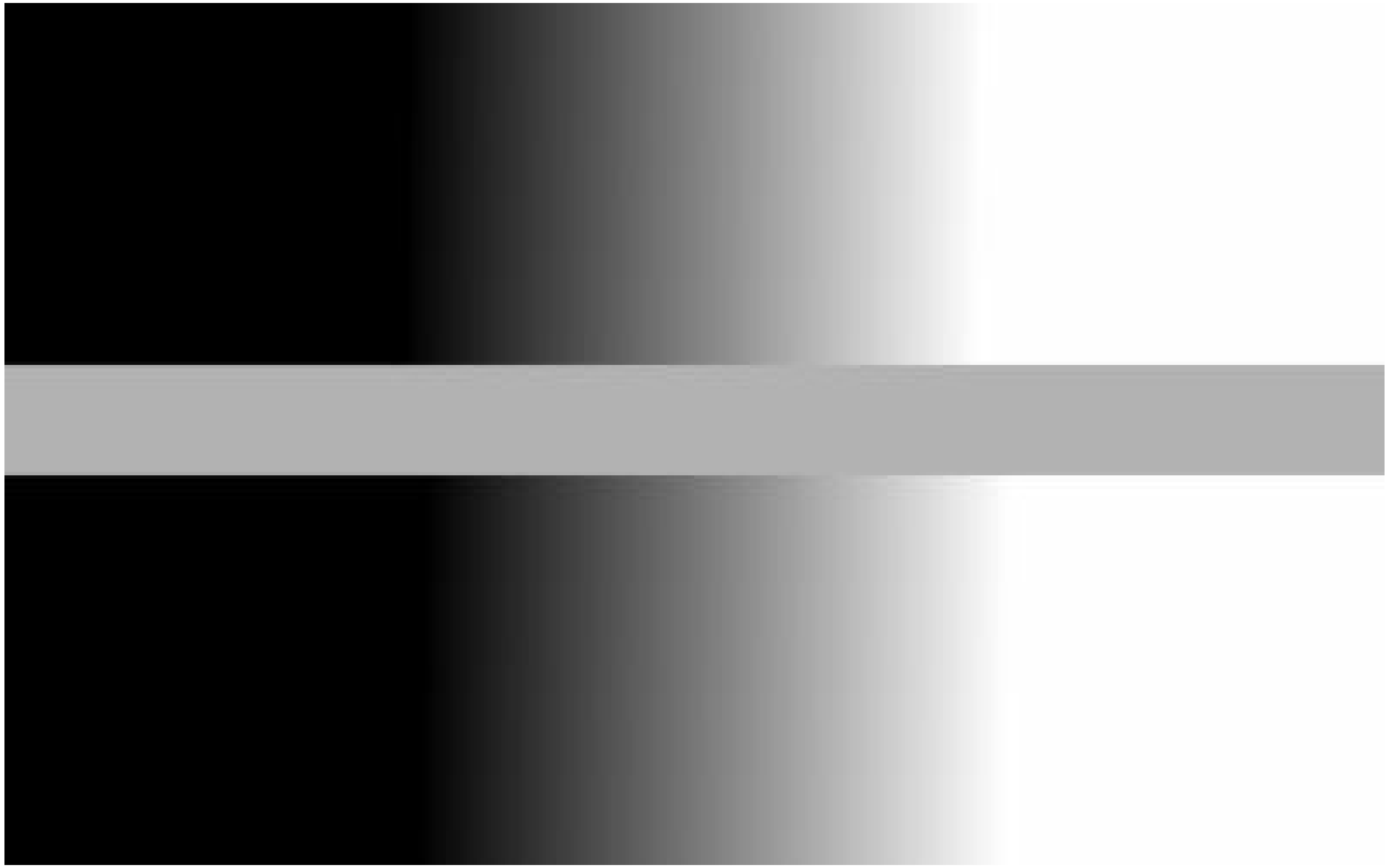
# Colour Perception and its physiological basis

- Basic phenomena of colour perception
  - Simultaneous contrast
  - Mach bands
  - Afterimages
  - Chromatic adaptation
  - Intuitions about pure colours
- Three-colour theories and the physiology of the retina
- opponent colour theories (four-colour theories) and the visual cortex

# Simultaneous contrast

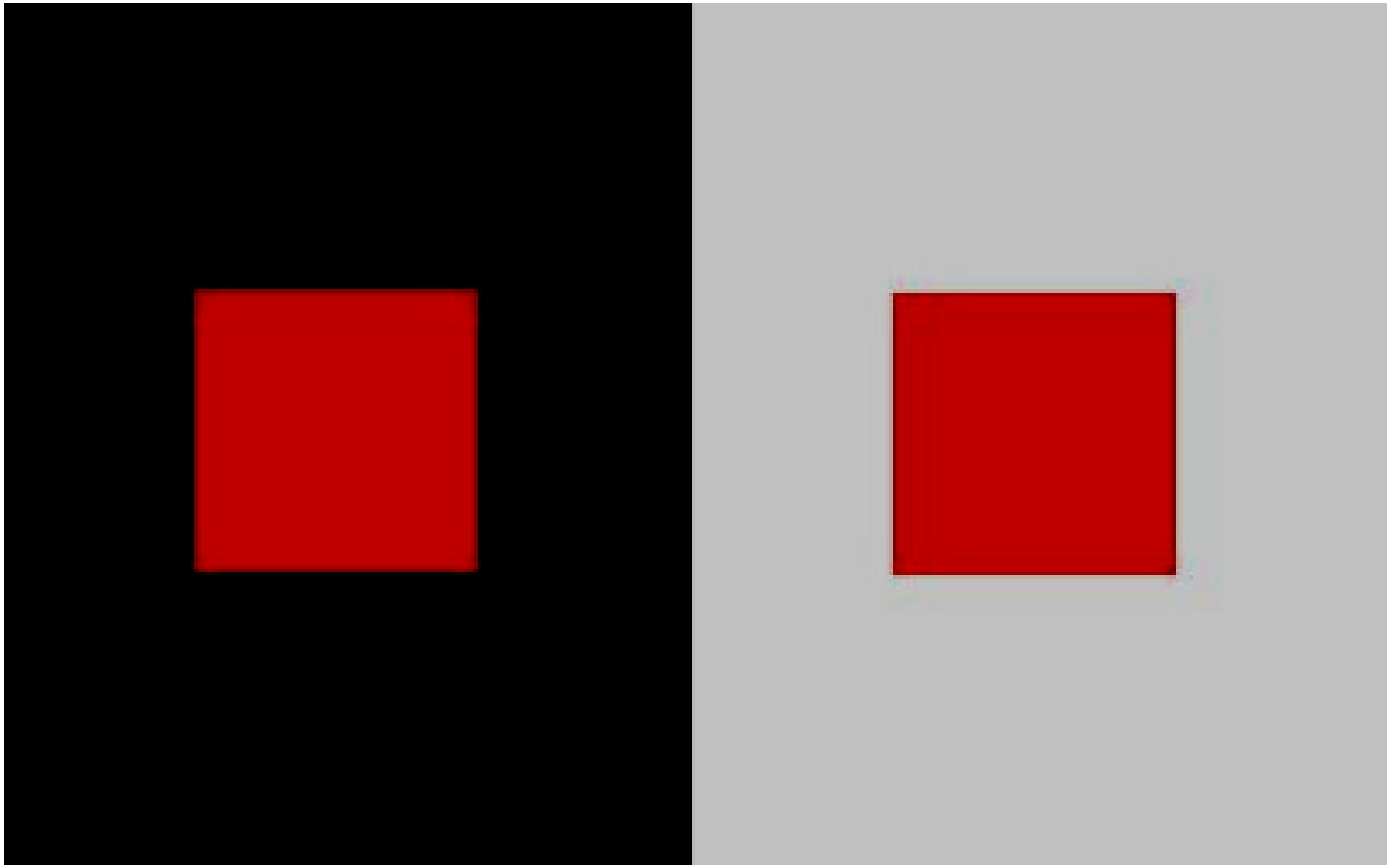
## Simultaneous contrast



The brightness of a region does not simply depend upon its intensity. The contrast with the surrounding region is important.

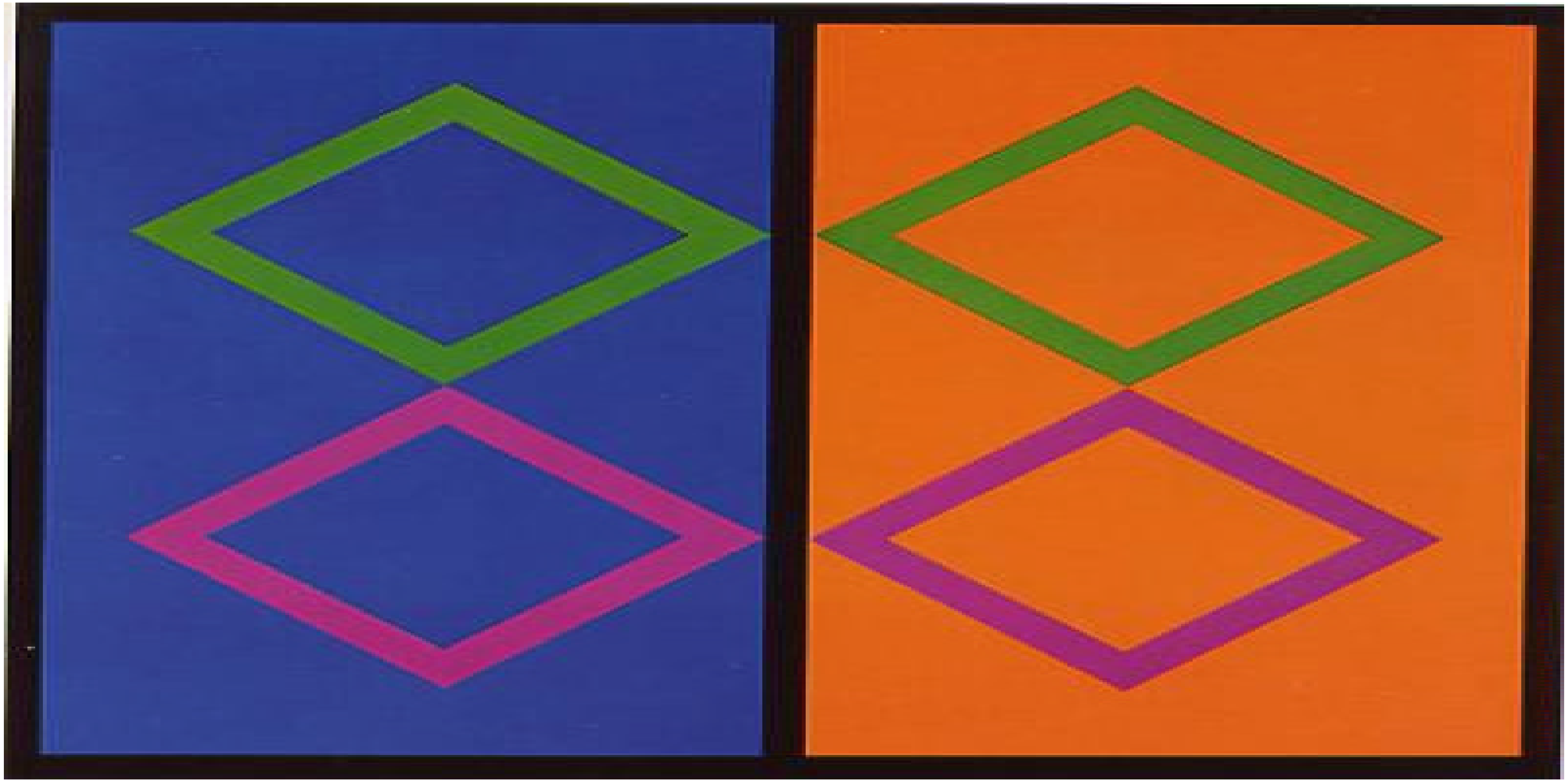
A region looks much darker when the surrounding region is more illuminated. This is important for brightness constancy (white paper in a dark room)

## Simultaneous colour contrast

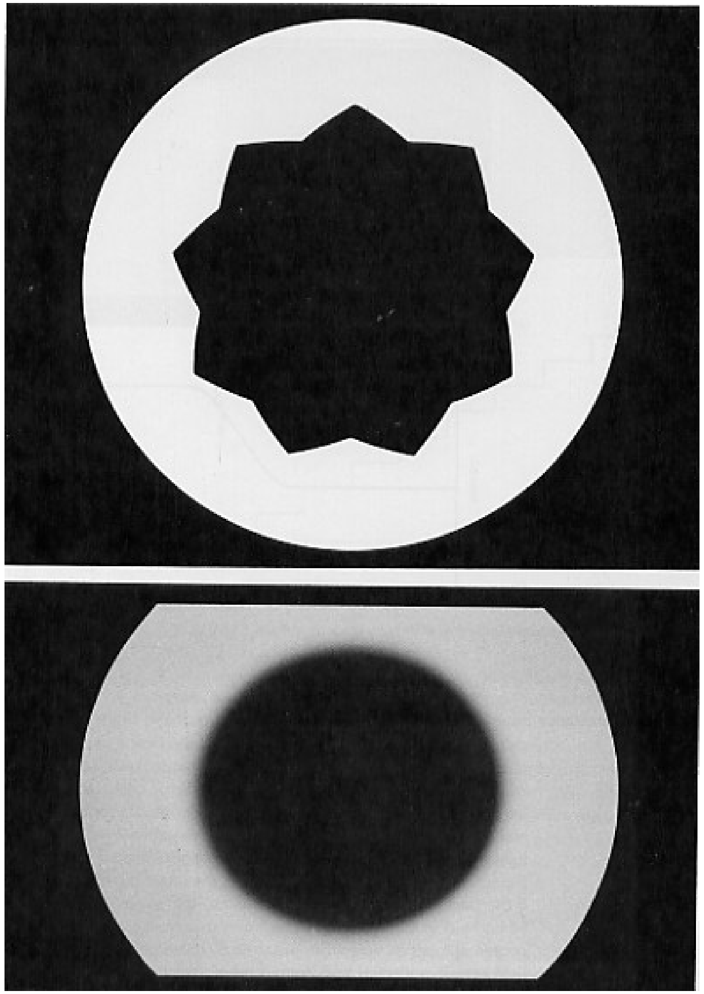


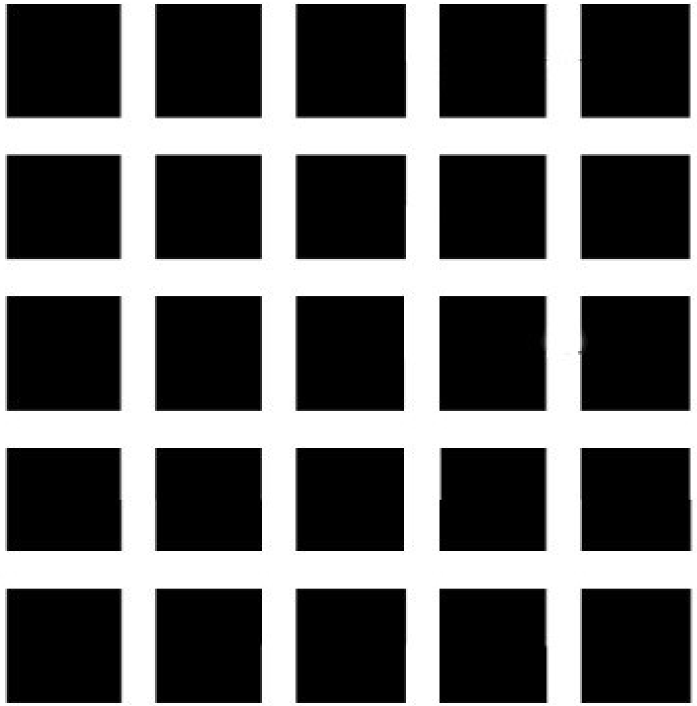
The same light stimulus can trigger different colour appearance – dependent on the colour of the surrounding region.

# Simultaneous colour contrast cont.



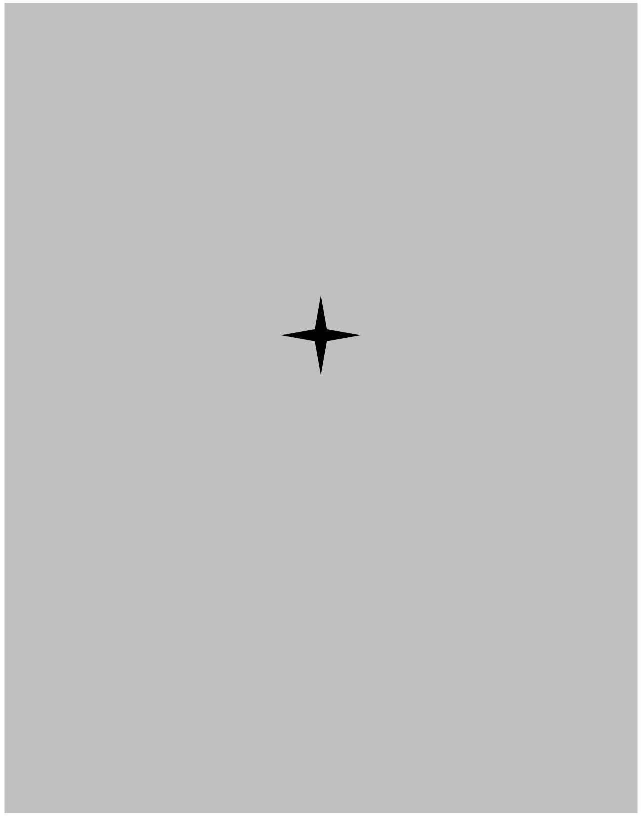
# Mach bands





The existence of Mach provides another powerful illustration that brightness is not a simple function of intensity.

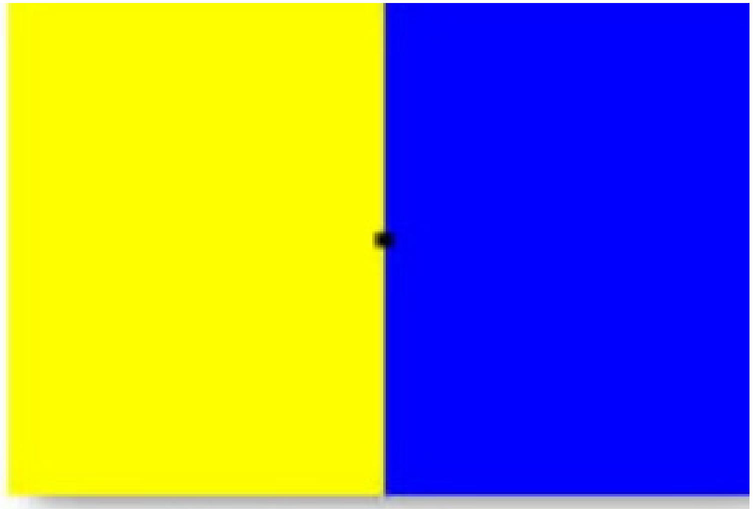
## Afterimages



Stare at the black star in the centre of the image for 30 seconds without letting your eyes wander. After the 30 seconds are up, look at the black star on the left!

## Chromatic adaptation

Fruit Basket Image



Adapting Image

Chromatic adaptation refers to the ability of the human visual system to compensate for changes in the prevailing colour of the viewing environment. By staring at the adapting image for 30 seconds, you have temporarily changed the colour responses of those areas of your visual system through chromatic adaptation

## Intuitions about pure colours

- We have exactly four pure colours and not only three (as trichromacy may suggest)

  Red Green Yellow Blue

- There is bluish and yellowish Red but no greenish red (or bluish yellow)

Both observations (which were already made by Johan Wolfgang von Goethe in his "Farbenlehre") are difficult to understand assuming *trichromacy*

## Three- and four-colour theories

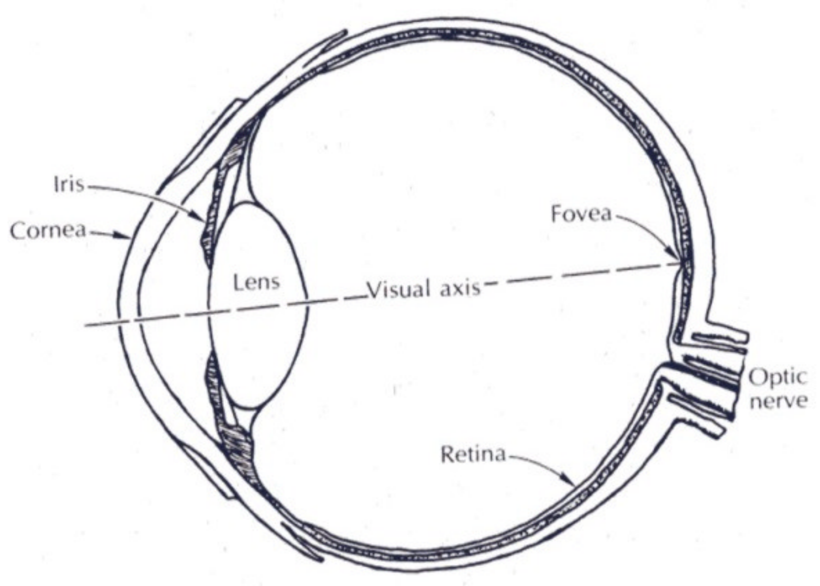
***Helmholtz' (1896) Trichromacy:*** His *principle of trichromacy* means that every colour can be realized by a linear combination of three primaries. (e.g., red, green, blue)

***Hering's (1875)* opponent colour theory:** The visual system is determined by three antagonistic processes (opposite colours: bright-dark, red-green, yellow-blue). Evidence comes from the reality of afterimages and the existence of four pure colours.

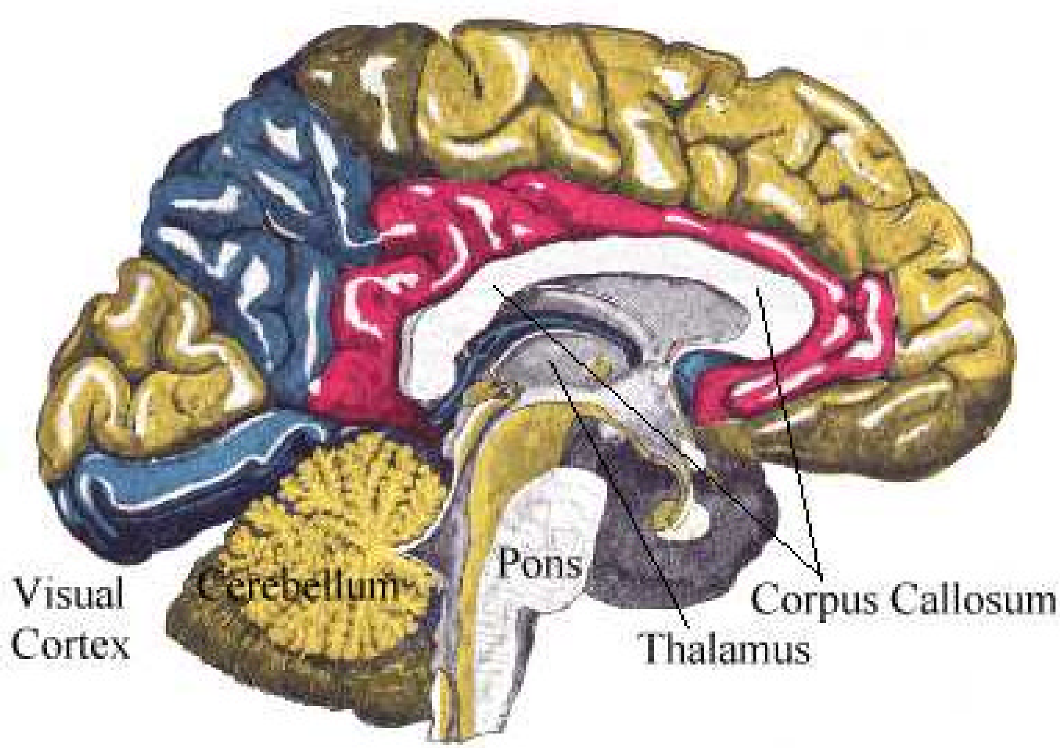
It is important that both theories conform to a three-variable scheme. Hence, the theoretical issue is not the number of parameters but the explanation of certain psychological and physiological phenomena.

## The physiological basis of colour

(A) The Retina (*trichromacy*)

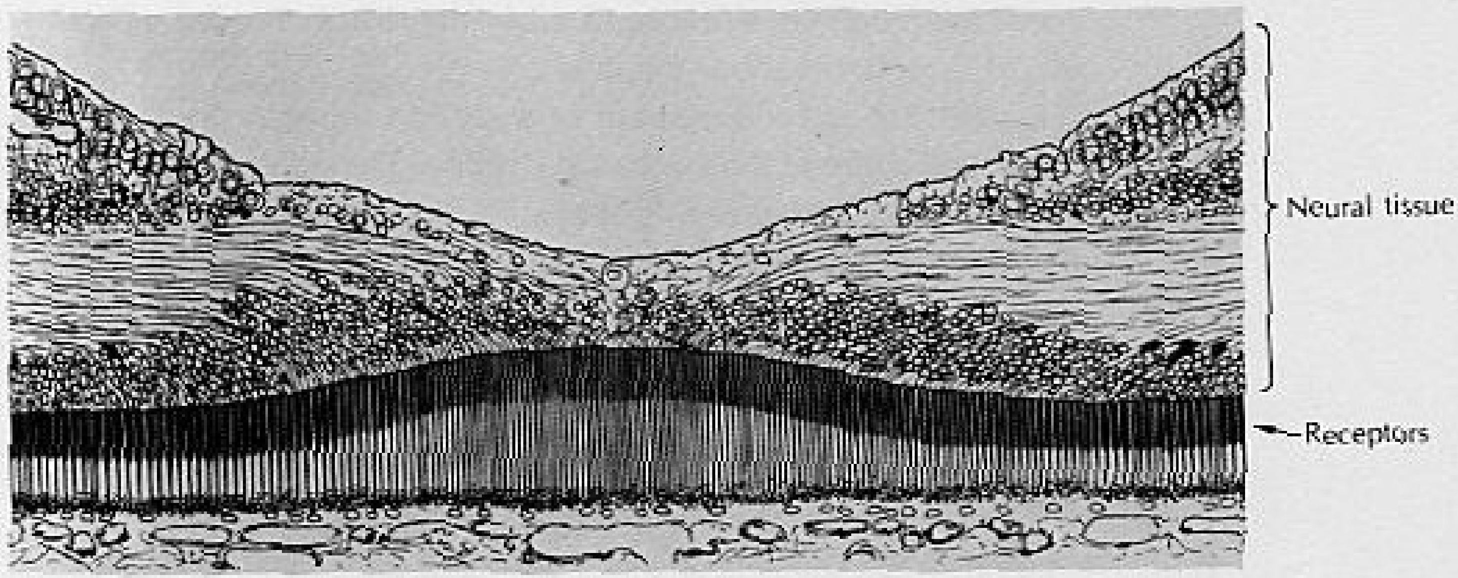



(B) The visual cortex (*tetrachrromacy*)



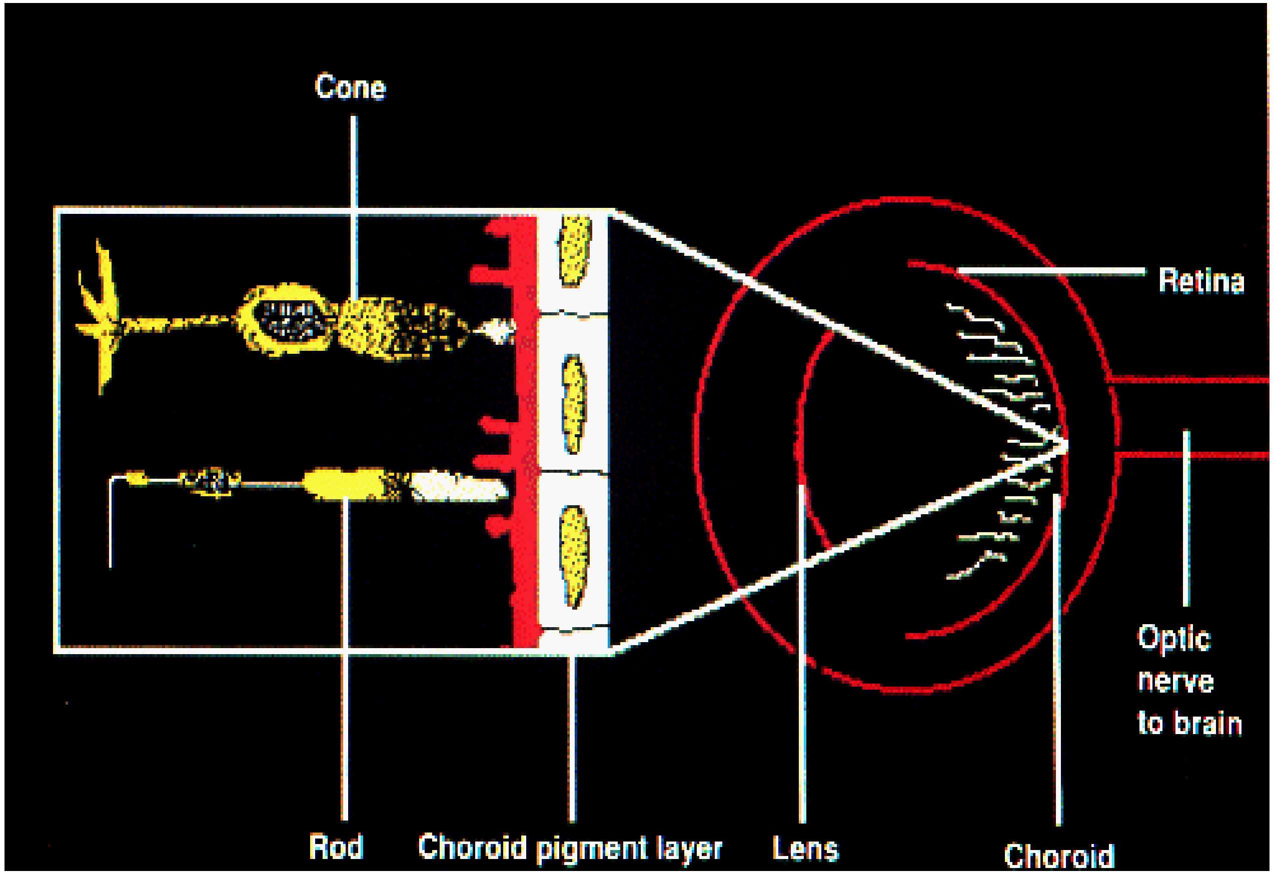
## Three-colour theories and the physiology of the retina

Wald and Brown in 1965 confirmed the Young-Helmholtz tristimulus theory of colour vision photochemically by identifying three kinds of photopigments in retinal cones.




Sketch of a cross section through the region of the *fovea* in the human eye. The front of the eye would be above the top of the page. [*From Polyak (1957) Copyright © 1957 by the University of Chicago Press.*]

# Cones in the retina

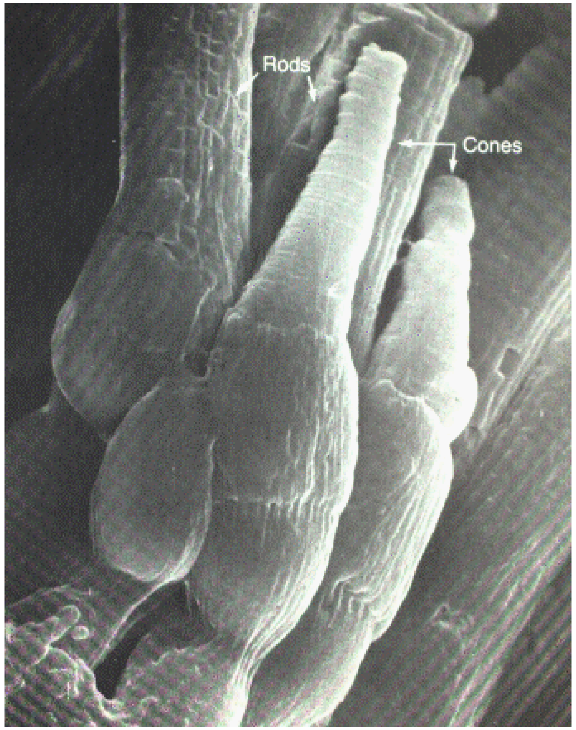


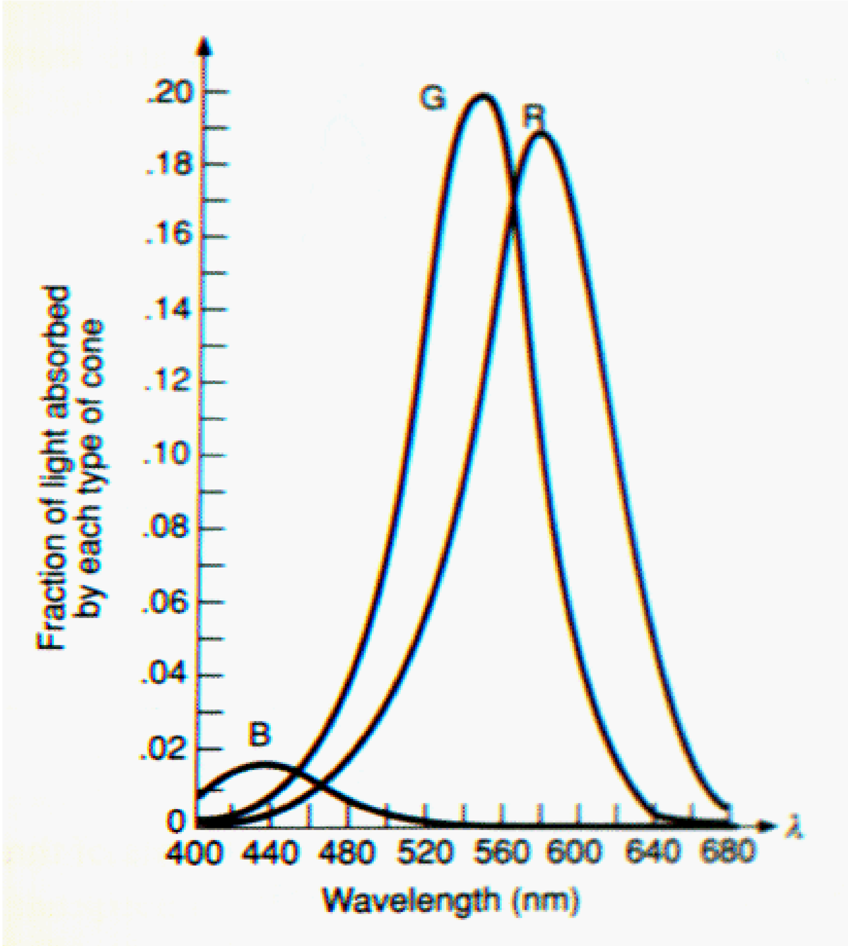

Within the human eye are two element which are responsib-le for the perception of light: *rods* and ***cones***.

The rods contain the elements that are sensitive to light intensities. They are used almost exclusively at night for humans night vision.

The cones provide humans with vision during the daylight and are separated into three types, where each type is more sensitive to a particular wavelength.

## Three types of cones



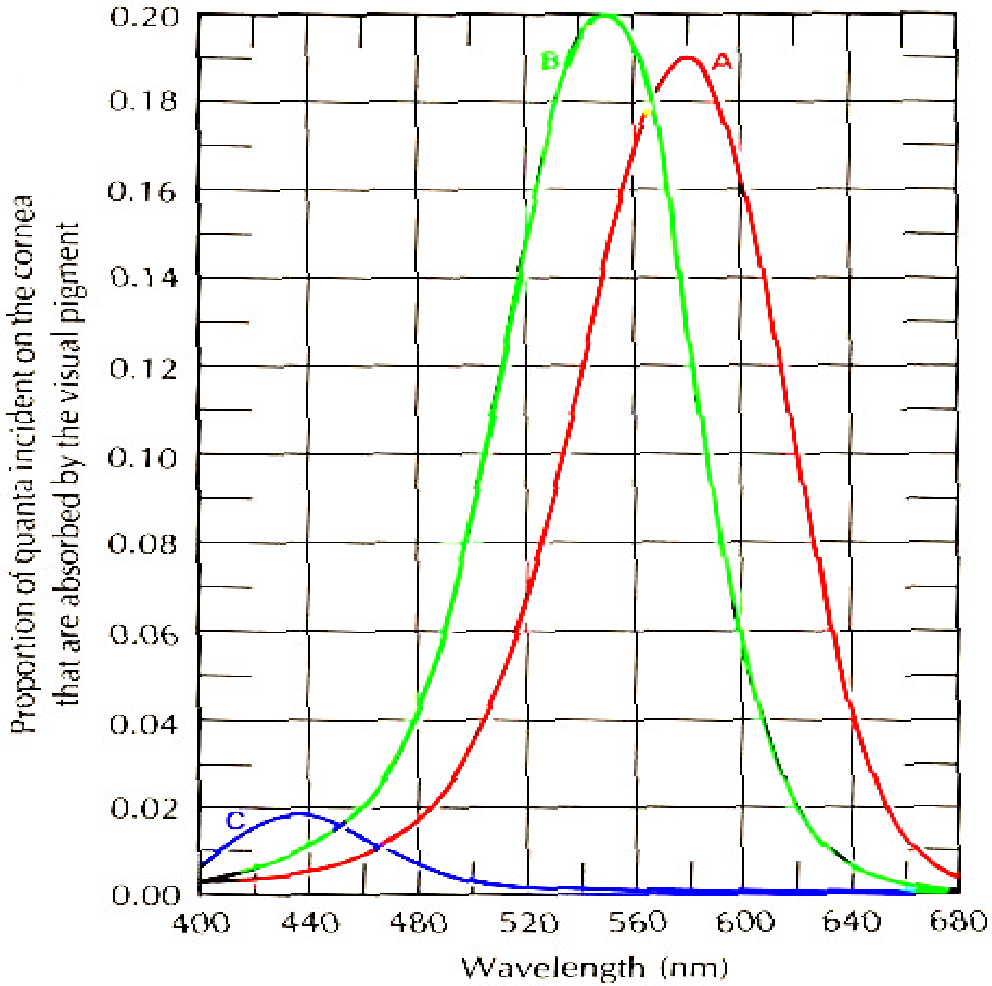

The three types are distinguished by containing three different kinds of the pigment *Rhodopsin:* α,β,γ–Rhodopsin. This leads to 3 different spectra for the absorbed light.

## Colour matching functions

- To developing device-independent colour spaces (CIE), people were asked to match a given colour with R, G and B primaries (e.g., R= 645nm, G=523nm, B=444nm). This results in three functions, r(l), g(l) and b(l), the RGB *colour matching functions* of the CIE system.

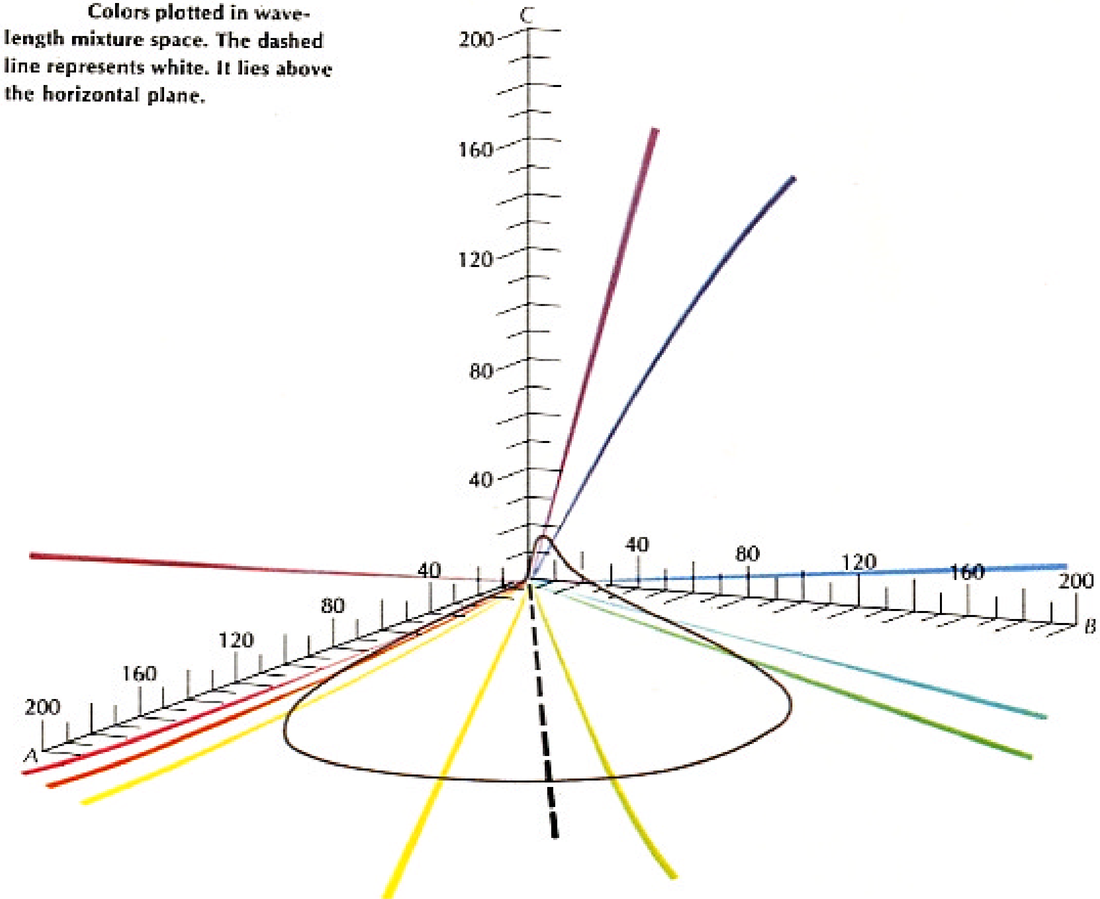
- Matching functions representing the different absorption spectra of the three different kinds of the pigment *Rhodopsin* are appropriate to describe the colour characteristics of the human eye.

# Absorption spectra on the retina




**Estimates of the absorption spectra of the three color-systems in a human subject with normal color vision. These curves are actually derived from psychophysical measurements that agree well with direct physical measurement, such as will be described in the text. They are estimates of the absorption spectra of the visual pigments as seen from the cornea, that is, after having been affected by the absorption of the nonvisual pigments of the eye, and by the relative numerosities of cones containing the different pigments. According to Wald, who published these curves, the** *C* **curve is about three times higher in this subject than that in the average subject.** [*From Wald (1964) assuming 80% losses. Copyright, 1964, by the American Association for the Advancement of Science.*]

**Three dimensional wavelength micture mixture space**

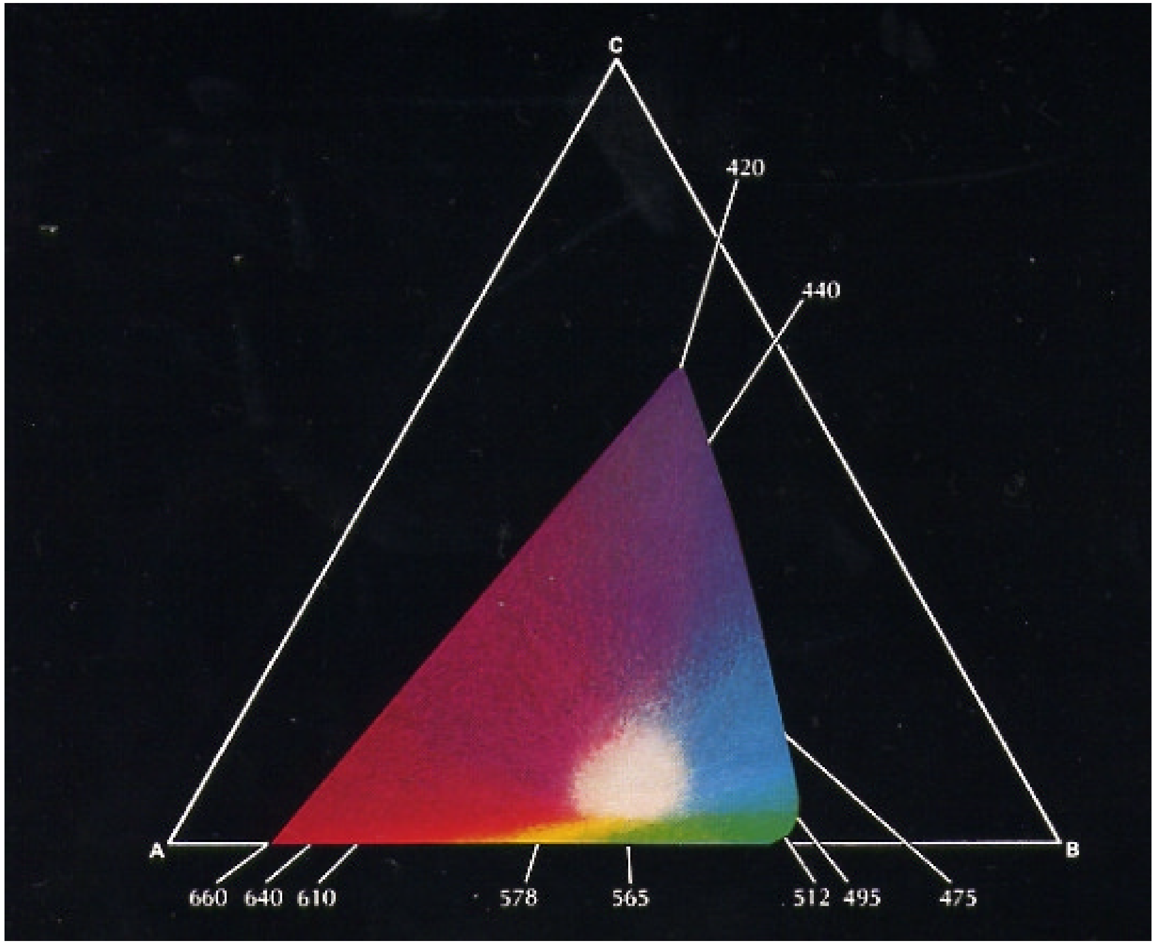


Colors plotted in wave-length mixture space. The dashed line represents white. It lies above the horizontal plane.

Corresponding to the normative XYZ space, an ABC space reflecting the colour properties of the retina can be constructed using the given absorption spectra.

In the figiure, the dashed line represents white and the black curve the 1000 quanta spectral locus (400-700nm)

## Section through wavelength micture space

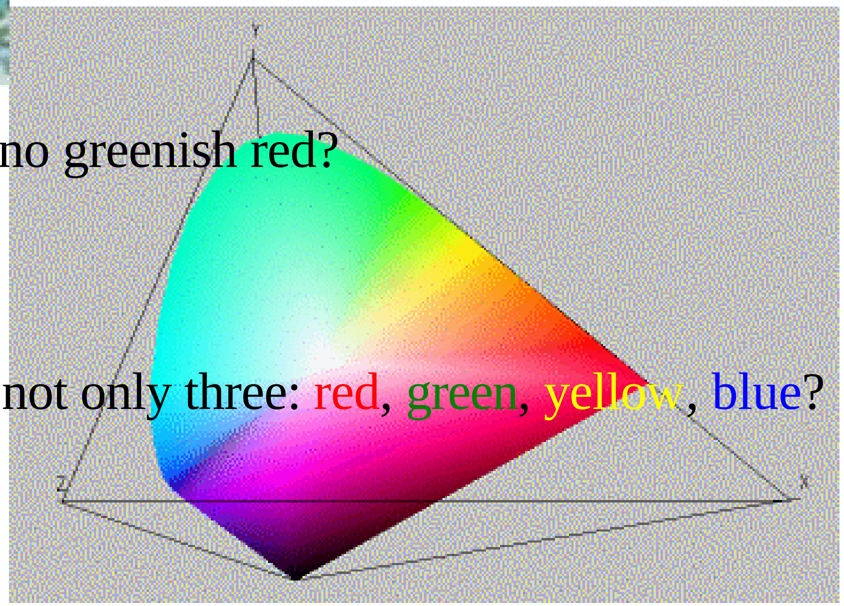



A section through wavelength mixture space that forms an equilateral triangle with the axes. This corresponds to A+B+C=constant and is appropriate to represent the two chromatic values (due to hue and saturation) and fixing luminance. The close relation to the chromatic coordinates x and y of the CIE system is obvious (though there are many differences).

## The problems for trichromatic colour theories

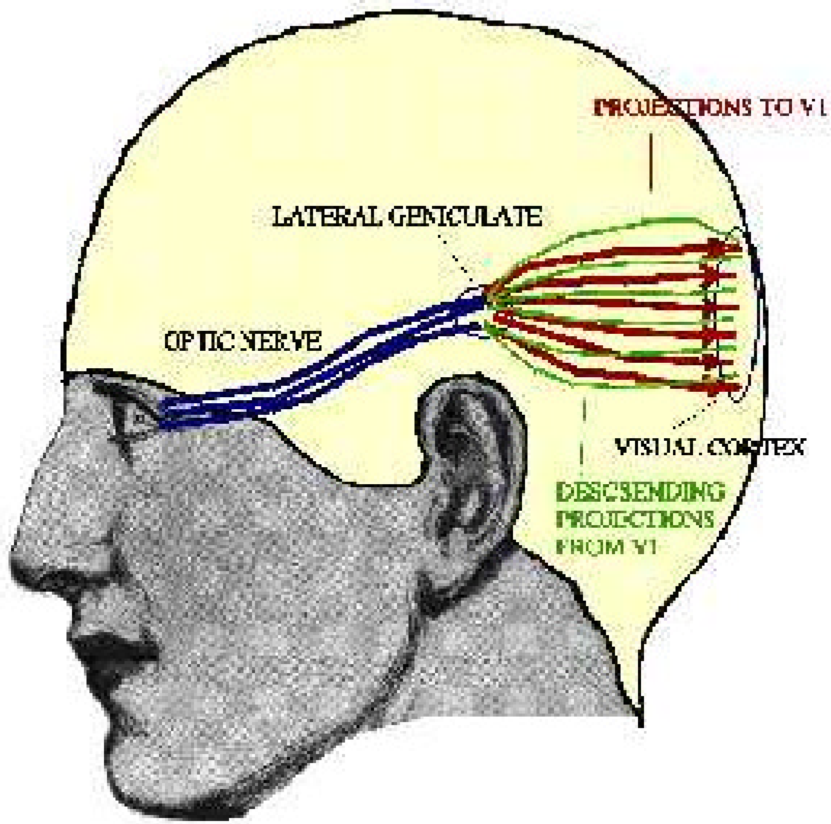
- The existence of afterimages

- Why do we have bluish and yellowish Red but no greenish red?
- Why do we have exactly four pure colours and not only three: red, green, yellow, blue?



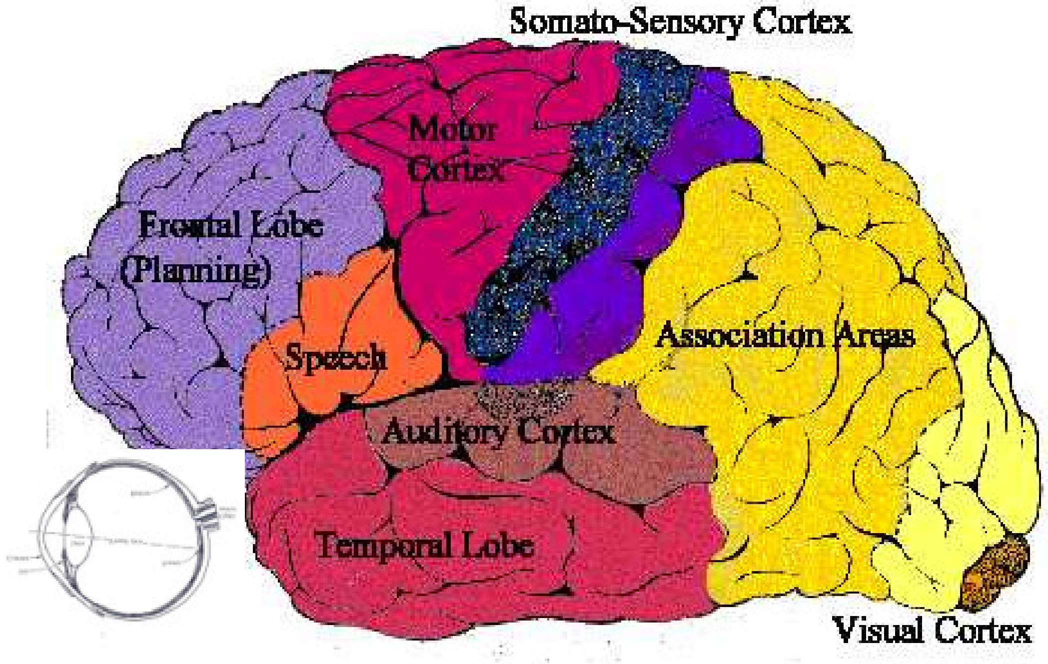
## The path of colour (when a pattern of light is affecting the retina)

"A representation on your retina is transformed by going through a trillion little synapses into a new pattern at the LGN that is projected forward to V1 (the primary visual cortex), (where it is) transformed by another population of synaptic connections in to a third pattern. It rather looks like the basic mode of representation in the brain is in patterns of activation across populations of neurons, and the basic mode of computation is transformation from one pattern to another pattern, to another pattern. Transformations which co-opt relevant kinds of information. Information that is relevant to its day-to-day behaviour." [Churchland at Tucson II]



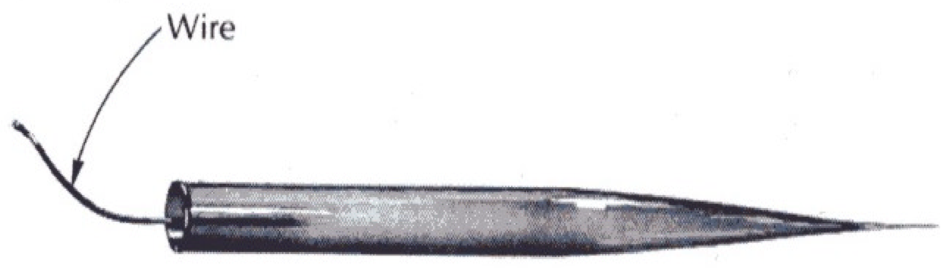
## Opponent colour theories and the visual cortex

Colour perception is not alone determined by the receptors on the retina but primarily by properties of the visual cortex.



## De Valois et al (1966)

Studies by De Valois et al (1966) and others, which have used microelectrodes to monitor single neurons, have been concerned with the neural representation of colour in the neural pathway between the eye and the brain.



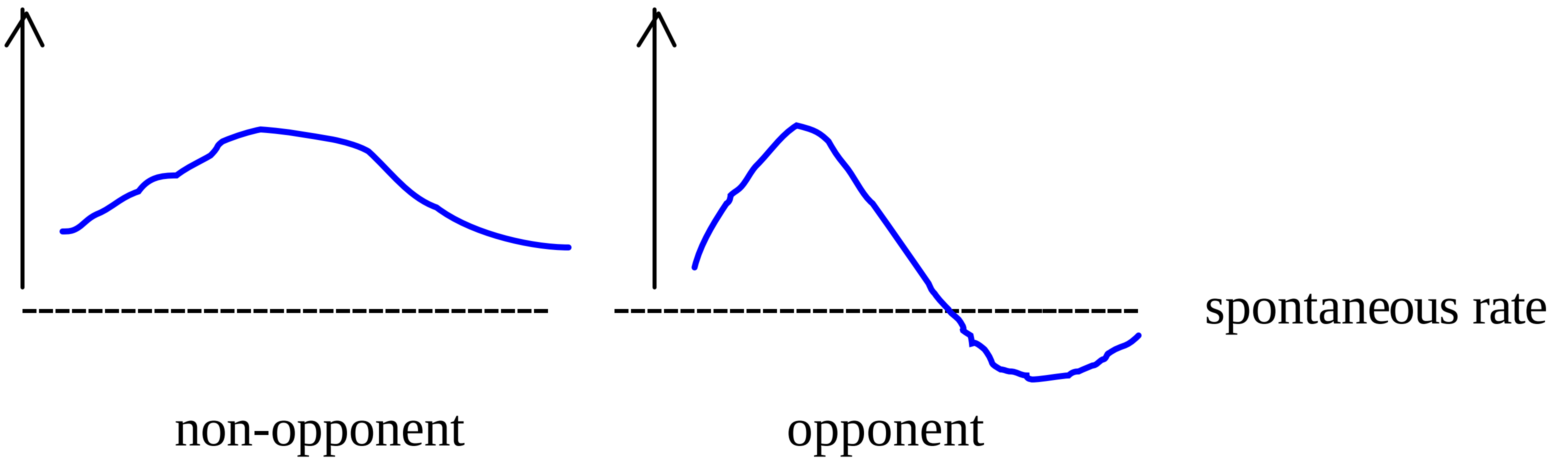

The result of heating a hollow glass tube in the middle and pulling it sharply. The tube has a very fine point and the hole runs all the way through.

They found opponent response nerve cells that correspond to Hering's opponent systems : red-green, yellow-blue.

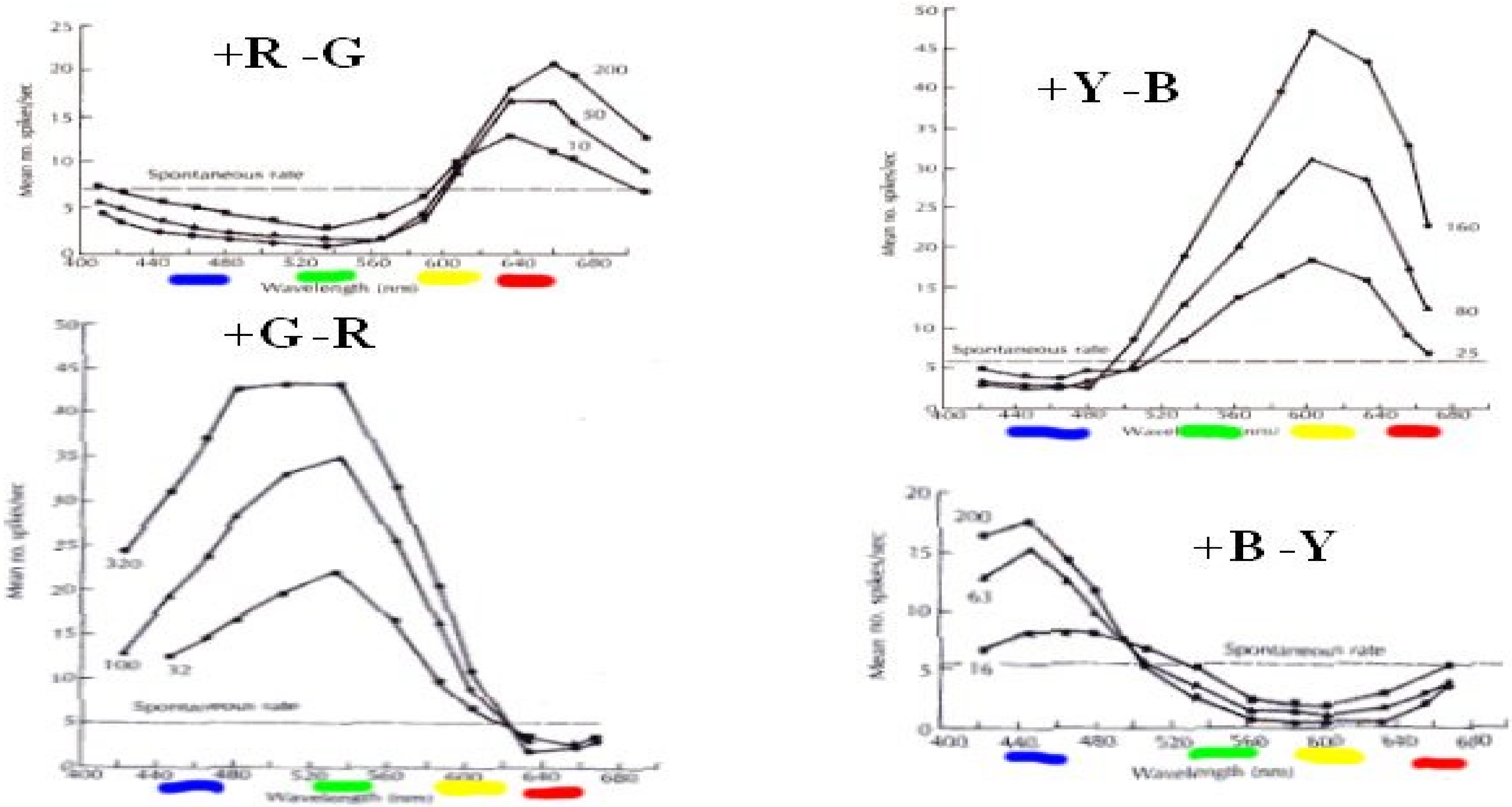
## Opponent response cells

- They have a spontaneous rate of firing – a basal response rate that they maintain without extern stimulation.

- They show an increased rate of firing in the presence of light of a certain region of the visual spectrum while lights from the complementary regions will decrease its rate of firing below its basal rate.

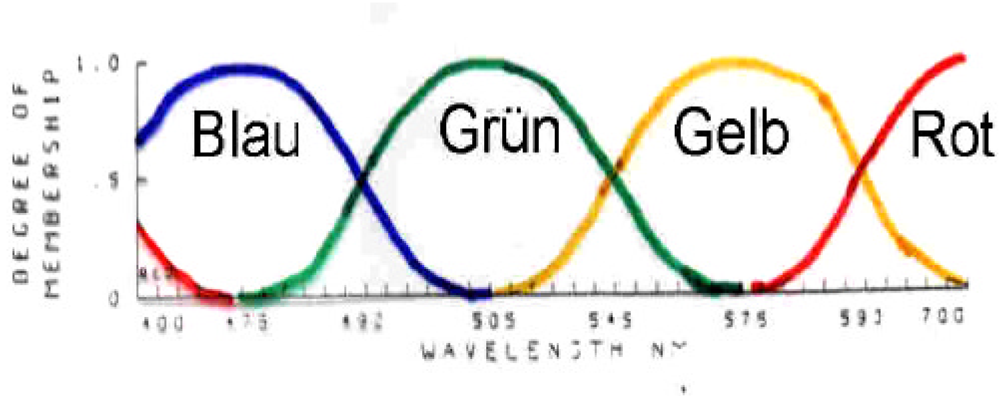


# Four type of opponent cells in the macaque's LGN *(lateral geniculate nucleus)*



## Opponent colour theory

De Valois etal. (1966) argue, with respect to the cell types that are opposed between the same region of the spectrum, that "it seems reasonable to say the excitation in one type [e.g., +R –G] carries the same information as inhibition in the other [+G -R]. This gives two different response distributions which can be schematised as follows.




Together with two further types of cells (excitatory and inhibitory) that carry luminosity information, we have presented an analysis very close to Hering's opponent colour theory.

# Summary: Three- and four-colour theories

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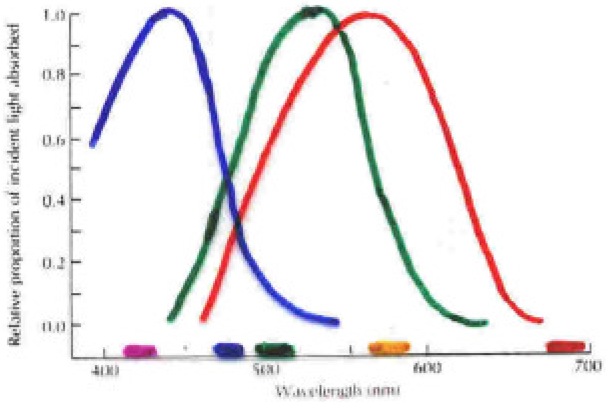
<tr>
<td>3 types of cones in the retina containing α,β,γ–Rhodopsin<br>
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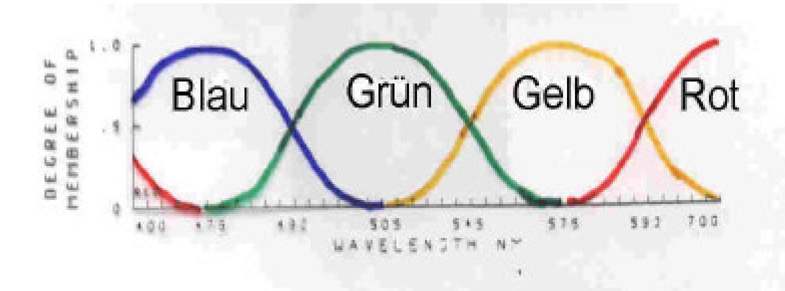
<td>3 opponent cell pairs in the visual cortex. Red-green, blue-yellow, bright-dark.<br>This defines 6 primary colours:<br>RED, GREEN, YELLOW, BLUE, WHITE, BLACK.<br>
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<td>Helmholtz' Trichromacy:<br>His principle of trichromacy means that every colour can be realized by a linear combination of three primaries. (e.g., red, green, blue)</td>
<td>Hering's opponent colour theory:<br>The visual system is determined by three antagonistic processes (opposite colours).<br>Evidence: Afterimages, existence of four pure colours</td>
</tr>
</table>

## General conclusions

- Colours can be represented by points in a colour space

- When are two colour spaces equivalent?
  - The existence of a one-to-one mapping is not enough
  - Respect the role of colour distances
  - Respect the role of complementary processes (afterimages)
  - The role of relations to other systems (music, emotions)

- Colour is not a simple function of the external stimulus: The same light stimulus can trigger different colour appearance – dependent on internal (adaptation) and external factors (effects of surrounding regions) .

- What about Colour Realism? (colours as reflecting parts of the outer world)