Visual Neuroscience

Colour Vision Phenomenology

a guided tour of
colour opponency
&
colour constancy

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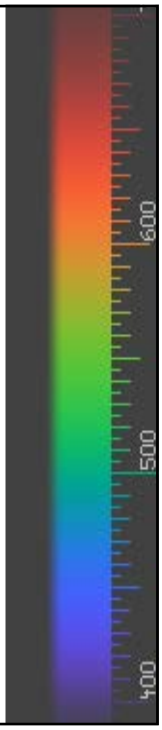
NAMING SEQUENCE			WAVELENGTH	TRADITIONAL SPECTRUM
Red	R		668	Red
Reddish-yellow	R	Y	600	Orange
Yellow		Y	580	Yellow
Yellowish-green	G	Y	550	'Chartreuse'
Green	G		520	Green
Greenish-blue	G	B	490	Cyan
Blue		B	464	Blue
Bluish-red	R	B	440	Indigo
				Violet



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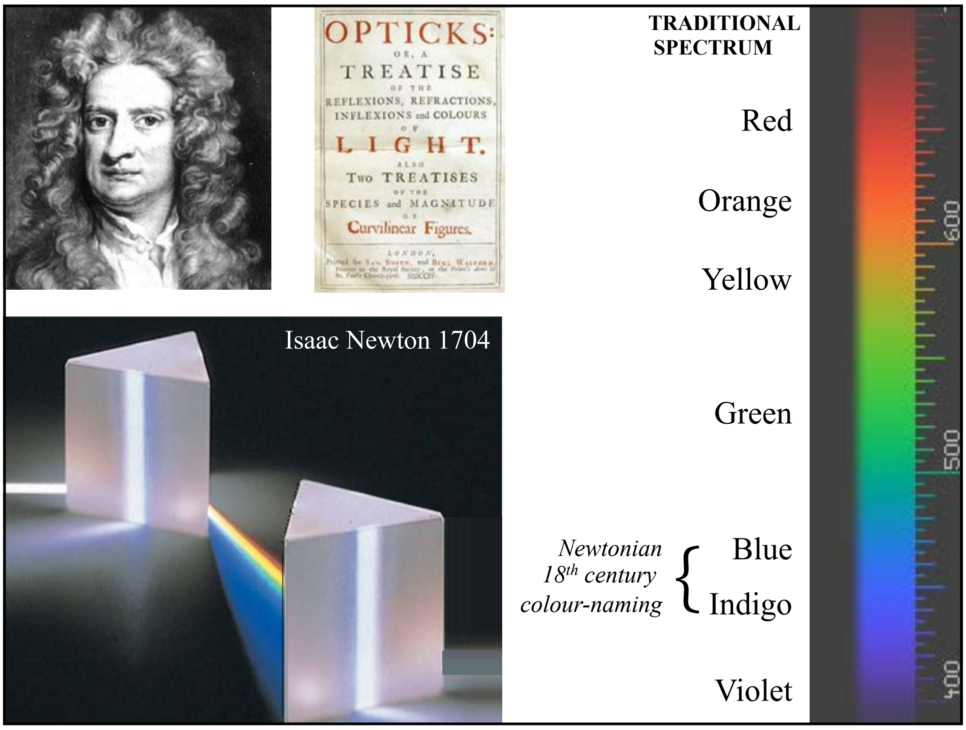
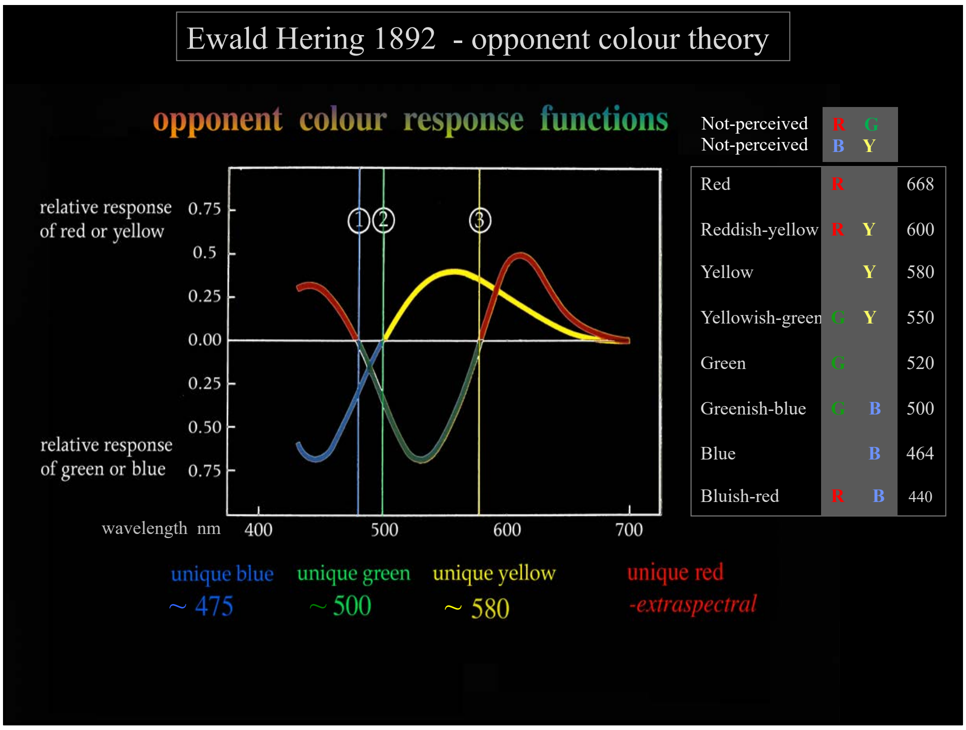

OPTICKS: OR, A TREATISE OF THE REFLEXIONS, REFRACTIONS, INFLEXIONS and COLOURS OF LIGHT.
ALSO Two TREATISES OF THE SPECIES and MAGNITUDE OF Curvilinear Figures.
Isaac Newton 1704
TRADITIONAL SPECTRUM
Red
Orange
Yellow
Green
Newtonian 18th century colour-naming
Blue
Indigo
Violet
600
500
400

3


Ewald Hering 1892 - opponent colour theory
opponent colour response functions
relative response of red or yellow
relative response of green or blue
0.75
0.5
0.25
0.00
0.25
0.50
0.75
1
2
3
wavelength nm
400
500
600
700
unique blue ~ 475
unique green ~ 500
unique yellow ~ 580
unique red -extraspectral
Not-perceived R G
Not-perceived B Y
Red R 668
Reddish-yellow R Y 600
Yellow Y 580
Yellowish-green G Y 550
Green G 520
Greenish-blue G B 500
Blue B 464
Bluish-red R B 440

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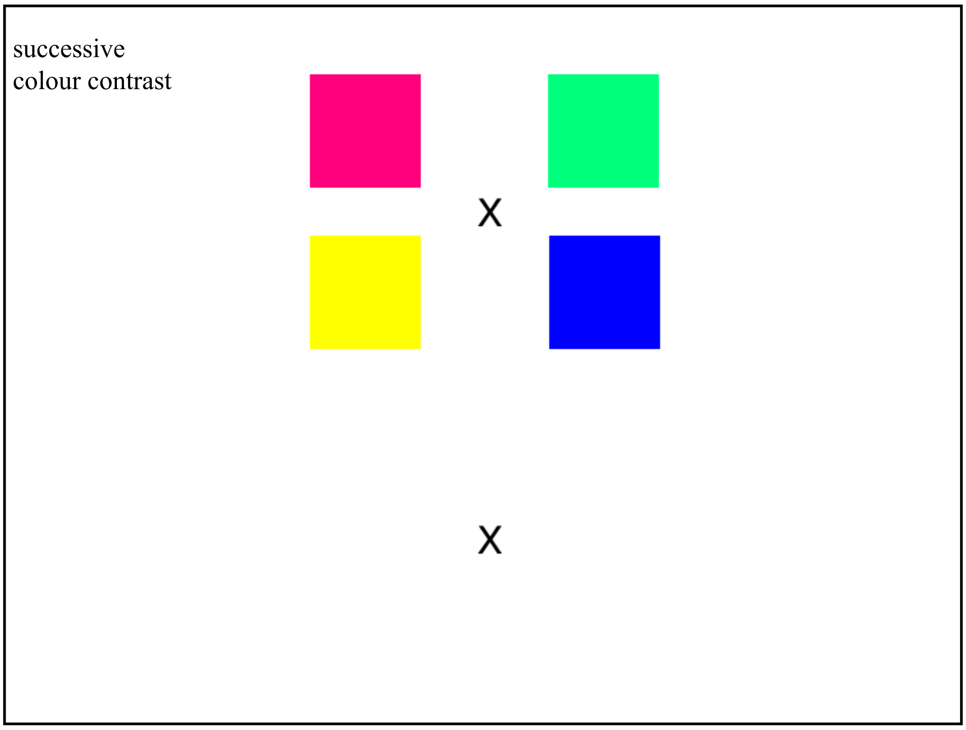
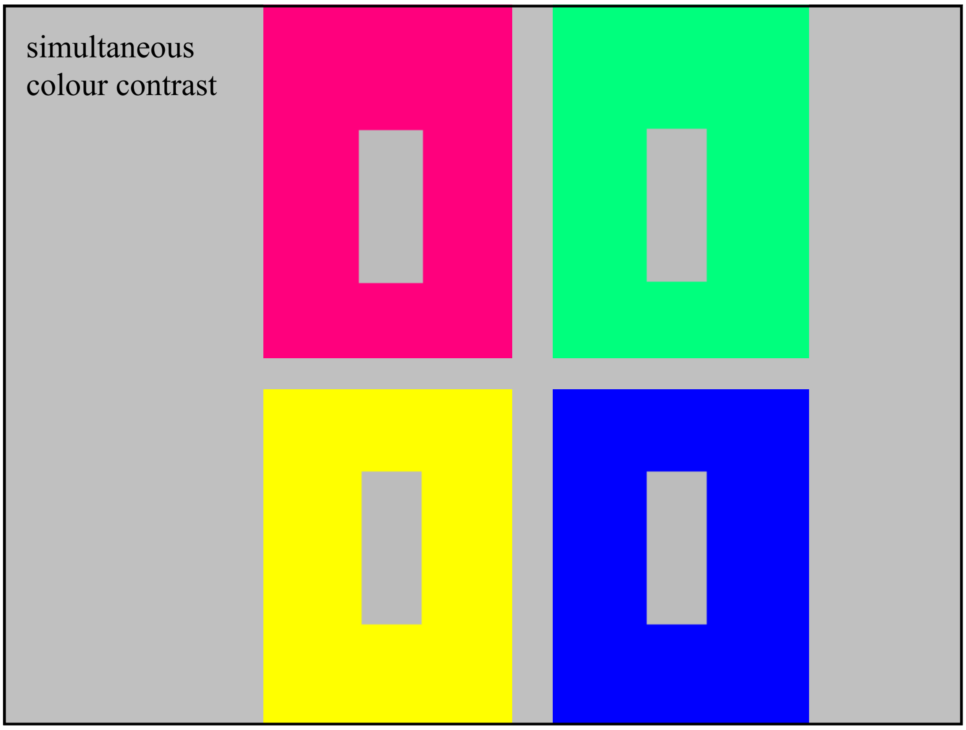
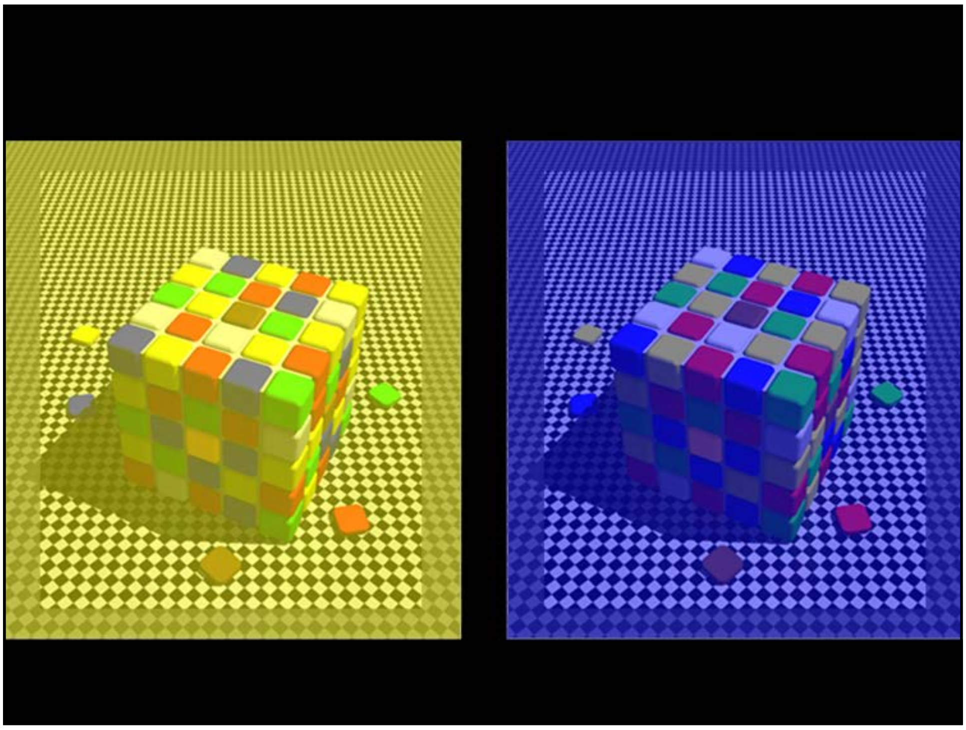

successive
colour contrast
X
X

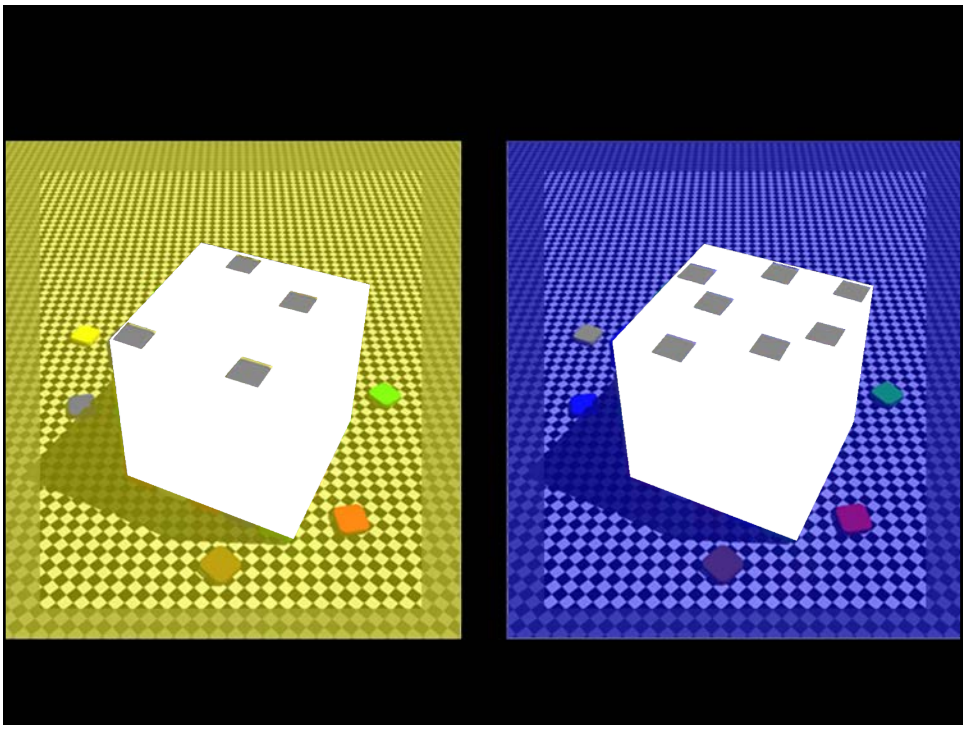
5


simultaneous
colour contrast

6



7



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Opponent colour perceptual phenomenology

Appearance
No hue combines redness & greenness, nor blueness & yellowness

Induction
One member of an opponent pair induces its complementary colour:
- *successive colour contrast*
- *simultaneous colour contrast*

Cancellation
The colours of an opponent pair should cancel to achromatic white (or grey)

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'COLOUR' is an illusion created by the brain as a perceptual correlate of spectral wavelength.

There is nothing in the nature of the physical universe, nor the physics of light to compel colour-opponency.

Colour-opponency is entirely caused by biology & by the construction of our nervous system.

So what is the PHYSIOLOGY of colour perception ?

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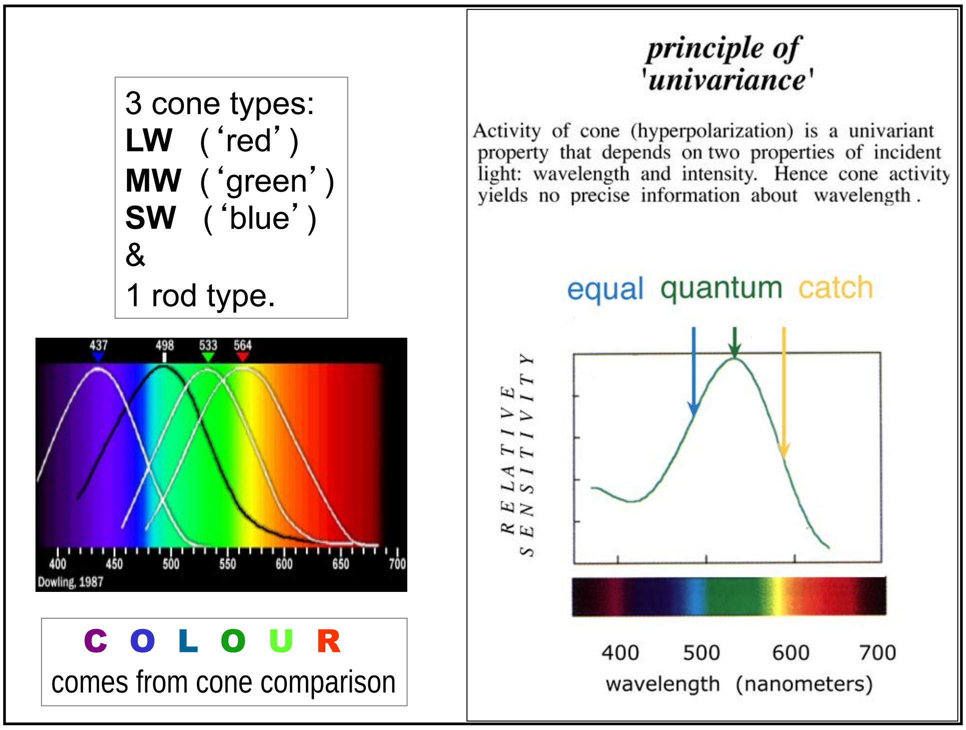
3 cone types:
LW ('red')
MW ('green')
SW ('blue')
&
1 rod type.
437
498
533
564
400
450
500
550
600
650
700
Dowling, 1987
C O L O U R
comes from cone comparison
principle of 'univariance'
Activity of cone (hyperpolarization) is a univariant property that depends on two properties of incident light: wavelength and intensity. Hence cone activity yields no precise information about wavelength.
equal quantum catch
RELATIVE SENSITIVITY
400
500
600
700
wavelength (nanometers)

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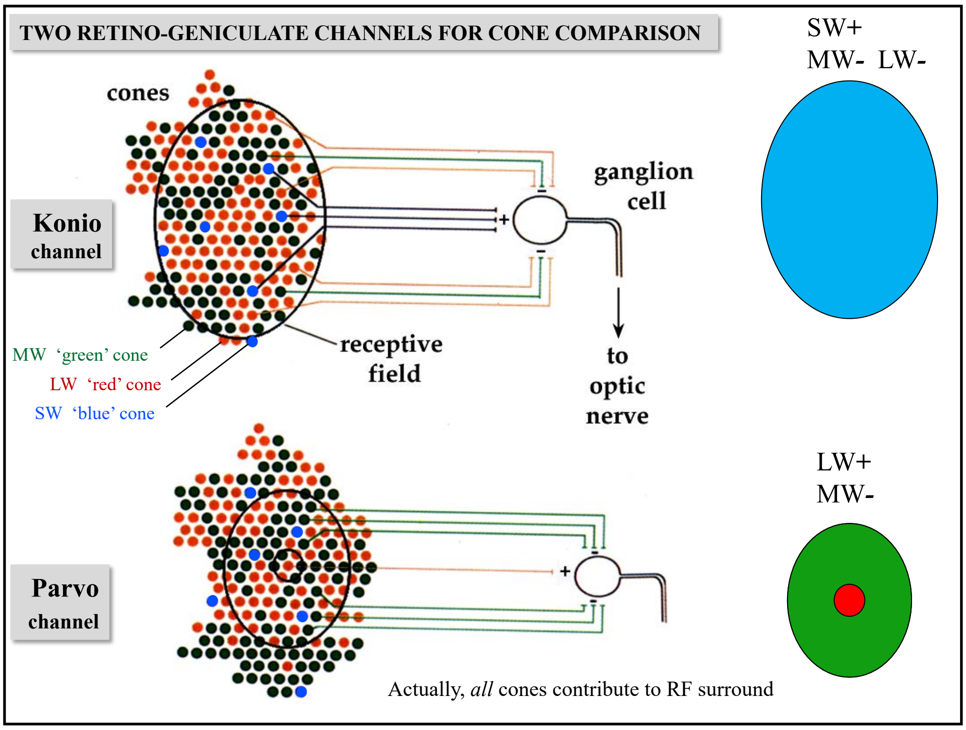
TWO RETINO-GENICULATE CHANNELS FOR CONE COMPARISON
cones
Konio channel
ganglion cell
receptive field
to optic nerve
MW 'green' cone
LW 'red' cone
SW 'blue' cone
SW+
MW- LW-
Parvo channel
LW+
MW-
Actually, *all* cones contribute to RF surround

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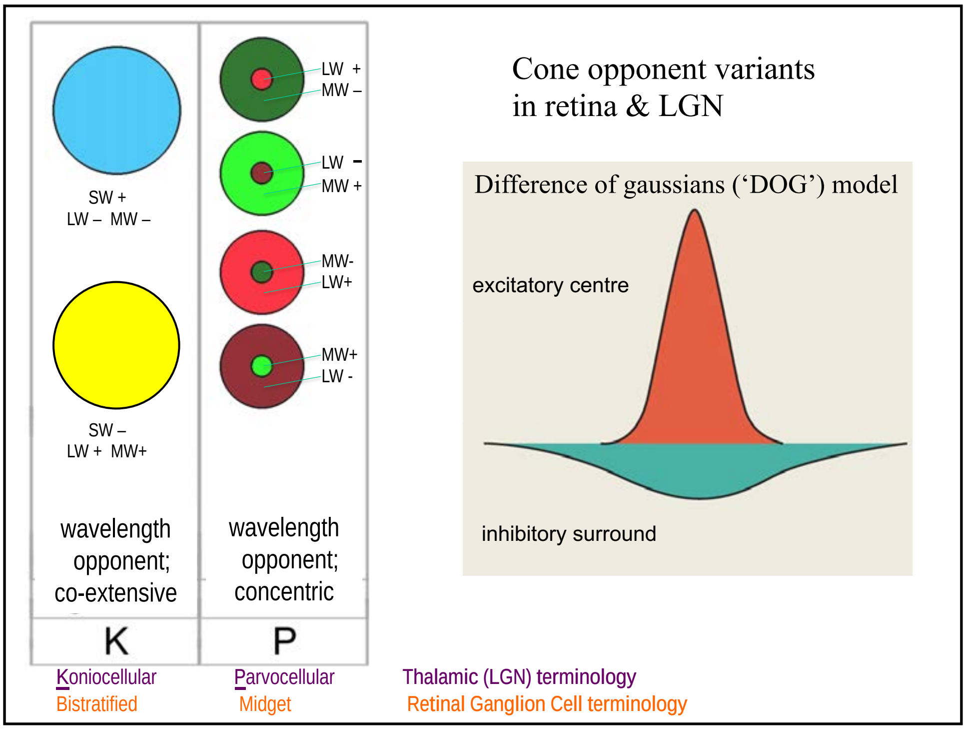
Cone opponent variants
in retina & LGN
SW +
LW – MW –
SW –
LW + MW+
LW +
MW –
LW -
MW +
MW-
LW+
MW+
LW -
wavelength opponent; co-extensive
wavelength opponent; concentric
K
P
Koniocellular
Bistratified
Parvocellular
Midget
Thalamic (LGN) terminology
Retinal Ganglion Cell terminology
Difference of gaussians ('DOG') model
excitatory centre
inhibitory surround

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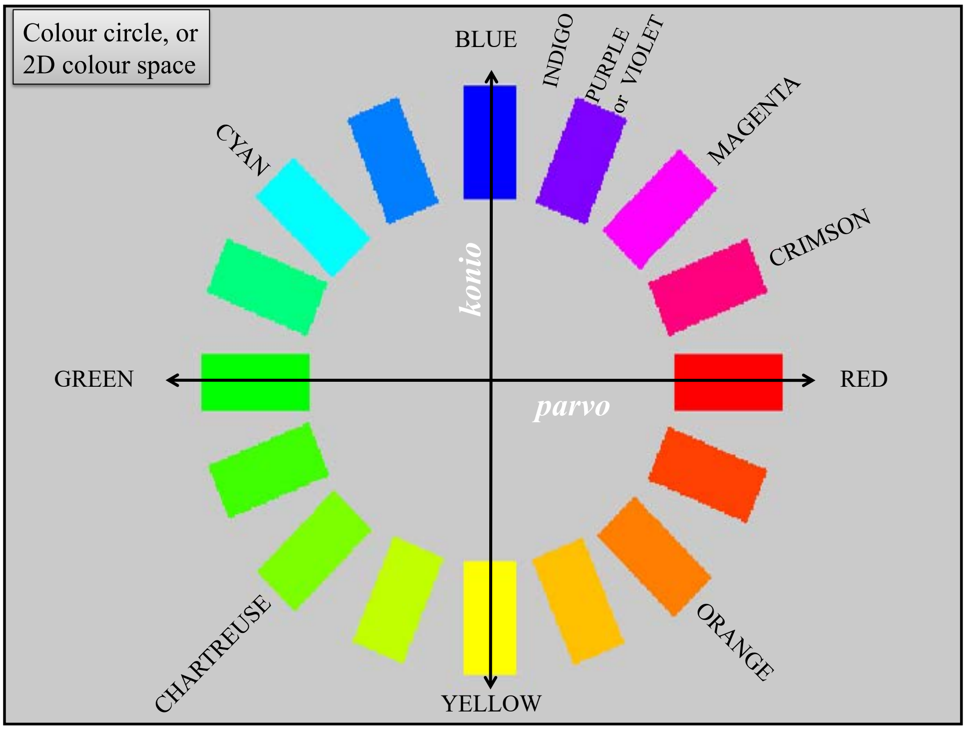
Colour circle, or
2D colour space
BLUE
INDIGO
PURPLE
or VIOLET
MAGENTA
CRIMSON
RED
ORANGE
YELLOW
CHARTREUSE
GREEN
CYAN
konio
parvo

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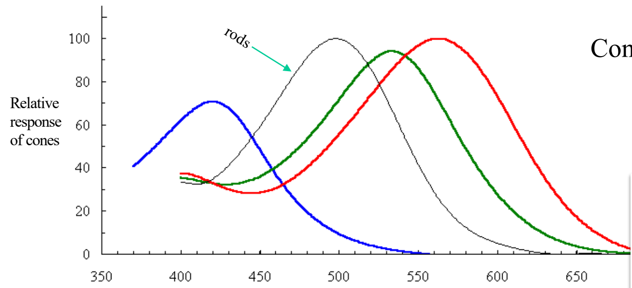
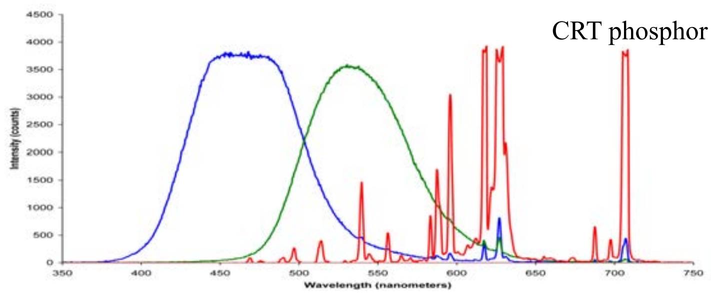
Cone opponent colour space



Cone photoreceptor sensitivity

Can calculate the exact ratio of cone activities produced by any given trio of RGB screen settings.



CRT phosphor emission

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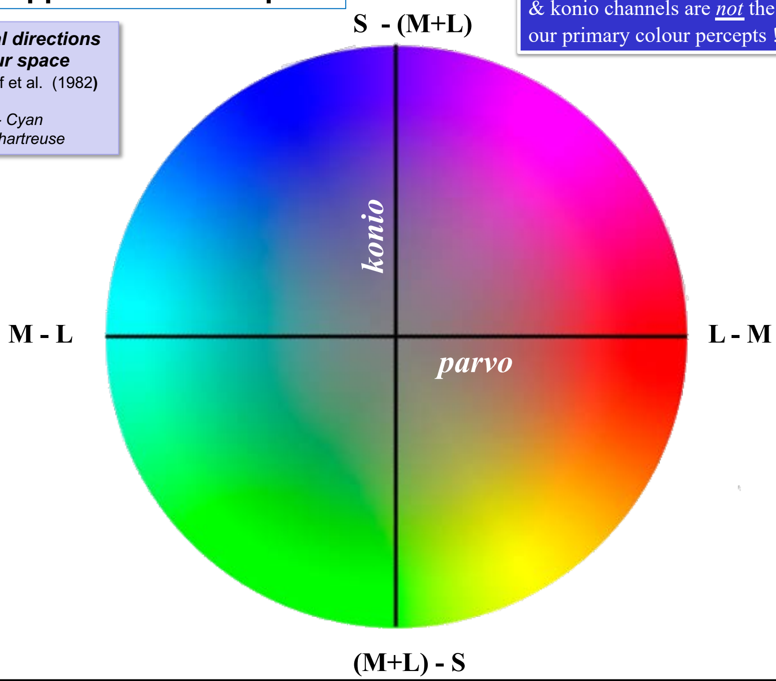
Cone opponent colour space

Cardinal directions of colour space
Krauskopf et al. (1982)

Crimson - Cyan
Violet - Chartreuse

The spectral characteristics of parvo & konio channels are *not* the basis of our primary colour percepts !



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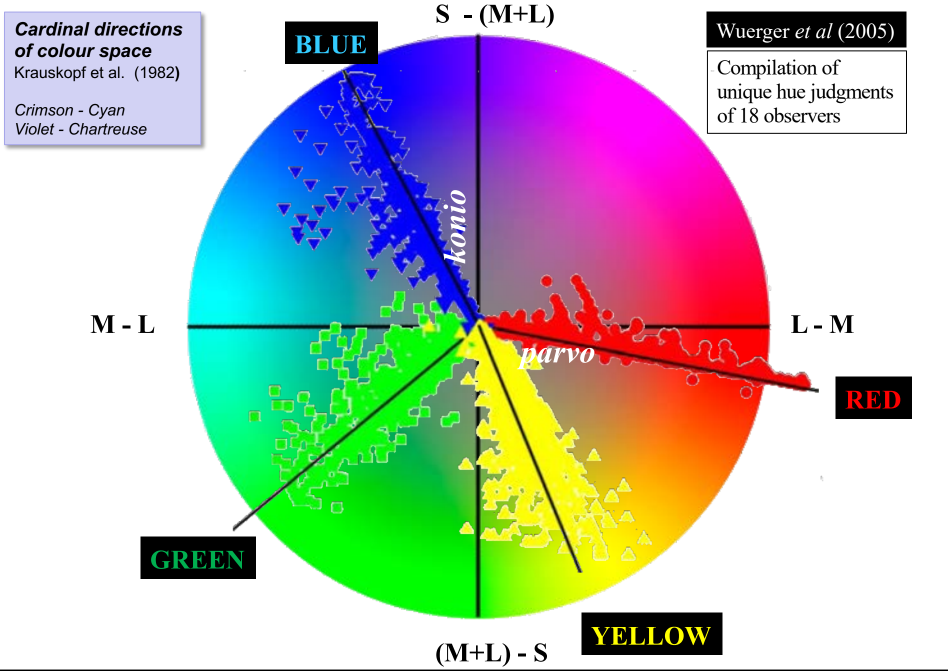
Cone opponent colour space



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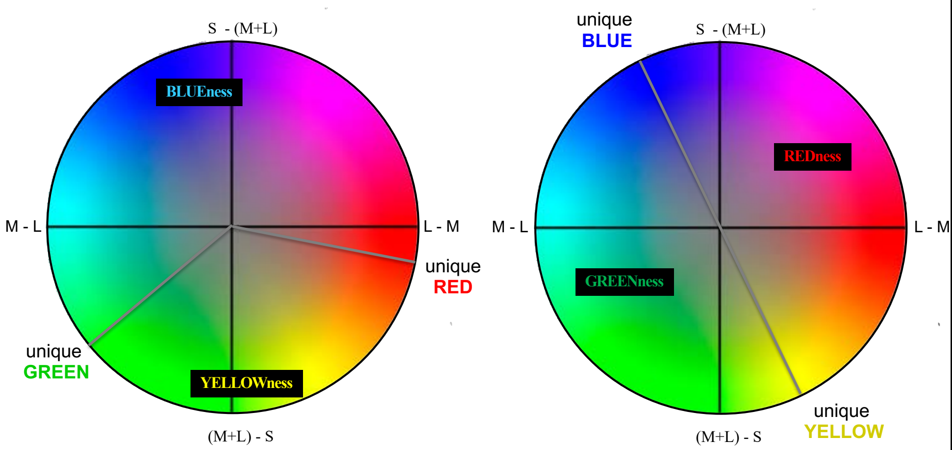
Cone-opponent colour space



The unique red – unique green axes divide cone-opponent colour space into asymmetric zones of blueness and yellowness.

The unique blue – unique yellow axes divide cone-opponent colour space into symmetric zones of redness and greenness.

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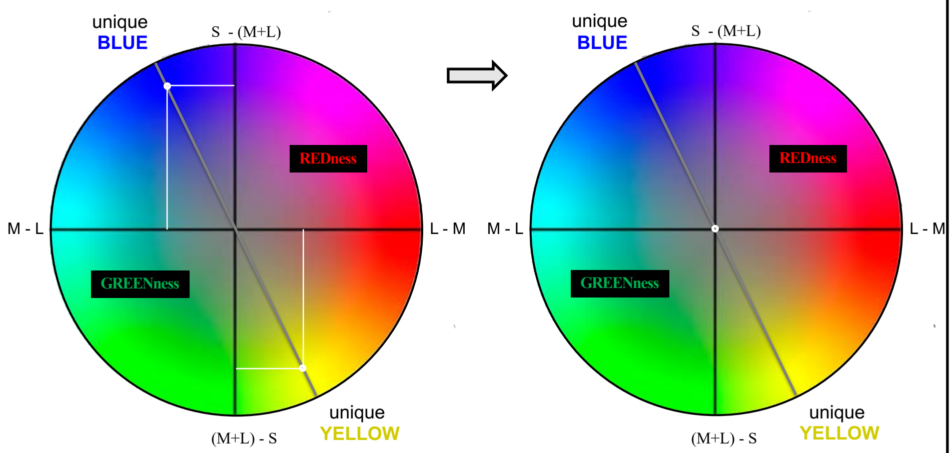
Cone-opponent colour space



Unique blue and unique yellow add to give achromatic white

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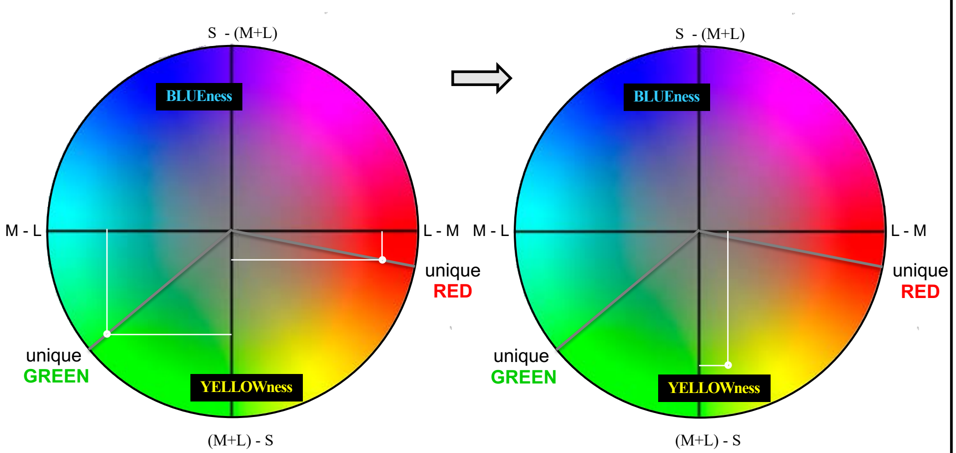
Cone-opponent colour space



Unique green and unique red add to give a hue that is mainly yellow

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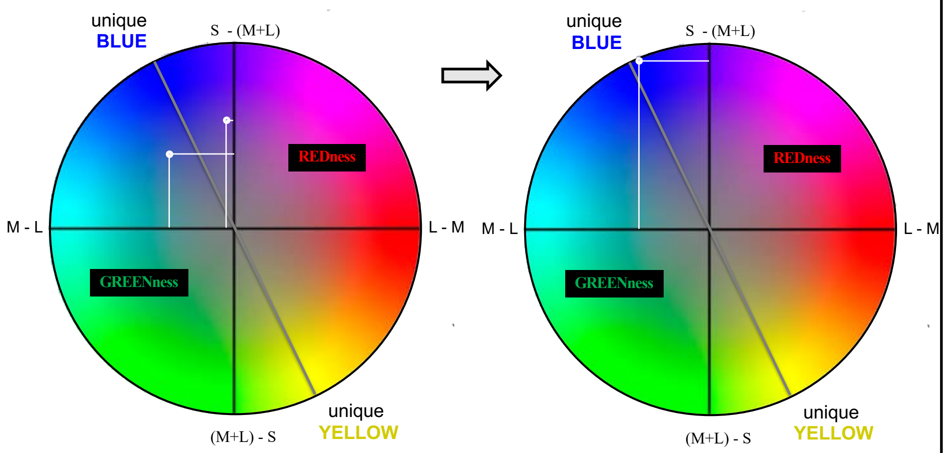
Cone-opponent colour space



Reddish-blue and greenish-blue add to give blue

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Anthropological studies confirm that different languages/cultures (not just English) have primary colour terms for 'red', 'green', 'blue' and 'yellow' (and not orange, magenta, cyan & chartreuse, for instance).

The cardinal axes of colour space are (crimson) red-cyan & violet-chartreuse - not red-green & blue-yellow – hence the retinogeniculate parvo and konio cone-opponent channels cannot be the direct basis of human primary colour perception. Instead, we must infer that cortical mechanisms recombine the retinogeniculate channels (much as the parvo and konio channels themselves recombine cone signals), and that these cortical recombinant channels are the basis of primary colour perception.

The location of unique blue, unique yellow, unique red, and unique green in the cardinal axes (i.e. cone-opponent) colour space explains, or rationalises, why blue & yellow cancel to give white, but red and green cancel to give yellow.

Cortical recombination …?
Going by the colour phenomenology, we would infer that:
Redness is supported by L-M and S-(L+M) [the latter component rationalising the violet colour of light at the SW end of the spectrum];
Greenness is supported by M-L and (L+M)-S;
Yellowness is supported only by M-L;
Blueness is supported by S-(M+L) and M-L, plus a minor contribution from L-M !

BUT – direct physiological evidence to support such a systematic cortical recombination of the retinogeniculate colour channels has yet to be obtained.

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Colour constancy

The computational principles of colour constancy can be understood by first examining achromatic lightness constancy…

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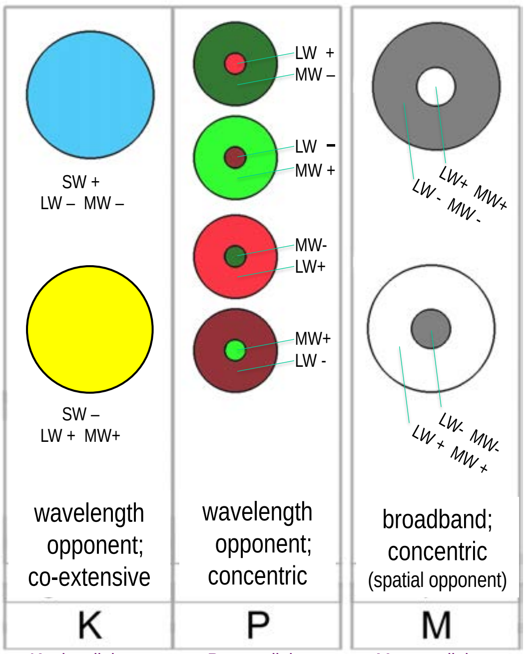

Two forms of opponency in retinal ganglion cell & lateral geniculate nucleus (LGN) receptive field organisation:-

1. **cone opponency** (‘K’ & ‘P’)
2. **spatial opponency** (‘M’ & ‘P’)

Koniocellular | Parvocellular | Magnocellular — Thalamic (LGN) terminology

Bistratified | Midget | Parasol — Retinal Ganglion Cell terminology

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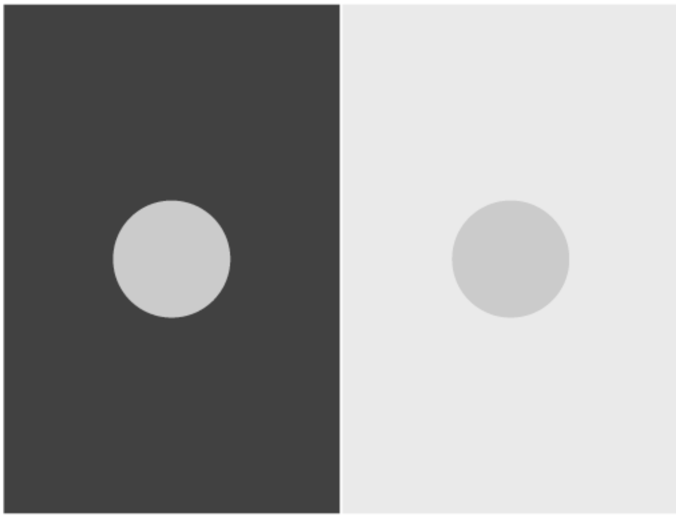
achromatic simultaneous contrast



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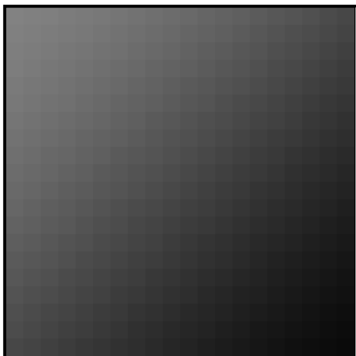
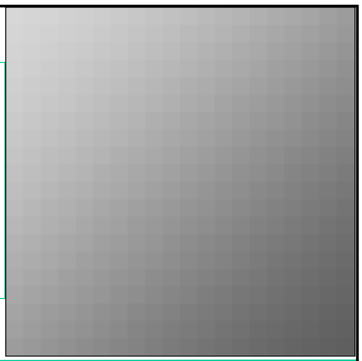
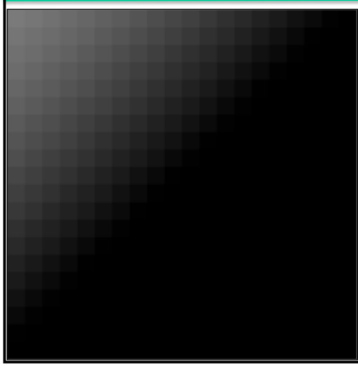
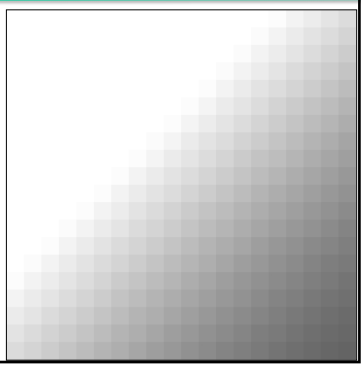


If the retina signals *contrast*, it allows small differences in brightness to be distinguished over a wide range of illumination intensity





If the retina were to signal *absolute intensity*, much of this sensitivity would be lost.



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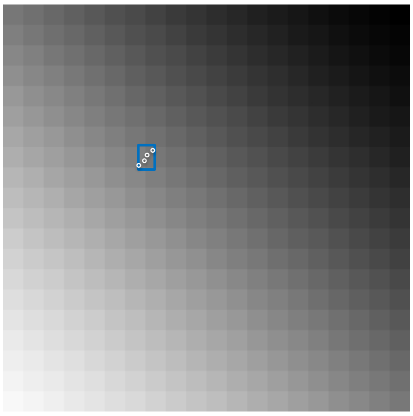
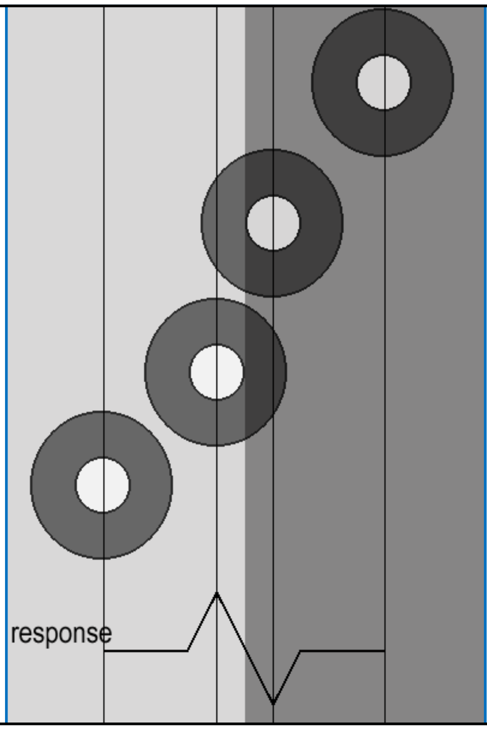
How do the responses of a RGC (e.g. ON centre, OFF surround) vary at different positions across a light dark edge?





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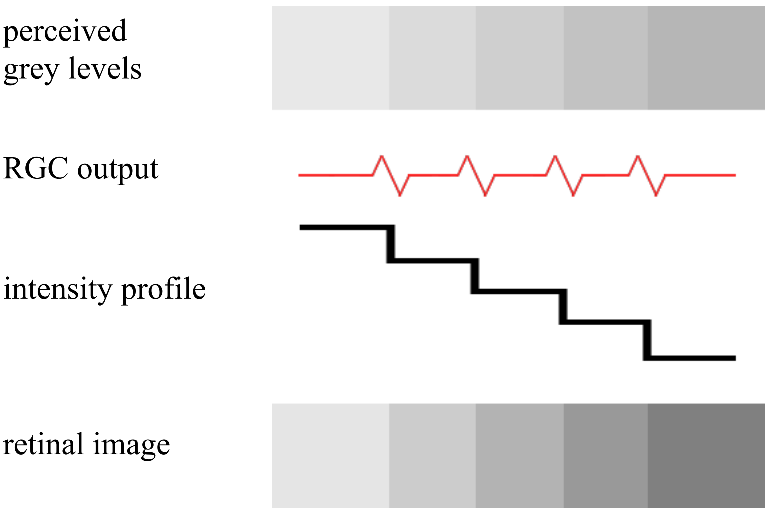

Apparent surface brightness is reconstructed from contrast across edges;
- but there is no guarantee that absolute perceived brightness is veridical: does the brain guess ?

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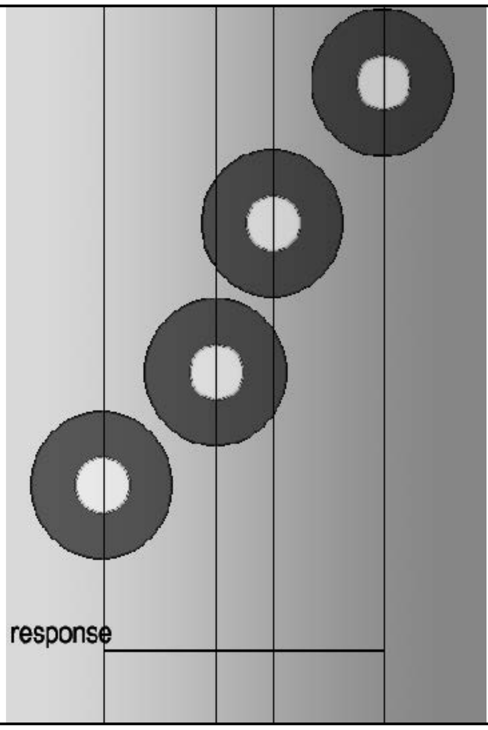

The retinal ganglion cell centre-surround RFs are not efficient at detecting intensity gradients…

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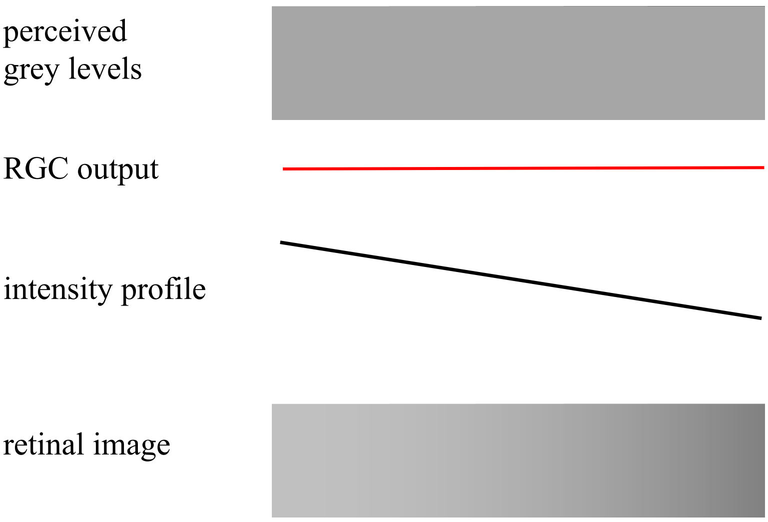

Apparent surface brightness is reconstructed from contrast across edges…
- Problem for detecting fuzzy edges (lightness gradients) ..?

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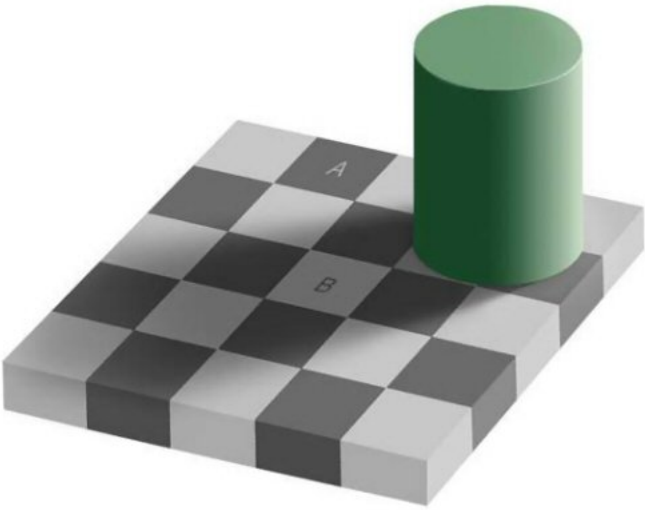

Is this an illusion, or an example of ‘lightness constancy’ ?

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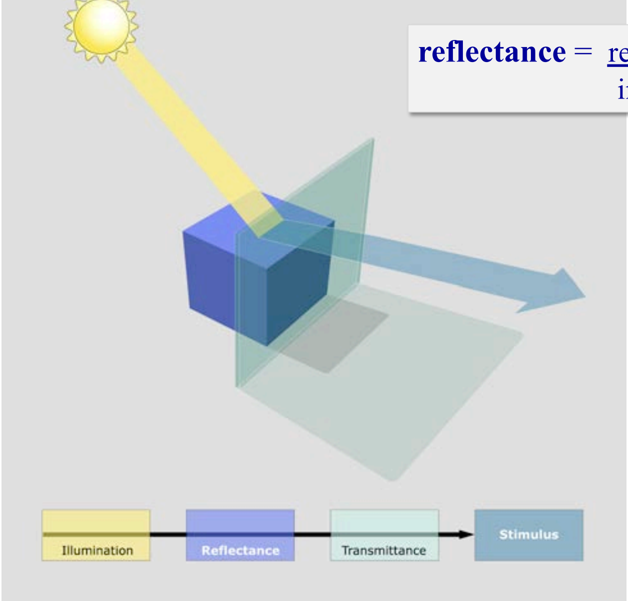
‘REFLECTANCE’

$$\textbf{reflectance} = \frac{\text{reflected light intensity}}{\text{incident light intensity}}$$



The goal of brightness perception is to perceive the reflectance of the surfaces in view.

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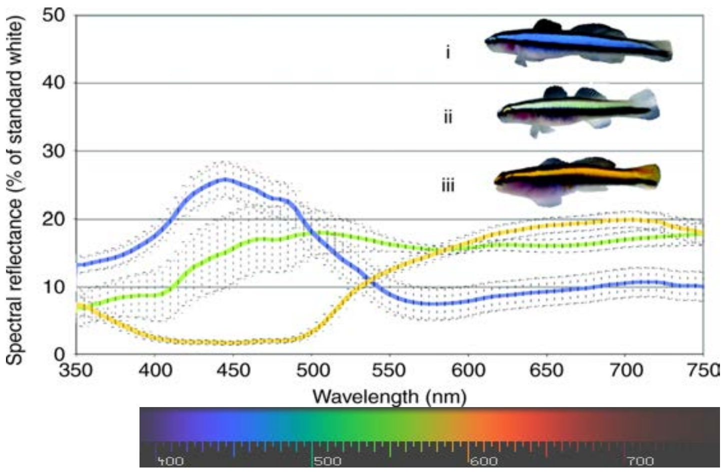
Different coloured surfaces have different spectral reflectance curves, including fish...



The goal of colour perception is to perceive the *spectral* reflectance of the surfaces in view.

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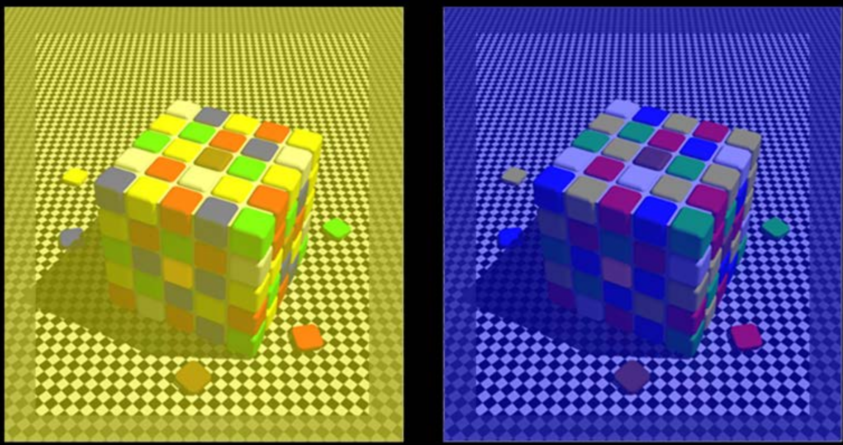
Colour constancy depends on 'discounting the illuminant'



Think of this as being not an image on a screen, but a real-world situation, in which a multi-faceted (Rubik's cube) type object is illuminated by very yellowish or blue-ish light; in which case it would be advantageous to see the real blue (left) or yellow (right) colours of the elements, as opposed to the achromatic (grey) spectral composition of the light actually reaching the eye.

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SHADE

DIRECT LIGHT

WHITE/GOLD..?

OR

BLUE/BLACK..?

(PERIWINKLE /BROWN)

It all depends upon a subjective (& individually variable) interpretation of lighting conditions. Objects viewed in shade have excess blue light, hence the brain's percept tends to discount some blueness from the retinal image. People differ in thinking that the dress is or is not in the shade!
- Shows how prior assumptions can influence perception *(predictive coding)*.

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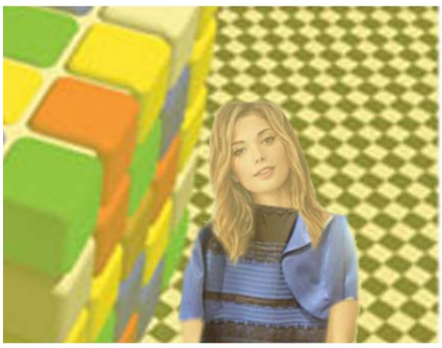

Rosa Lafer-Sousa (background by Beau Lotto)

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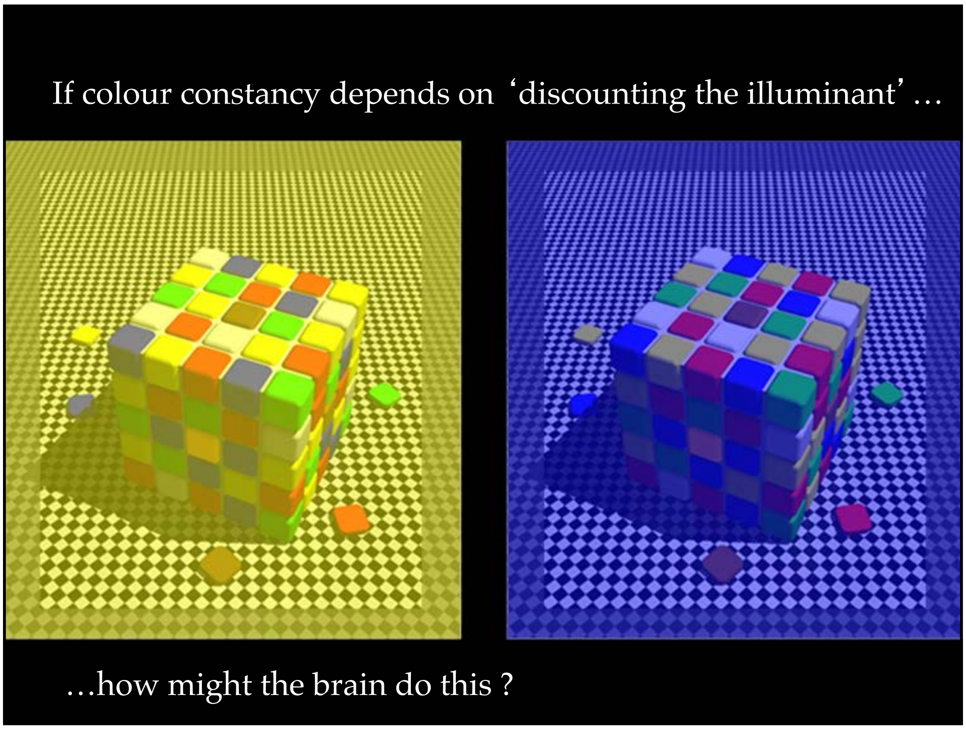
If colour constancy depends on 'discounting the illuminant' …
…how might the brain do this ?

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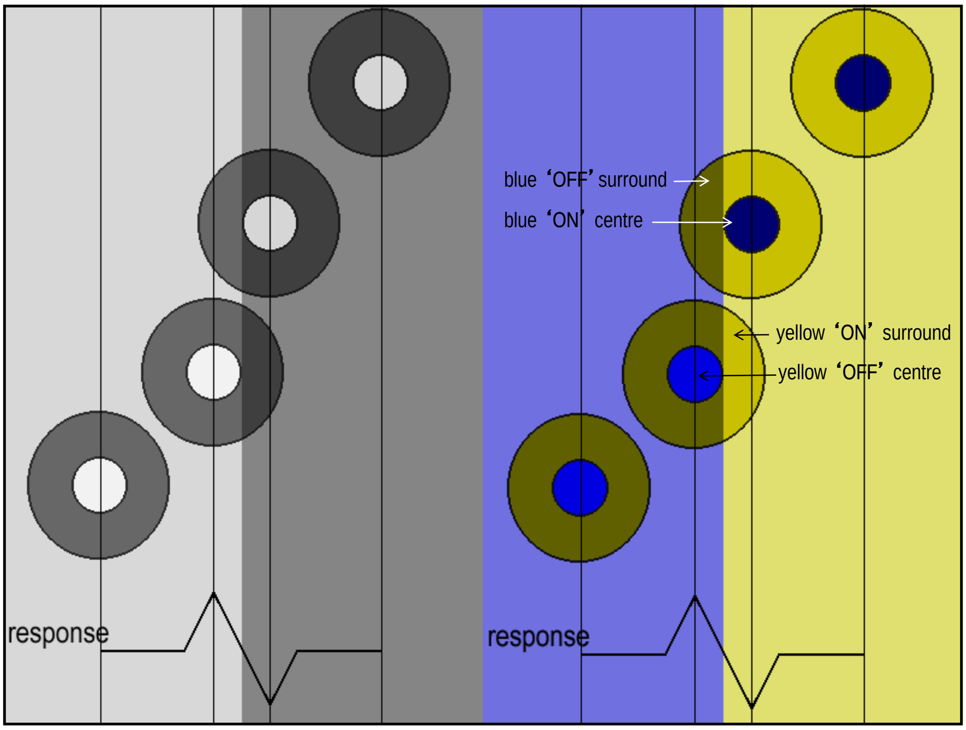
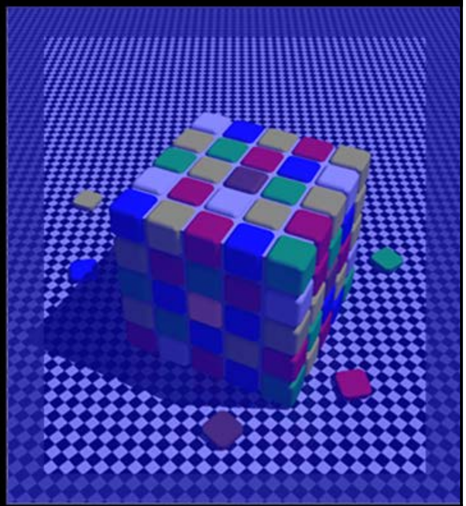

blue 'OFF' surround
blue 'ON' centre
yellow 'ON' surround
yellow 'OFF' centre
response
response

40

Colour constancy depends on 'discounting the illuminant'

How does the differential blue detector respond with an excess of blue illumination ?



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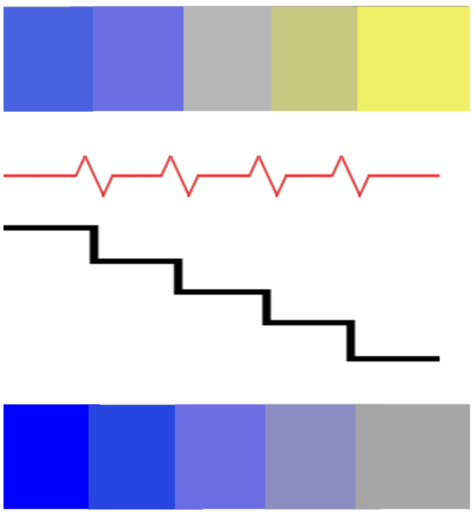
Perceived blueness/yellowness

Differential blue detector

Blueness profile

Retinal image



In theory, the brain might reconstruct a blue/yellow profile from chromatic edge signals, and then adjust for overall excess of blue (or yellow) light.

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Edwin Land (d.) … pictured with his multicoloured display

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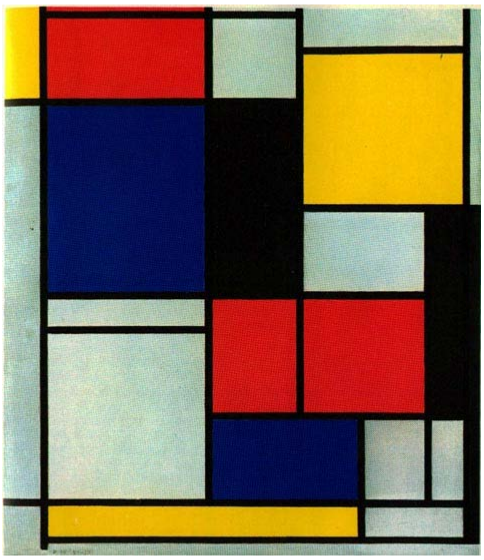

Piet Mondrian 1872 - 1944

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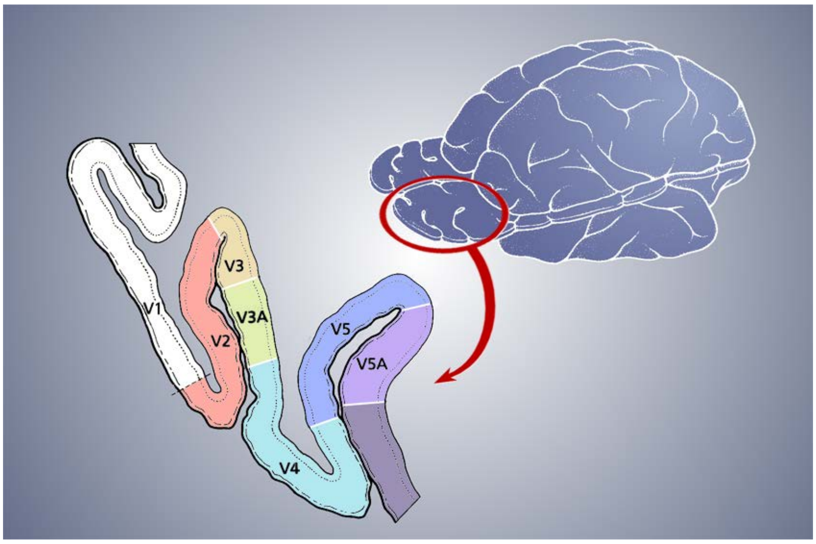
Multiple visual areas in prestriate cortex of macaque monkey



Recordings of colour cells in area V1 and V4, using Mondrian stimuli

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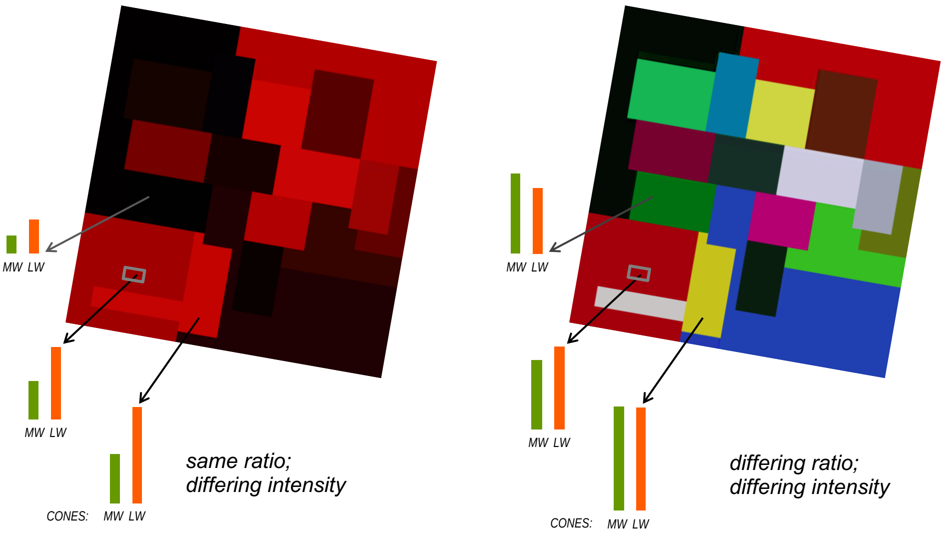
LW illumination

'White light' illumination



V1 *'red' neuron responds well to red area*

V1 *'red' neuron responds mildly to red area*

V1 *'red' neuron: responds whenever LW light is dominant within RF*
- i.e. when LW:MW cone ratio > 1

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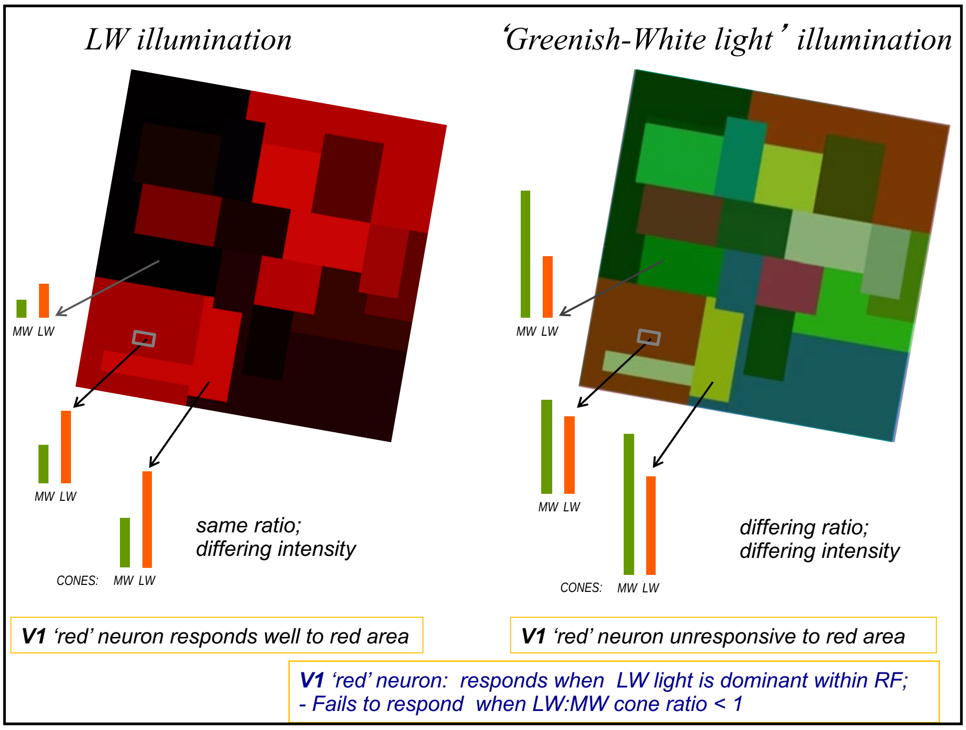
LW illumination
'Greenish-White light' illumination
MW LW
MW LW
CONES: MW LW
same ratio;
differing intensity
MW LW
MW LW
CONES: MW LW
differing ratio;
differing intensity
V1 'red' neuron responds well to red area
V1 'red' neuron unresponsive to red area
V1 'red' neuron: responds when LW light is dominant within RF;
- Fails to respond when LW:MW cone ratio < 1

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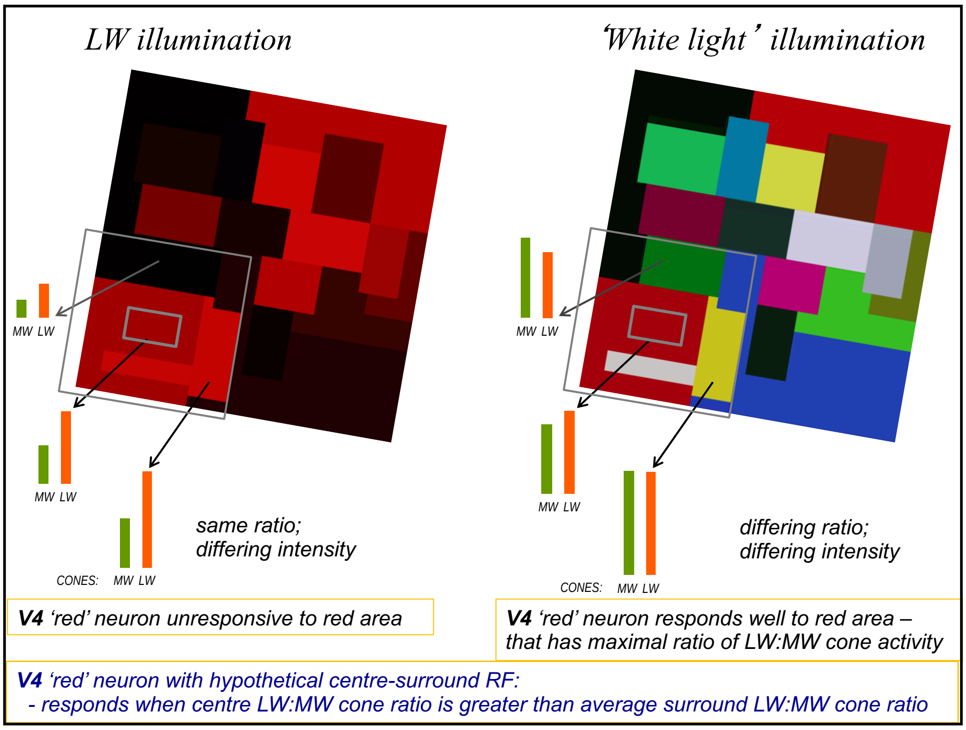
LW illumination
'White light' illumination
MW LW
MW LW
CONES: MW LW
same ratio;
differing intensity
MW LW
MW LW
CONES: MW LW
differing ratio;
differing intensity
V4 'red' neuron unresponsive to red area
V4 'red' neuron responds well to red area – that has maximal ratio of LW:MW cone activity
V4 'red' neuron with hypothetical centre-surround RF:
- responds when centre LW:MW cone ratio is greater than average surround LW:MW cone ratio

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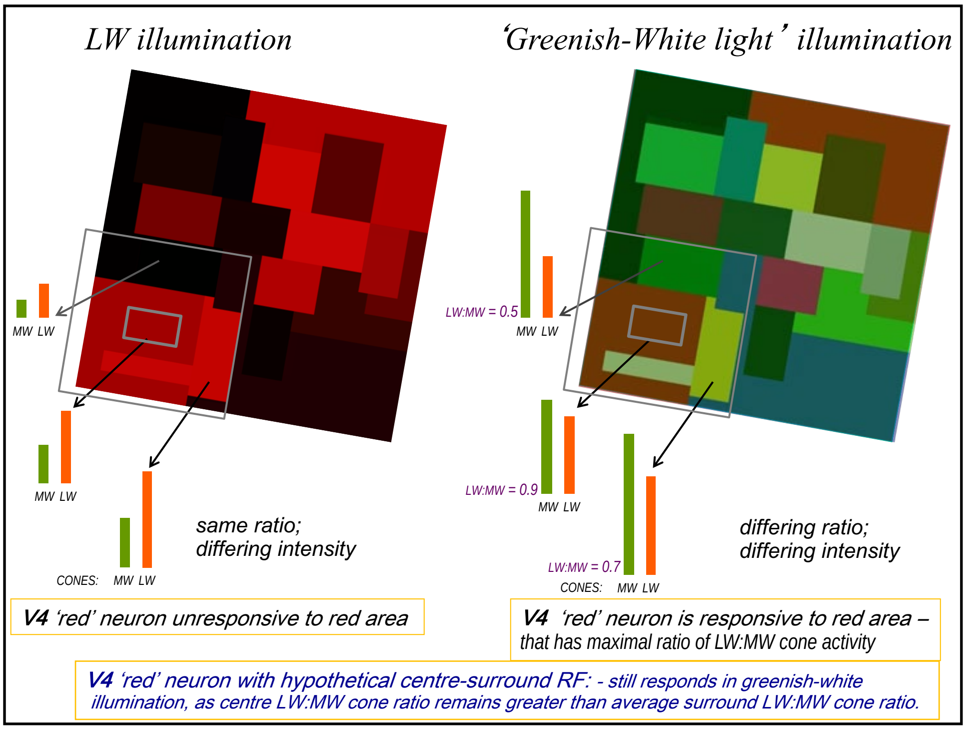
LW illumination
'Greenish-White light' illumination
MW LW
MW LW
CONES: MW LW
same ratio;
differing intensity
LW:MW = 0.5
MW LW
LW:MW = 0.9
MW LW
LW:MW = 0.7
CONES: MW LW
differing ratio;
differing intensity
V4 'red' neuron unresponsive to red area
V4 'red' neuron is responsive to red area – that has maximal ratio of LW:MW cone activity
V4 'red' neuron with hypothetical centre-surround RF: - still responds in greenish-white illumination, as centre LW:MW cone ratio remains greater than average surround LW:MW cone ratio.

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