What is colour?

What physical aspect of the world does our sense of colour inform us about?

Spectral colors

There are about 200 distinguishable color shades in the spectrum but overall we can see around 1,000,000 shades of color: which colors are missing and “where” are they?
What is colour?

- Colour vision informs us about the spectral reflectance of a surface
- It allows us to distinguish between surfaces or objects with different spectral reflectances.

How do we see colour? ....

Different colours are produced by the mixing of three lights: e.g. TV, computer screen etc

Neutral greys are at the centre. Lights and darks are in front of or behind the color plane, respectively.

The colour circle: uses all colors, not just those associated with monochromatic light
Mixing red and green lights to match yellow (Raleigh match)

A and B. Green and red lights on the top are mixed by the subject to match the yellow light presented on the bottom.

C. The red–green mixture perfectly matches the yellow.

The same match as it appears to a deuteranomalous observer.

Principle of Trichromacy

- Mixing together three coloured lights in suitable proportions enables an exact match to be made to any other colour.
- The 3 mixing lights are called primaries.
- The match is called metameric since identical colour sensations are produced even though the two stimuli are physically different.

3 mixing lights

L1 + L2 + L3

Light to be matched

Mixing red and green lights to match yellow (Raleigh match)

The same match as it appears to a deuteranomalous observer.

Three cones types of human retina:

Wavelength (nm)

Long

Medium

Short

Log relative sensitivity

Distribution of rods and cones (120 million rods and 5 million cones)

visual eccentricity (deg)

macula lutea

spatial density (cells/square mm)

cones

rods

retinal eccentricity (mm)
The distribution of rods and cones across the retina: the receptor mosaic

Periphery

Figure 2.16. The mosaic of rods and cones in the peripheral retina of a monkey. The small circles are rods and the larger ones, cones. The cones appear larger because the retina has been sliced across the receptor’s inner segments, which are fatter for the cones compared to the rods, in the peripheral retina. The cones that are stained yellow are the S-cones. (From deMonasterio et al., 1981.)

Spectral sensitivities of L, M & S cones

Wavelength (nm)

Log relative sensitivity

Long
Medium
Short

False color images of the arrangement of human cones taken 1 deg from the living fovea using an Adaptive Optics Scanning Laser Ophthalmoscope. From the lab of Austin Roorda UC Berkeley.

Bell shaped response curve of a single receptor

Relative absorbance %

Wavelength (nm)

L1 = 2 (L2)

Response curve for a single receptor

Relative absorbance %

Wavelength (nm)
**Principle of Univariance**

- The response of a photoreceptor to any wavelength can be matched to any other simply by adjusting the relative intensities of the two stimuli.

Comment: The response of rods and cones varies only with the amount of light absorbed. The wavelength of the light affects only the amount of light absorbed.

Therefore: Any single receptor type is colour blind

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**How can colour be specified by the cones?**

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**How is colour coded?**

- Each colour produces a unique set of relative activities in the three cone types
- We use this pattern of activities in the three cone types to see colour
The basis of colour mixing in a two receptor (dichromatic) system

Each light is absorbed by the M and L cones in a certain proportion.

A dichromatic system requires 2 mixing lights. A trichromatic (three receptor) system requires 3 mixing lights (primaries).

The mixture of red and green light looks the same as the yellow light because the red-green mixture and the yellow the same proportional absorptions in the L and M cones.

The basis of colour mixing in a two receptor (dichromatic) system

The mixture of red and green light looks the same as the yellow light because the red-green mixture and the yellow the same proportional absorptions in the L and M cones.

Colour matching & metamers

- Two colours with different wavelength distributions look identical if they produce the same ratio of light absorptions in the L, M and S cone types
- These two identically perceived colours, which are physically different, are called metamers
• A trichromatic (three receptor) system requires 3 mixing lights (primaries) to match any other colour
• A dichromatic system requires 2 mixing lights
• A monochromatic system sees all wavelengths as identical. We are all monochromats at night as we use only rods.

Inherited color vision deficiencies: trichromats, dichromats and monochromats

Mixing red and green lights to match yellow (Raleigh match):

A and B. Green and red lights on the top are mixed by the subject to match the yellow light presented on the bottom. C. The red-green mixture perfectly matches the yellow.

The mixture in C as it appears to a deuteranomalous observer.

In anomalous trichromats one of the three cone types is anomalous and its spectral absorbance function is shifted towards the other.
Anomalous trichromats

- **Three** colours are required to match any other
- See a full range of colours, but with poorer discrimination in some regions

Types
- Protanomalous = anomalous L cones 1% (m)
- Deuteranomalous = anomalous M cones 5% (m)
- ‘Tritanomalous’ = incidence unknown

Red-green colour deficiencies are sex-linked. Genes for the L (OPN1LW) & M (OPN1MW) cone pigments lie nose to tail on the Q arm of the X chromosome (Xq28). Among individuals with normal color vision there is variability in the number of OPN1LW and OPN1MW genes per X-chromosome array, with more variability in the number of OPN1MW than in OPN1LW genes; thus, contrary to expectation, most people with normal color vision do not have just one L and one M gene.

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Due to their similarity, the L and M opsin genes are prone to unequal homologous recombination. Frequent mutations occur making these the most rapidly mutating genes in the human genome. Subsequent amino acid differences shift the spectral peaks of the L and M cone photo pigments causing color vision differences. Many rearrangements have occurred in the L and M opsin genes over the course of human history.

In dichromats one of the three cone types is missing

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3075382/
**Dichromats**

- Only need two colours to match any other
- Sees a much reduced range of colours

**Types**
- Protanope = lacks L cones 1% (male)
- Deuteranope = lacks M cones 1% (male)
- Tritanope = lacks S cones 0.002% ?

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**Ishihara test for RG color blindness**

- Transformation plates are #2 to 8 – defective observer sees a different number to the normal e.g. 6 > 5 or 5 > 2
- Vanishing plates are #9 to 17 – defective observer does not see a number
- Hidden digit plates – normal subject sees a path and the defective observer sees a number
- Classification plates – differentiate between deutsans and protans. Normal subject sees both digits equally. Deuteranopes see the first digit. Protanopes see the second digit. In mildly color deficient (anomalous) observers the diagnostic digit is seen but is less visible.

http://www.colorblindness.com/2012/10/22/ishihara-test-for-colour-deficiency/38-plates-edition#prettyPhoto

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**Monochromats**

No colour vision: any colour matched with any other

- Rod monochromat (0.003%) (also called 'complete achromatopsia'). All cones are functionally absent: subjects have no colour vision, low acuity, photophobia and nystagmus
- Blue cone monochromat (also called 'incomplete achromatopsia' or 'atypical monochromat'). Only S cones are present (0.001%): subjects have no colour vision, low acuity, no photophobia, no nystagmus. Worse in artificial illumination.

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**U tube video of Ishihara**

https://www.youtube.com/watch?v=hwGDOJyZJnk

See sheet handed out.
Score is out of 16 and excludes first plate (12) and the 4 classification plates.

**U tube video of Farnsworth Munsell Panel D15**

https://www.youtube.com/watch?v=ysk4HLsWZ8M
Example images simulated to show color ranges as seen by trichromats, dichromats (protanopes, deuteranopes, tritanopes) and monochromats.

End of part 1.
Note: slides after this one were not used in the presentation.
Chromatic receptive fields: L/M cone opponent pathways for color vision

1. L/M (red-green) cone opponency: P cells of retina & LGN (80%). Respond to one color not to color differences.

2. S cone opponency (blue-yellow): bistratified ganglion cell & K cells of LGN (5%). Respond to one color not to color differences.

3. Luminance (black/white or achromatic): P cells and M cells. Parasol (M) cells are specialized for flicker and project to the motion sensitive areas of the brain – form about 10% of retinal ganglion cells. Respond to luminance differences (contrast).

This represents the receptive field of an L/M cone opponent P cell. In terms of color, this cell responds best to a red uniform field. It doesn’t respond well to color contrast (i.e., color differences). Thus the cell has no spatial tuning and no orientation tuning for colored visual. It does respond to achromatic contrast (black & white). This cell type is found in the retina, LGN and in the first stages of processing in the primate visual cortex and was termed a ‘Type 1’ neuron by Hubel & Weisel (1966).

Chromatic receptive fields: Many single opponent cells may be combined to form a double opponent cell – found in primate cortex

Illustration of how RG color vision varies across the visual field showing that L/M cone opponency is more confined to the central visual field than achromatic vision.

A pattern with colors that activate only the L vs M ('red-green') cone opponent process

A pattern with colors that activate only the S vs L+M ('blue-yellow') cone opponent process

http://www.wellesley.edu/Neuroscience/Faculty_page/Conway/science/color_cell_movies/spatial_color_opp.mov
Human contrast sensitivity to isoluminant red/green and luminance gratings