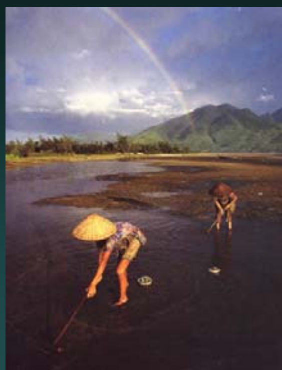
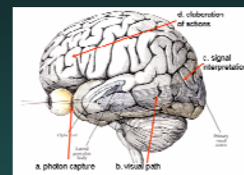


Color perception

Rolf Kuehni

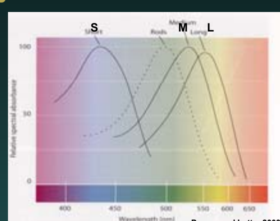
Color: Stimulus versus perception

Color stimuli: Generally, **lights entering the eyes**. Exceptions: dreams, drugs, concussions.



Color perceptions: Stimuli interact with the color vision machinery in eyes and brain, resulting in **conscious color experiences**.

Spectral sensitivity of human sensors

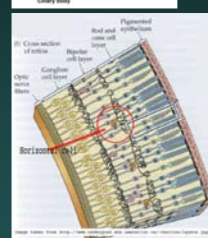


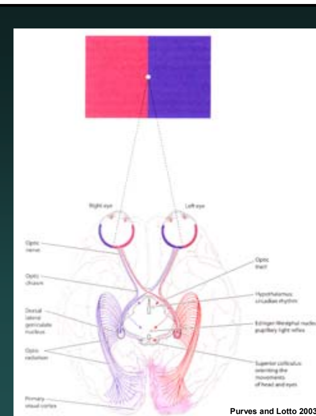
RH1 sensor: rods, night vision, B&W only.

S and L sensors (cones): **genetically ancient**.
M sensor (cone): genetic modification of L cone, dated to about 35 MYA.

Brain generates **colored conscious experiences** (perceptions) from electrochemical signals of the 3 cone types L, M, and S.

Human visual path





Example of what it looks to us in consciousness (and in dreams).

We can perceive about 1 million different object colors.

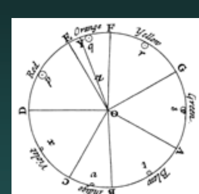
Is there a way we can put all different color perceptions into some kind of order?

Among colors some look similar, others much different.

In what way do they look similar or different?

Isaac Newton, in the late 17th c., first described 3 different aspects (attributes) of color perceptions:

- *Colour* (his term for **hue**)
- *Luminosity* (brightness, **lightness** in case of objects)
- *Intenseness* (saturation, **chroma** in case of objects)

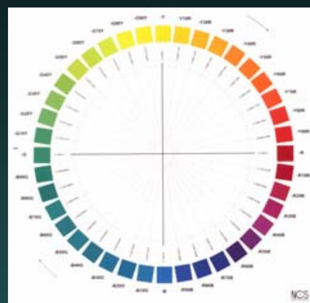


He developed a color circle explaining the results of mixture of lights of different wavelengths.

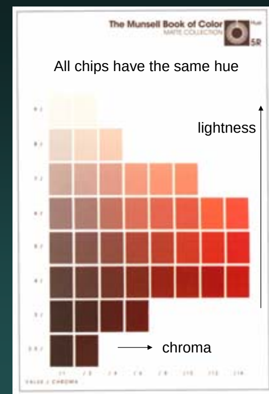
He recognized 7 major different hues in the spectrum.

Hue circles

The first handcolored printed hue circle from 1708

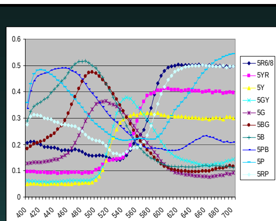


A modern hue circle (NBS)

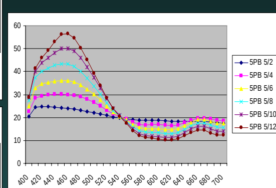


Constant hue but changes in chroma and lightness

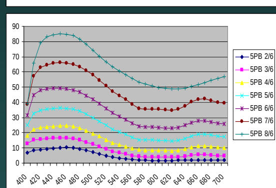
How do the three attributes differ as stimuli?



Only hue changes

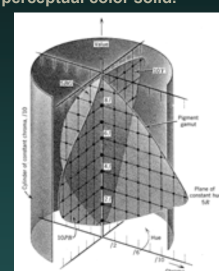


Only chroma changes



Only lightness changes

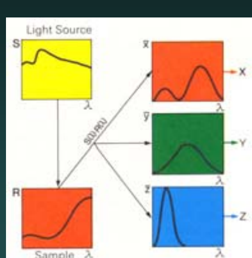
Arranging all possible object colors in this fashion results in an irregular perceptual color solid.



Four hue planes of the Munsell color solid

Is there a comparable space based on color stimuli?

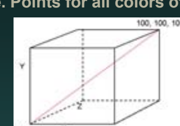
Color stimulus: light of a given spectral power distribution as reflected from an object



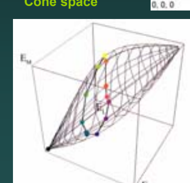
The stimulus is absorbed or filtered by the three **cone types** (or their twins, **the color matching functions**).

Result: 3 numbers representing the degree to which each cone type is stimulated by the reflected light.

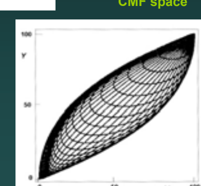
Each number is a value on a scale of 0 to 100. The 3 scales can be placed at right angles, forming a **space**.
The 3 numbers for a given object and light are represented as **a point** in this space. Points for all colors of objects form a **solid**.



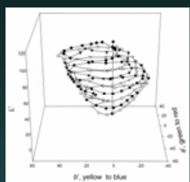
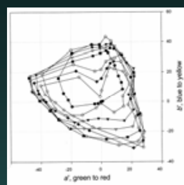
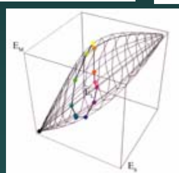
Cone space



CMF space



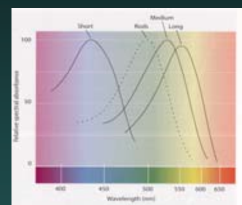
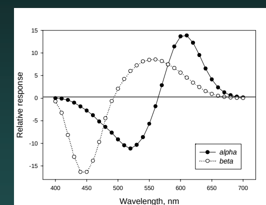
How do the perceptual and the stimulus spaces compare?

After absorption in the cones there are **many more steps** in the path between cones and perception.

Opponent color system or 'comparator' apparatus

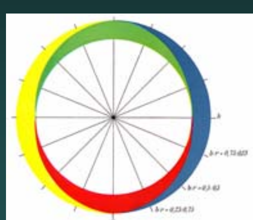
Wide overlap of *L* and *M* cone sensitivity functions. A 'comparator' system **comparing cone outputs** developed to improve distinction. Wavelength region distinction: α = *L* – *M*, and β = *S* – (*L*+*M*)

α and β cells exist in the LGN. What happens past LGN is not yet known. These *opponent color* functions are not in good agreement with perceptual data.

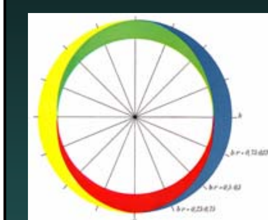
Perceptual opponent color system

Perceptually, we distinguish between 2 pairs of primary hues:
yellow vs. blue, and red vs. green.
The primary hues are known as **unique hues**.
In the 19th century **Ewald Hering** showed that, perceptually, all hues are UHs or mixtures of two UHs.



Hering placed the UHs in opposing pairs: red has no greenness and vice versa.
The same applies to yellow and blue.

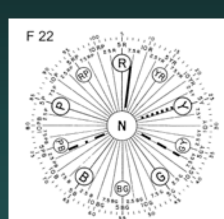
Does everybody perceive the UHs from the same color chips?




Experimental set-up with 40 Munsell color chips

Unique hue stimulus selection

• Choices of color normal people of the Munsell chips that represent **for them** the 4 UHs vary to a remarkable degree.
This points to an absence of a close relationship between stimulus and resulting perception.



Reflectance curves: closely related to color perceptions?

There are many facts that say no.

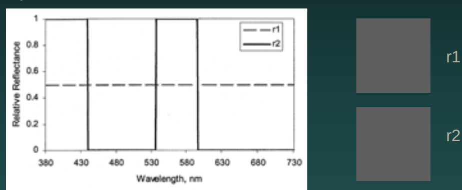
1. Variability in UH stimulus selection
2. Metamerism
3. Contrast effects
4. Adaptation effects
5. Color constancy effects
6. Helmholtz-Kohlrausch effect
7. Hue superimportance effect
8. Filling-in effect

etc.

2 Metamerism

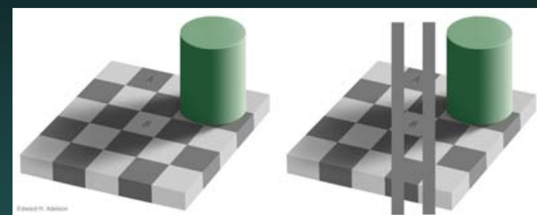
Infinite numbers of reflectance curves resulting in identical output from the 3 sensor types, thus looking identical in a given light.

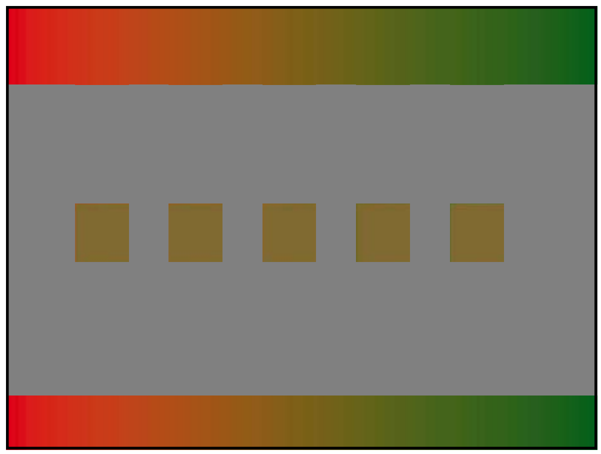
They are called metamers.



Metamers are technically important (visual displays, color photography) and technical problems (metameric matches).

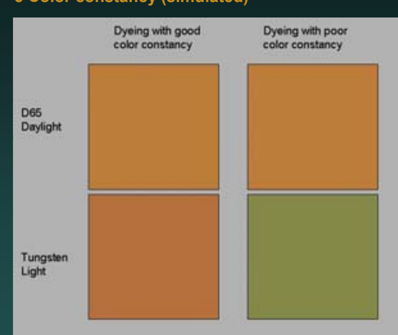
3a Simultaneous lightness contrast



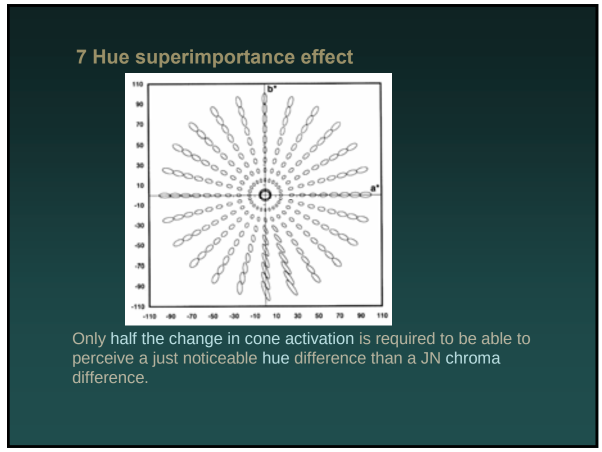


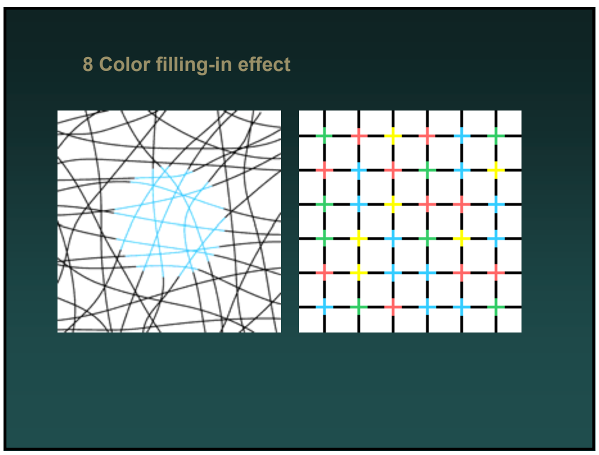
4 Adaptation to color of light

5 Color constancy (simulated)

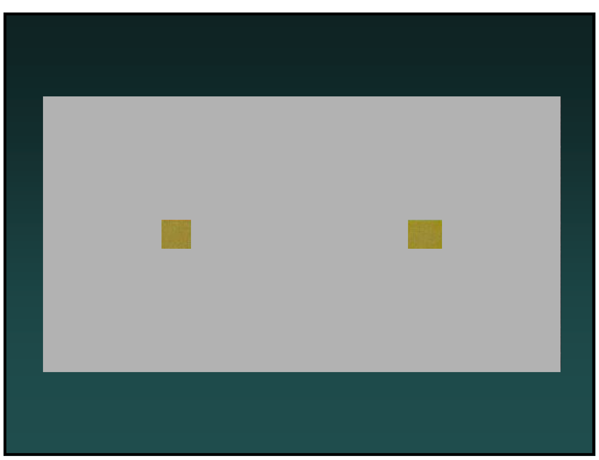


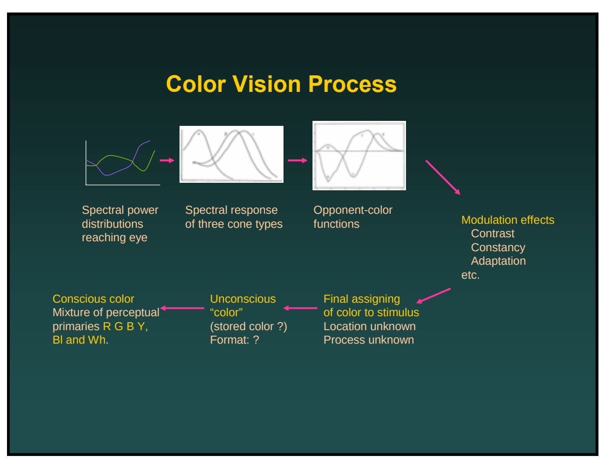

6 Helmholtz-Kohlrausch effect


7 Hue superimportance effect
b*
a*
Only half the change in cone activation is required to be able to perceive a just noticeable hue difference than a JN chroma difference.


8 Color filling-in effect


Complex effects
Purves and Lotto 2003
Contrast and apparent change of illumination




Color Vision Process
Spectral power distributions reaching eye
Spectral response of three cone types
Opponent-color functions
Modulation effects
Contrast
Constancy
Adaptation
etc.
Final assigning of color to stimulus
Location unknown
Process unknown
Unconscious "color" (stored color ?)
Format: ?
Conscious color
Mixture of perceptual primaries R G B Y, Bl and Wh.

Color perception:
Color (stimulus) mixture

Can we predict the result of mixtures of lights?

We can predict which lights have the same appearance (matches) but not what the appearance is.

Predictions are possible based on average cone functions (or their relatives color matching functions).

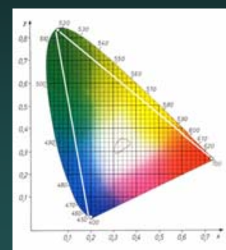
As shown earlier, stimuli with identical tristimulus values match for the average or standard observer.

This is best shown in a 2D slice through the color stimulus space.

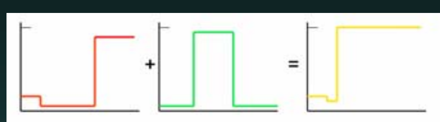
Mixing lights, additive mixture

The slice used in technology is the CIE chromaticity diagram.
It is similar to Newton's diagram but based on color matching functions.

Spectral lights fall on the horseshoe shape, "white" light near the center.



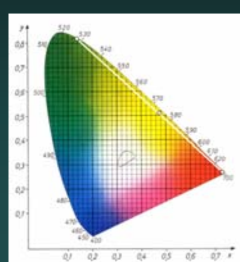
- Can be used to predict the result of mixing lights.
- Result of mixing any 2 lights falls on a straight line between them. If the line passes through the center the mixture of 2 highly chromatic lights can be "white"light.
- Result of mixing 3 or more lights can also be predicted.
- Any hue in most saturations can be obtained with 3 spectral lights.



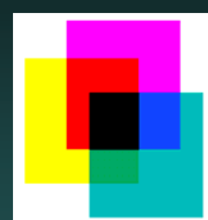
Additive mixture:

Adding red and green saturated light together results in yellow-appearing light.

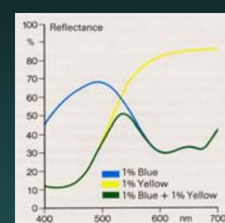
Mixtures of lights are brighter than either light alone.



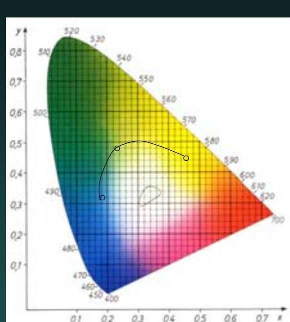
Mixing colorants (dyes or pigments) is more complex: subtractive mixture



Subtraction of light with 3 filters



Reflectance of mixture of a yellow and a blue dye



Chromaticities of mixtures of colorants do not fall on straight lines but on curves.

The mixtures are darker than the individual components.

Any hue can be obtained with 3 primary colorants, but the farther the mixture is away from one of the colorants, the lower the chroma of the mixture.

Can we measure color accurately?

Depends on definition of color

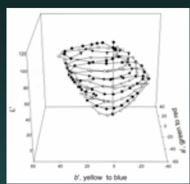
If color means stimulus: yes

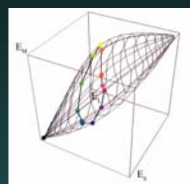
Reflectance and spectral power distribution can be measured accurately with instruments and proper methods.

If color means perception: no

Color normal people's experiences from a stimulus vary; also depend on lighting and surround.

Creating accurate models is difficult





A good model must accurately predict the shape on the left on basis of the shape on the right.

Mathematical models of color appearance

• There are many models of color appearance.
Among the technically most important are **color difference formulas**.
• Just as in case of unique hues **people differ widely** in their perception of color differences.
• No **absolute true values**.
• Formulas are fitted to the CIE standard observer and average color difference perception data.
• **Best formulas** represent average perceptual data with an accuracy of **about 65%**.
• Calculated differences are nevertheless important because reflectance measurement is much more accurate than individual visual judgments.

Conclusions

• Color vision process: very complex. We know only small portion.

• Three perceptual attributes of (object) color: hue, lightness, chroma.

• Several effects show: color percepts not directly related to reflectances.

• Color stimuli can be represented in psychophysical spaces, color percepts in psychological spaces: considerably different.

• Light mixture (additive) and colorant mixture (subtractive) are much different.

• Fitting psychophysical models to psychological data is complex, results approximately valid only for average observer. Nevertheless often useful.