , where "<=>" means having visually equal (indiscriminable) colors. Different light beams with the same color are called "**metamers**". In fact, for any given light beam,  $\mathcal{A}$ , there is an <u>infinite</u> set of metameric beams  $\mathcal{X}$  with the same color as  $\mathcal{A}$ ,  $\mathcal{A} \ll \mathcal{X}$ .

- Different light beams with the same color also have the following properties:
  - If  $\mathcal{A} \iff \mathcal{B}$ , and  $\mathcal{B} \iff \mathcal{C}$ , then  $\mathcal{A} \iff \mathcal{C}$ .
  - If  $A \ll B$ , and  $A + C \ll D$ , then  $B + C \ll D$  (where "+" denotes physical superposition of beams).

• Such relationships were summarized in 1853 by Grassmann. <u>Grassmann's laws</u> correspond to the statement that the space of colors, say  $\mathcal{C}$ , is a 3-dimensional linear vector space. Thus,  $\mathcal{C}$  is a projection of the infinite-dimensional vector space, say  $\boldsymbol{S}$ , of light beams.



• James Clerk Maxwell (1855, 1860) contributed the first empirical studies using Grassmann's laws to describe the mapping from light beams to color space. Such descriptive analyses of color space are called "colorimetry".

• The "explanation" for the 3-dimensionality of color space is physiological — based on the cone action spectra. Equivalence of colors implies equivalence of input to the brain. Thus, psychophysical equivalence can be used to identify equivalence of retinal signals.

• The figure at the upper left shows the spectrum of monochromatic light beams — an open line segment where the colors merge into black at each end of the segment. The purples are missing. The color circle at the lower left is a closed, continuous (periodic) arrangement that includes purples.

# **Color Matching**





To give a colorimetric description of the electromagnetic spectrum, one first selects a set of "primaries" — basis vectors, say  $\{\mathcal{P}_{l}, \mathcal{P}_{2'}, \mathcal{P}_{3}\}$ . (These primaries are light beams.) The choice of primaries is essentially arbitrary, except for the restriction that the three basis vectors are independent (orthogonal) i.e., there is no set of coefficients  $c_1 \neq 0$  such that  $c_1 \mathcal{P}_1$ +  $c_2 \mathcal{P}_2 + c_3 \mathcal{P}_3 \iff 0$ , where 0 is a 'null' vector corresponding to zero light energy. Next, a large set (N) of monochromatic light beams,  $M_{\lambda}$ , is matched, as indicated at the left, by adjusting the relative proportions of these three primaries (where  $\lambda$ designates the wavelength, say from 380 to 740 nm in 10 nm intervals). The coefficients give the relative magnitudes of the primaries needed to match any wavelength, forming an Nx3 matrix.

In general, any given beam of light,  $\mathcal{A}$  can be visually matched by a weighted sum of primaries,  $\mathcal{A} \iff \mathcal{R} +$  $g\mathcal{G} + \mathcal{B}$ . Sometimes 'negative' coefficients are required. The physical operation is shown at the lower left.

Notice that the sets of metamers (different light beams with the same color) are identical, regardless of the choice of primaries. The metamers are determined by the cone action spectra, but the primaries are not.





Note: As indicated on the preceding page, the components in this matching experiment need not be single wavelengths, but may be any beams of light. Typically, the 3 "primaries" on the right are not single wavelengths.





Mixing paints <u>subtracts</u> from the total amount of light (in contrast to additive color mixture, which adds light). Each new pigment absorbs more of the spectrum, similar to placing an additional filter in front of a single light source. The laws of subtractive color mixture are more complex than those for additive color mixture — partly because the perceived color of any pigment or material object depends jointly on the spectral composition of the <u>illuminant</u> and on the <u>reflection/absorption</u> spectrum of the material.

The "primaries" for subtractive color mixing differ from those for additive color mixture, as indicated above. Nevertheless, the additive and subtractive color spaces are related to one another. The color space obtained by additive color mixture is often represented as in inverted cone, with the purest colors represented in a circle at the base of the cone, and their mixtures ascending toward a white apex at the top of the cone, with the gray scale represented by the line from the apex to the center of the base. The colors obtained by subtractive color mixture are then represented as an upright cone extending from a black point at the bottom and expanding to the wider color circle at the top of the cone. The entire color space is then represented as a double cone. The achromatic, gray scale may be represented as a line through the center of the solid, from the black point at the bottom to the white point at the top. The shape of this color solid, may be geometrically transformed in several ways that preserve the psychophysical relations among the component colors. The shape of the subtractive space changes with the illuminant, for example.

### C.I.E. diagram:

a map from the infinite-dimensional space of wavelengths to a 2-D color space, where luminance (a visually based measure of intensity) is constant. The outside edge of this planar section is intended to vary in chromaticity but not in brightness or saturation. Warning: The construction of this CIE color space is based on a somewhat arbitrary choice of "primary" basis vectors. The construction of this space was based on the choices of a committee, the Commission International d'Eclairage in 1931.





# - How many color-sensitive receptors?

**Thomas Young** (1801) (McIlwain, p. 184-185) concluded that there must be at least 3 different light-sensitive "particles".

 If one receptor, then color vision would be impossible. Young pointed out that a given receptor could signal variations in only one dimension. This is now called the *principle of univariance*.

If two receptors, then there should be a <u>neutral point</u>: Some wavelength should be indiscriminable from white light. Young could find no such neutral point.

James Clerk Maxwell (1855): Any perceived color may be matched by an additive mixture of 3 primaries (McIlwain, Fig. 3, p. 187). This is the <u>fundamental law of additive color mixture</u>. For about 100 years (until the 1960s), this fact constituted the principal evidence for the "trichromatic theory" of color vision. This was not the only theory, but it was the dominant theory.

Helmholtz (1867) and the "Young-Helmholtz trichromatic theory".

Definitive evidence in the 1960's for trichromatic theory came from microspectro-photometry experiments on individual cones. (see McIlwain, pp. 186–187)

More than 90% of the cones in human retinae are L and M; S-cones comprise less than 10% of the total. Receptors in the central 0.1° of the fovea are almost all L- and M-cones; the S-cones increase to about 6% at 1°. The L/M cone ratio is highly variable between individuals and even between retinal regions in a given individual (see photographs on next page from Williams & Hofer, 2004). Nevertheless, the subjective appearances of colors and the subjective boundaries between colors (e.g., a unique yellow) seem to be unaffected by these variations in relative proportions of L and M cones. The absorption peaks of the L-, M-, and S-cones are ~ 565, 535, and 440 nm, respectively, as shown below. Note the extensive overlap of the L- and M-cone absorption spectra.



COLUL FISION



Figure 11.2. Spectral absorbances of human S-, M-, and L-cone pigments. B, G, Y, and R refer to the regions of the spectrum that appear to humans as blue, green, yellow, and red. (Adapted from H. J. A. Dartnall, J. K. Bowmaker, and J. D. Mollon: Microspectrophotometry of human photoreceptors. In *Color Vision*, ed. J. D. Mollon and L. T. Sharpe, pp. 69–80. London: Academic Press. Copyright 1983, with permission of Academic Press, Ltd.)



The illustrations at the left are from D.R. Williams & H. Hofer (2004). Formation and acquisition of the retinal image. In L.M. Chalupa & J.S. Werner (Eds.) *The visual neurosciences* (pp. 795-810). Cambridge, MA: MIT Press.

PLATE 30 Images of the cone mosaics of 10 subjects with normal color vision, obtained with the combined methods of adaptive optics imaging and retinal densitometry. The images are false colored so that blue, green, and red are used to represent the S, M, and L cones, respectively. (The true colors of these cones are yellow, purple, and bluish-purple). The mosaics illustrate the enormous variability in L/M cone ratio. The L/M cone ratios are A, 0.37, B, 1.11, C, 1.14, D, 1.24, E, 1.77, F, 1.88, G, 2.32, H, 2.36, I, 2.46, J, 3.67, K, 3.90, L, 16.54. The proportion of S cones is relatively con-

stant across eyes, ranging from 3.9 to 6.6% of the total population. Images were taken either 1 or 1.25 degrees from the foveal center. For two of the 10 subjects, two different retinal locations are shown. Panels D and E show images from nasal and temporal retinas respectively for one subject; J and Kshow images from nasal and temporal retinas for another subject. (Images C, J, and K are from Roorda and Williams, 1999. All other images were made by Heidi Hofer.) (See Fig. 50.13.) The "<u>Purkinje shift</u>" in spectral sensitivity: As illumination decreases from photopic to scotopic vision, greatest sensitivity shifts from yellow toward blue-green. Colors change with illumination. This color shift is a sign of the duplex design of the visual system. (See McIlwain, p. 92; Tovee, p. 31.)





FIG. 4.6 Relative radiance required for rod and cone vision at different wavelengths. Positioning of the two curves is based on the fact that the thresholds for rods and cones are most similar in the red beyond about  $625 \text{ m}\mu$ . The precise form of the curve and the values of radiance required for the rods will depend upon the duration of exposure, the area of stimulus, and its retinal position. The same considerations apply to the curve for the cones. In consequence, the precise relationship of one curve to another will depend upon the values of these parameters. The curves shown here may be considered to apply to conditions that give minimum thresholds for each type of receptor. (From Hecht and Hsia, 1945.)

# Classical evidence against trichromatic theory, favoring opponent processes:

D Phenomemology: Yellow is subjectively unique, different from R, G, or B.

2 Color blindness: The basic varieties of color blindness and color

- deficiency are explained by trichromatic theory by postulating that
- individuals may be lacking in one of the 3 component pigments. BUT:
- Why are perceived colors lost in pairs? Persons lacking in either the L pigment (protanopes) or the M pigment (deuteranopes) are both poor at
  - distinguishing red-green differences. Persons deficient in the S pigment
    - are poor at discriminating blue-yellow differences, but red-green
  - discriminations may be unaffected.
    - ③ Negative afterimages: Why should prolonged exposure to red (green) light produce a green (red) afterimage? More puzzling: Why should exposure to blue light produce a <u>yellow</u> afterimage?
    - ④ Simultaneous color contrast.



## Additional problems for trichromatic theory:

- Sensitivity of color discriminations: How can we discriminate hundreds of thousands of different colors with thresholds ~ 1 nm using filters that are so *broad* (half-heights ~ 100 nm) and so *similar* (where peaks of the L- and M-cones differ by about 30 nm)?
  - Color constancy: Why do objects appear to maintain the same reflected colors under changes in the illumination spectrum?
  - **8** Ed. Land's effect: How can apparently good RGB colors be
  - obtained by combining images with contrast variations in just red light and white light?
    - **Object surfaces and materials:** How do we explain the colors of materials e.g., gold and silver?





- Color is a visual property, not present in wavelengths of light as such.
  - The 3-dimensionality of visual colors—as reflected in additive color mixture—derives from the trichromacy of visual photoreceptors.
- Converging lines of physiological evidence definitively validate the trichromatic theory.
  - This theory does not account for several important phenomena, however.