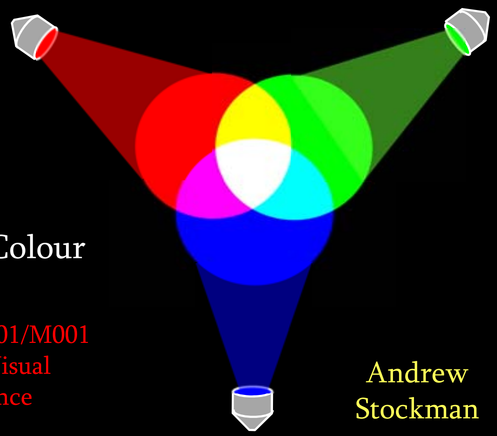


Advanced Colour

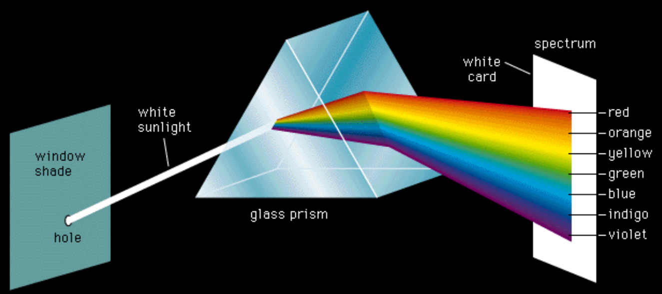
NEUR 3001/G001/M001
Advanced Visual
Neuroscience

Andrew
Stockman

INTRODUCTION

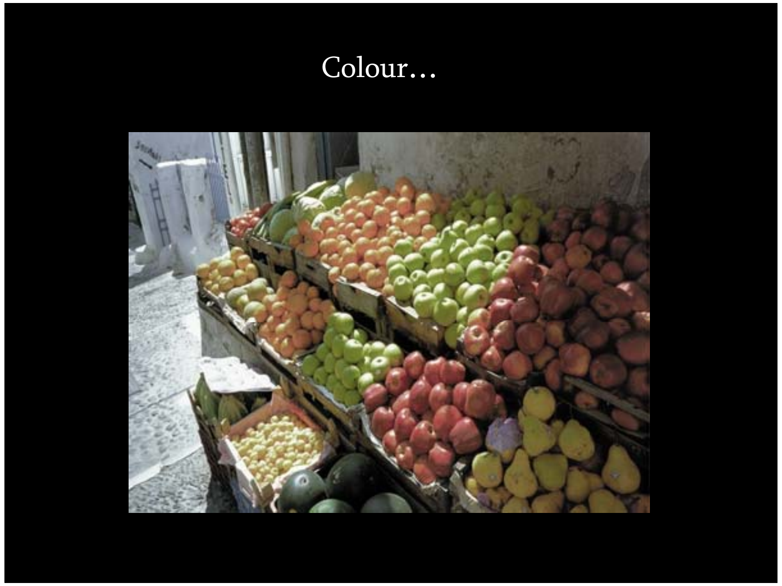
Light

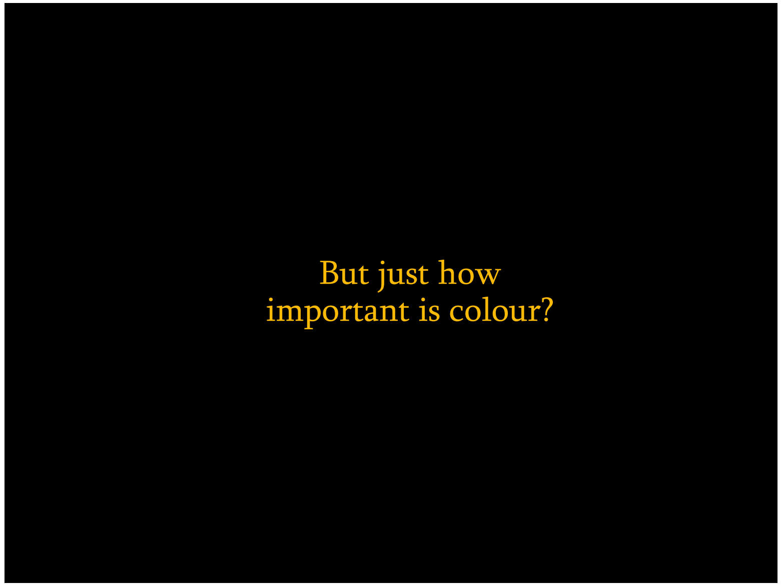
400 - 700 nm is important for vision

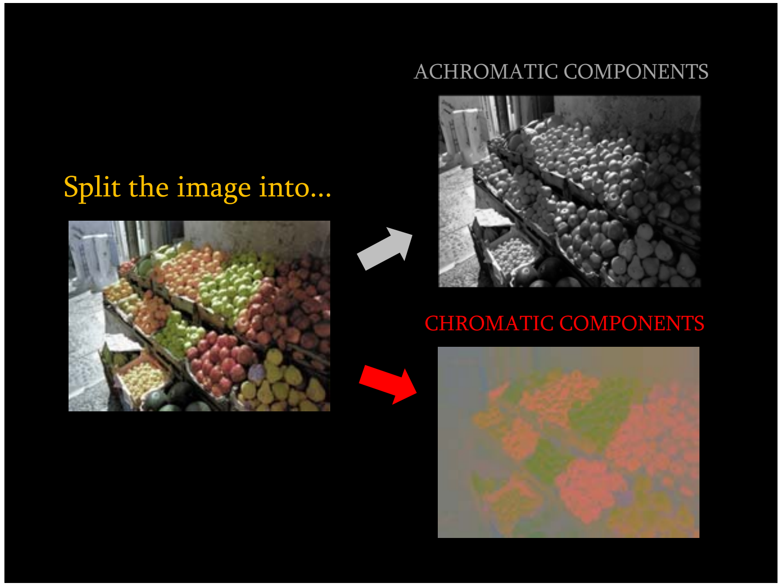


How dependent are
we on colour?

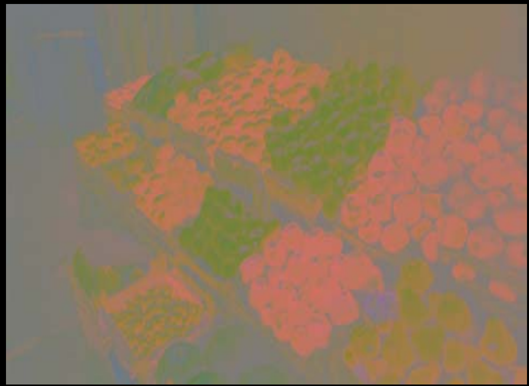

No colour…


Colour…


But just how
important is colour?


Split the image into...
ACHROMATIC COMPONENTS
CHROMATIC COMPONENTS

CHROMATIC COMPONENTS



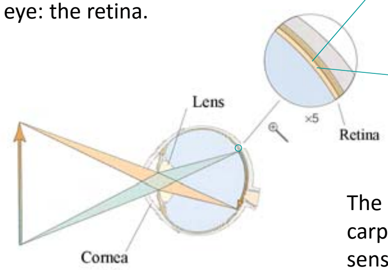
Chromatic information *by itself* provides relatively limited information…

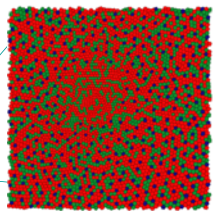
ACHROMATIC COMPONENTS

Achromatic information is important for fine detail …

How do we see colours?

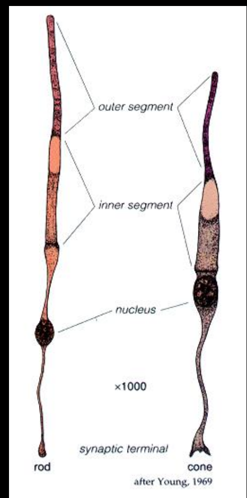
An image of the world is projected by the cornea and lens onto the rear surface of the eye: the retina.





The back of the retina is carpeted by a layer of light-sensitive photoreceptors (rods and cones).

Human photoreceptors



- Rods
  - Achromatic night vision
  - 1 type

Rod

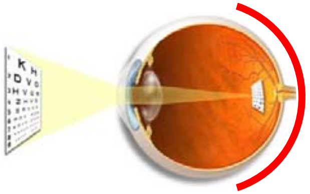
- Cones
  - Daytime, achromatic *and* chromatic vision
  - 3 types

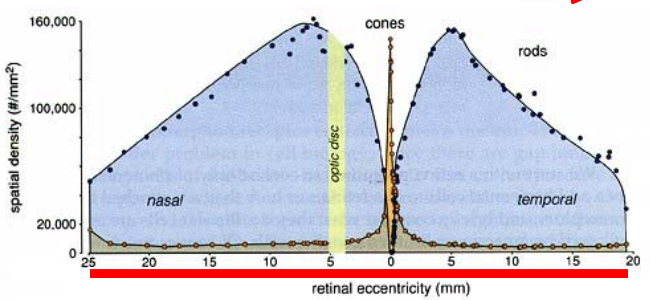
Long-wavelength-sensitive (L) or “red” cone

Middle-wavelength-sensitive (M) or “green” cone

Short-wavelength-sensitive (S) or “blue” cone

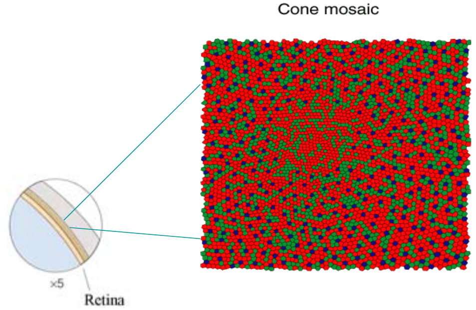
Rod and cone distribution



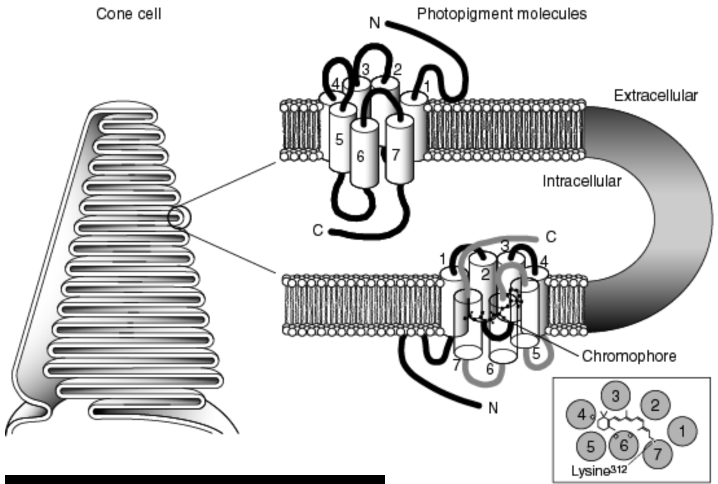


0.3 mm of eccentricity is about 1 deg of visual angle

after Østerberg, 1935; as modified by Rodieck, 1988



Central fovea is rod-free, and the very central foveola is rod- and S-cone free

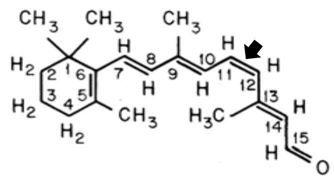


Photopigment molecule (cone)

From Sharpe, Stockman, Jägle & Nathans, 1999

Chromophore

(*chromo-* color, + *-phore*, producer)
Light-catching portion of any molecule

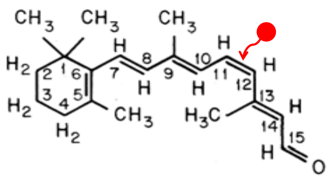


11-*cis* retinal.

The molecule is twisted at the 11th carbon.

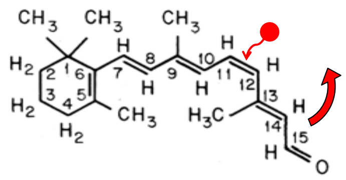
Chromophore

A photon is absorbed



Chromophore

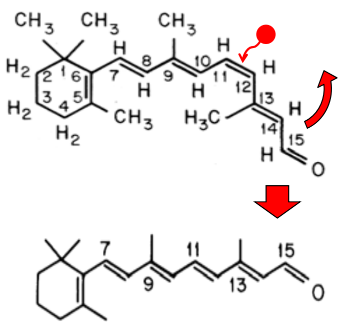
A photon is absorbed



the energy of which initiates a conformational change to…

Chromophore

A photon is absorbed

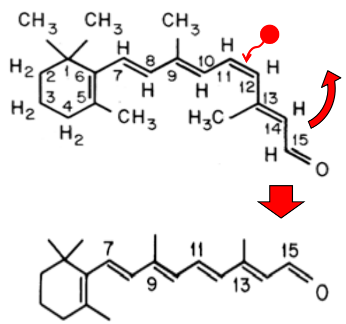


the energy of which initiates a conformational change to…

all-*trans* retinal

(side chains omitted for simplicity).

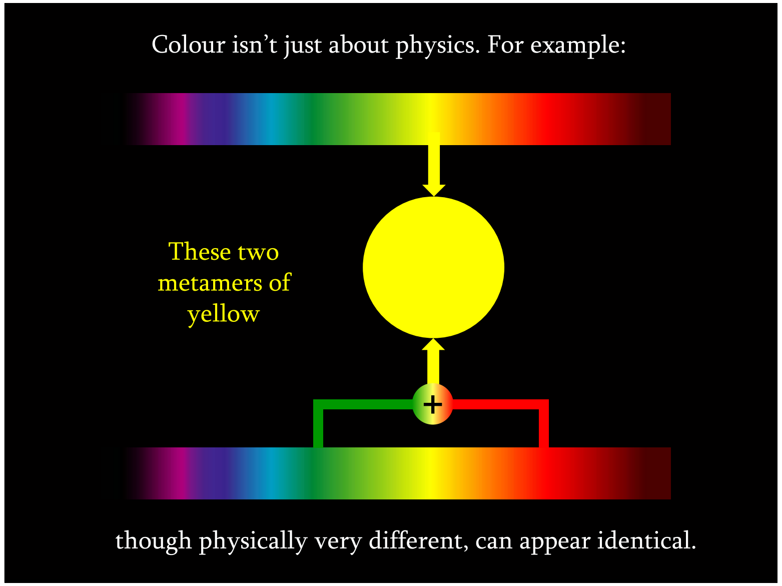
Chromophore



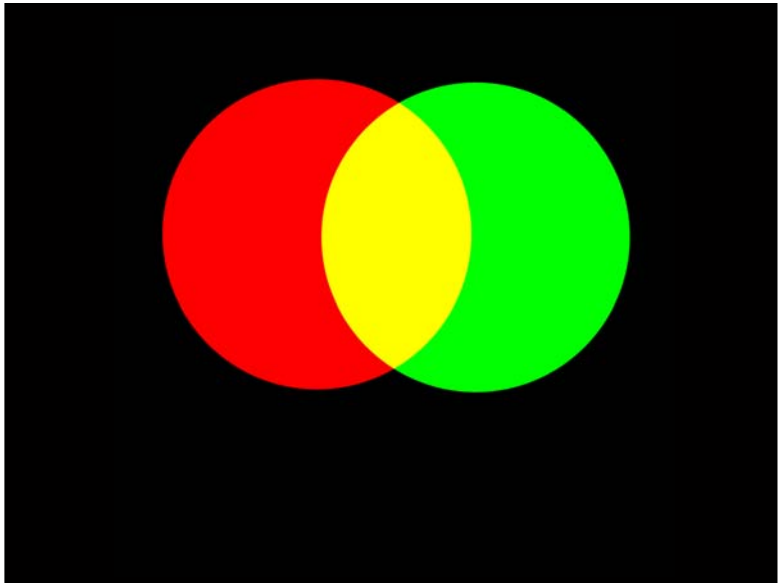
This process is binary: all (1) or nothing (0).

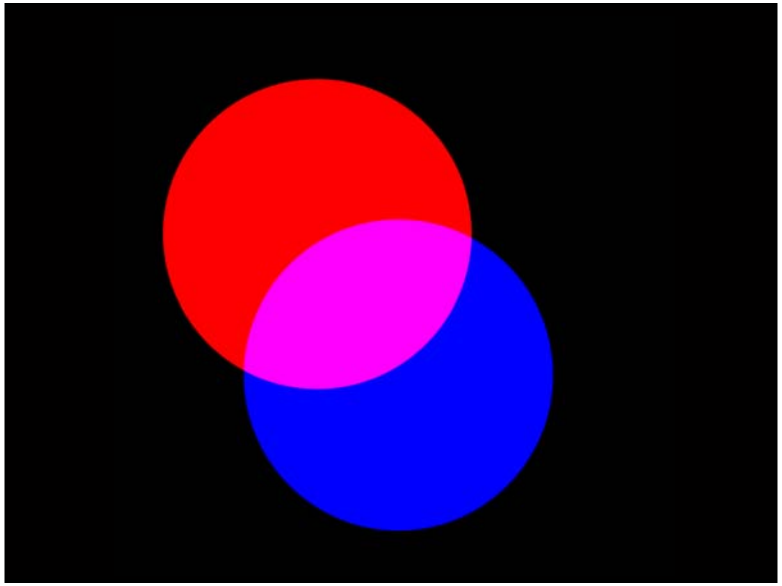
What does that tell us about how wavelength be encoded?

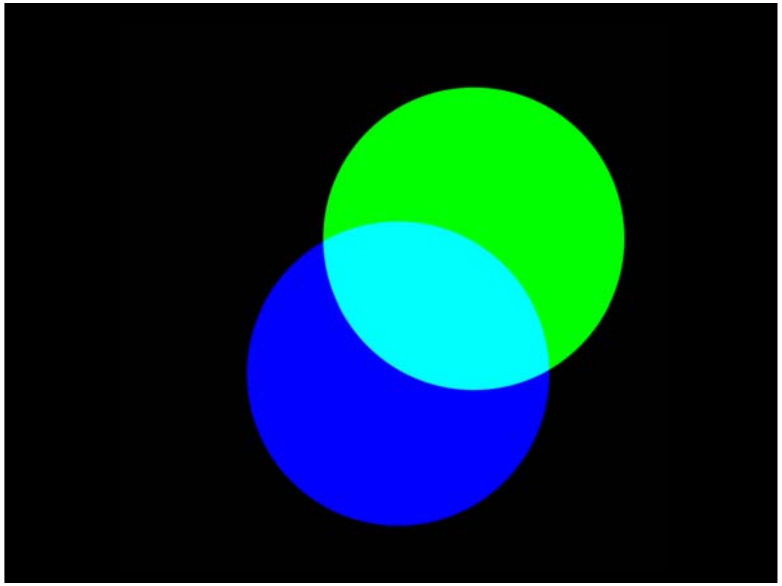
Is colour, as we perceive it, mainly a property of physics or biology?

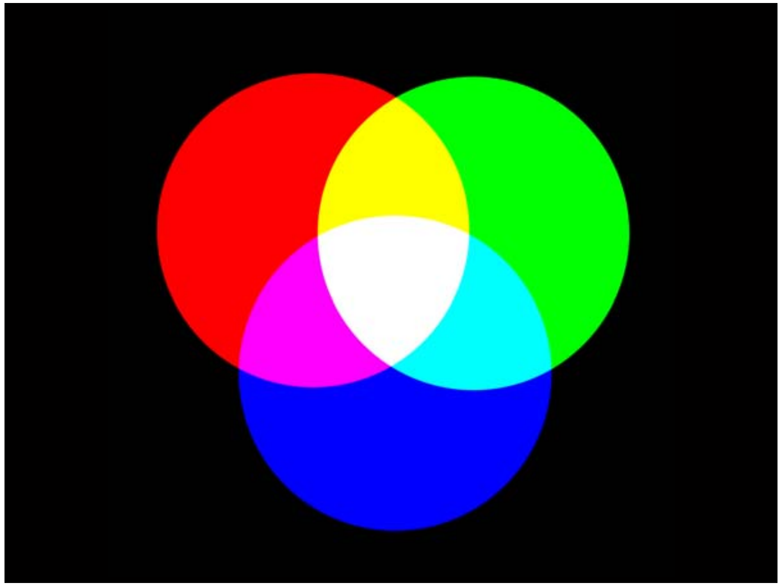


There are many other such metamers or matches…

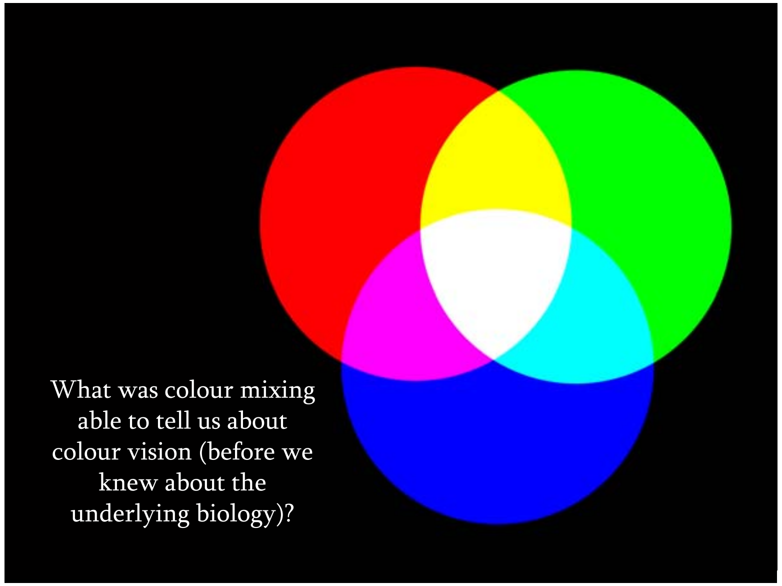


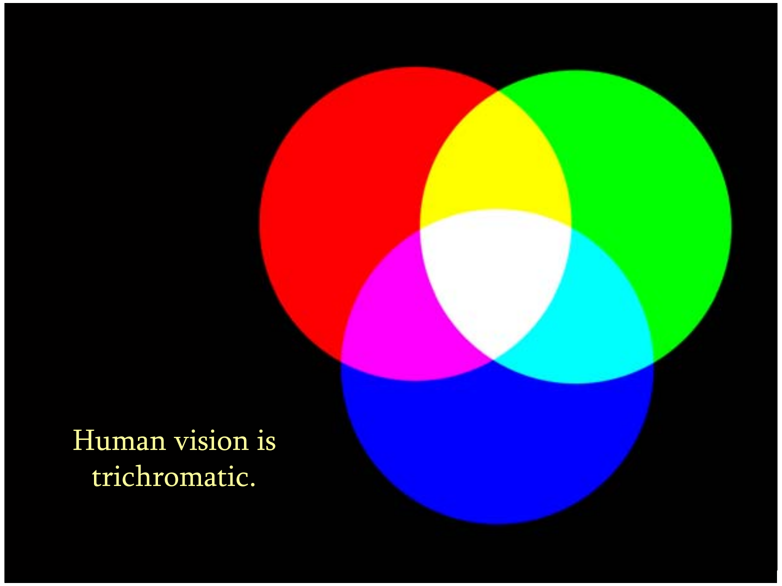


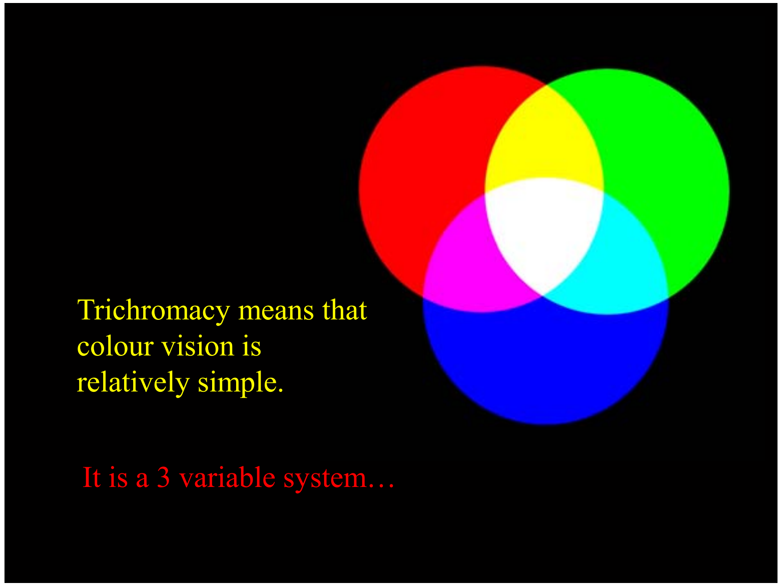


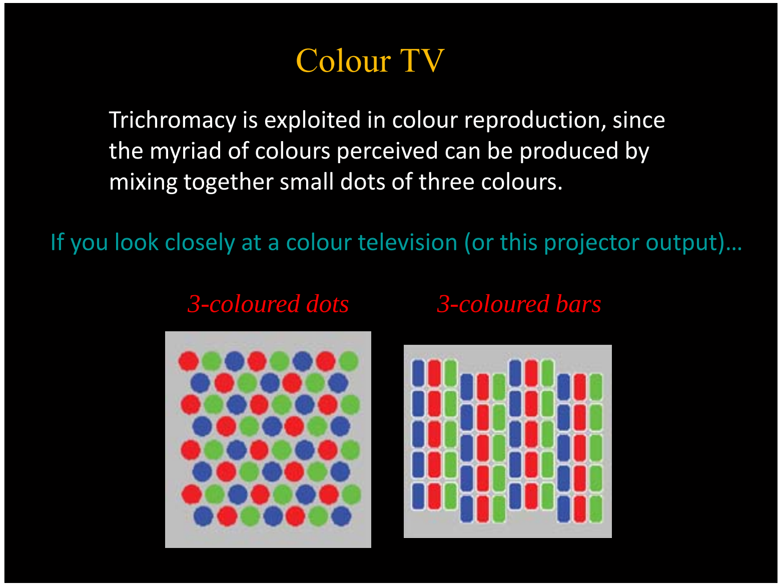


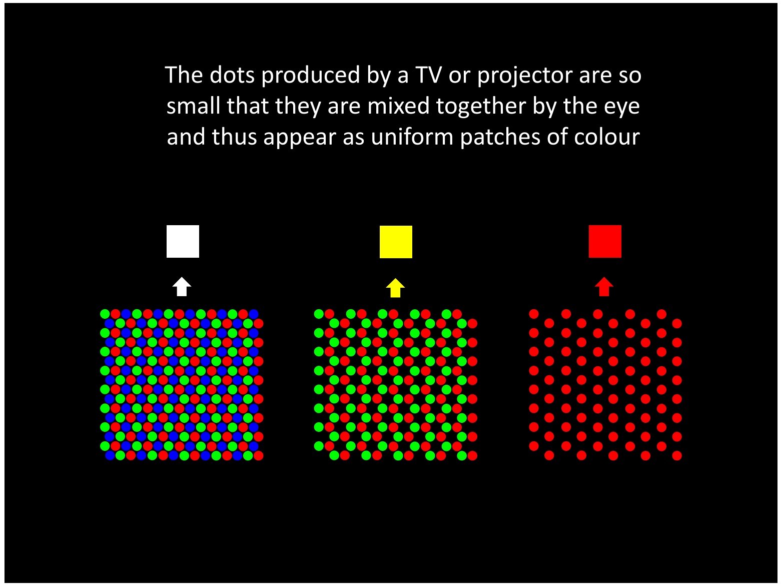

COLOUR MIXING
Brightness 255
Brightness 255
Brightness 255

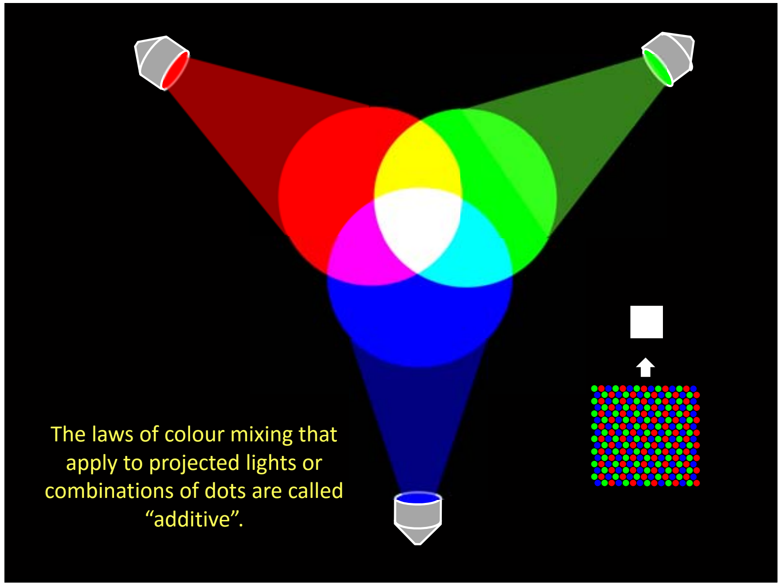

What was colour mixing able to tell us about colour vision (before we knew about the underlying biology)?

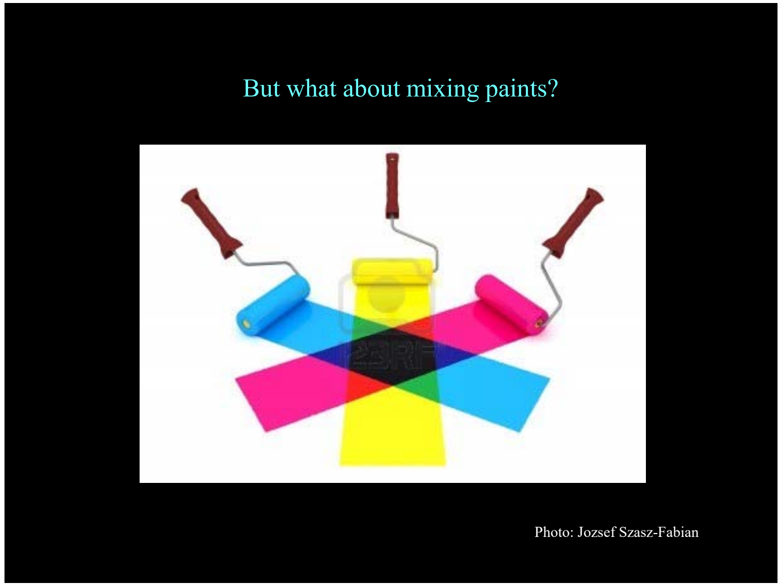

Human vision is trichromatic.

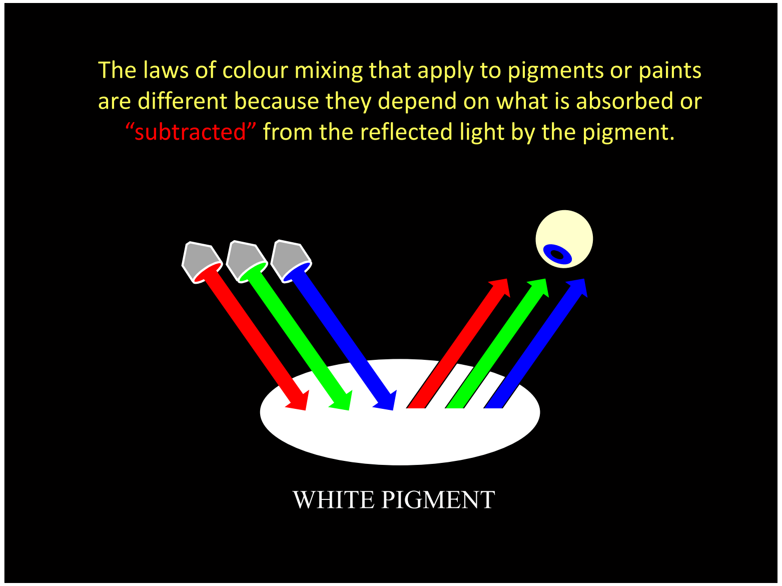

Trichromacy means that colour vision is relatively simple.
It is a 3 variable system…

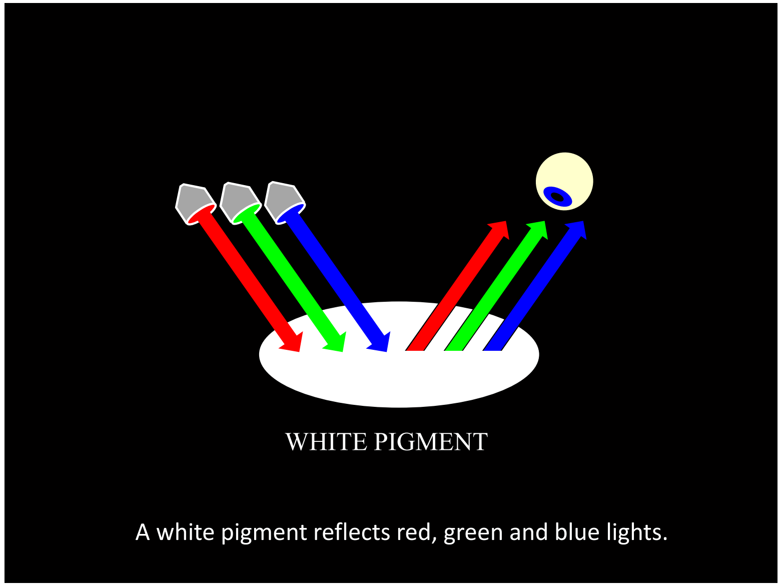

Colour TV
Trichromacy is exploited in colour reproduction, since the myriad of colours perceived can be produced by mixing together small dots of three colours.
If you look closely at a colour television (or this projector output)…
3-coloured dots
3-coloured bars

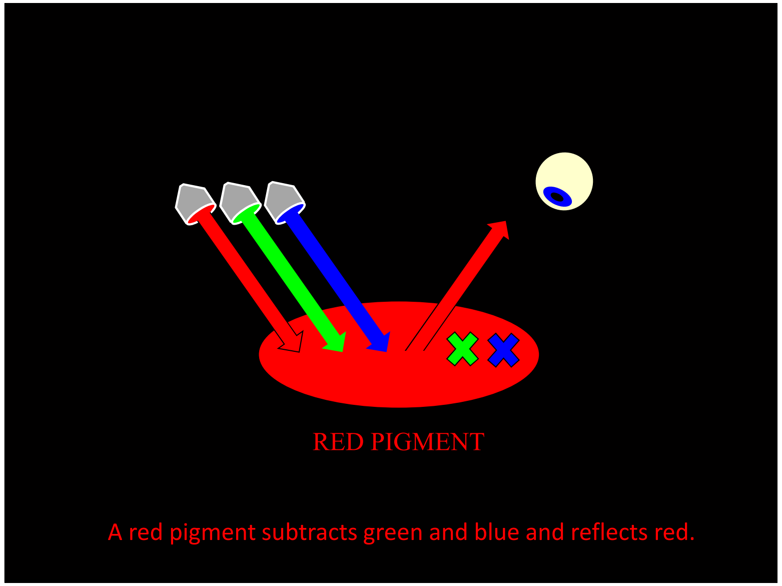

The dots produced by a TV or projector are so small that they are mixed together by the eye and thus appear as uniform patches of colour

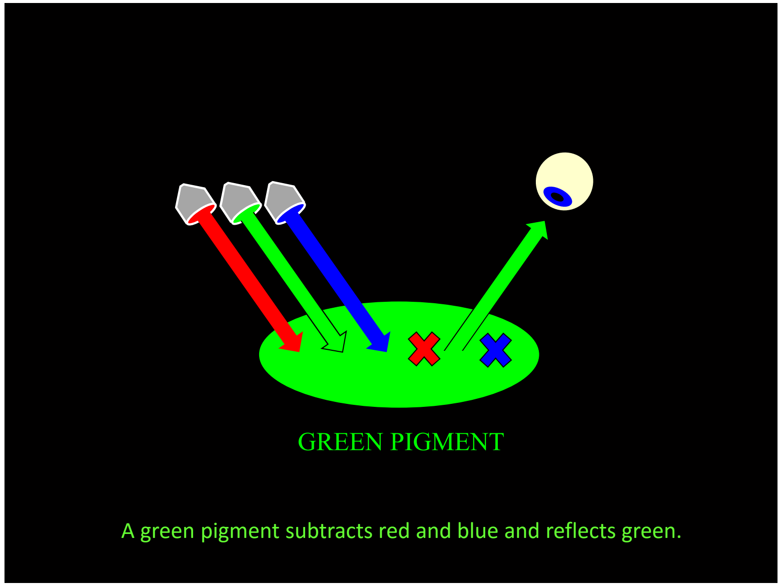

The laws of colour mixing that apply to projected lights or combinations of dots are called "additive".

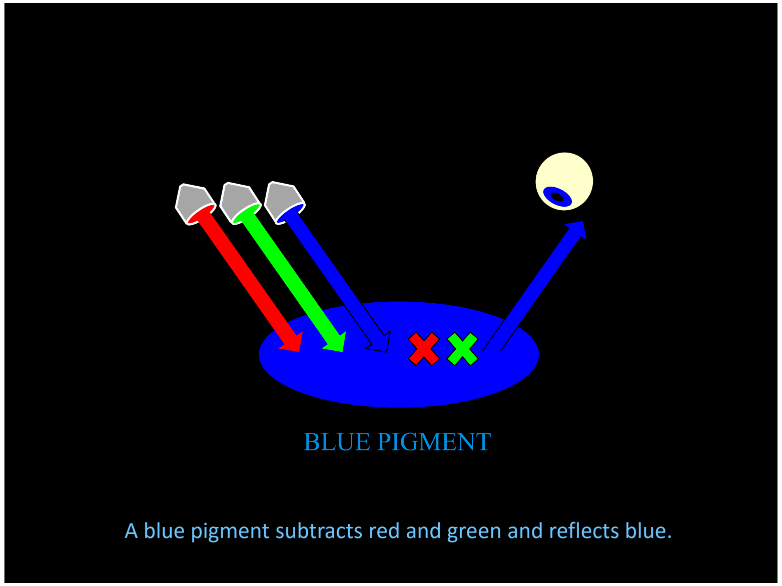

But what about mixing paints?
Photo: Jozsef Szasz-Fabian


The laws of colour mixing that apply to pigments or paints are different because they depend on what is absorbed or "subtracted" from the reflected light by the pigment.
WHITE PIGMENT


WHITE PIGMENT
A white pigment reflects red, green and blue lights.

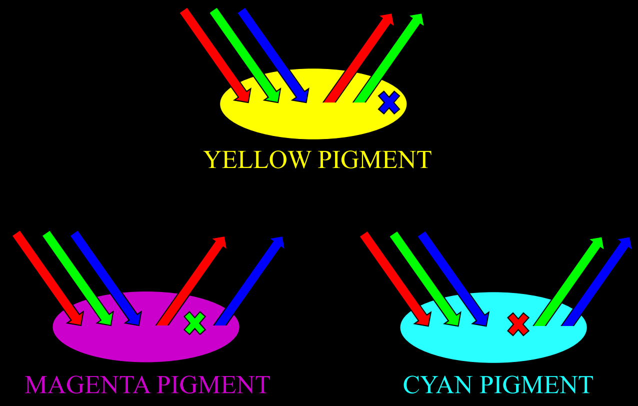

RED PIGMENT
A red pigment subtracts green and blue and reflects red.


GREEN PIGMENT
A green pigment subtracts red and blue and reflects green.

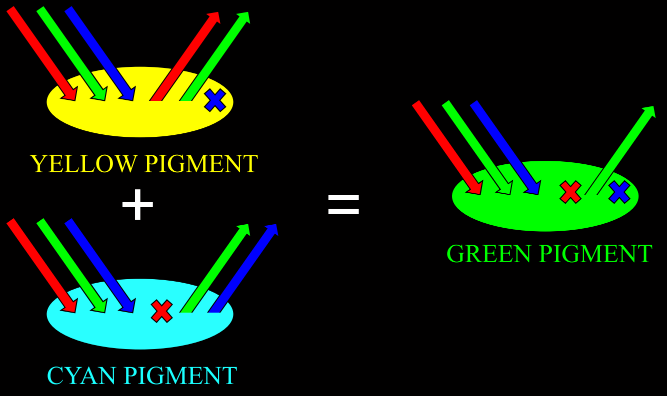

BLUE PIGMENT
A blue pigment subtracts red and green and reflects blue.

Laws of subtractive colour mixing
(of paints or pigments)

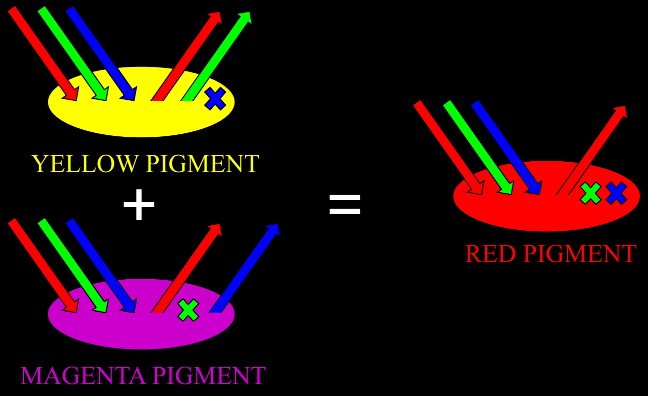
Subtractive colour mixing (of paints or pigments)

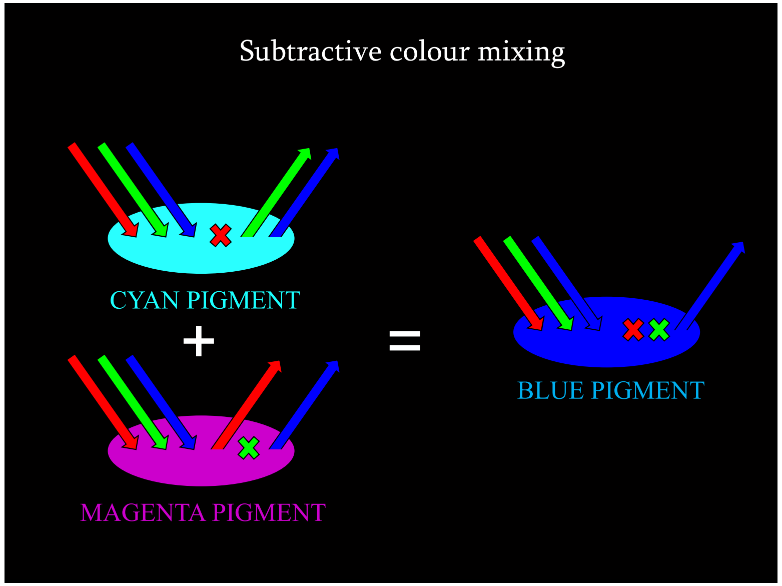


Subtractive colour mixing

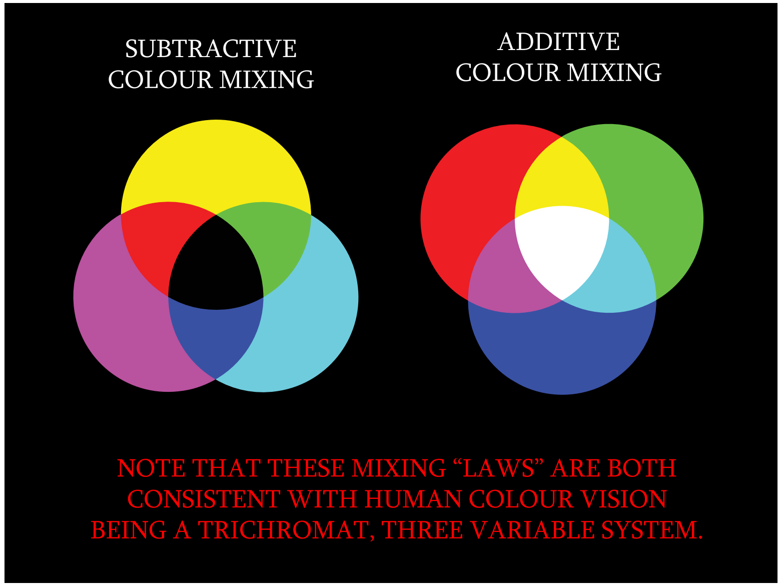


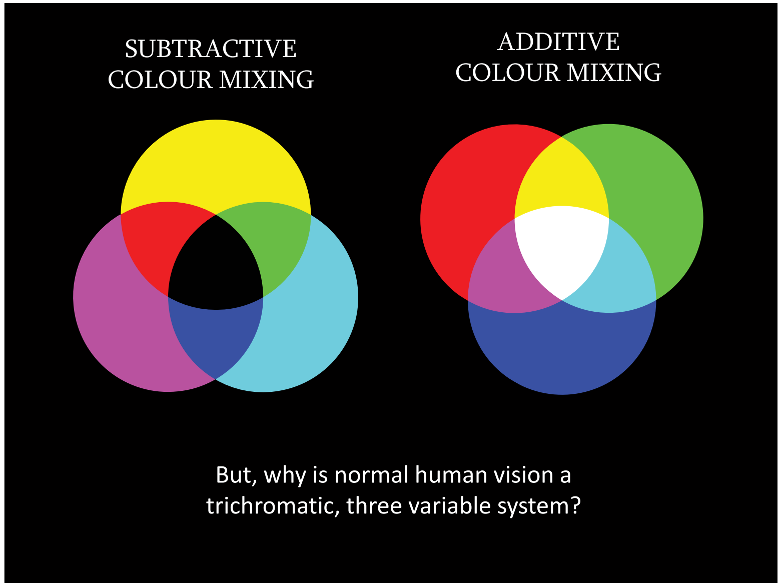
Subtractive colour mixing

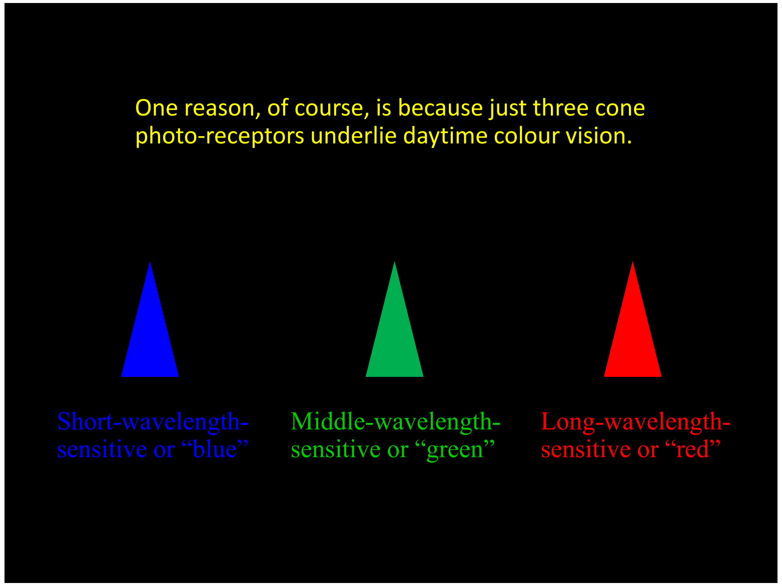


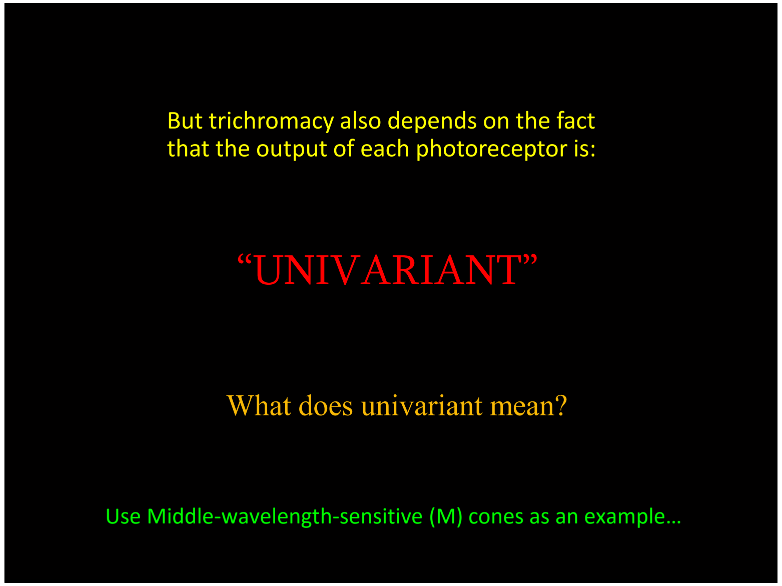

Subtractive colour mixing
CYAN PIGMENT
MAGENTA PIGMENT
BLUE PIGMENT

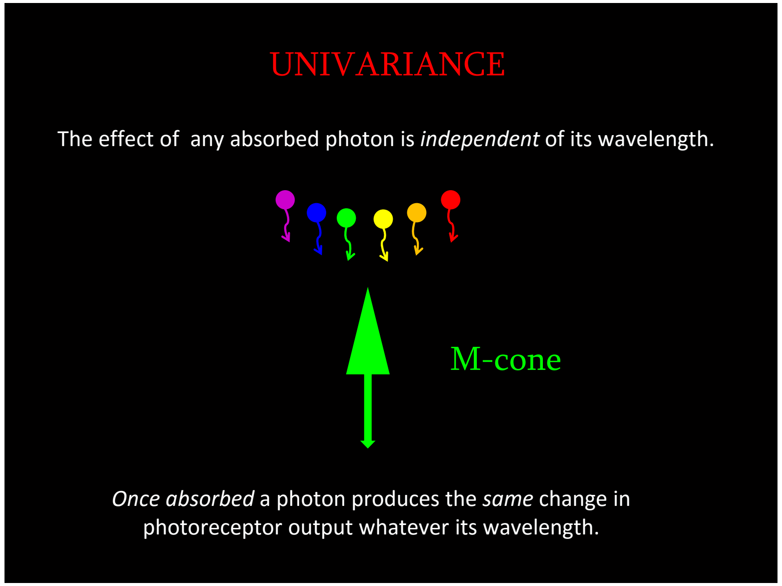

SUBTRACTIVE COLOUR MIXING

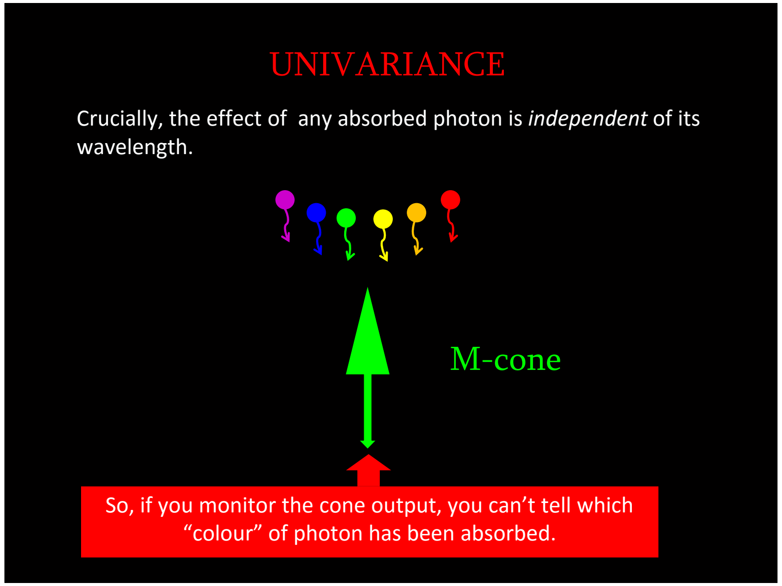

SUBTRACTIVE COLOUR MIXING
ADDITIVE COLOUR MIXING
NOTE THAT THESE MIXING "LAWS" ARE BOTH CONSISTENT WITH HUMAN COLOUR VISION BEING A TRICHROMAT, THREE VARIABLE SYSTEM.

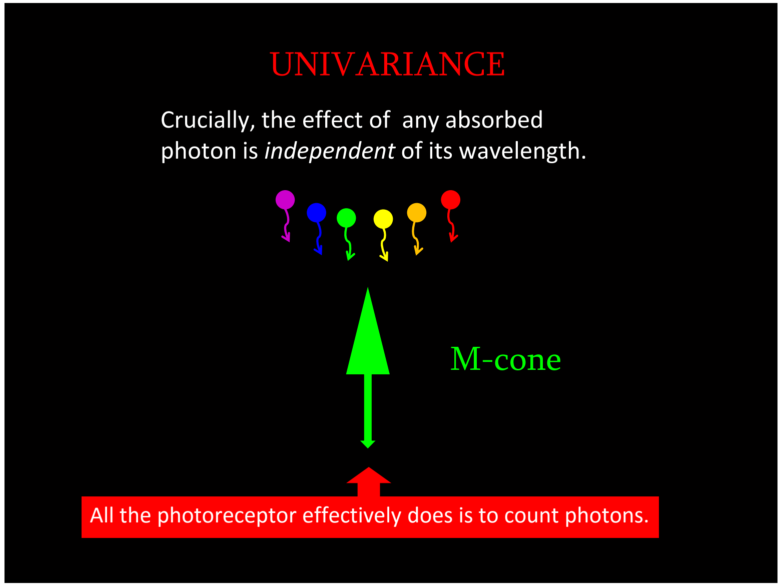

SUBTRACTIVE COLOUR MIXING
ADDITIVE COLOUR MIXING
But, why is normal human vision a trichromatic, three variable system?

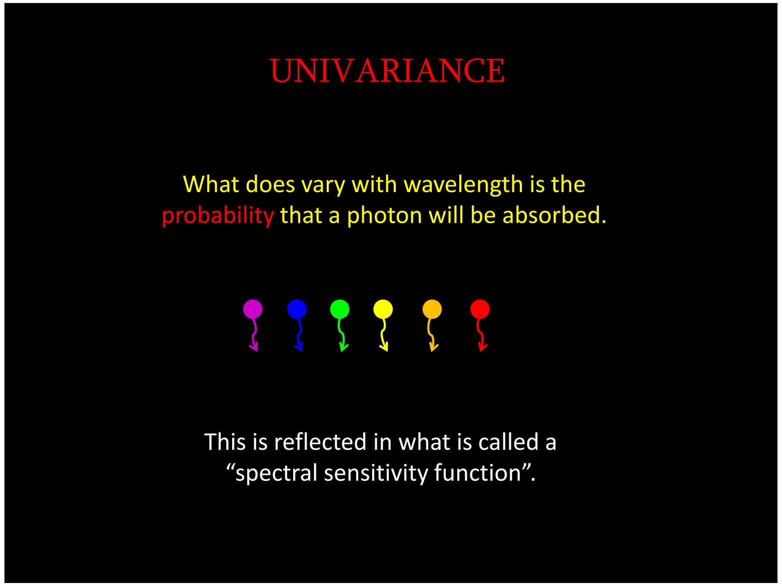

One reason, of course, is because just three cone photo-receptors underlie daytime colour vision.
Short-wavelength-sensitive or "blue"
Middle-wavelength-sensitive or "green"
Long-wavelength-sensitive or "red"

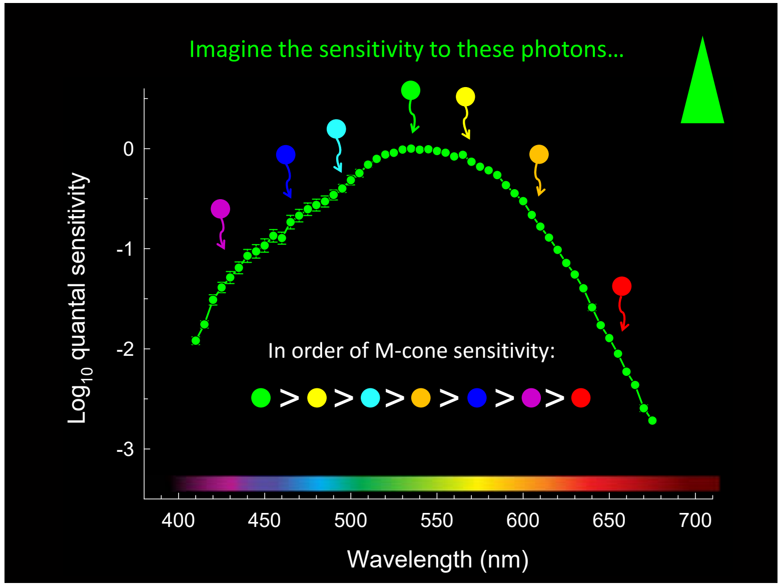

But trichromacy also depends on the fact that the output of each photoreceptor is:
"UNIVARIANT"
What does univariant mean?
Use Middle-wavelength-sensitive (M) cones as an example…

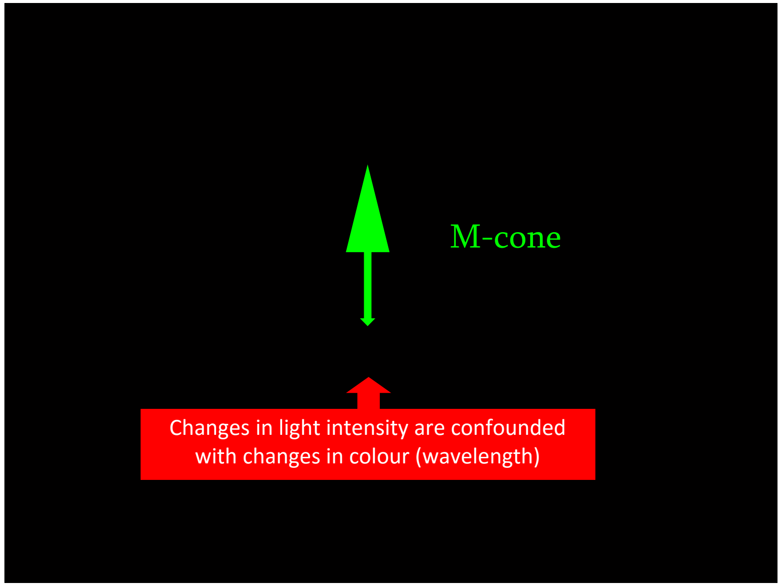

UNIVARIANCE
The effect of any absorbed photon is *independent* of its wavelength.
M-cone
Once absorbed a photon produces the *same* change in photoreceptor output whatever its wavelength.


UNIVARIANCE
Crucially, the effect of any absorbed photon is *independent* of its wavelength.
M-cone
So, if you monitor the cone output, you can't tell which "colour" of photon has been absorbed.


UNIVARIANCE
Crucially, the effect of any absorbed photon is *independent* of its wavelength.
M-cone
All the photoreceptor effectively does is to count photons.

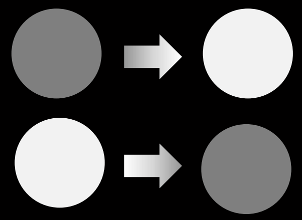

UNIVARIANCE
What does vary with wavelength is the probability that a photon will be absorbed.
This is reflected in what is called a "spectral sensitivity function".


Imagine the sensitivity to these photons...
Log_{10} quantal sensitivity
0
-1
-2
-3
In order of M-cone sensitivity:
> > > > > >
400
450
500
550
600
650
700
Wavelength (nm)


M-cone
Changes in light intensity are confounded with changes in colour (wavelength)

UNIVARIANCE

A change in photoreceptor output can be caused by a change in intensity or by a change in colour. There is no way of telling which.



Each photoreceptor is therefore ‘colour blind’, and is unable to distinguish between changes in colour and changes in intensity.

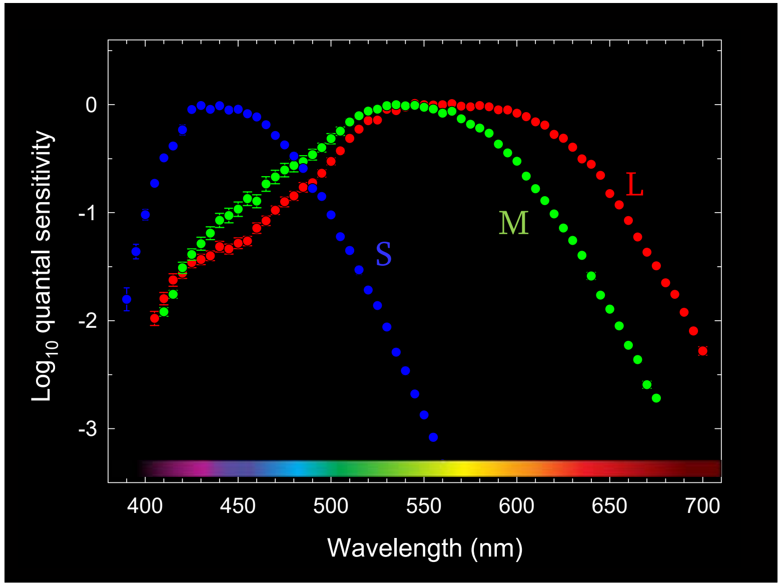
Univariance

If a cone is *n* times less sensitive to light A than to light B, then if A is set to be *n* times brighter than B, the two lights will appear identical whatever their wavelengths.

If we had only one photoreceptor, we would be colour-blind…

Examples: night vision, blue cone monochromats

People with normal colour vision have three univariant cones with different spectral sensitivities…



Their colour vision is therefore three dimensional or:

TRICHROMATIC

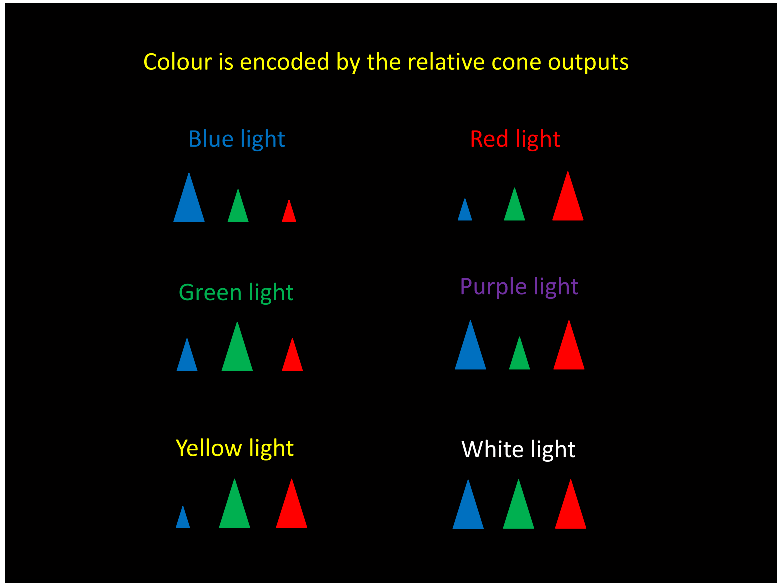
Trichromacy means our colour vision is actually limited

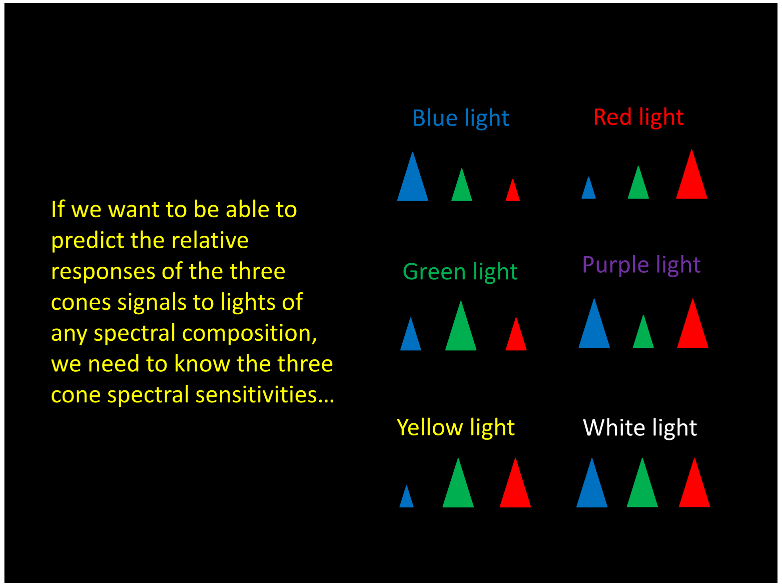
We confuse many pairs of colours that are spectrally very different. Such pairs are known as metameric pairs.

Many of these confusions would be obvious to a being with 4 cone photoreceptors—just as the confusions of colour deficient people are obvious to us.

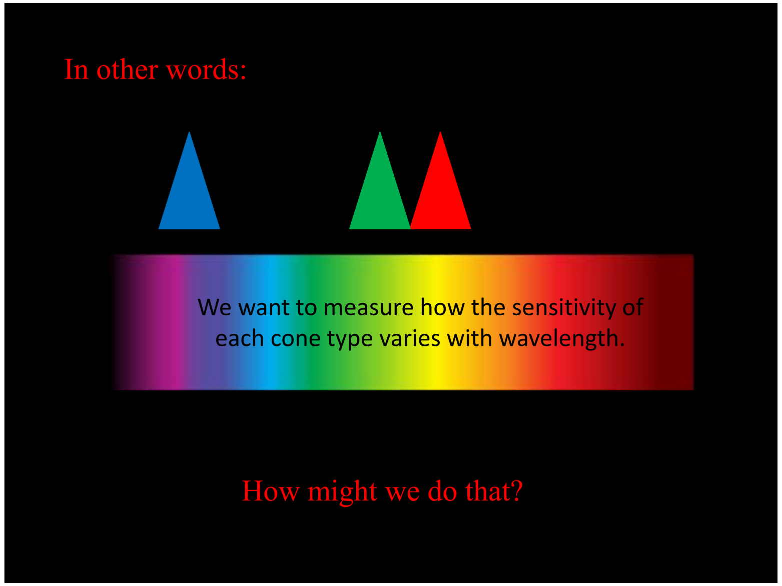
So, if each photoreceptor is colour-blind, how do we see colour?

Or to put it another way:
How is colour encoded at the input to the visual system?



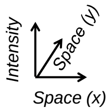


DETERMINING CONE SPECTRAL SENSITIVITIES



Spectral sensitivity measurements

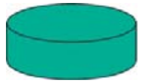
Flashing or flickering light

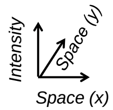


Observer sets the threshold for detecting the flash or flicker as a function of the wavelength of the light.

Spectral sensitivity measurements

Flashing or flickering light

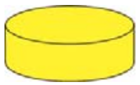


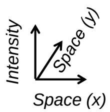


Observer sets the threshold for detecting the flash or flicker as a function of the wavelength of the light.

Spectral sensitivity measurements

Flashing or flickering light

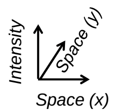




Observer sets the threshold for detecting the flash or flicker as a function of the wavelength of the light.

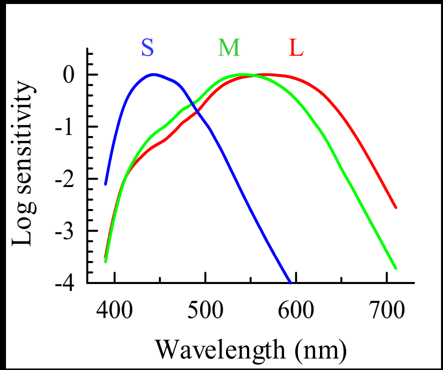
Spectral sensitivity measurements

Flashing or flickering light



Observer sets the threshold for detecting the flash or flicker as a function of the wavelength of the light.

But the cone spectral sensitivities overlap throughout the spectrum.



Consequently, to measure them *separately* we have to use special subjects or special conditions.

M- and L-cone measurements

Use two special types of subjects:

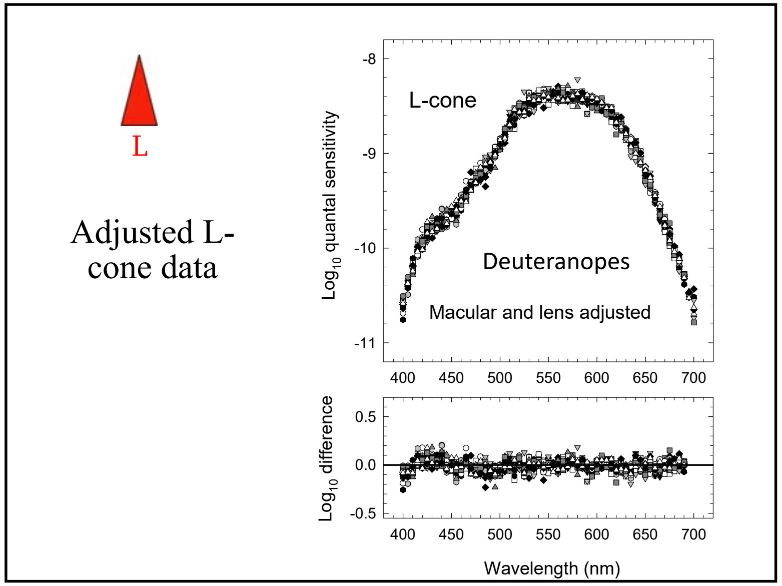
- Deuteranopes
- Protanopes

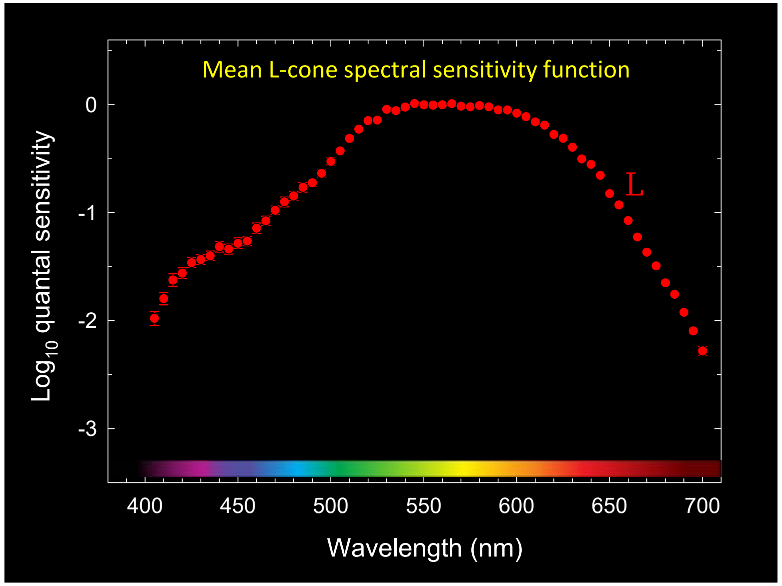
Normal | Protanope

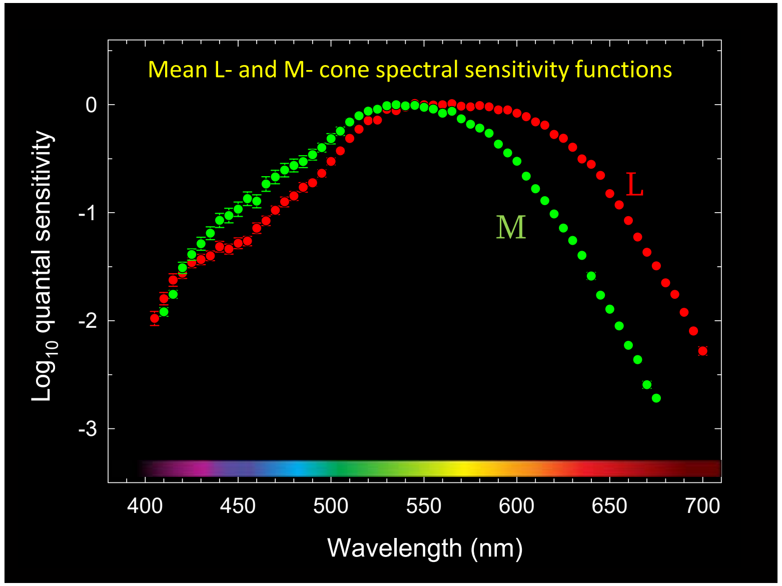
Protanopia

Normal | Deuteranope

Deuteranopia



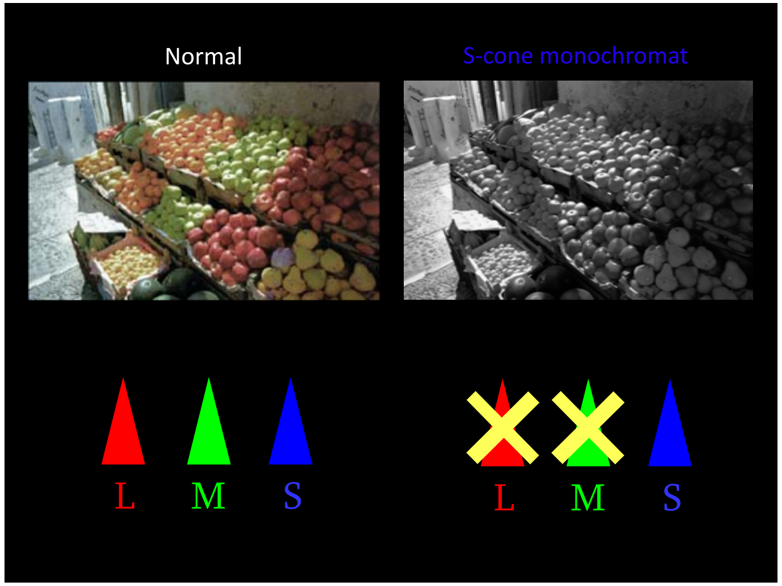


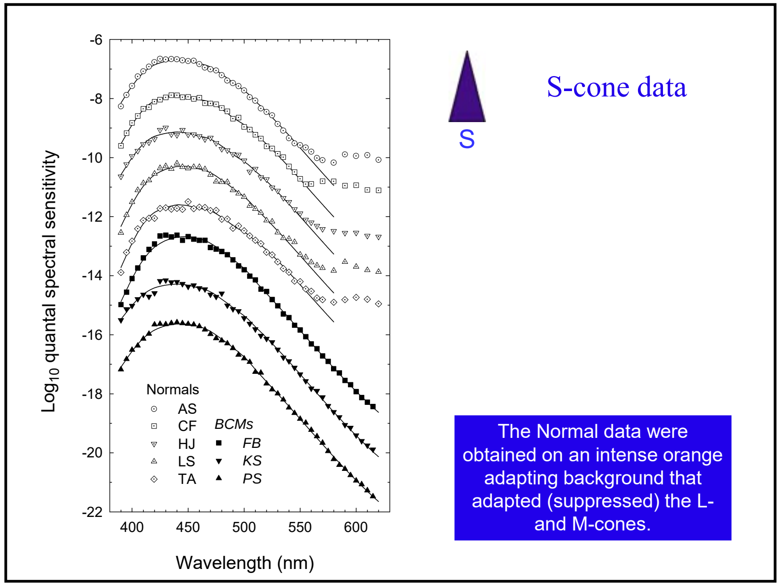


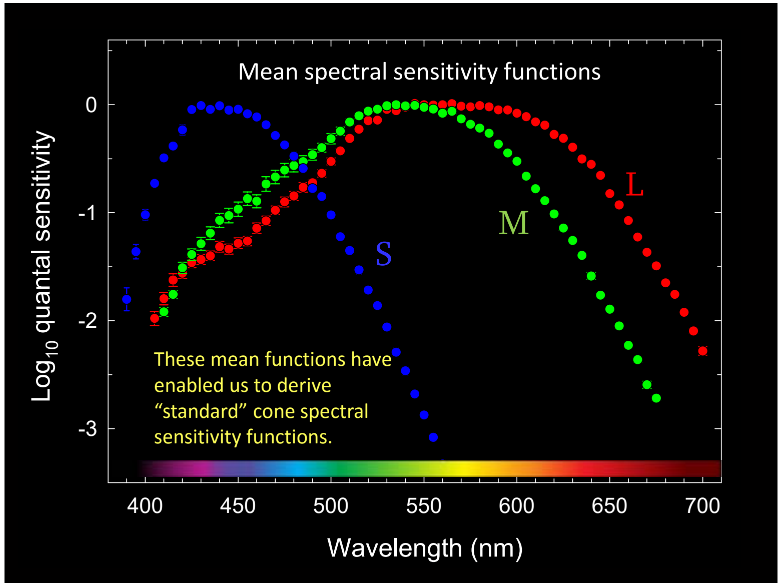
S-cone measurements

Two types of subjects:

- S-cone (or blue cone) monochromats
- Colour normals

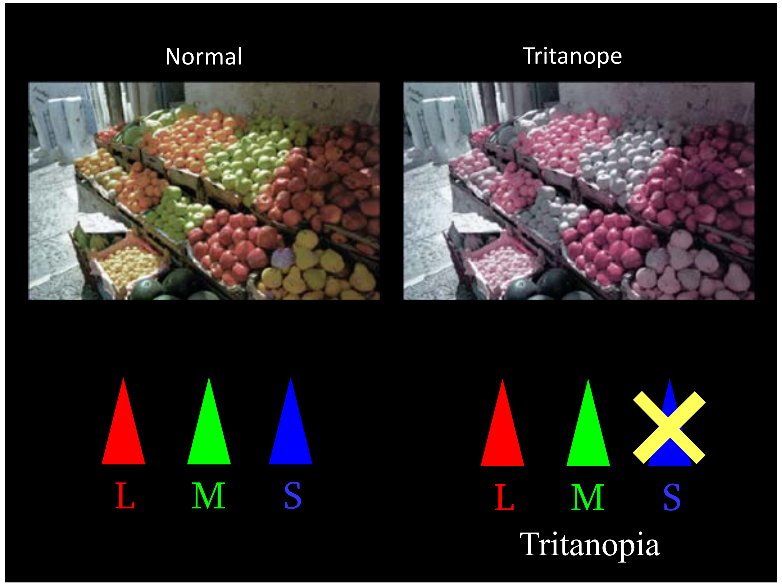


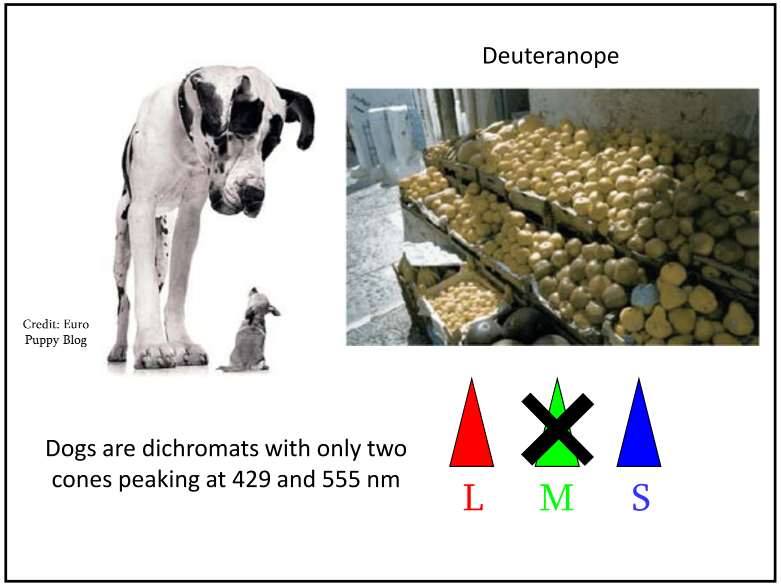




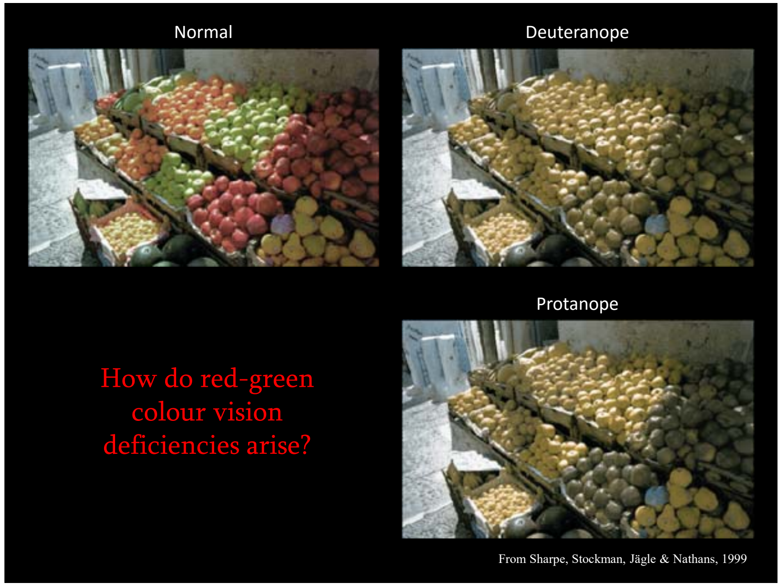
Why study spectral sensitivities?

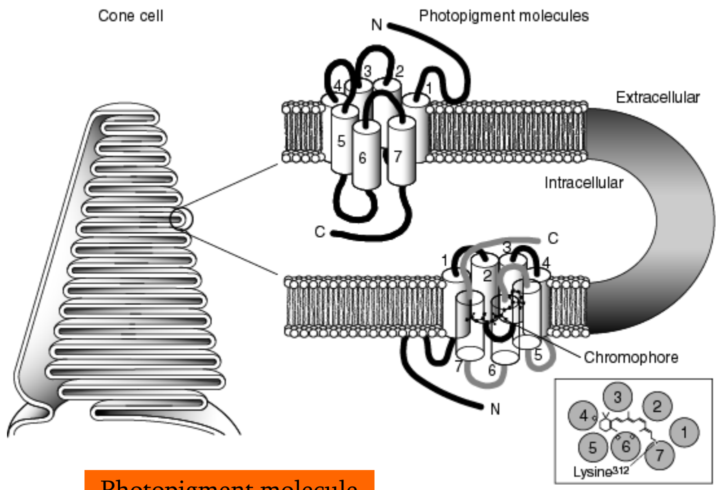
- A knowledge of the spectral sensitivities of the cones is important because it allows us to accurately and simply specify colours and to predict colour matches—for both colour normal and colour deficient people (and to understand the variability between individuals).
- Practical implications for colour printing, colour reproduction and colour technology.





COLOUR VISION AND MOLECULAR GENETICS

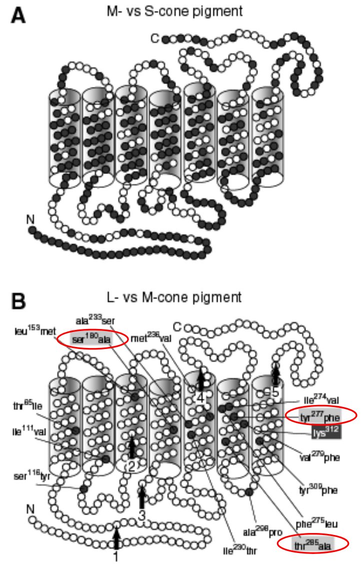




Photopigment molecule

From Sharpe, Stockman, Jägle & Nathans, 1999

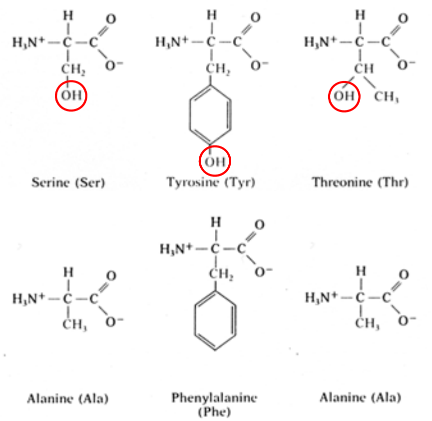
Amino acid differences between photopigment opsins



From Sharpe, Stockman, Jägle & Nathans, 1999

POLAR

NON-POLAR



LWS
all with OH group

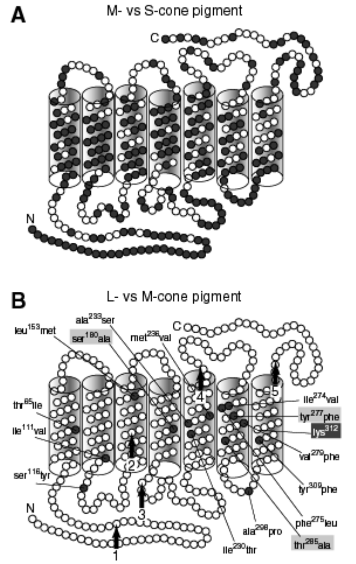
MWS

180	277	285

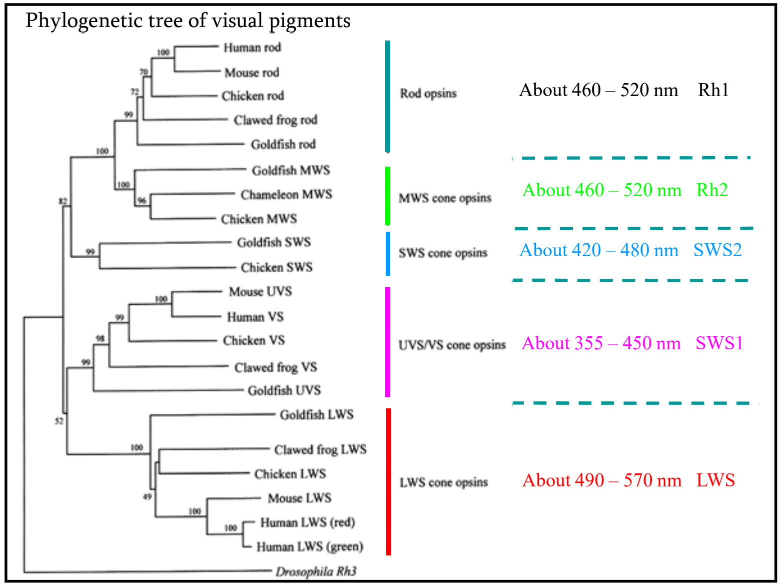
Spectral shifts ~ 5 nm ~ 25 nm

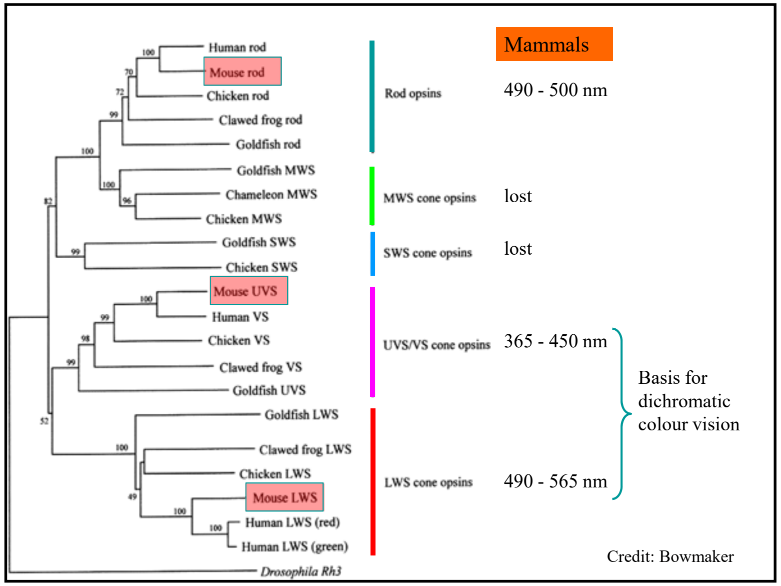
Amino acid differences between photopigment opsins

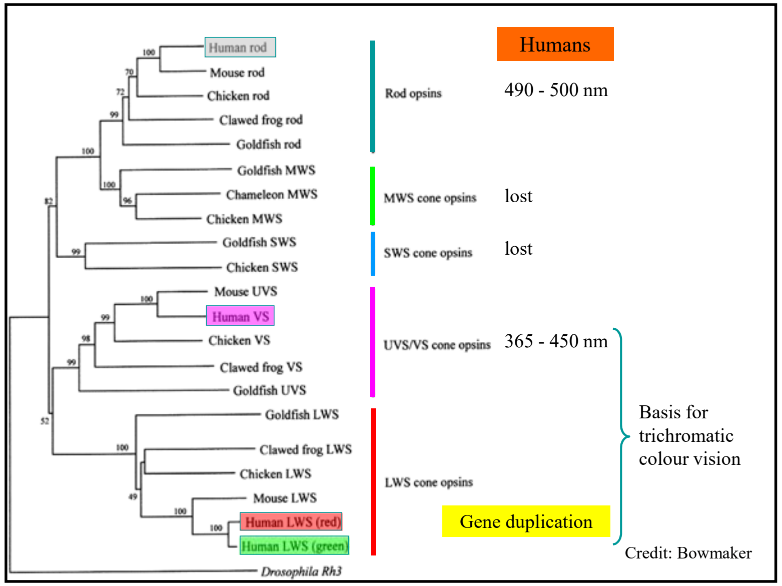
Why are the M- and L-cone opsins so similar?

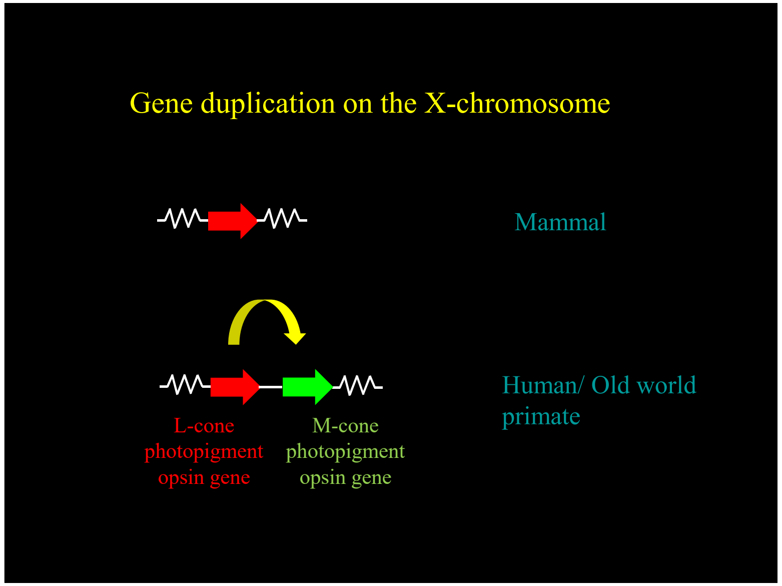


From Sharpe, Stockman, Jägle & Nathans, 1999

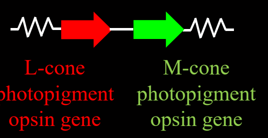

Phylogenetic tree of visual pigments
Human rod
Mouse rod
Chicken rod
Clawed frog rod
Goldfish rod
Goldfish MWS
Chameleon MWS
Chicken MWS
Goldfish SWS
Chicken SWS
Mouse UVS
Human VS
Chicken VS
Clawed frog VS
Goldfish UVS
Goldfish LWS
Clawed frog LWS
Chicken LWS
Mouse LWS
Human LWS (red)
Human LWS (green)
Drosophila Rh3
Rod opsins
About 460 – 520 nm Rh1
MWS cone opsins
About 460 – 520 nm Rh2
SWS cone opsins
About 420 – 480 nm SWS2
UVS/VS cone opsins
About 355 – 450 nm SWS1
LWS cone opsins
About 490 – 570 nm LWS


Mammals
Rod opsins
490 - 500 nm
MWS cone opsins
lost
SWS cone opsins
lost
UVS/VS cone opsins
365 - 450 nm
Basis for dichromatic colour vision
LWS cone opsins
490 - 565 nm
Credit: Bowmaker

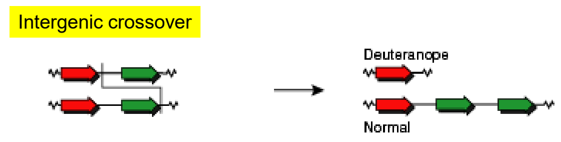

Humans
Rod opsins
490 - 500 nm
MWS cone opsins
lost
SWS cone opsins
lost
UVS/VS cone opsins
365 - 450 nm
Basis for trichromatic colour vision
LWS cone opsins
Gene duplication
Credit: Bowmaker


Gene duplication on the X-chromosome
Mammal
Human/ Old world primate
L-cone photopigment opsin gene
M-cone photopigment opsin gene

Because these two genes are in a tandem array, and are very similar…



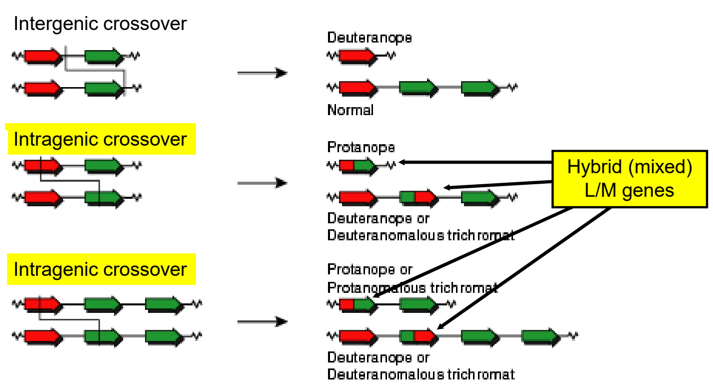
Crossovers during meiosis are common:



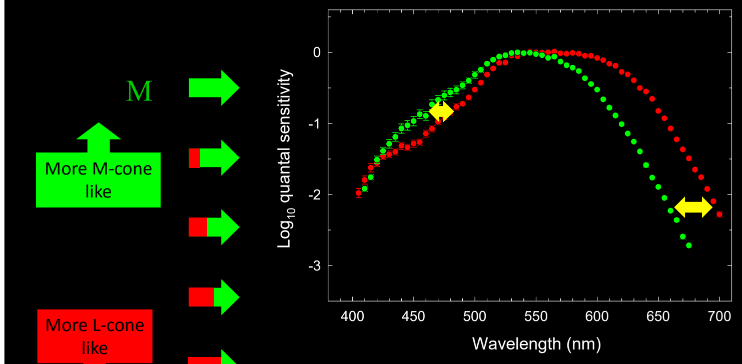
Intergenic crossovers produce more or less L and M-cone genes on each X chromosome

From Sharpe, Stockman, Jägle & Nathans, 1999

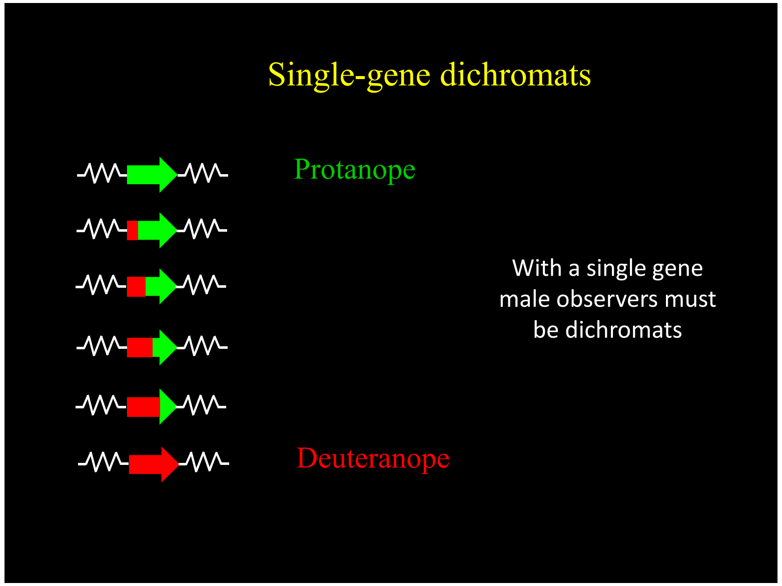
Intragenic crossovers produce hybrid or mixed L and M-cone genes

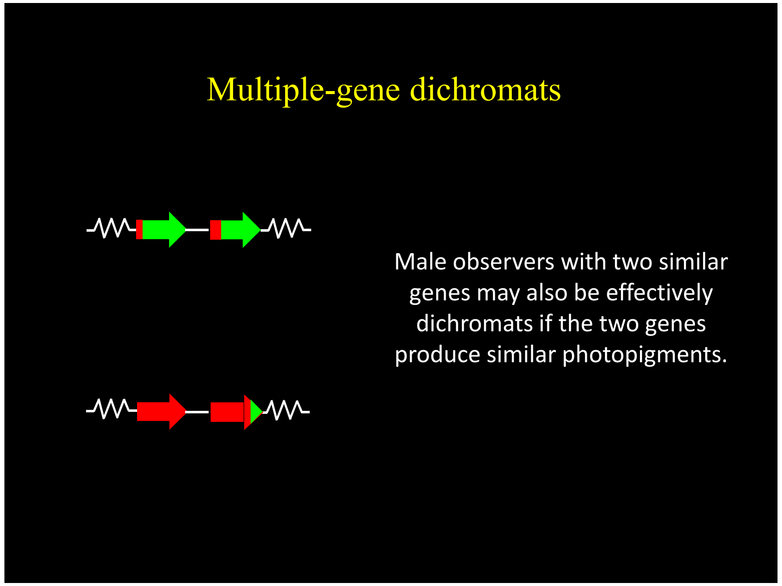


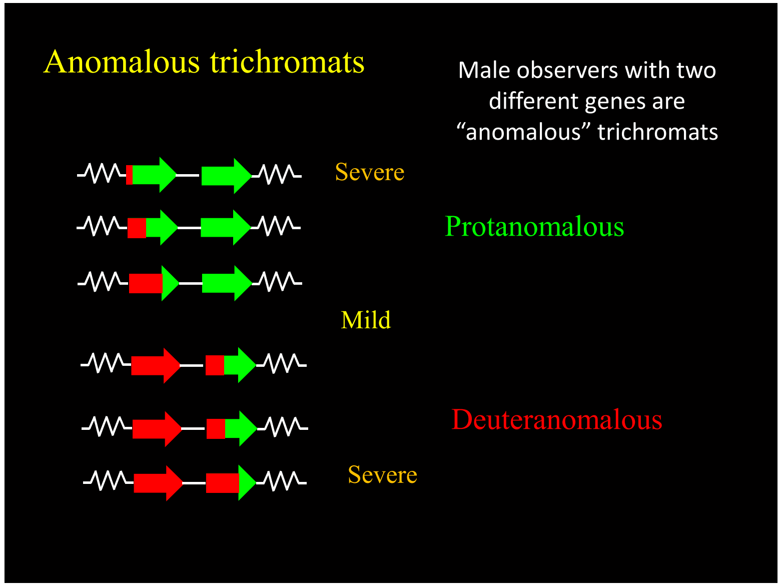
From Sharpe, Stockman, Jägle & Nathans, 1999

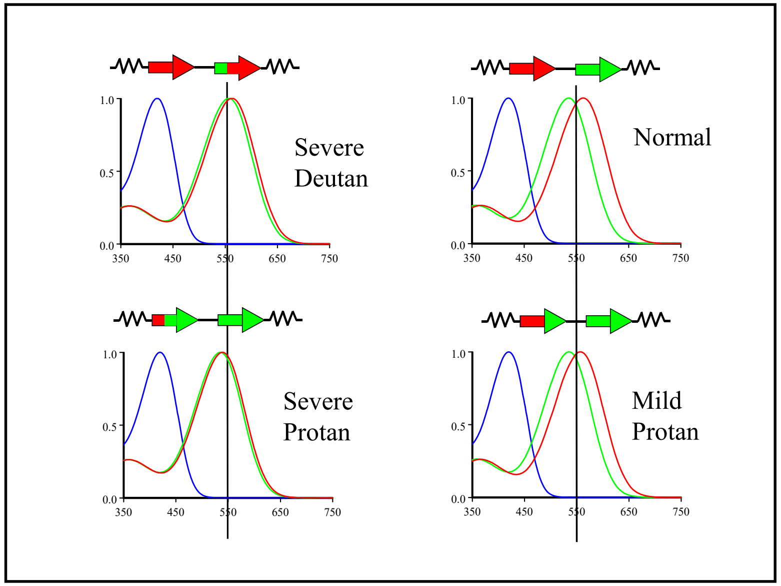


The spectral sensitivities of the hybrid photo-pigments vary between those of the M- and L-cones depending on where the crossover occurs.


Single-gene dichromats
Protanope
With a single gene male observers must be dichromats
Deuteranope


Multiple-gene dichromats
Male observers with two similar genes may also be effectively dichromats if the two genes produce similar photopigments.


Anomalous trichromats
Male observers with two different genes are “anomalous” trichromats
Severe
Protanomalous
Mild
Deuteranomalous
Severe


Severe Deutan
Normal
Severe Protan
Mild Protan

Main types of colour vision defects with approximate proportions of occurrence in the population.

Condition		percent in UK Male	percent in UK Female
Protanopia	no L cone	1.0	0.02
Protanomaly	milder form	1.0	0.03
Deuteranopia	no M cone	1.5	0.01
Deuteranomaly	milder form	5.0	0.4
Tritanopia	no SWS cone	0.008	0.008

XY inheritance

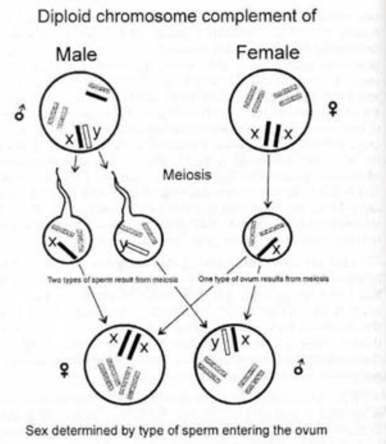


Figure 10.17 Prior to fertilization, meiotic division of germ cells results in two types of sperm, but only one type of ovum. Depending on which sperm is effective, the fertilized ovum will have two X cells and be female, or one X and one Y cell and be male. This diagram show why the X cell of the male offspring can come only from the mother. (From Watson, 1976, p. 14.)

The emergence of two longer wavelength (M- and L-cones) is thought to have occurred relatively recently in primate evolution.

Why is it important?

No red-green discrimination

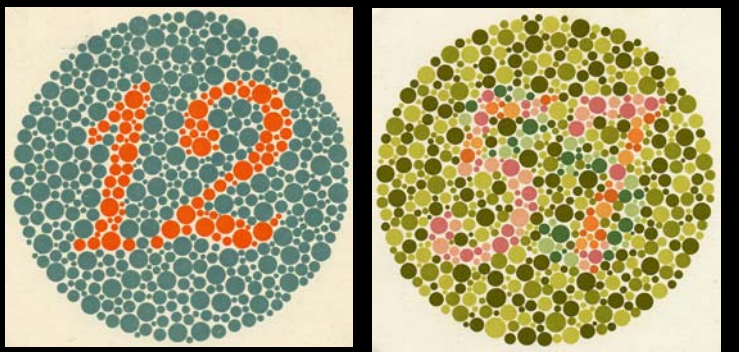
Source: Hans Irtel

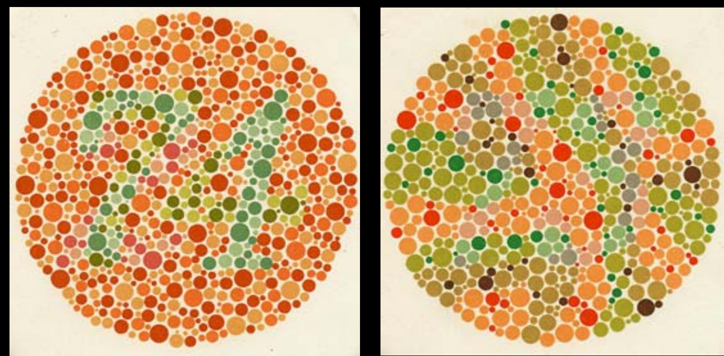
Red-green discrimination

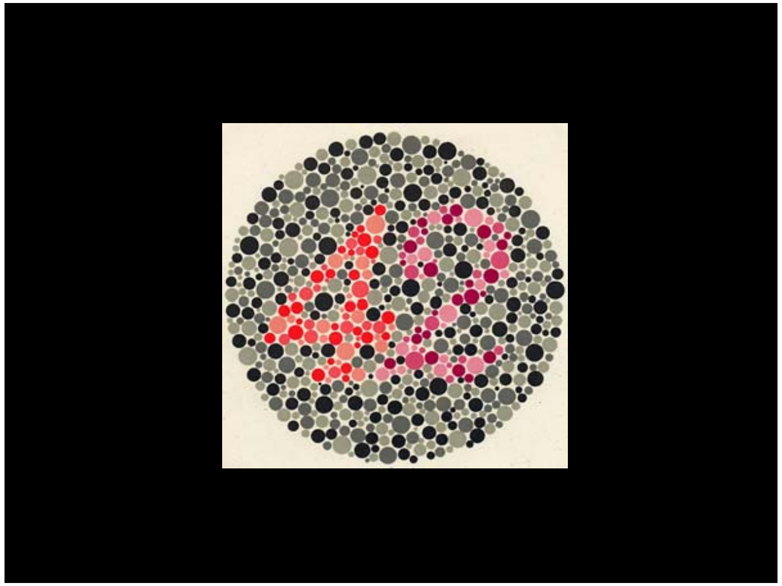
Source: Hans Irtel

DIAGNOSING COLOUR VISION DEFICIENCIES

Ishihara plates

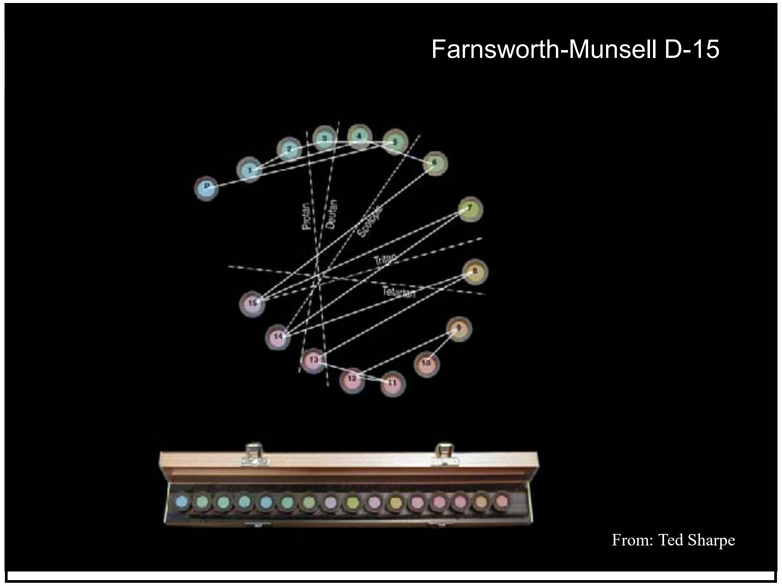






Tests measuring colour discrimination

- Farnsworth-Munsell D-15 test



D15 results

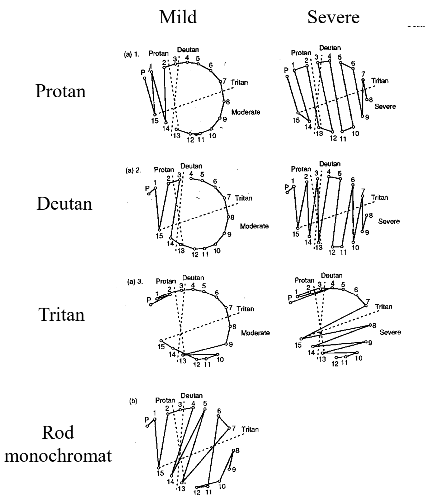
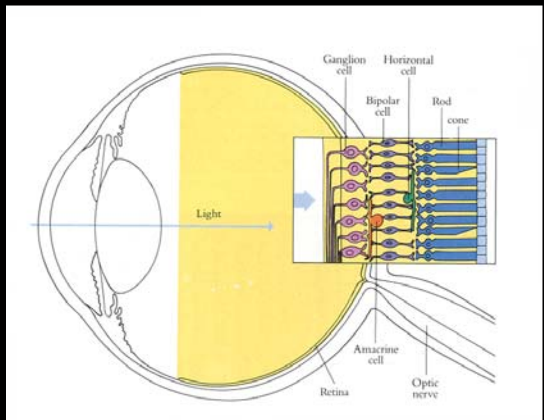


Fig. 7.1 Classification of the type of colour deficiency with the Farnsworth D15 test. (a) Protan, deutan, and tritan defects. 1. Moderate and severe protan defects. 2. Moderate and severe deutan defects. 3. Moderate and severe tritan defects. (b) Typical 'rod' monochromatism. The arrangement represents a lightness scale not isochromatic colour confusions.

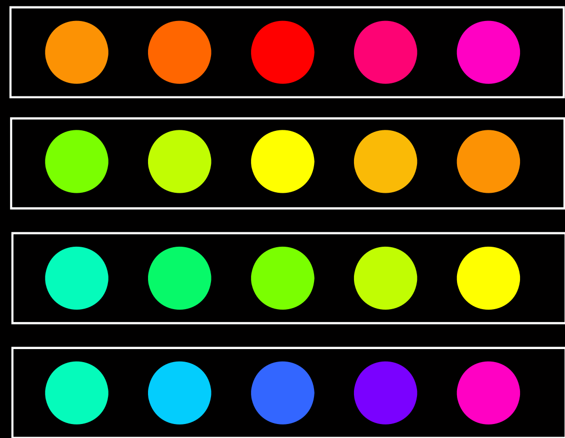
Credit: Jenny Birch

POSTRECEPTORAL COLOUR VISION

How is colour processed after the cones?



The colour opponent theory of Hering

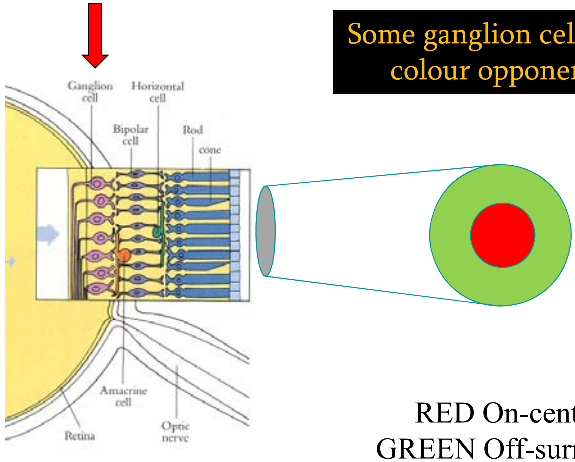


The colour opponent theory of Hering

is opposed to | R-G

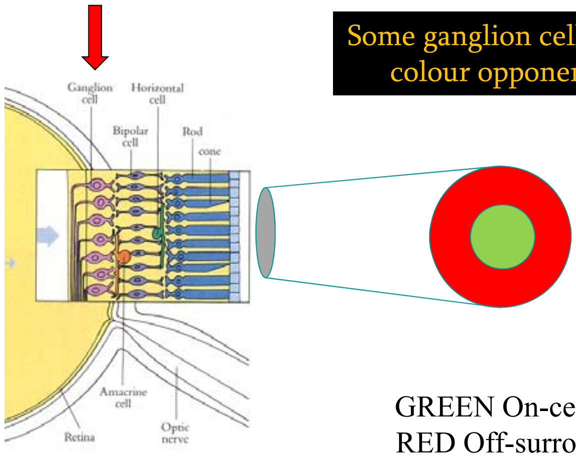
is opposed to | Y-B

How might this be related to visual processing after the cones?



Some ganglion cells are colour opponent

RED On-centre
GREEN Off-surround

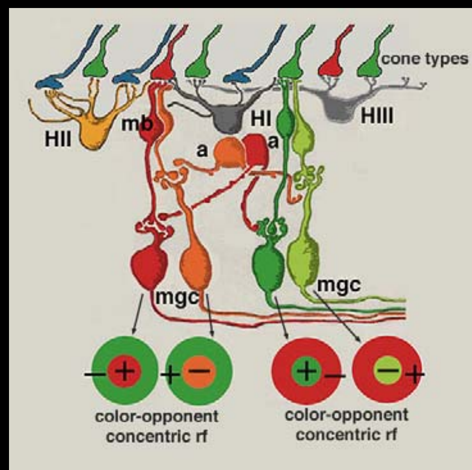


Some ganglion cells are colour opponent

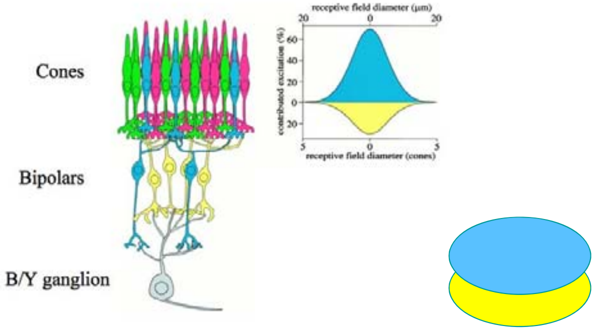
GREEN On-centre
RED Off-surround

Red-green colour opponency

Four variants

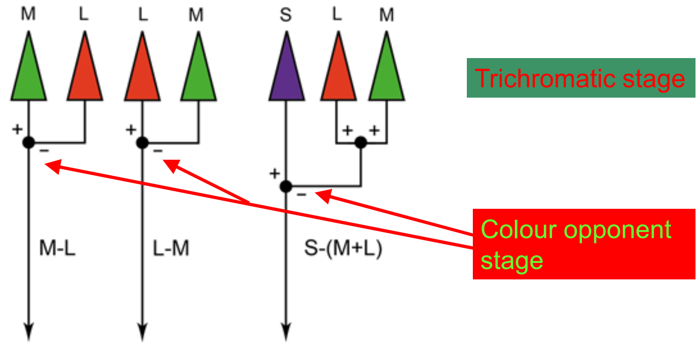


Blue/yellow pathway



Source: David Heeger

Summary



Chromatic pathways

So far, we've mainly been talking about the colours of isolated patches of light. But the colour of a patch depends also upon:

(i) What precedes it (in time)

COLOUR AFTER-EFFECTS

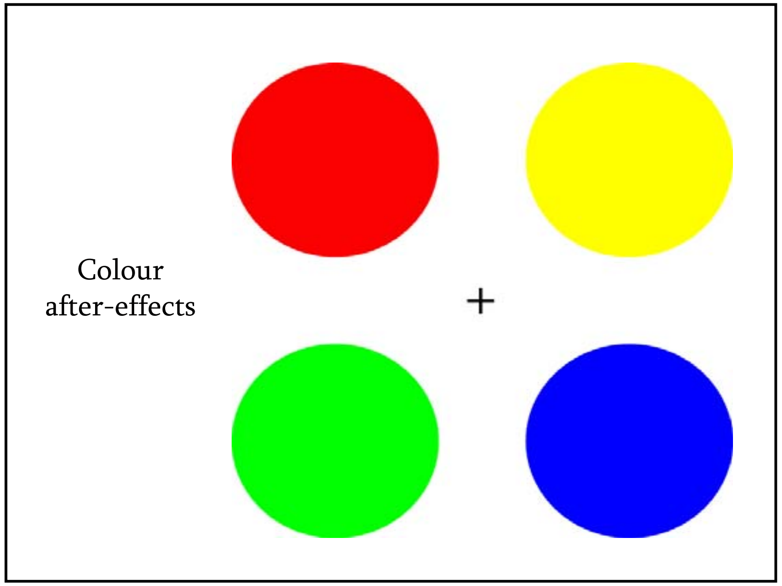
(ii) What surrounds it (in space)

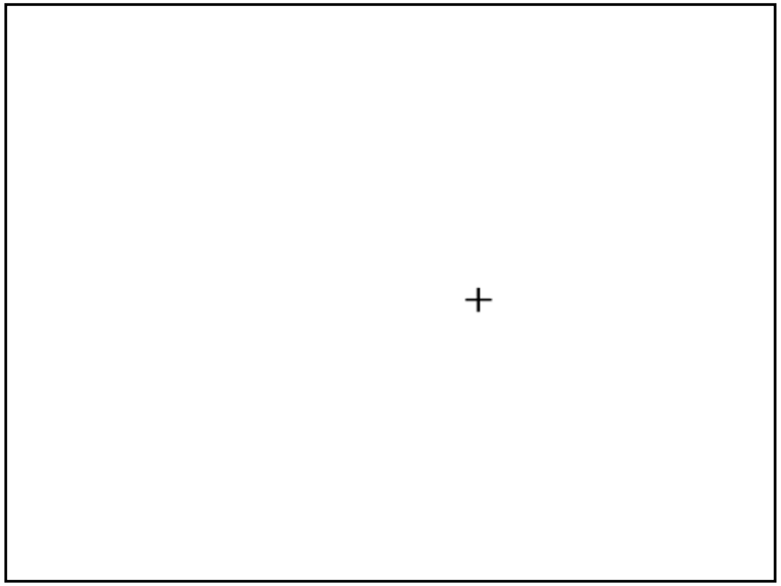
COLOUR CONTRAST

COLOUR ASSIMILATION

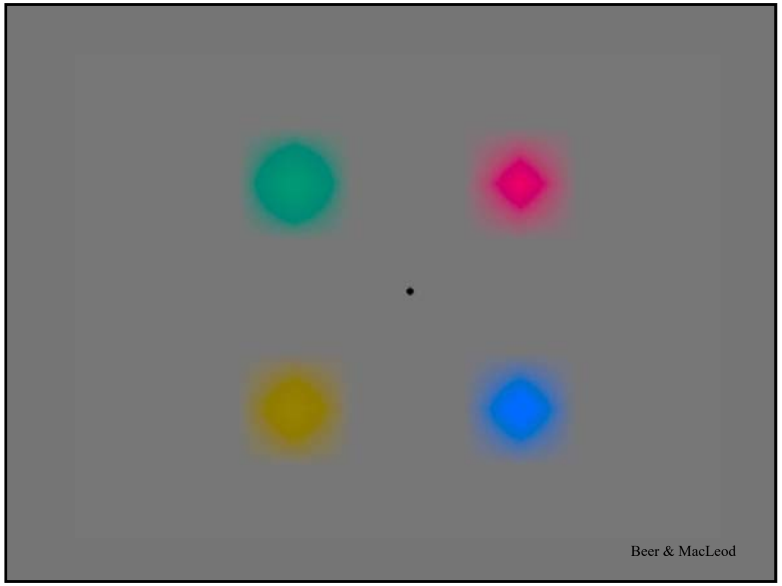
COLOUR AFTER-EFFECTS

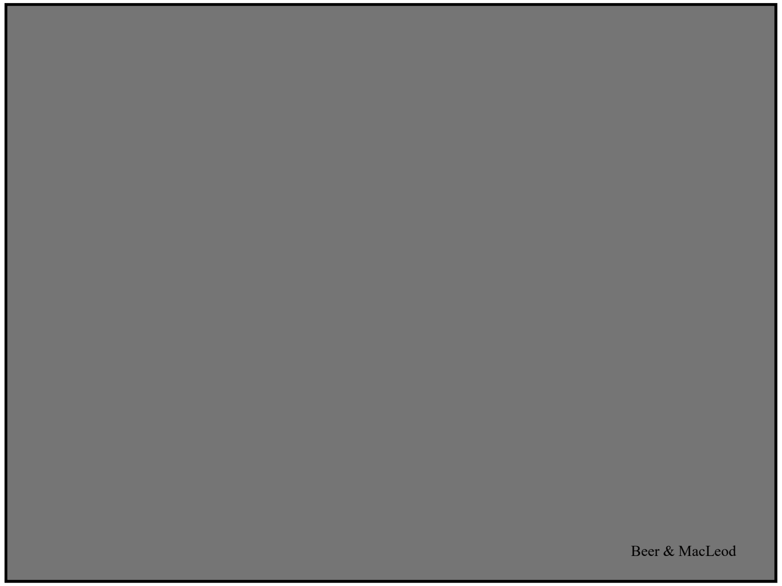
(what precedes the patch)



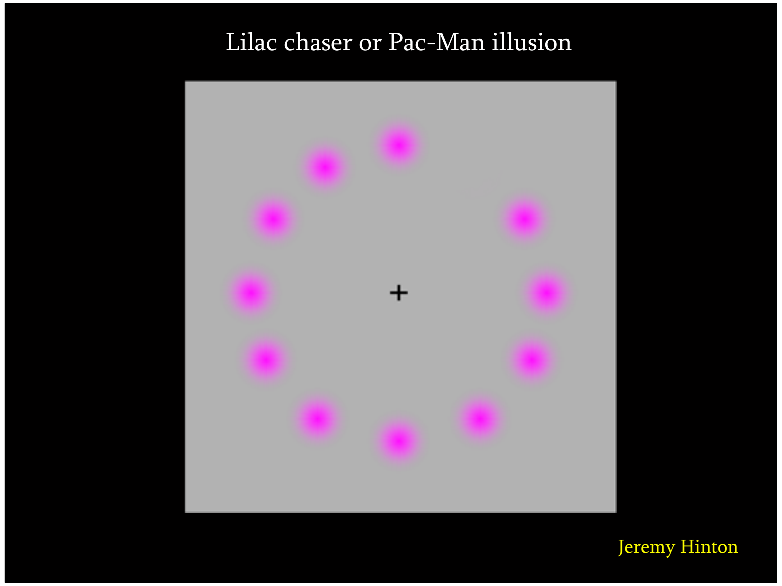


You don't have to see things for them
to produce an after-effect...




Beer & MacLeod


Mediafire


Lilac chaser or Pac-Man illusion
+
Jeremy Hinton

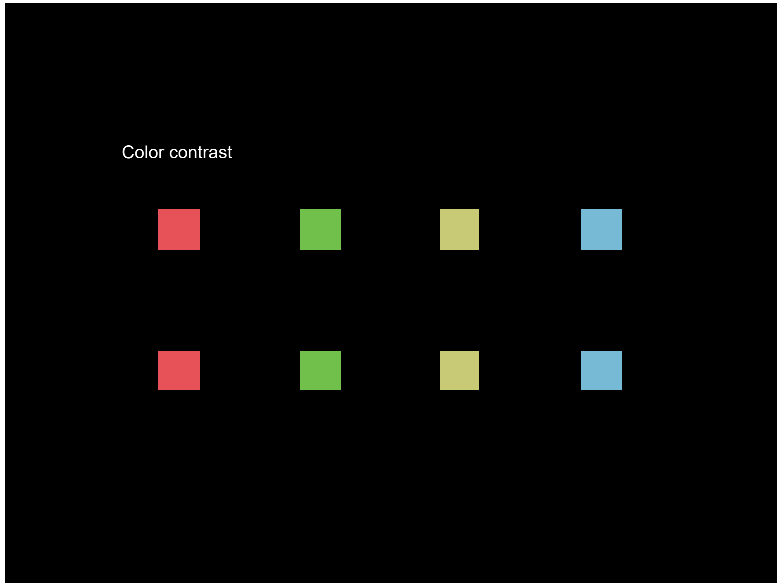
Lilac chaser or Pac-Man illusion

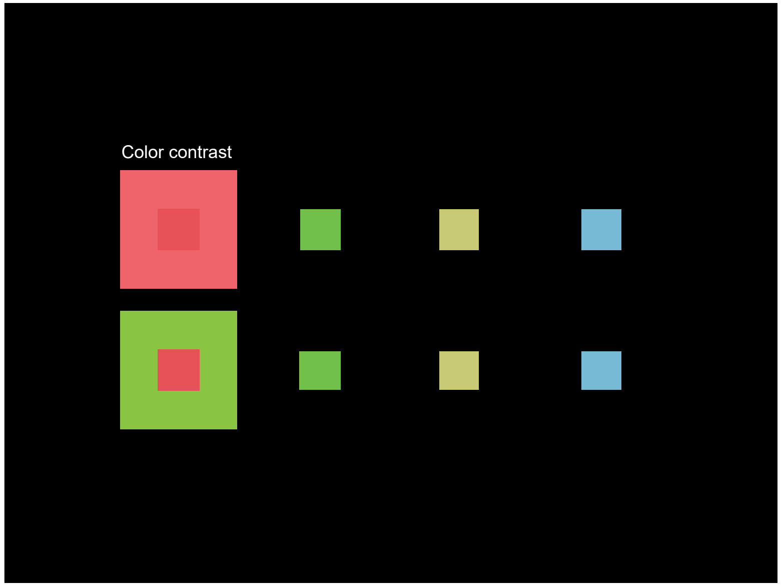
http://michaelbach.de/ot/index.html

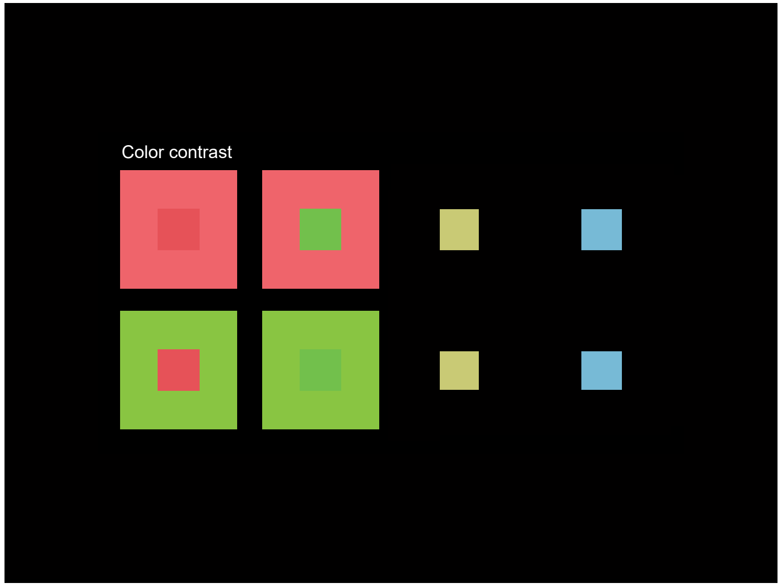
Michael Bach and Jeremy Hinton

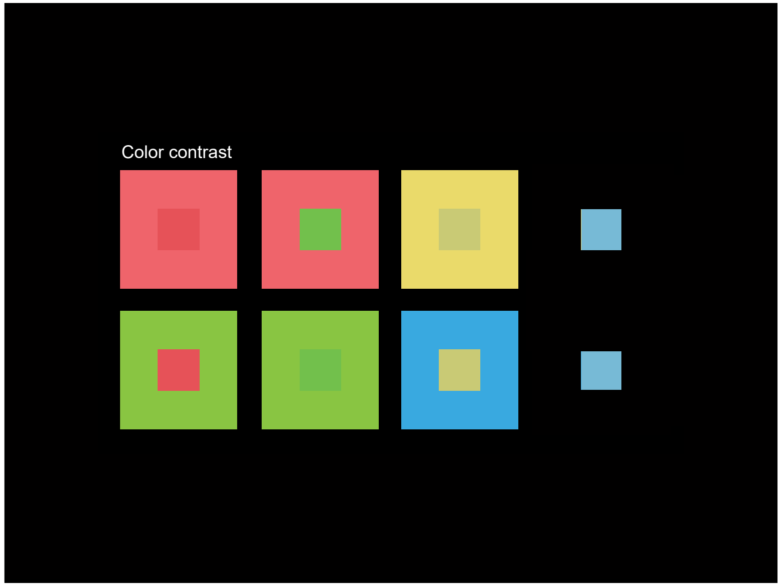
COLOUR CONTRAST

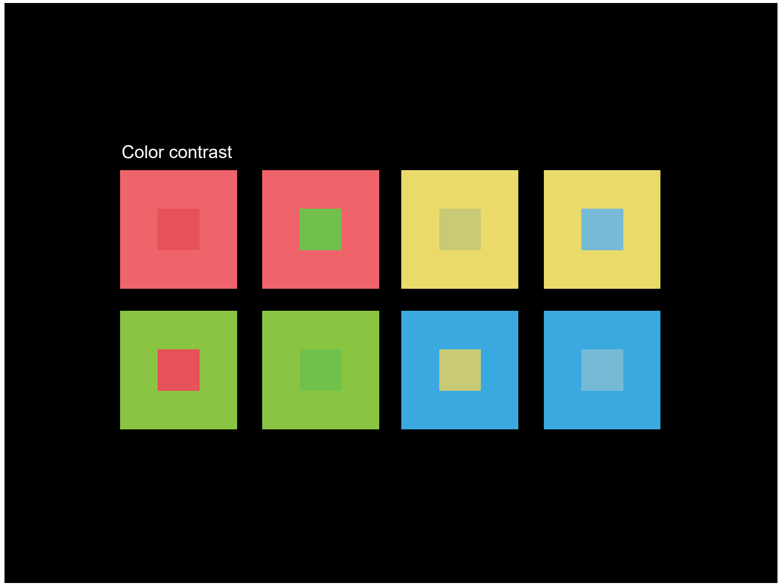
(what surrounds the patch)

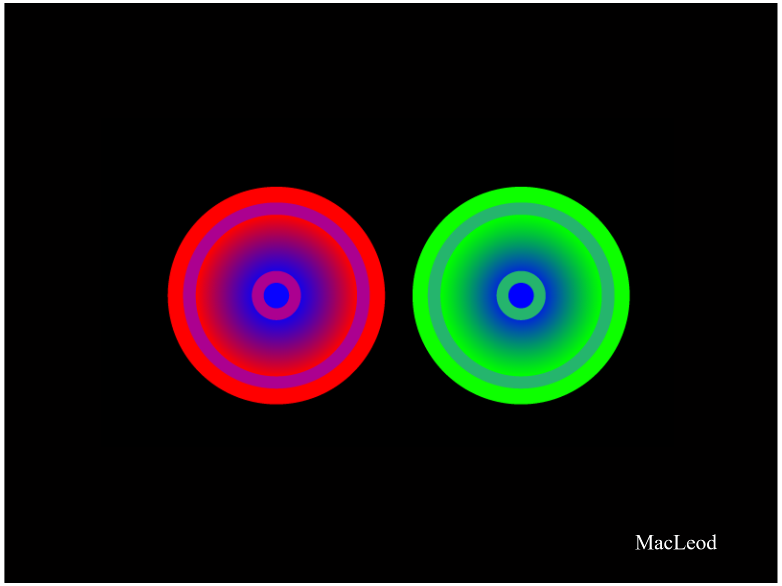


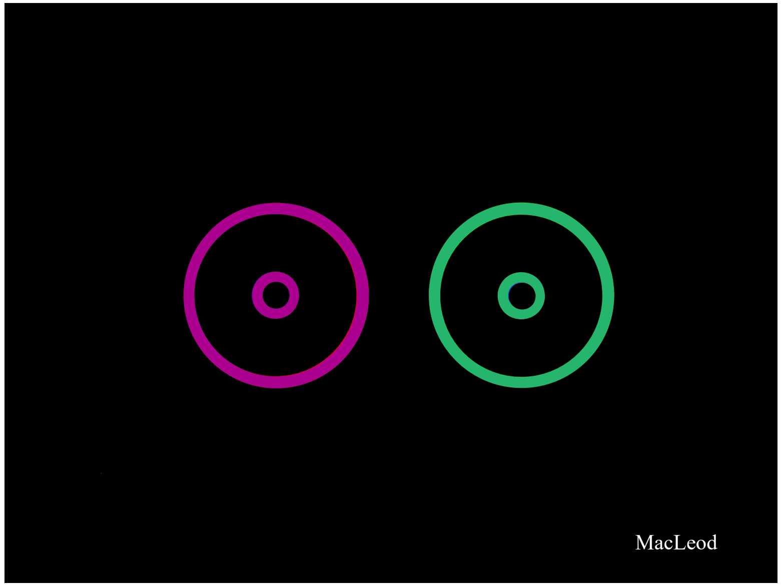



Color contrast

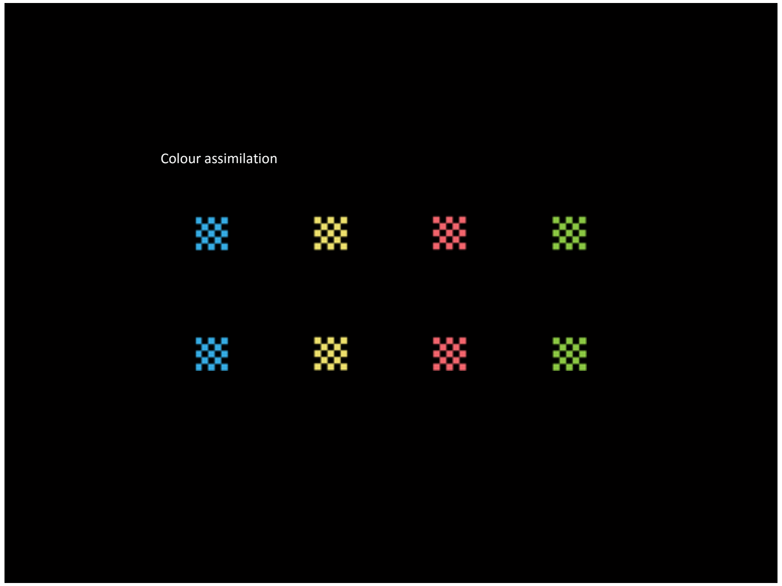

Color contrast

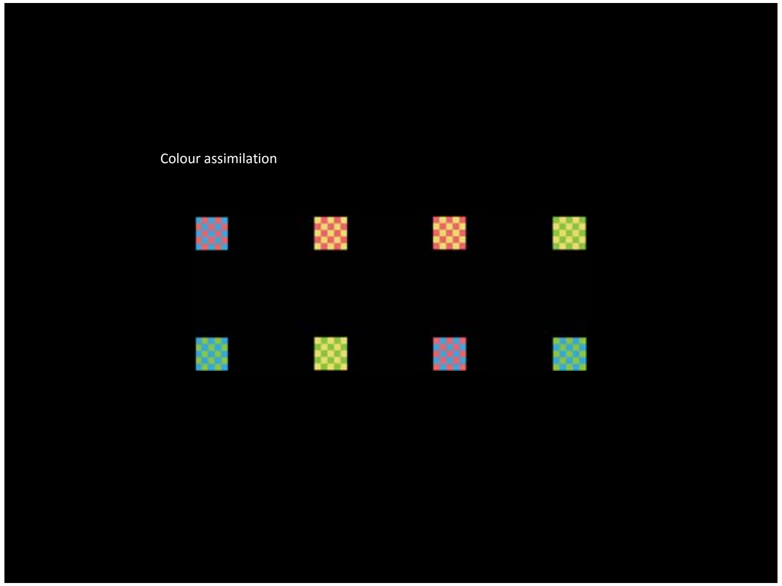

Color contrast

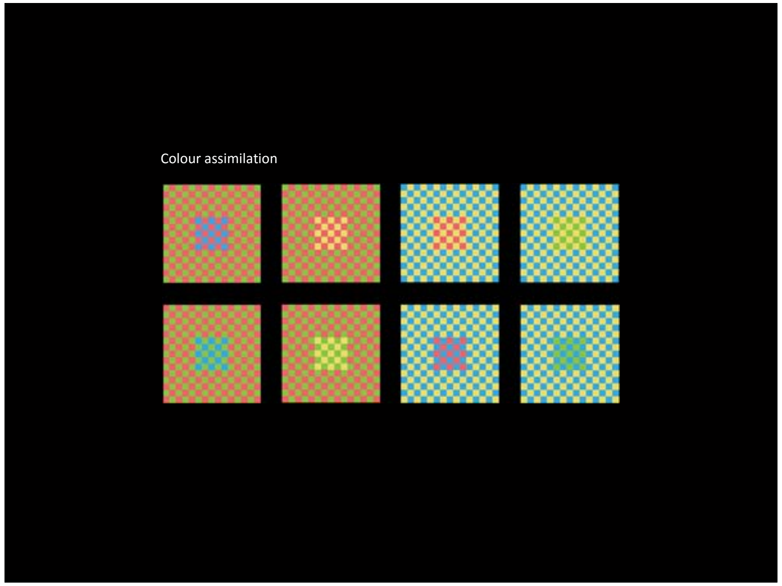

MacLeod

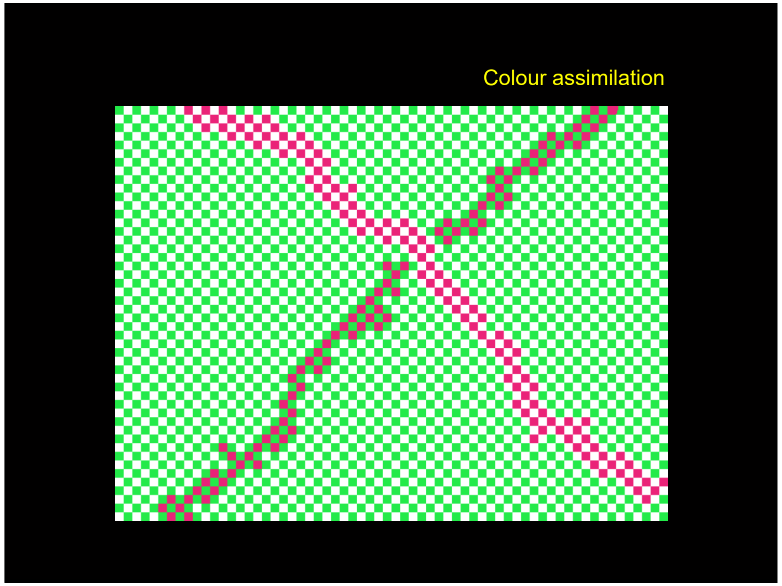

MacLeod

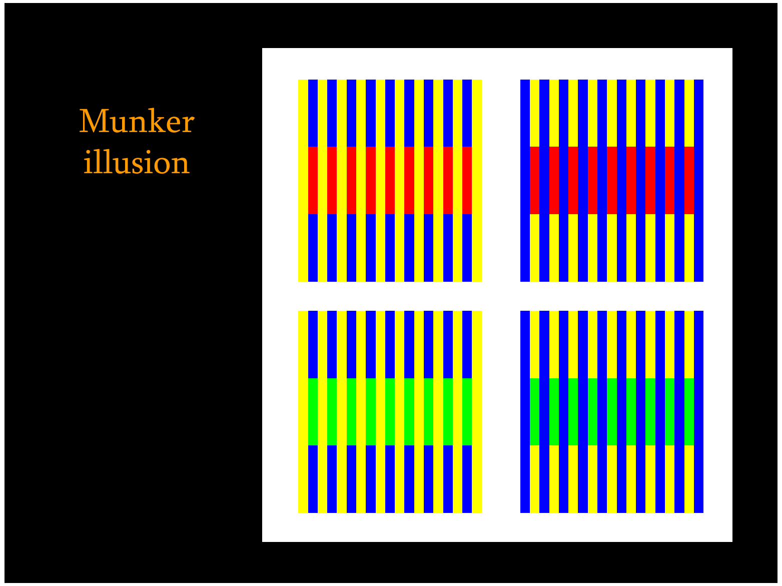

COLOUR ASSIMILATION


Colour assimilation


Colour assimilation

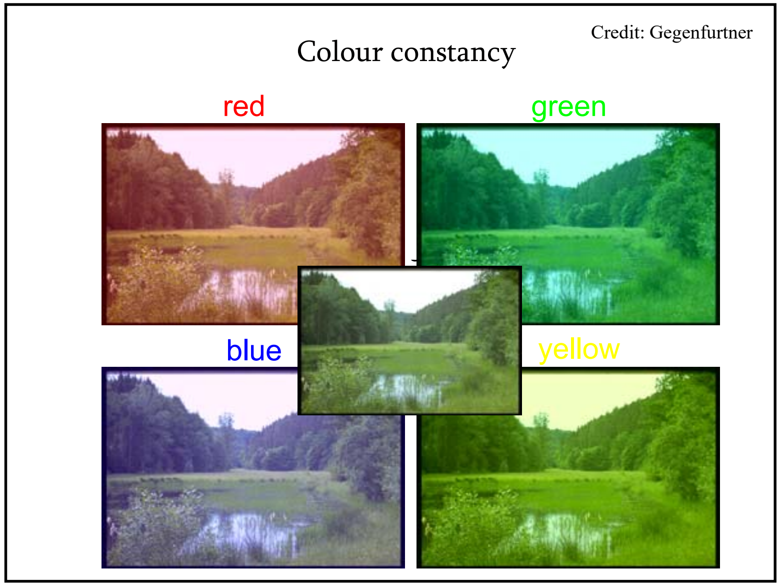

Colour assimilation

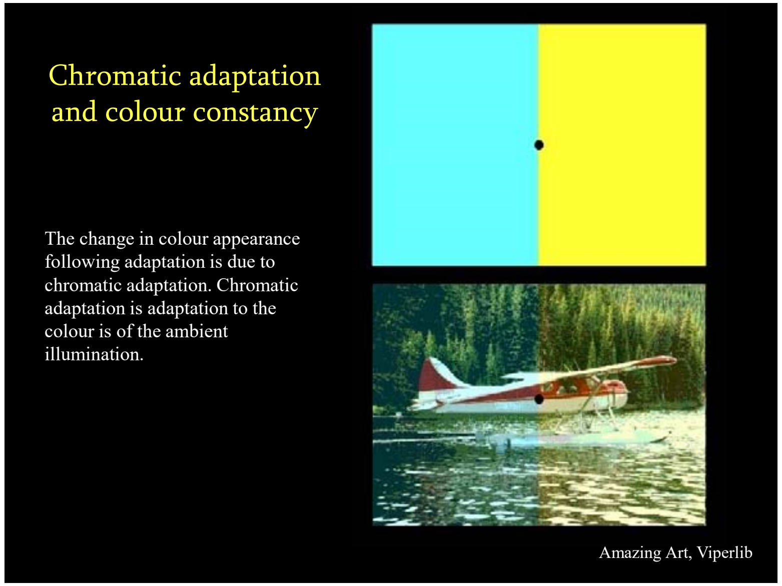

Colour assimilation

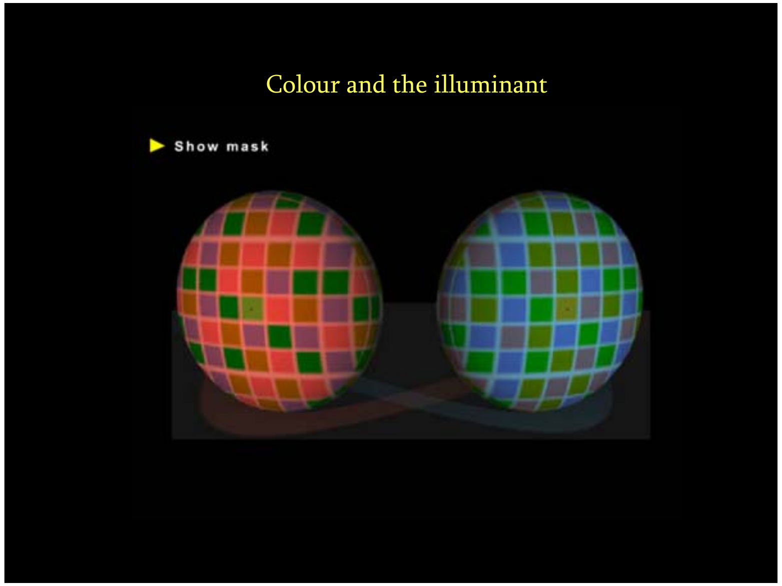

Munker
illusion

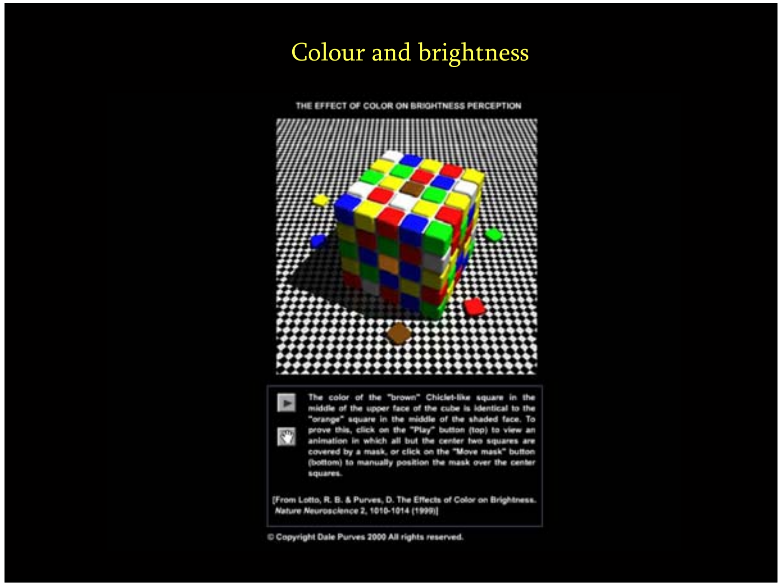

COLOUR CONSTANCY

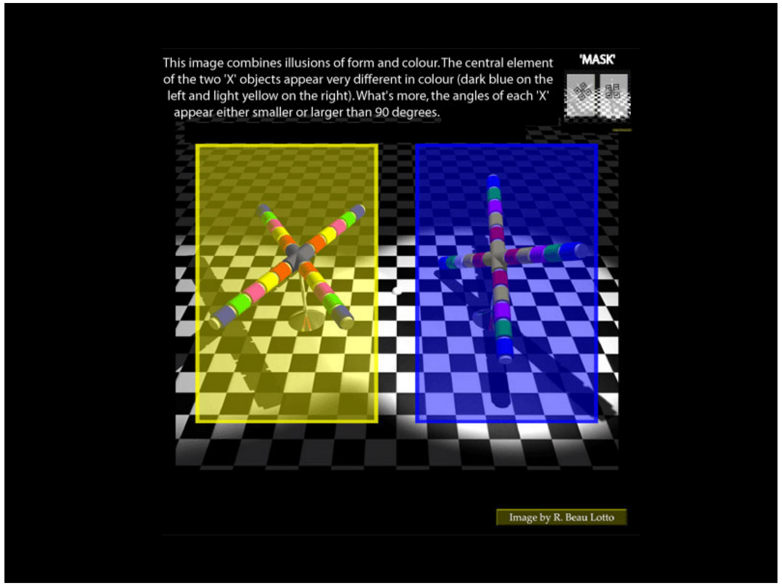

Colour constancy
The Color of Light
DAYLIGHT FILM
Tungsten Light (uncorrected)
Normal
Fluorescent Light (uncorrected)

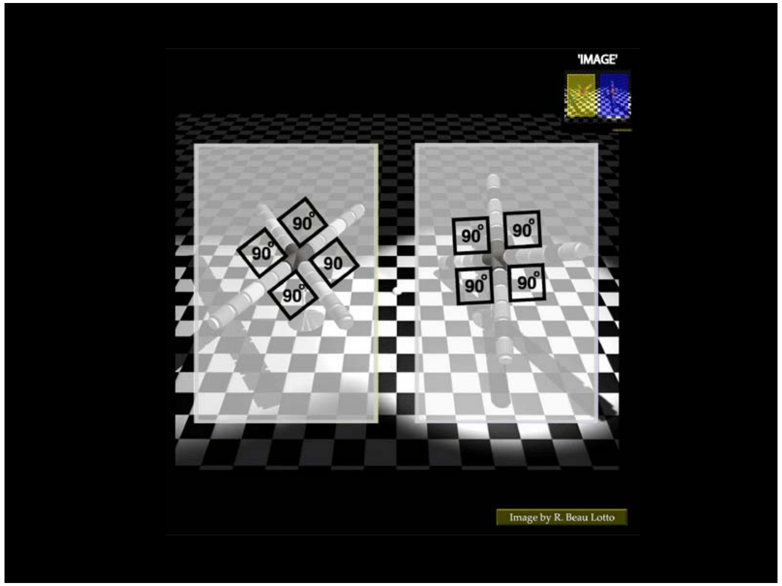

Colour constancy
Credit: Gegenfurtner
red
green
blue
yellow


Chromatic adaptation and colour constancy
The change in colour appearance following adaptation is due to chromatic adaptation. Chromatic adaptation is adaptation to the colour is of the ambient illumination.
Amazing Art, Viperlib

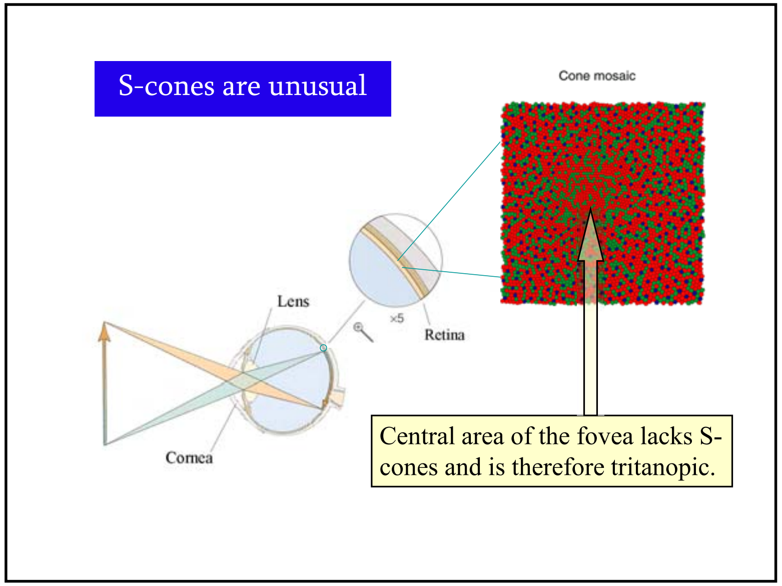

Colour and the illuminant
Show mask

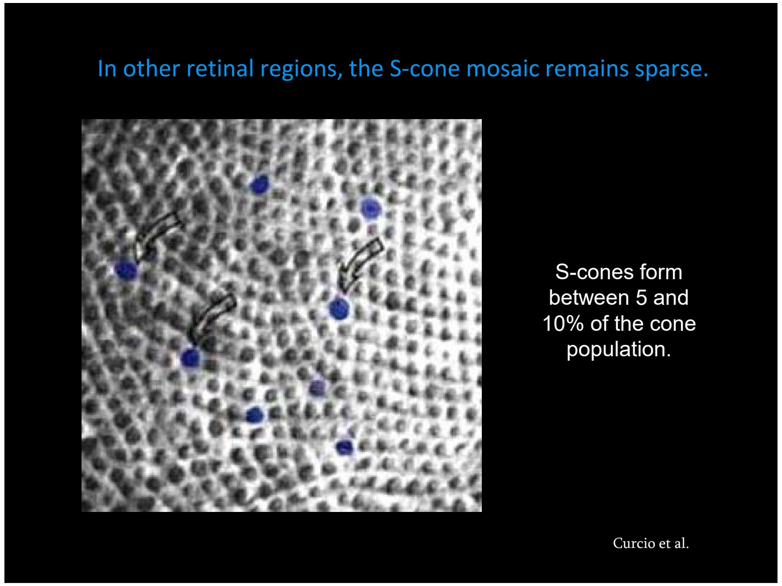


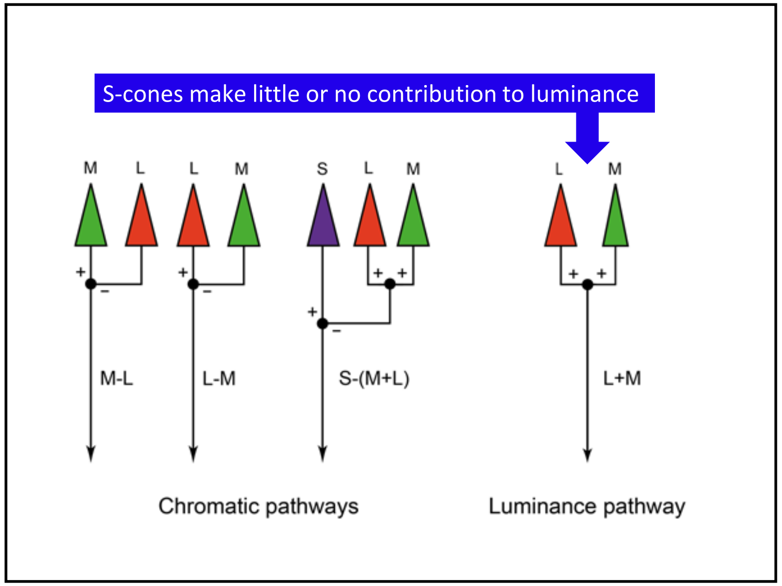


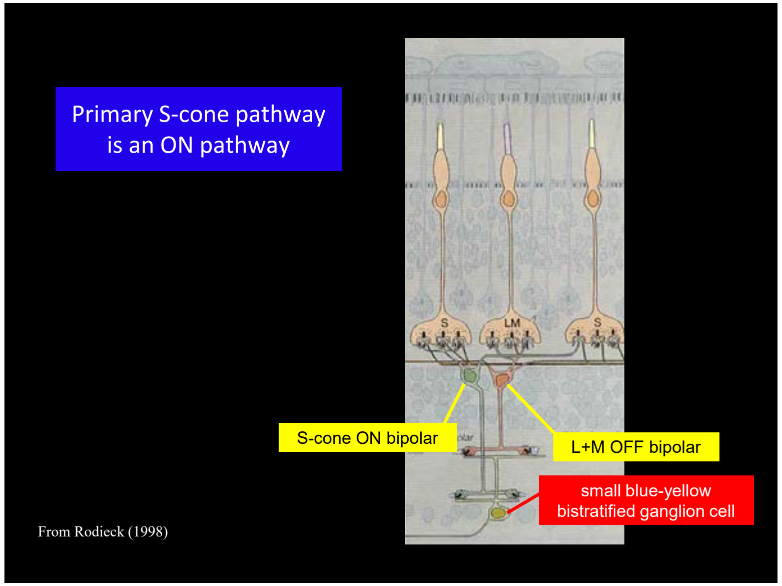


S-CONE MEDIATED VISION IS UNUSUAL

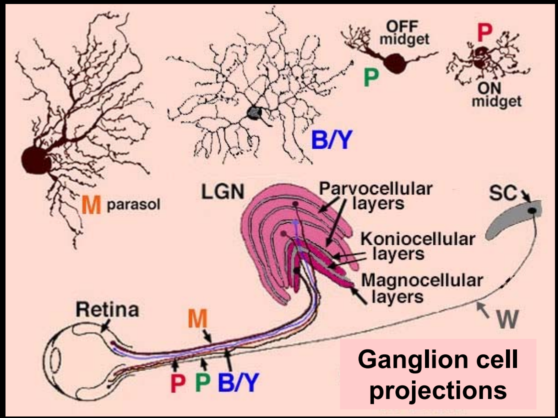

S-cones are unusual
Cone mosaic
Lens
×5
Retina
Cornea
Central area of the fovea lacks S-cones and is therefore tritanopic.


In other retinal regions, the S-cone mosaic remains sparse.
S-cones form between 5 and 10% of the cone population.
Curcio et al.


S-cones make little or no contribution to luminance
M L L M S L M L M
M-L
L-M
S-(M+L)
L+M
Chromatic pathways
Luminance pathway


Primary S-cone pathway is an ON pathway
S-cone ON bipolar
L+M OFF bipolar
small blue-yellow bistratified ganglion cell
From Rodieck (1998)

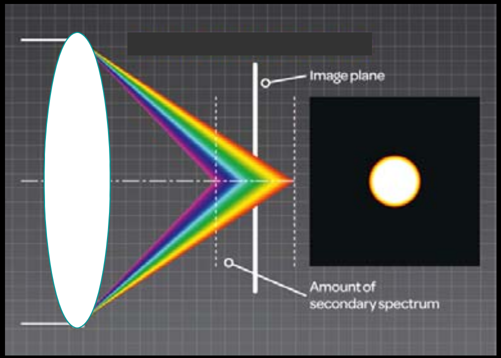
LGN pathways



S-cone vision is slow

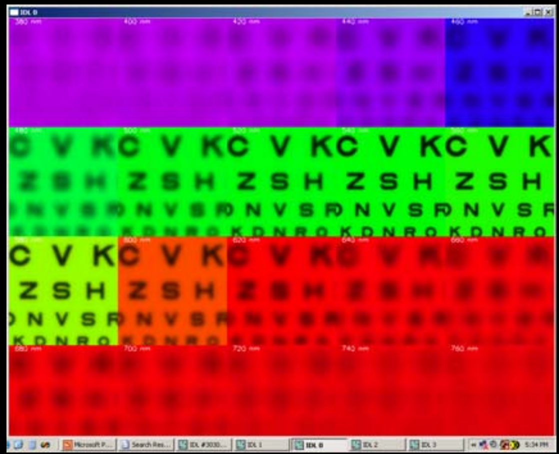
Why is S-cone vision sparse?

Chromatic aberration



Base picture: Digital camera world

Effect of chromatic blur on eye chart



Jim Schwiegerling, U. Arizona

COLOUR AND COGNITION

Stroop effect

Say to yourself the colours of the **ink** in which the following words are written -- as fast as you can.

So, for **RED**, say "red".

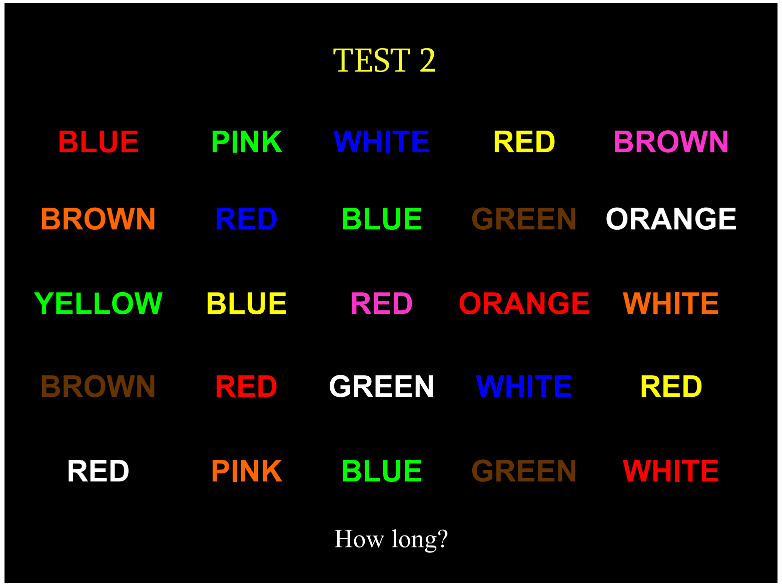
But for **RED**, say "green"

Ready, steady…

TEST 1

RED	GREEN	BLUE	YELLOW	PINK
ORANGE	BLUE	GREEN	BROWN	WHITE
GREEN	YELLOW	PINK	RED	ORANGE
BROWN	RED	WHITE	BLUE	YELLOW
WHITE	ORANGE	GREEN	BROWN	RED

How long?


TEST 2
BLUE PINK WHITE RED BROWN
BROWN RED BLUE GREEN ORANGE
YELLOW BLUE RED ORANGE WHITE
BROWN RED GREEN WHITE RED
RED PINK BLUE GREEN WHITE
How long?