Color vision

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Humans have 3 kinds of cones

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Trichromacy

- To specify a light's spectrum requires an infinite set of numbers.
- Each cone gives a single number (univariance) when stimulated by a given light.
- There are three cone types.
- Thus the "color" of any light can be specified by three numbers (e.g., the photons caught by each cone type).
- This makes television, color photography, etc., feasible.

Think of the first stage in color vision as a mapping from the space of spectra to the space of cone responses.

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- This spectrum is the sum of 31 monochromatic lights, spaced every 10nm. To specify the mixture, you need 31 numbers, i.e., a vector of length 31. (Can also say: 31 degrees of freedom, or 31 dimensions).
- Most colors in nature are have continuous spectra. To specify a continuous spectrum you need an infinite set of numbers. I.e., it is infinite dimensional.
- The output of a single cone, when stimulated by a given spectrum, is a single number. Thus a cone maps an infinite dimensional vector into a single number.
- Three cones together map an infinite dimensional vector to a 3 dimensional vector. Another way to say it: each spectral distribution is a point in an infinite dimensional space. The cones project this point to a point in a 3-dimensional space.

Metamers: different mixtures of light that excite the cones in the same way.

Univariance + 3 cones implies existence of metamers.

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Why should cone spectra be broad and overlapping?

Naive engineer #1
uses non-overlapping spectra to prevent mixing of signals.
Problem: gaps in spectrum.

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Naive engineer #2
Uses squared-off filters to avoid mixing.
Problem: over large ranges of wavelength, only a single receptor is responding, so different wavelengths can't be distinguished.

Adding colors is like adding vectors.

Let’s work in the long end of the spectrum, where the S-cones have almost zero response. (Response here really means number of photons absorbed per sec.)

Red light stimulates the L-cones a lot, the M-cones a little. The slope of the response vector is determined by the ratio. The length is determined by the intensity of the light.

Yellow light stimulates L and M about equally, producing a vector of unit slope.

Summing the red and yellow lights produces an orange light, whose vector is the sum of the two other vectors.

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Metamers produce exactly the same neural response, starting at the cones.

The lights A and B have different spectra, but they stimulate all three cones in the same way and so are indistinguishable.

No later processing in the brain can tell them apart. The information was lost at the moment of photon absorption.

Suppose you adapt to a uniform red field, which reduces the gain (sensitivity) of the L cones. Everything looks more greenish afterward. So A and B will both look more greenish than they did, but they will look the same.

If a “wash” light is added to the scene, A and B both look different than they did before, but they still look the same as each other. Why is this?

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Color deficiency (“color blindness”)

- Most color deficiencies are due to one or more cone type being missing or abnormal.
- Dichromacy occurs when one cone is missing.
- Deuteranopia: missing the M cone.
- Protanopia: missing the L cone.
- Tritanopia: missing the S cone.

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Pseudoisochromatic plates test for color deficiency

Anomolous trichromacy

- Anomolous trichromacy: one cone type has a slightly odd spectral sensitivity.
- Deuteranomoly
- Protanomoly

Genetics of “color blindness”

Most color defects involve the M and S cones (“red-green color blindness”), and are coded on the X chromosome. About 8% of males have such a defect. (Females have two X chromosomes, and thus have the defect more rarely).

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Some other color defects

- Rod monochromacy: no cones at all.
  - Note: we are all rod monochromats at low light levels
- Cortical color blindness (achromatopsia).

Hering's opponent color theory

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Observation:
A red can look yellowish or bluish
but not greenish

(Image removed due to copyright considerations.)

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Observation:
A yellow can look greenish or reddish
but not bluish

Inference:
Two opponent color axes:
Red-Green and Blue-Yellow

3-D opponent color space

To get full color space,
use three opponent axes:
Blue-Yellow
Red-Green
Black-White (dark-light)

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Gray is neutral:
neither green nor red
nor blue nor yellow

How to reconcile Young-Helmholtz with Hering: first cones, then opponency.

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Colored afterimages

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Varying Hue, Saturation, and Value (Brightness)

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Hue: is it red or blue or what?

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Saturation: How pure is it?

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Value: How light or dark is it?

Some idealized basic colors

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Natural colors

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Natural colors tend to be broad and smooth.

Additive and subtractive color mixing

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Additive mixture of two colors (by spatial mixing)

Squint your eyes or stand far away to make the colors blend.

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CRT (television) shadow mask for additive mixture

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The same additive principle is used LCD displays.

Subtractive color (as in film)

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A color slide is a sandwich of 3 layers. Each layer blocks some of the light, using cyan, magenta, or yellow dye. If all three dyes are present, no light gets through, so the slide is black. Different combinations of dyes lead to different colors being transmitted.

What about the artists' color wheel, with red, blue, yellow?

(Images removed due to copyright considerations.)

Yes, blue and yellow can make green. Paints are usually colored particles in a clear medium. Both additive and subtractive mixing is going on when paints are mixed. It's more complex than pure additive or pure subtractive.

Some say that the choice of red, blue, and yellow as primaries is partly a historical result of the fact that some colors are easier to manufacture than others.

How paint works.

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Why does a bottle of yellow food coloring look red?

A real-world yellow filter has a broad absorption spectrum.
A filter absorbs some percentage of light at each wavelength.
Thus a filter multiplies each wavelength by a number between 0 and 1. If the filter transmits 50% at some wavelength, then two filters stacked will transmit 0.5 x 0.5 = 0.25, i.e., 25%. With many filters stacked, yellow can look orange or red.

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Color reproduction types

Additive: TV's and computer monitors use spatial mixing. Some computer projectors use a spinning color wheel for temporal mixing.

Subtractive: color film, color printing, inkjet printers.

RGB components (additive)

White occurs when all three are on.

Green occurs when G is on, R & B are off.

Yellow occurs when R & G are on, B is off.

Etc.

(Images removed due to copyright considerations.)

CMY components (subtractive)

Cyan ("minus red"), magenta ("minus green"), and yellow ("minus blue") are the three color inks used in printing. Ideally, these three suffice. In practice, it's hard to make a good black, so black ink is used as well, giving 4-color printing called CMYK (K is black).

White occurs when no ink is used

Green occurs when cyan and yellow are used.

Etc.

(Images removed due to copyright considerations.)

L-a-b components (opponent)

L = luminance (the achromatic signal)
a and b are chromatic axes ("chrominance")
a = red-green axis
b = yellow-blue axis

There are several schemes like this.
NTSC TV uses Y-I-Q, where Y is the luminance signal, I and Q are chrominance.

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How to print a grayscale image with black and white dots?

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Color printing with halftone screens

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Isoluminance looks strange

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