Perception: Psychophysics and Modeling

14 | Colour Vision I

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Literature

B.A. Wandell (1995). *Foundations of Vision*. Sinauer Associates, Inc.
ch. 4, Wavelength Encoding, pp. 69–101, and
ch. 9, Color, pp.287–338.

Note: You find a PDF of chapter 4 on ILIAS, however, chapter 9 is only available online:
https://foundationsofvision.stanford.edu/chapter-9-color/

Supplementary reading

Krantz, D. H. (1975). Color measurement and color theory: I. representation theorem for Grassmann structures. *Journal of Mathematical Psychology*, 12(3):283–303.

Neitz, J. & Jacobs, G. H. (1986). Polymorphism of the long-wavelength cone in normal human colour vision. *Nature*, 323:623–625.

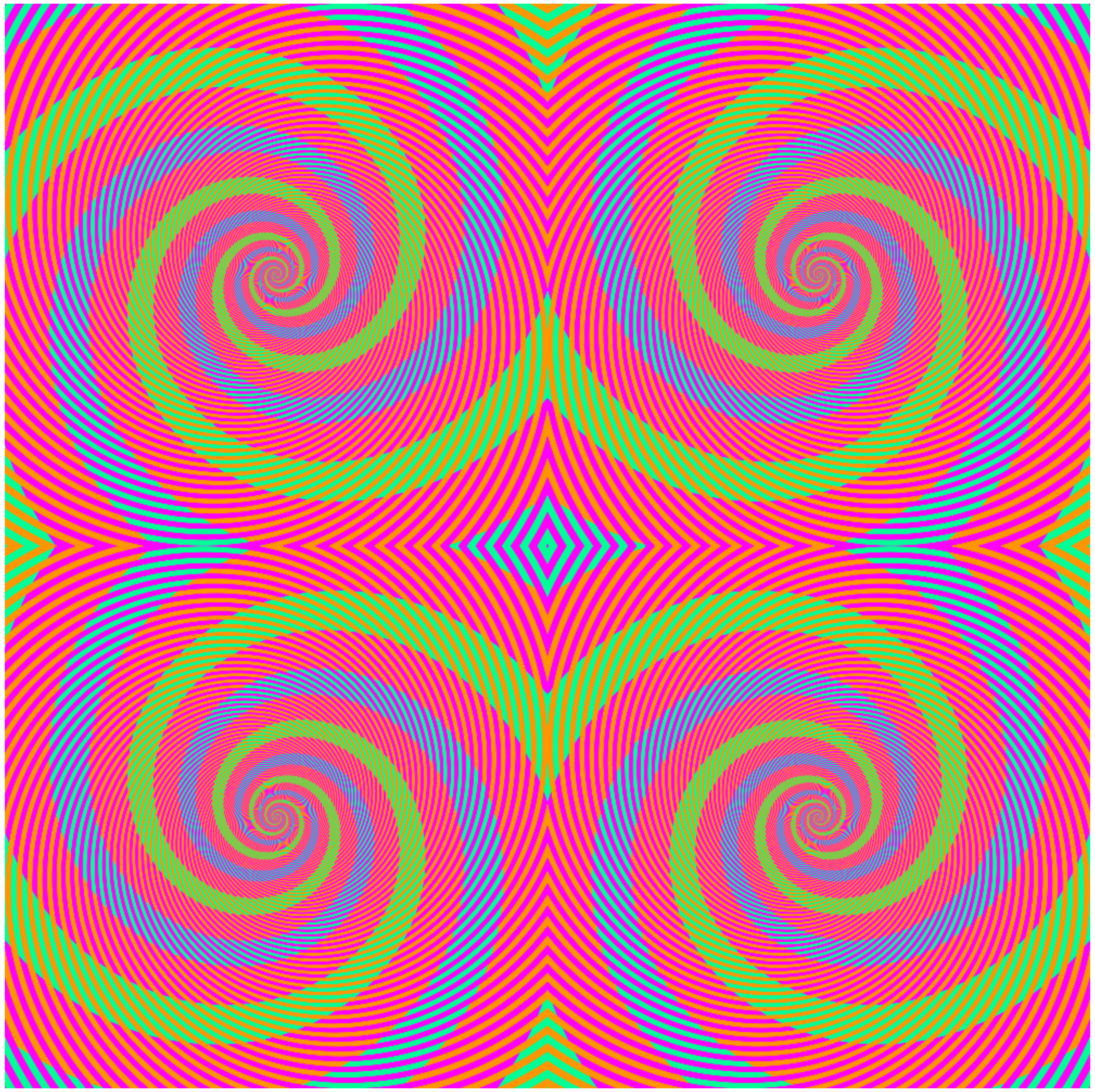
Perception of Colour (VL14, today)

- **Colour is purely psychological—the world and physics does not know colours!**
- **Spectral power distribution (light) and spectral or surface reflectance functions**
- **Basic Principles of Colour Perception**
  - **Step 1: Colour Detection**
  - **Step 2: Colour Discrimination**
  - Step 3: Colour Appearance (VL15)
- Individual Differences in Colour Perception
- From the Colour of Lights to a World of Colour (VL15)
- What Is Colour Vision Good For? (VL15)

Colour Perception

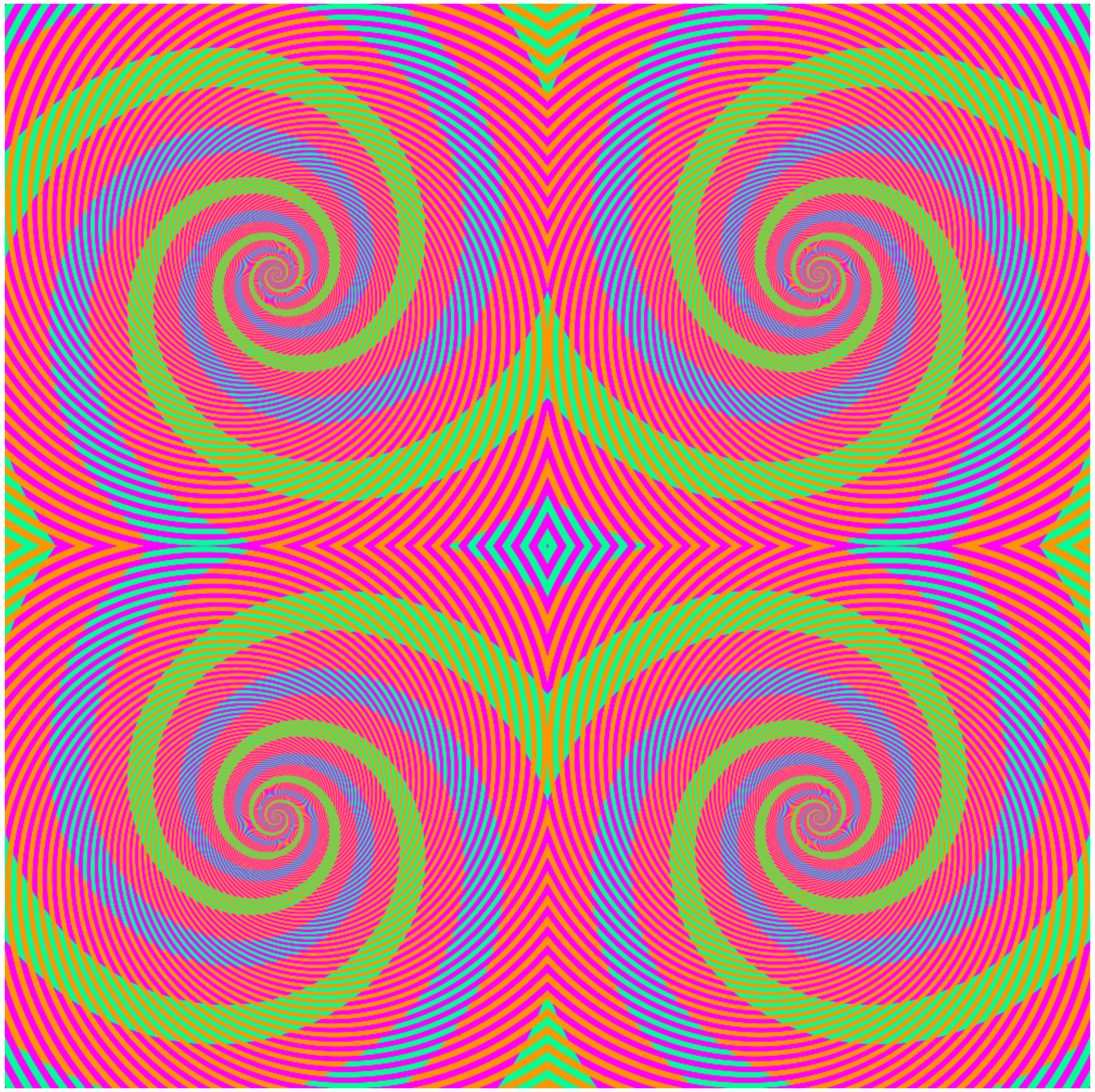
Colour is not a physical property, but a psychological property:

"The rays to speak properly are not coloured" — Isaac Newton



Akiyoshi Kitaoka

Colour Perception



Akiyoshi Kitaoka

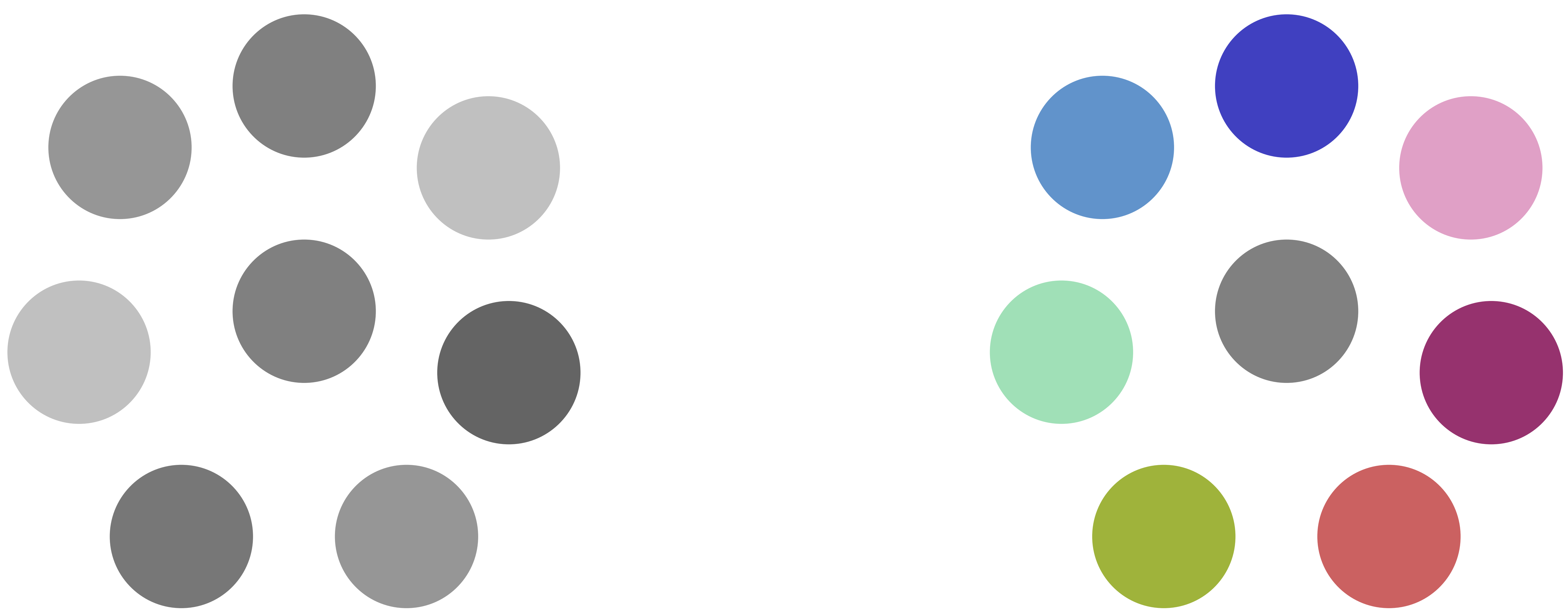
Colour Perception

In the eye, there are three types of cones that convert light into nerve impulses

These are transformed into opponent colours in the retinal ganglion cells.

In the brain, these excitation patterns are then interpreted as colours

Colour is the sensation that allows us to distinguish two surfaces without structure of the same brightness



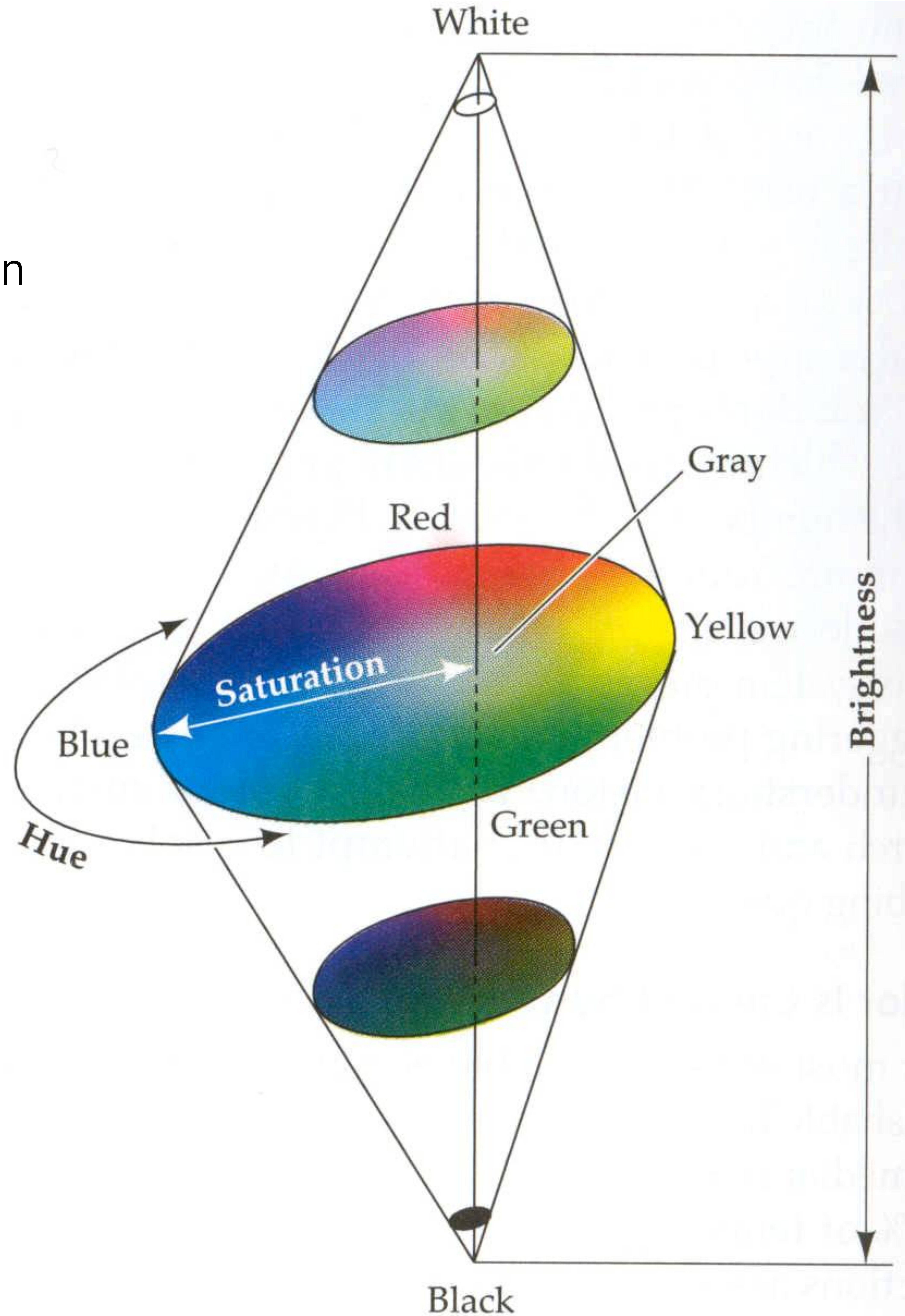
Colour perception

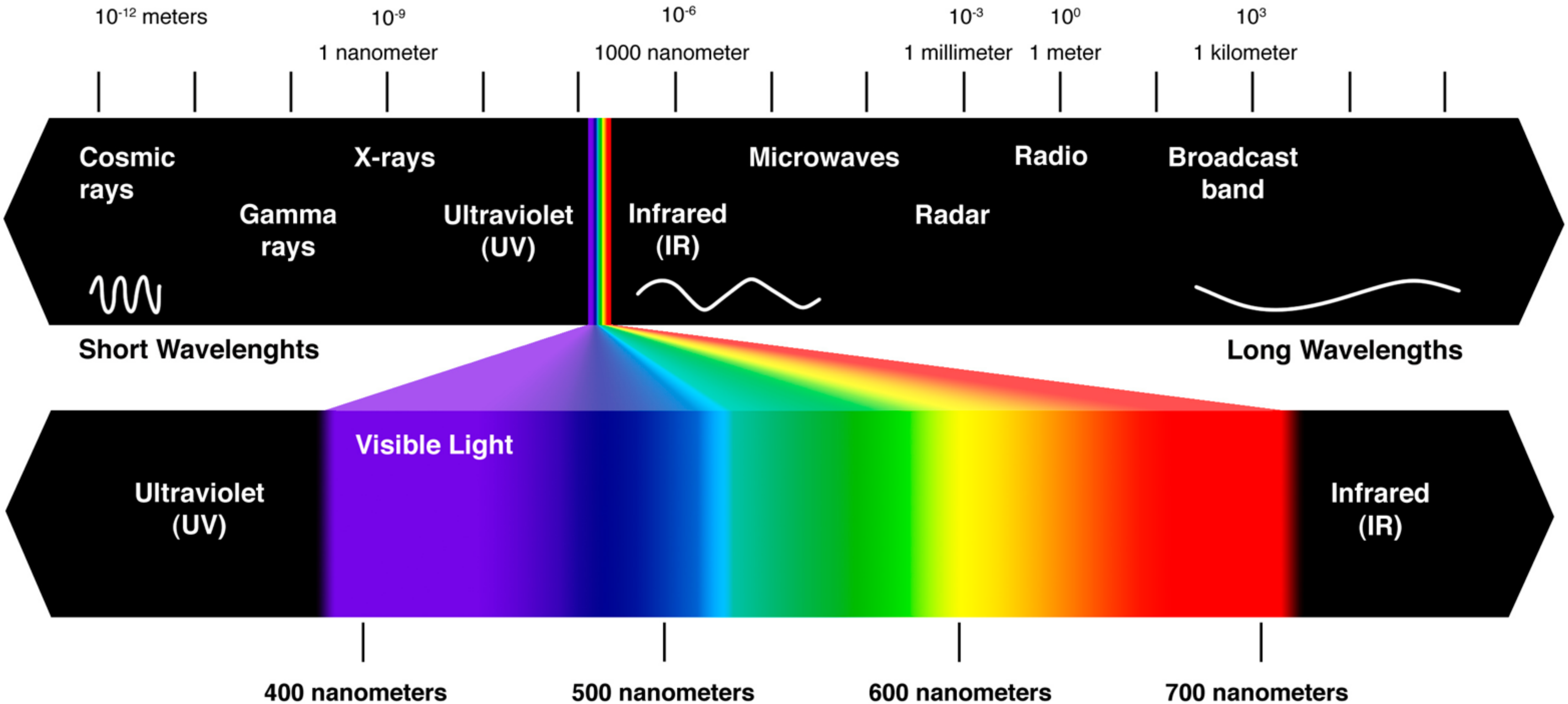
At least 2 million colour shades can be distinguished

over 200 shades (hue)

over 20 saturation levels (saturation)

over 500 brightness values (brightness)



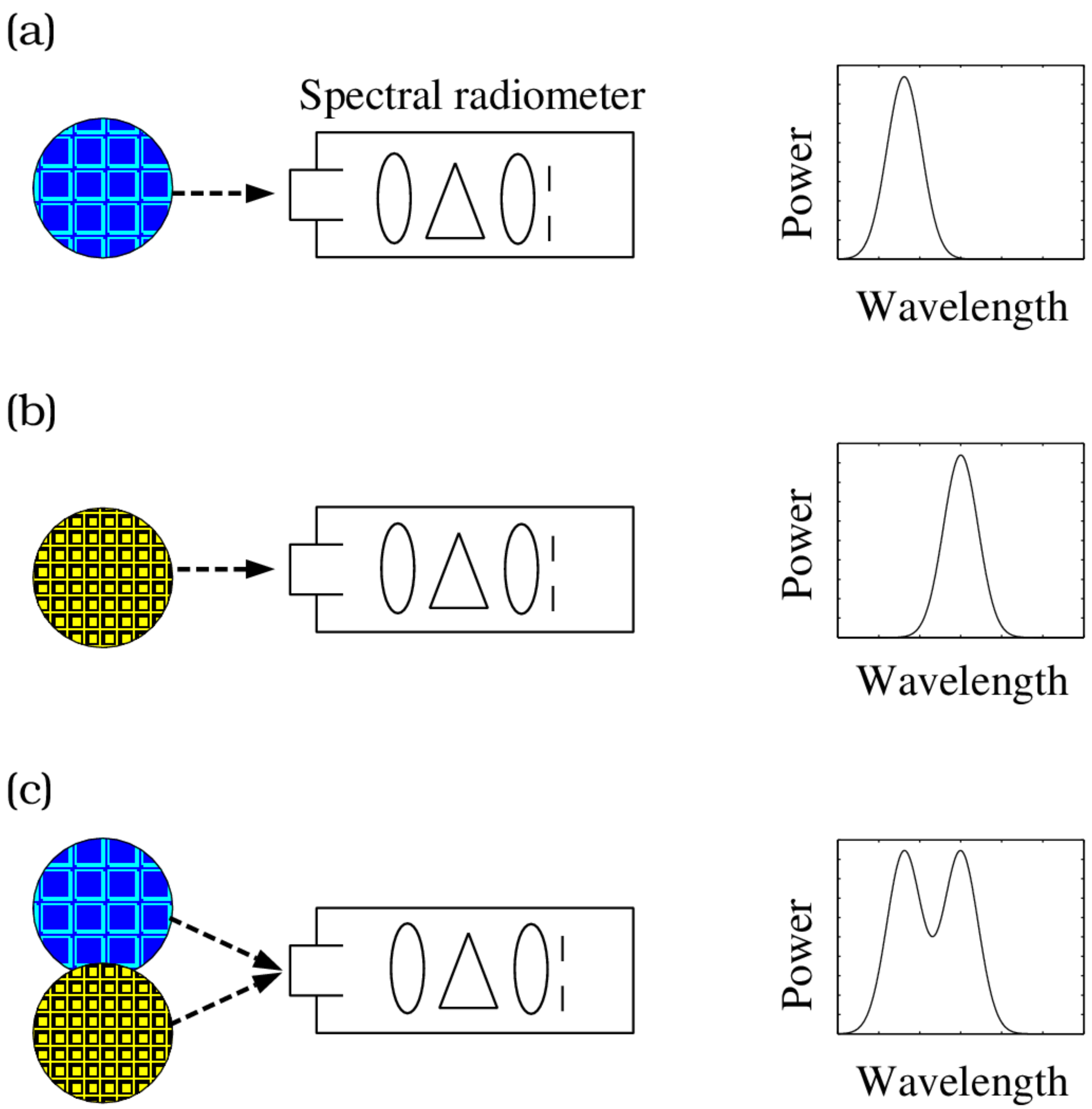


10^{-12} meters
10^{-9}
1 nanometer
10^{-6}
1000 nanometer
10^{-3}
1 millimeter
10^{0}
1 meter
10^{3}
1 kilometer
Cosmic rays
Gamma rays
X-rays
Ultraviolet (UV)
Infrared (IR)
Microwaves
Radar
Radio
Broadcast band
Short Wavelenghts
Long Wavelengths
Visible Light
Ultraviolet (UV)
Infrared (IR)
400 nanometers
500 nanometers
600 nanometers
700 nanometers

Superposition of light

Recall: superposition = homogeneity (proportionality) + additivity

Spectral power distributions obey superposition



Wandell (2015)

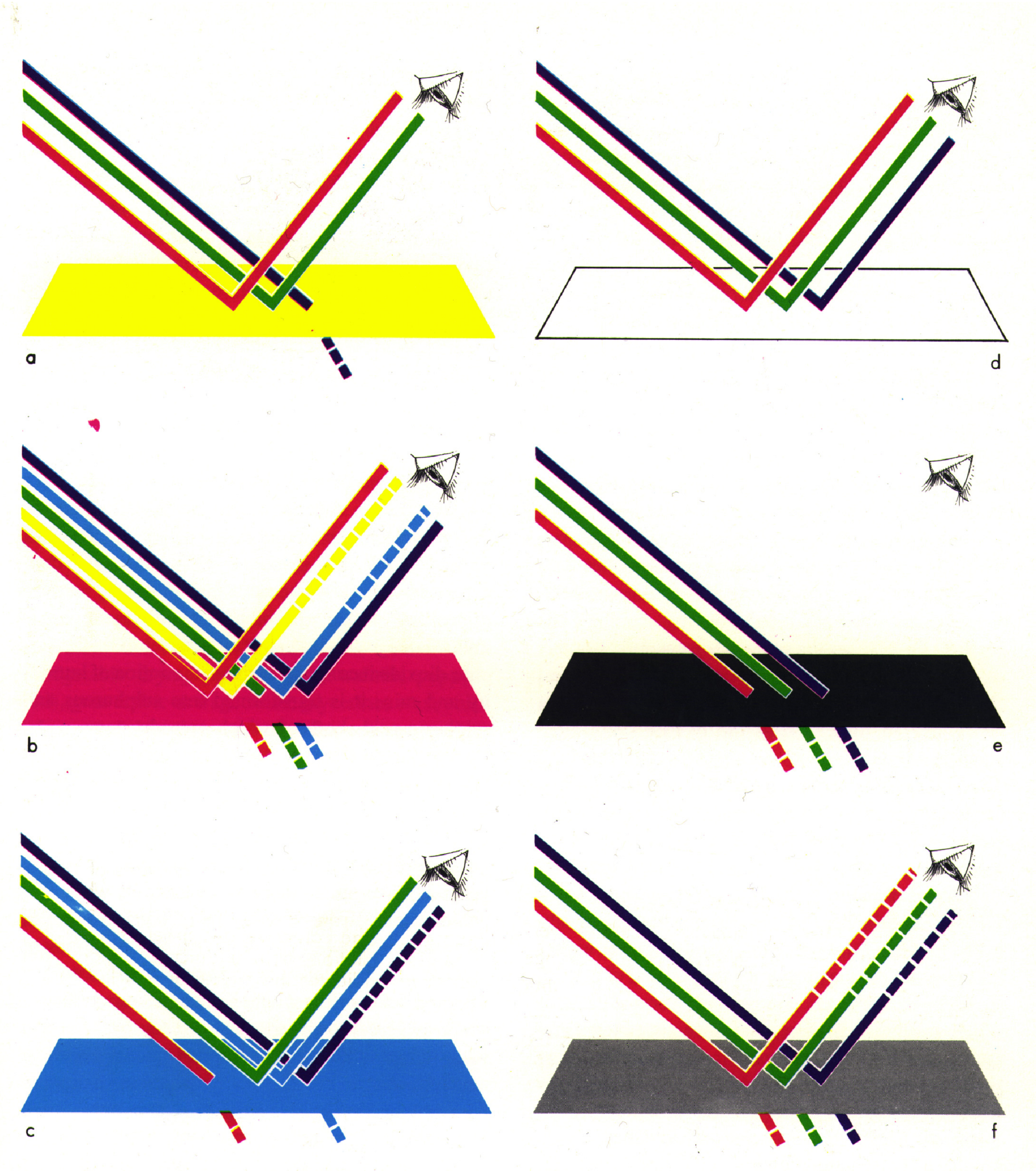
Reflectance and absorption

Part of the incident light is reflected, the other part absorbed

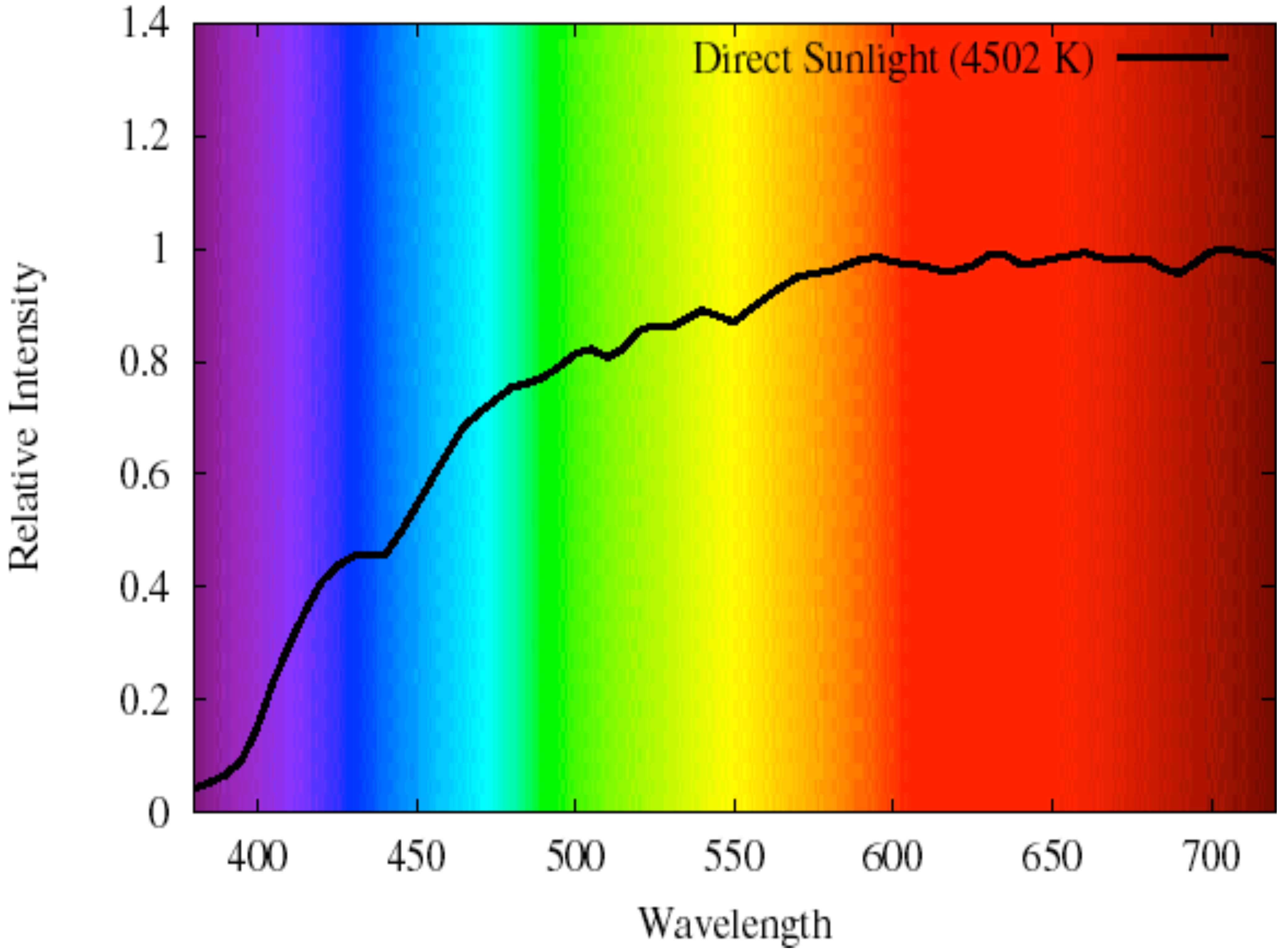
If the illumination changes, the spectral composition of the light that catches the eye changes.

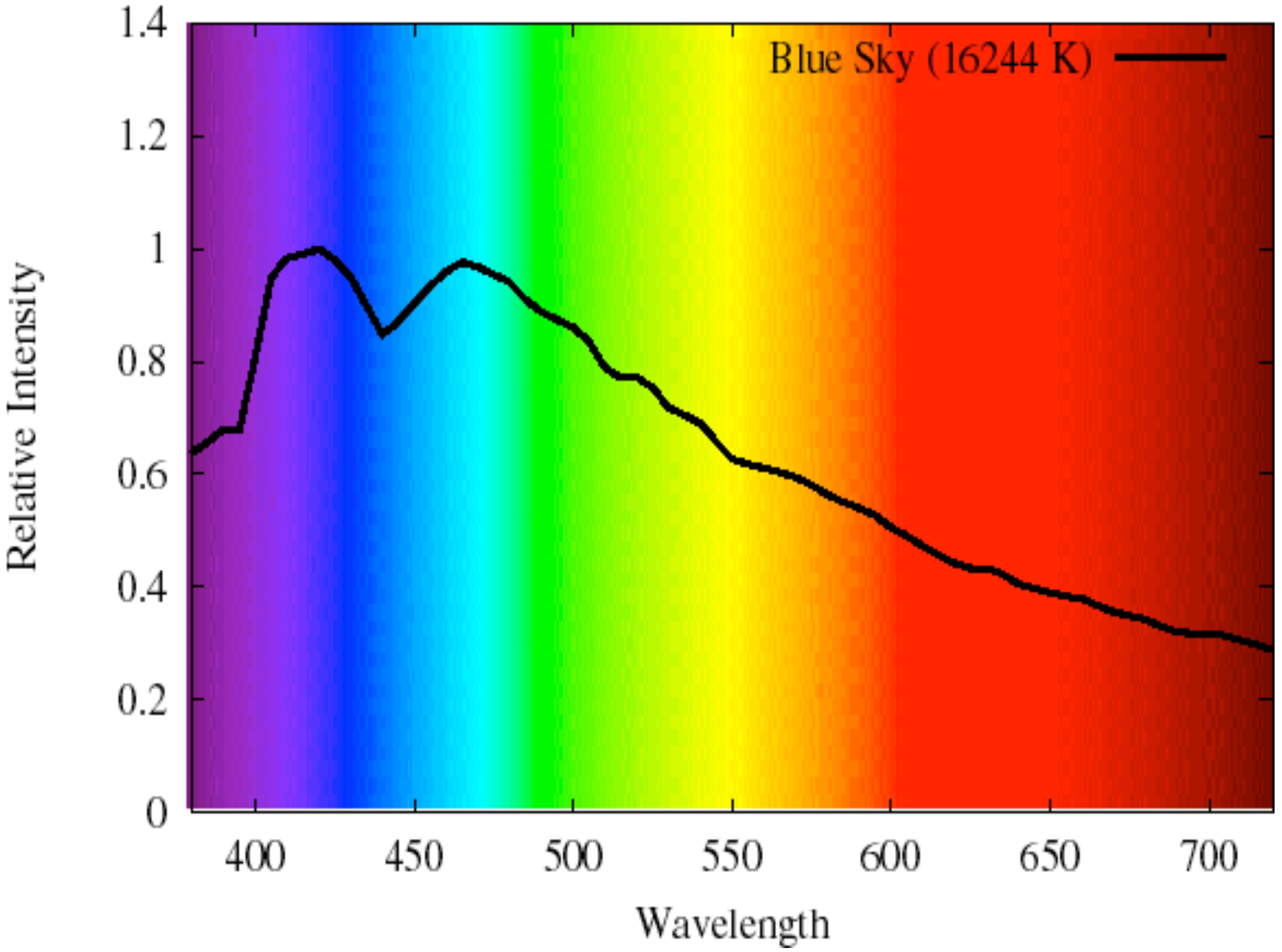
Spectral power distribution: distribution of energy over wavelength. A property of light

Spectral reflectance function: the proportion of energy at each wavelength reflected by a surface. A property of the surface.

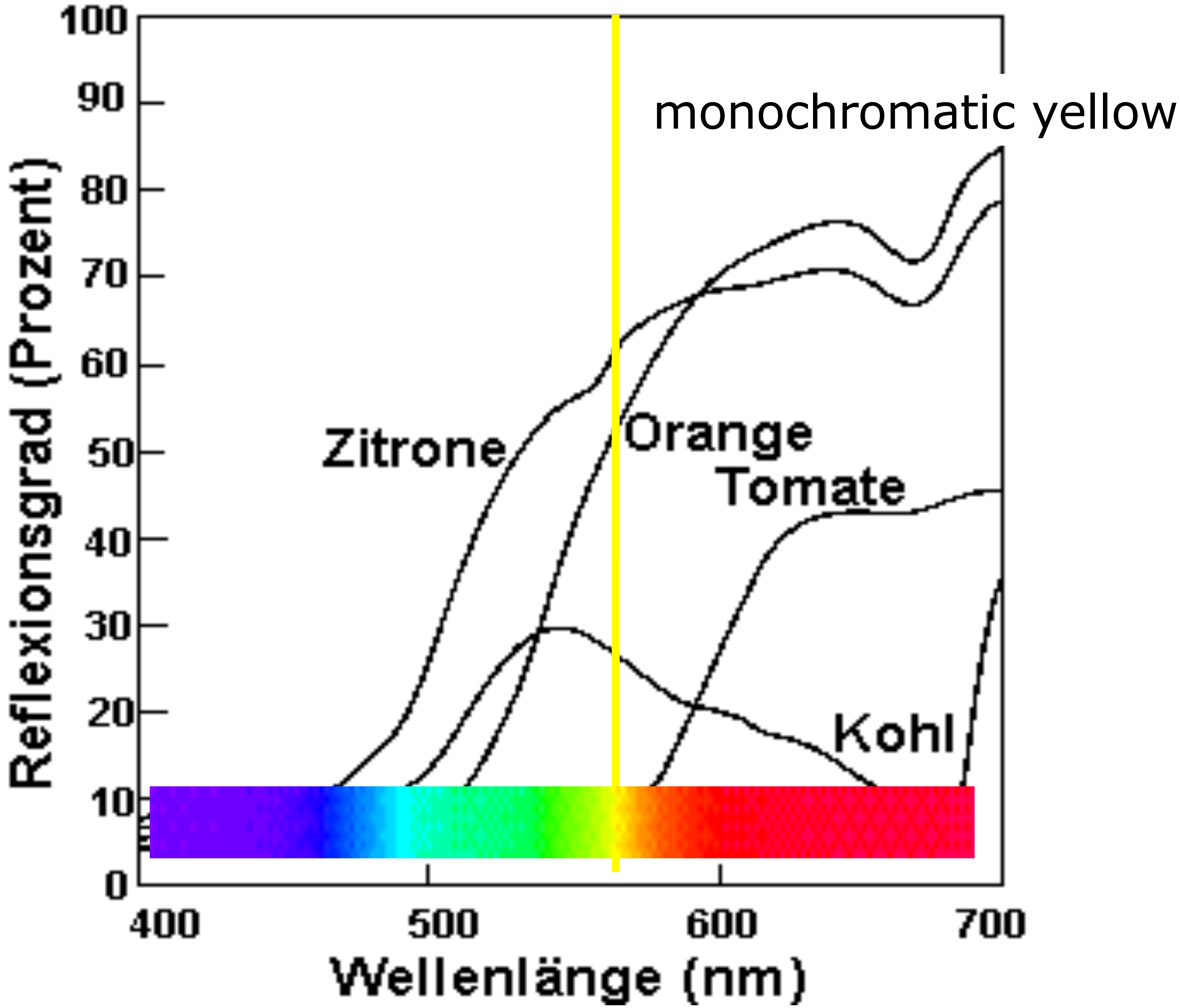


Natural Spectra

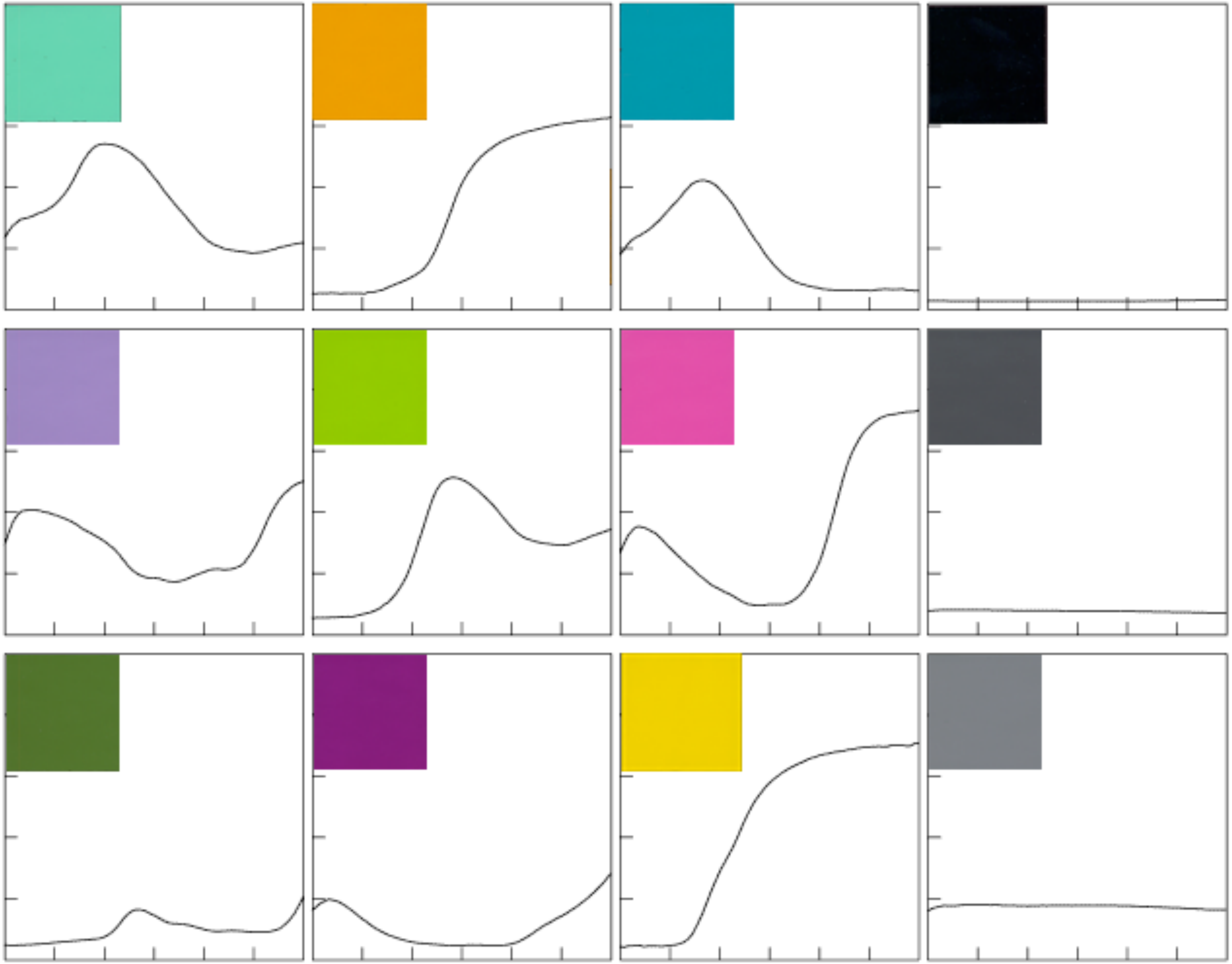




Spectral Reflectance Functions (Food)



Spectral Reflectance Functions (Coloured Paper)

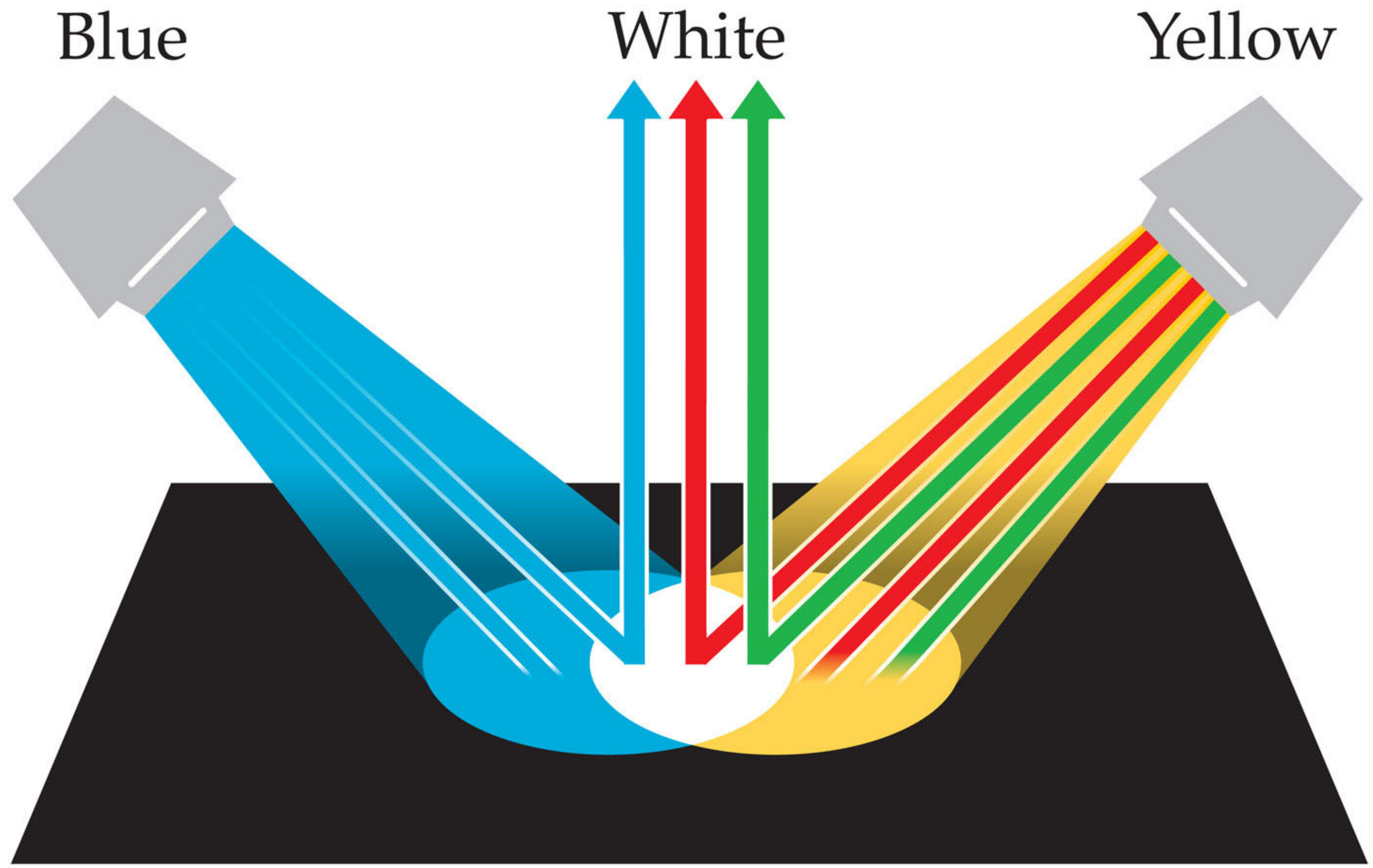


Basic Principles of Color Perception

Additive color mixing: A mixture of lights

If light A and light B are both reflected from a surface to the eye, in the perception of color, the effects of those two lights add together.

Shining a light that looks blue and a light that looks yellow on an area of paper, the wavelengths add, producing an additive color mixture



SENSATION & PERCEPTION 4e, **Figure 5.10**

Pointillism

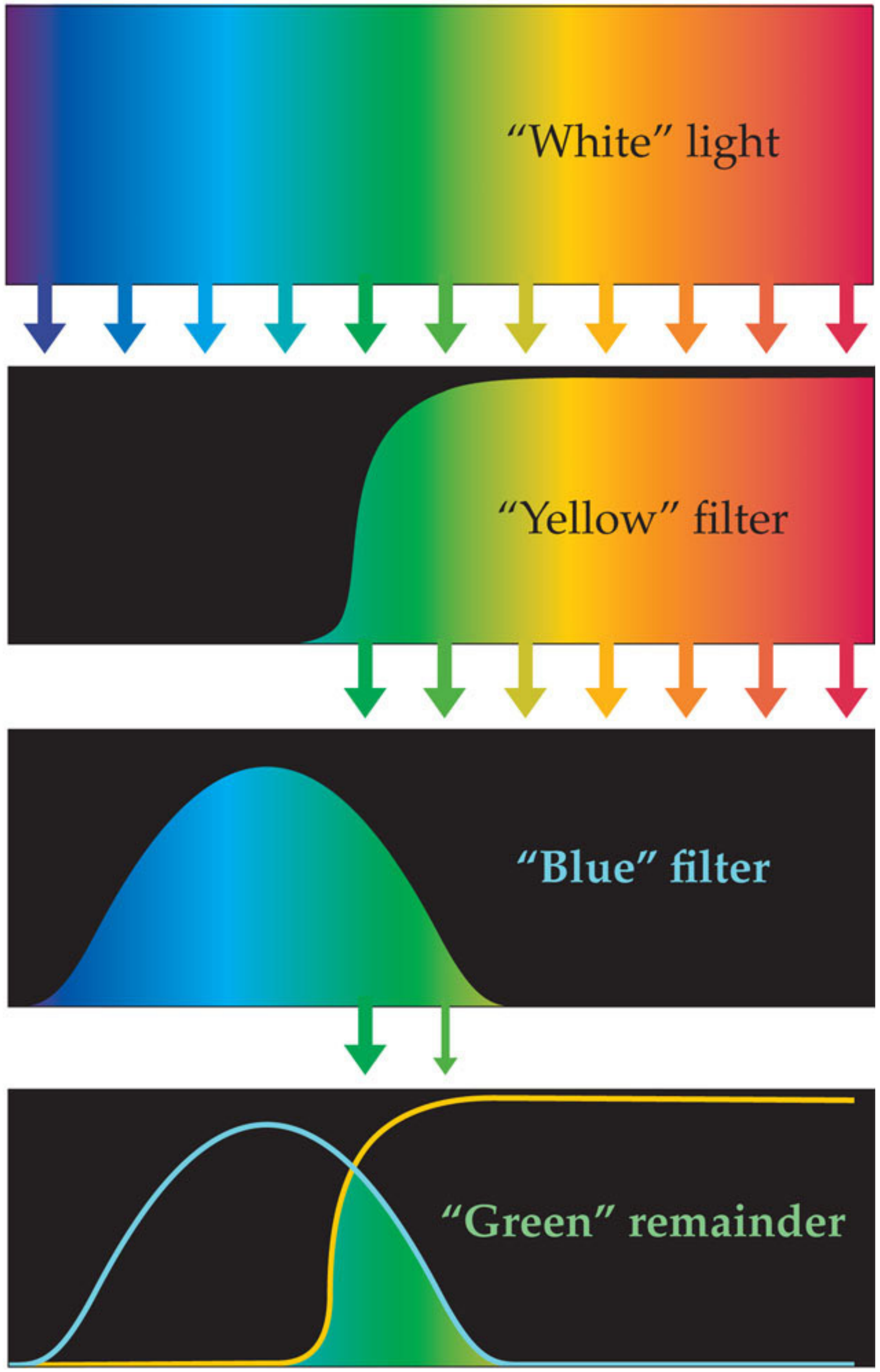
***SENSATION & PERCEPTION 4e,* Figure 5.11**

Basic Principles of Color Perception

Subtractive color mixing: A mixture of pigments

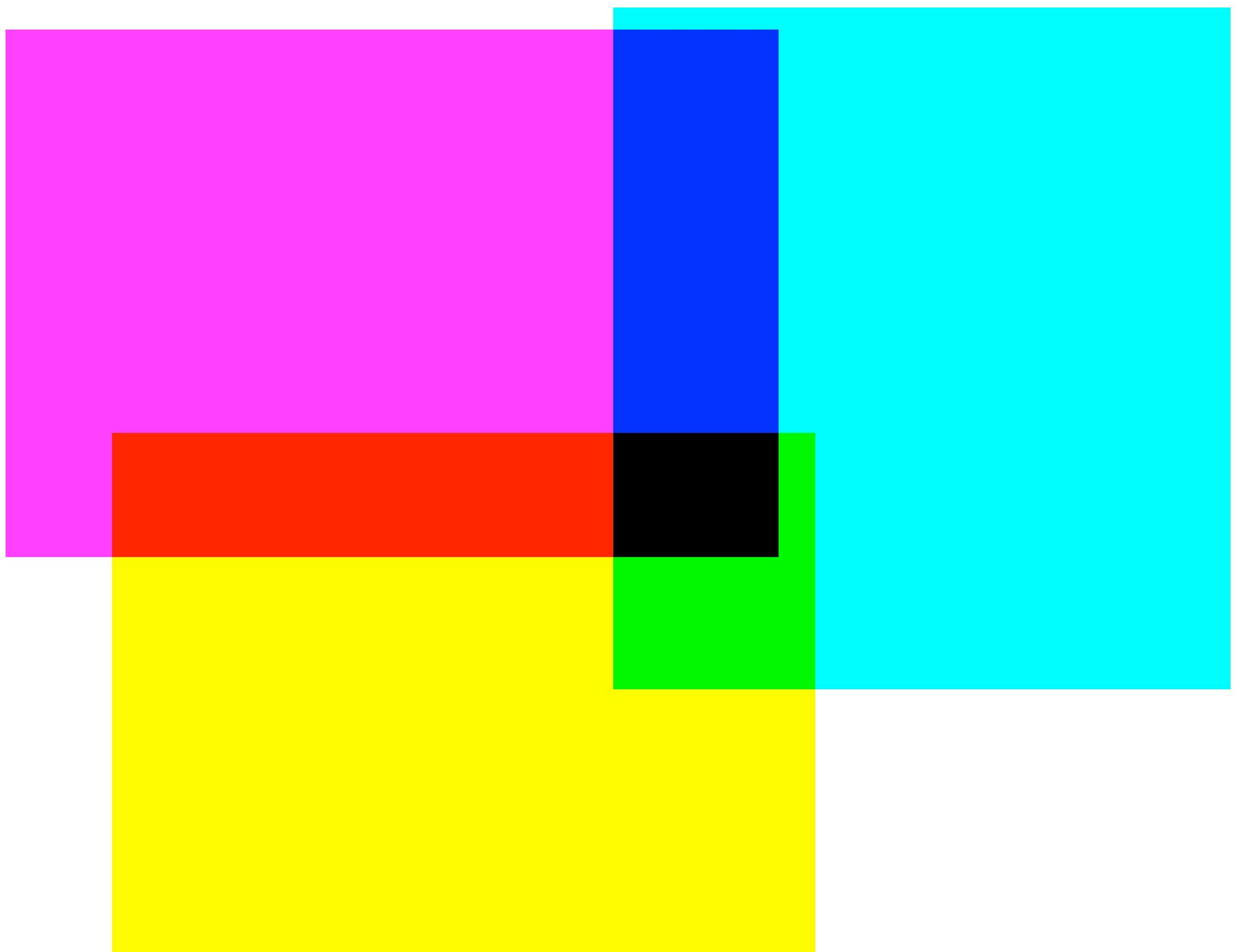
If pigment A and B mix, some of the light shining on the surface will be subtracted by A and some by B. Only the remainder contributes to the perception of color.

1. Take "white" light that contains a broad mixture of wavelengths.
2. Pass it through a filter that absorbs shorter wavelengths. The result will look yellowish.
3. Pass that through a bluish filter that absorbs all but a middle range of wavelengths.
4. The wavelengths that make it through both filters will be a mix that looks greenish.

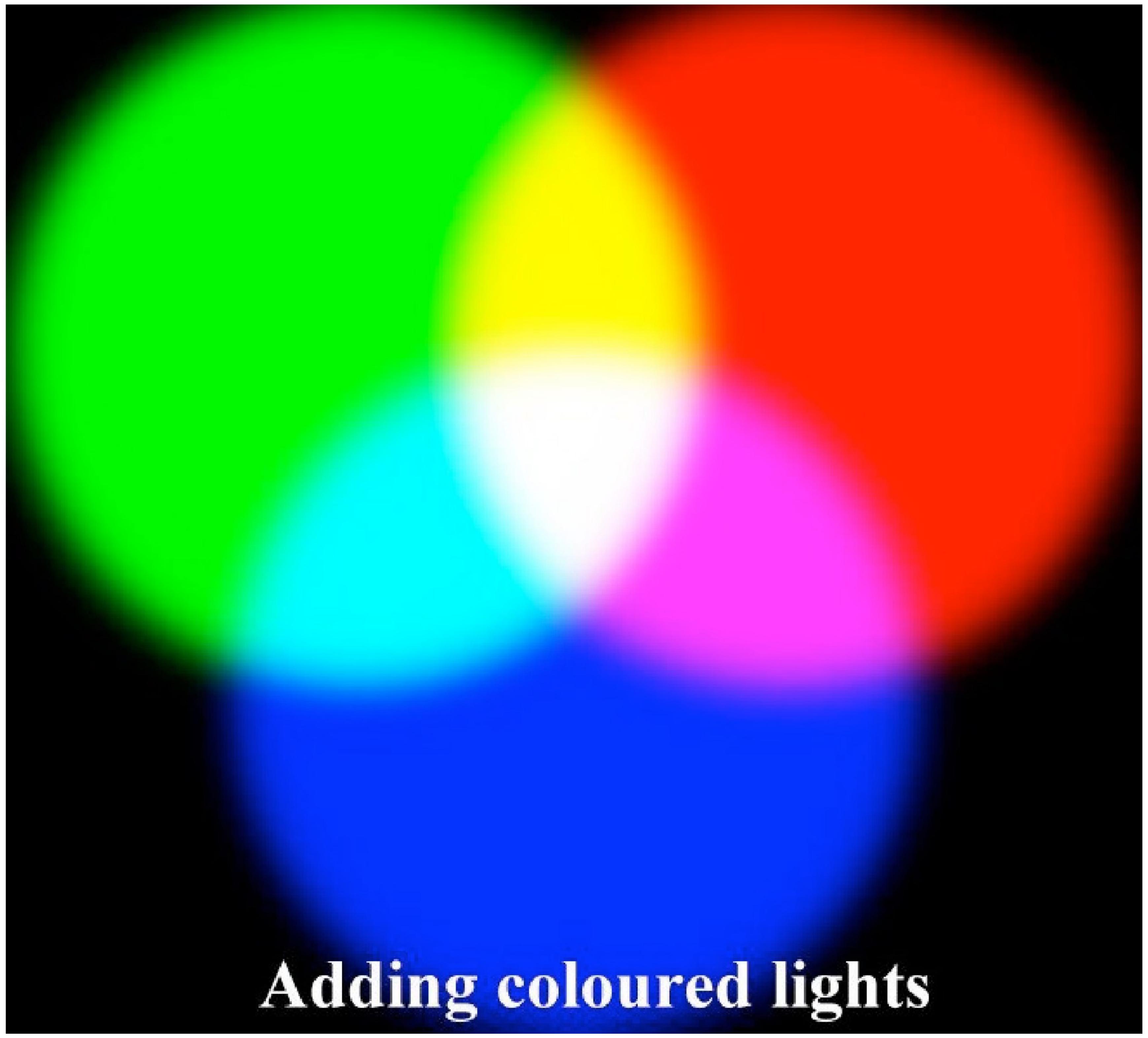


SENSATION & PERCEPTION 4e, **Figure 5.9**

Subtractive and Additive Colour Mixture



Taking light away



Basic Principles of Colour Perception

Most of the light we see is reflected.

The illumination is provided by the sun, light bulbs or fire.

Three steps to colour perception

1. Detection: Wavelengths of light must be detected in the first place.

2. Discrimination: We must be able to tell the difference between one wavelength (or mixture of wavelengths) and another.

3. Appearance: We want to assign perceived colours to lights and surfaces in the world and have those perceived colours be stable over time, regardless of different lighting conditions.

Step 1: colour detection

Light detection by the photoreceptors

Three types of cone photoreceptors

S-cones detect short wavelengths.

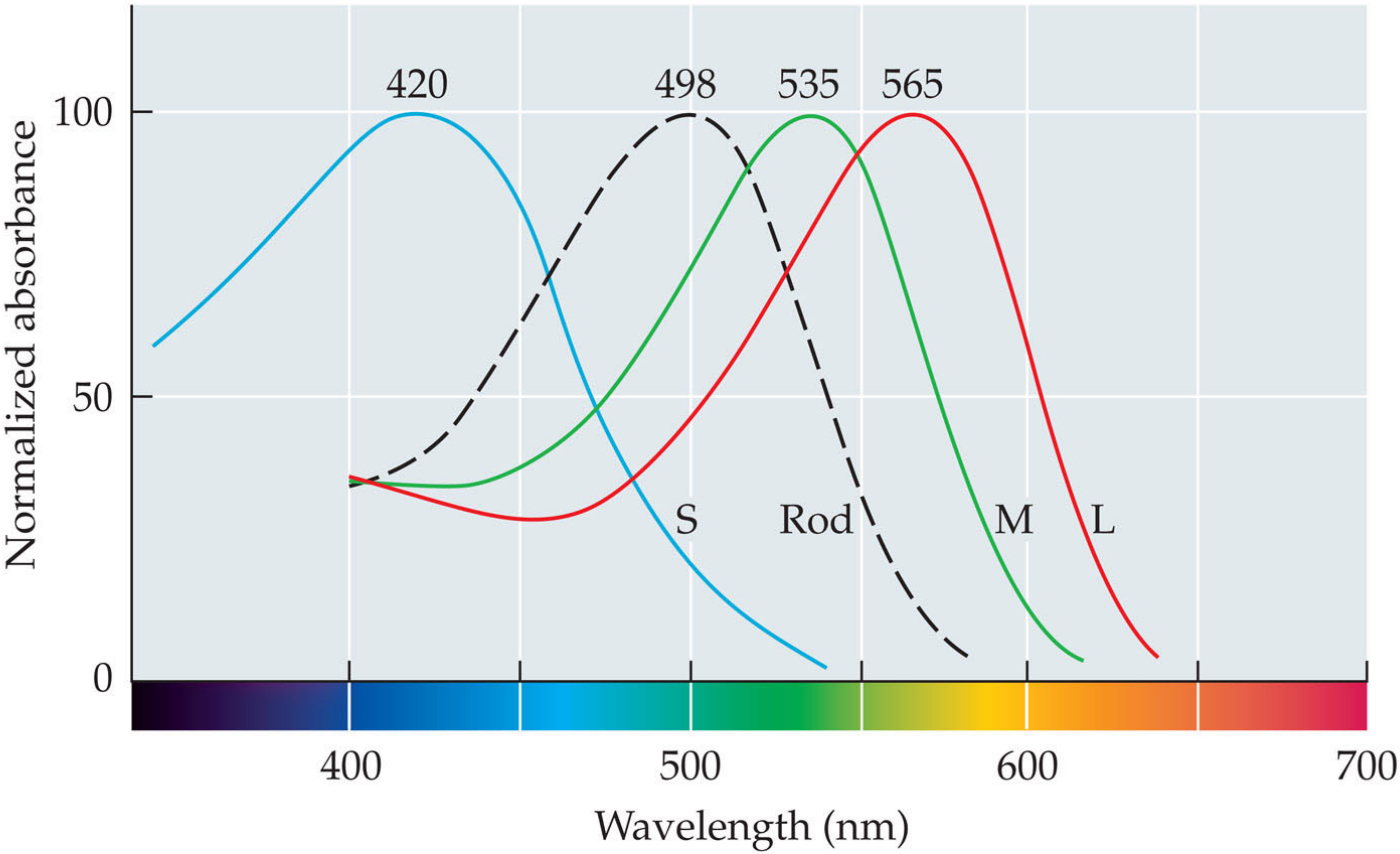
M-cones detect medium wavelengths.

L-cones detect long wavelengths.

More accurate to refer to them as "short," "medium," and "long" rather than "blue," "green," and "red," since they each respond to a variety of wavelengths

The L-cone's peak sensitivity is 565 nm, which corresponds to yellow, not red!

The retina contains four types of photoreceptors



SENSATION & PERCEPTION 4e, **Figure 5.1**

Cone mosaic

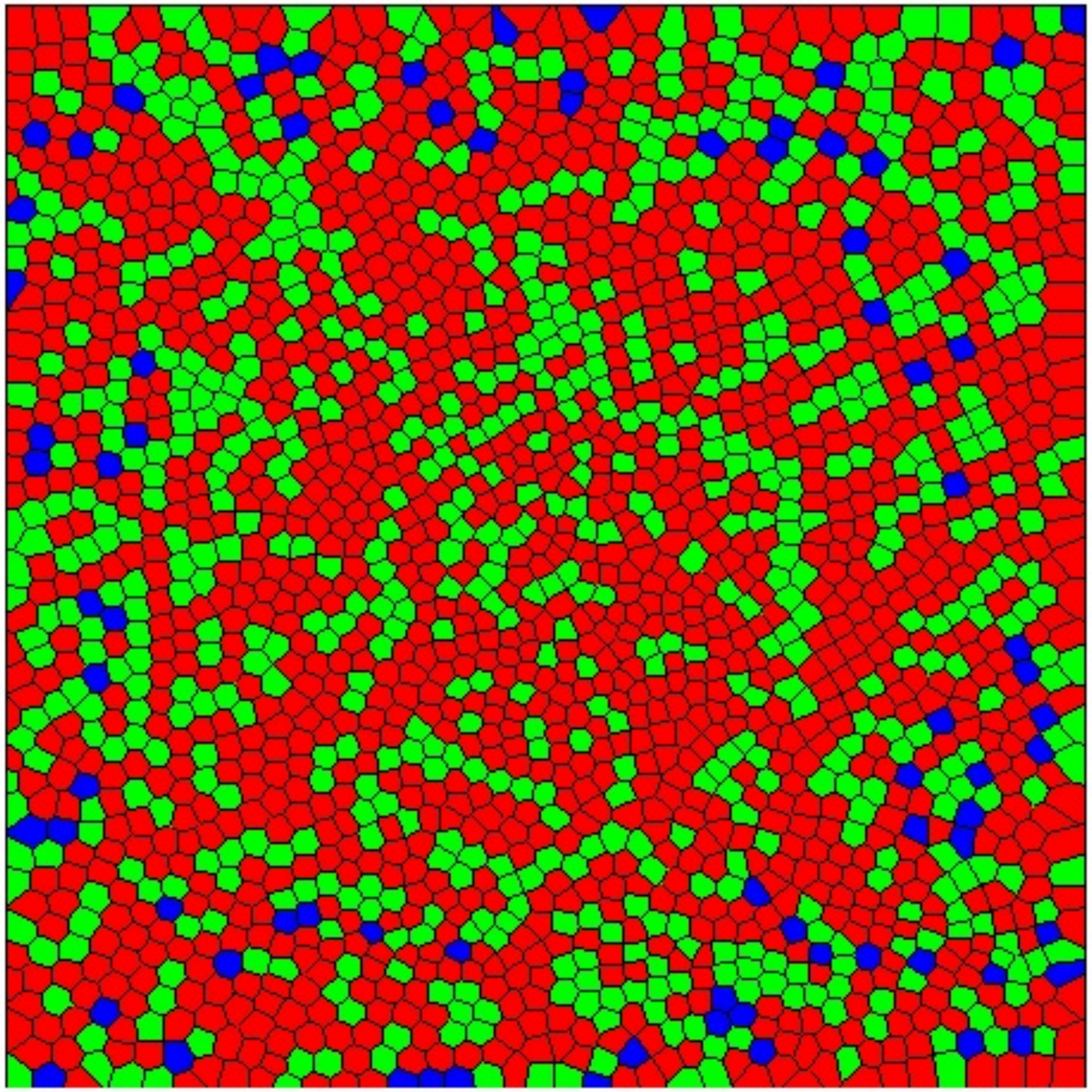
Three types of cones in human retina.

They are arranged in a mosaic.

At one location in space there is only one type of cone.

For most people there are roughly twice as many L than M cones

Only about 10% of all cones are S cones (none in the central fovea)



Light detection at different illumination levels

Photopic: Light intensities that are bright enough to stimulate the cone receptors and bright enough to "saturate" the rod receptors to their maximum responses.

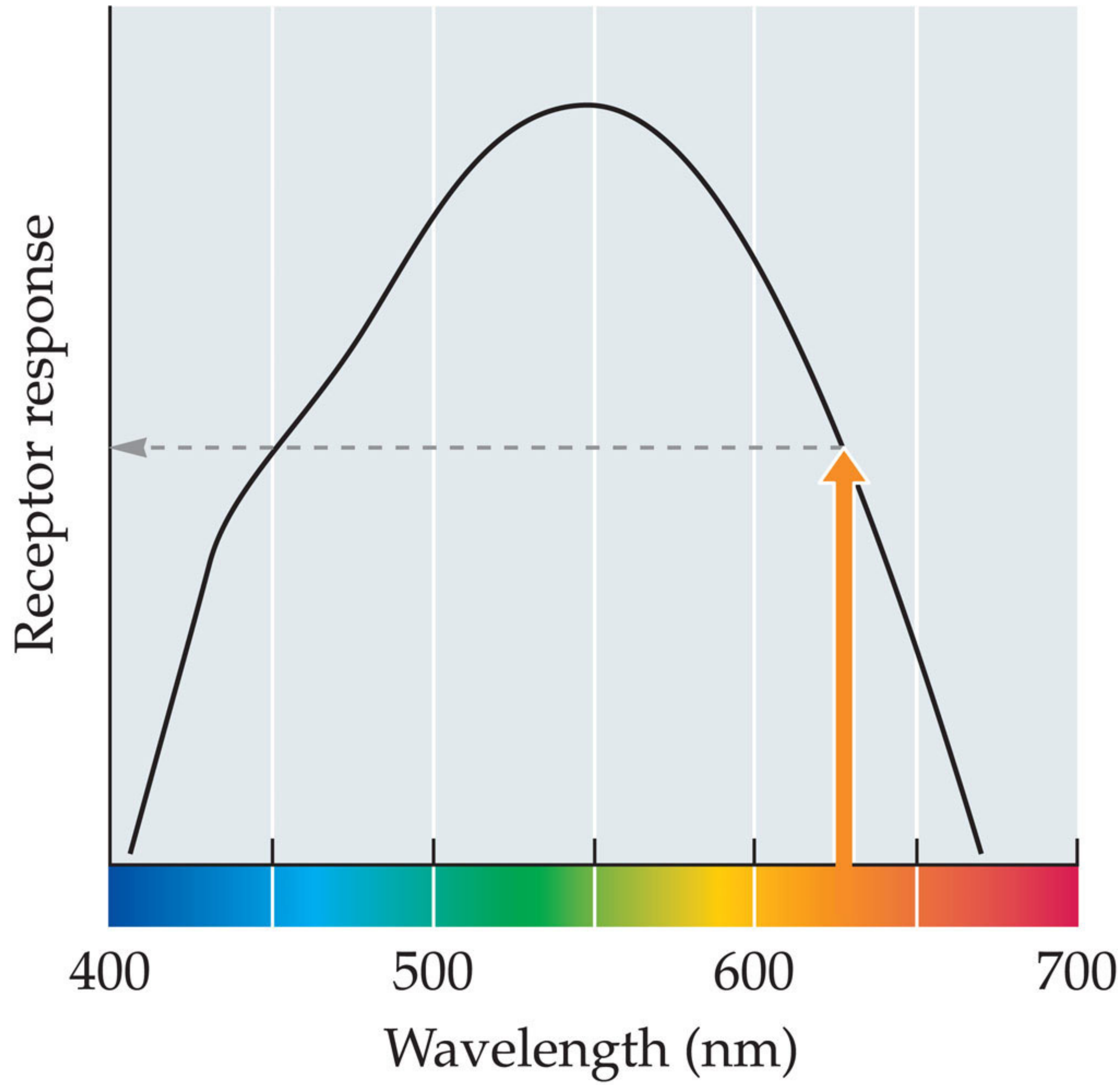
Sunlight and bright indoor lighting are both photopic lighting conditions.

Scotopic: Light intensities that are bright enough to stimulate the rod receptors but too dim to stimulate the cone receptors.

Moonlight and extremely dim indoor lighting are both scotopic lighting conditions.

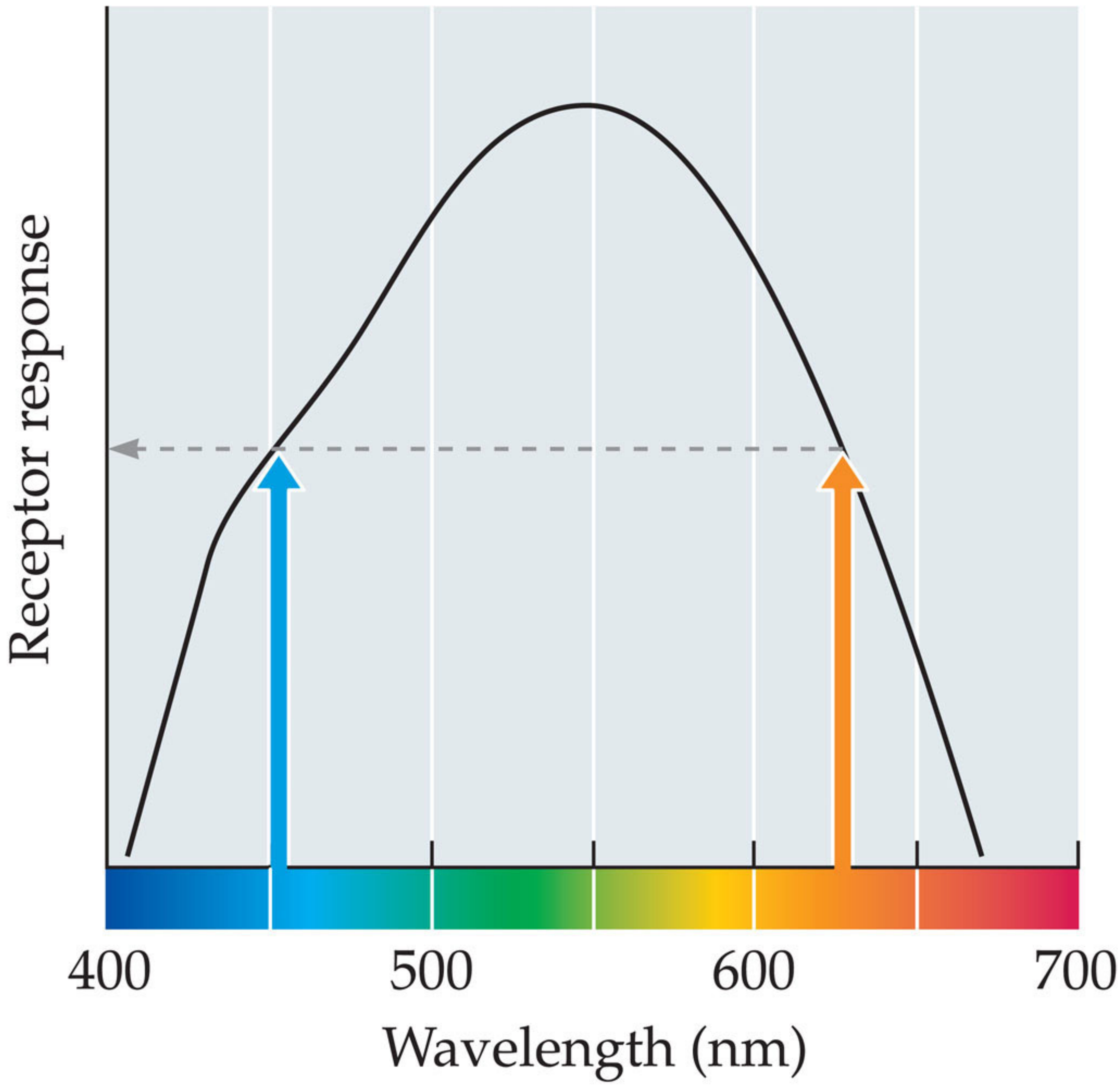
Step 2: colour discrimination

A single photoreceptor shows different responses to lights of different wavelengths but the same intensity



SENSATION & PERCEPTION 4e, **Figure 5.2**

Lights of 450 and 625 nm each elicit the same response from the photoreceptor whose responses are shown here



SENSATION & PERCEPTION 4e, **Figure 5.3**

The principle of univariance

Photoreceptors absorb light energy via opsins.

A single opsin type maps *all* visible light, no matter wavelength, to a one-dimensional response (hence ''univariance'')

This response perfectly confounds the *wavelength* of light with its *intensity*.

Even though light at lower wavelengths (~blue) has more energy per quanta than light at higher wavelengths (~red), the opsin reaction is the same for the absorption of each quantum

An infinite set of different wavelength-intensity combinations can elicit exactly the same response from a single type of photoreceptor.

Therefore, one type of photoreceptor cannot make colour discriminations based on wavelength

Why the world appears colourless at night

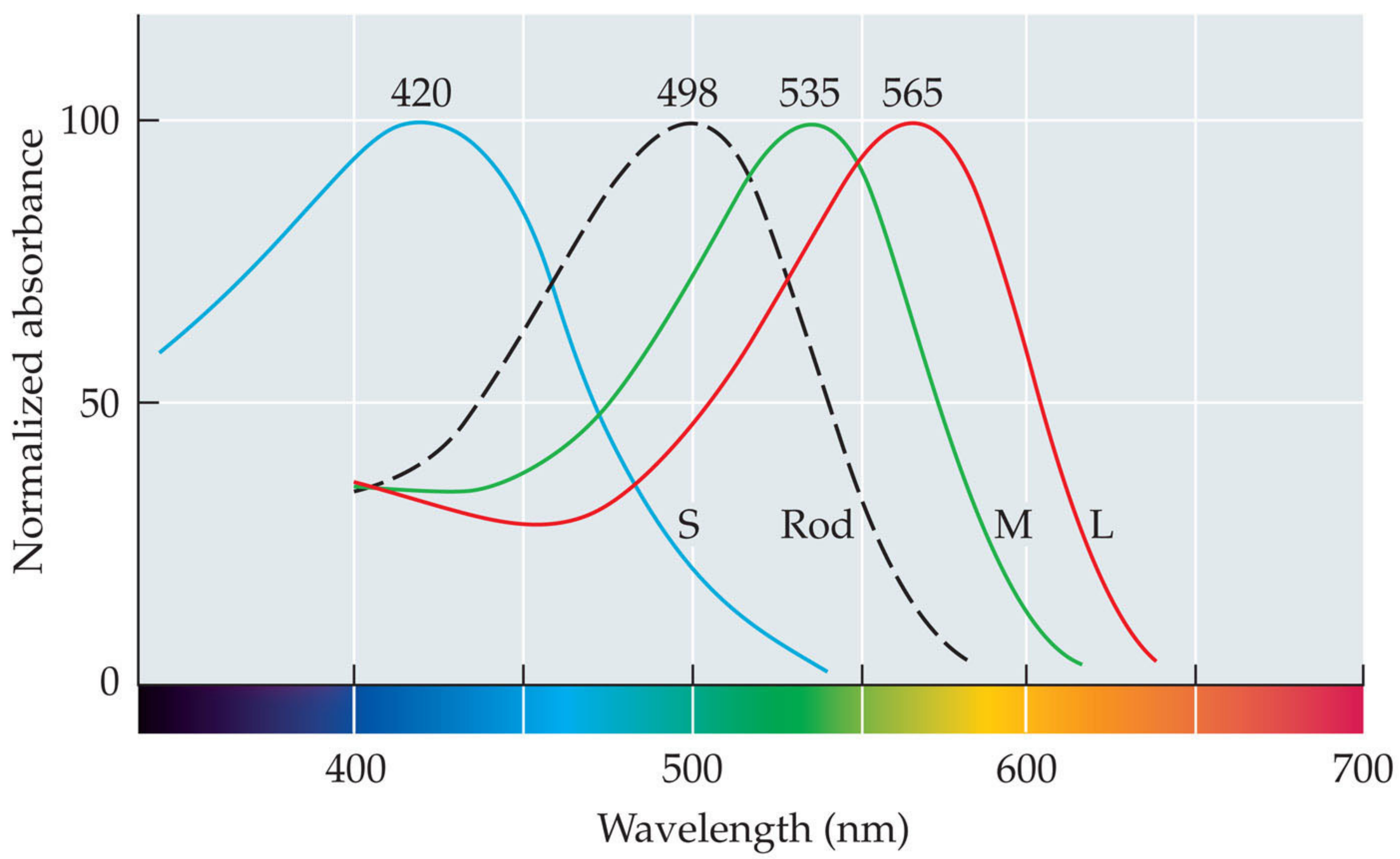
Rods are sensitive to scotopic light levels.

All rods contain the same photopigment molecule: rhodopsin.

All rods have the same sensitivity to various wavelengths of light.

Therefore, rods obey the principle of univariance and cannot sense differences in color.

Under scotopic conditions, only rods are active, so that is why the world seems drained of color.



SENSATION & PERCEPTION 4e, Figure 5.1

The moonlit world appears devoid of color because we have only one type of rod photoreceptor transducing light under these scotopic conditions

SENSATION & PERCEPTION 4e, **Figure 5.4**

Colour discrimination in photopic light levels

Trichromacy: The theory that the color of any light is defined in our visual system by the relationships of three numbers: the three cone outputs

Therefore, in photopic conditions, we avoid the principle of univariance. Changing the intensity of a light changes the absolute cone activations, but not their relative relationships.

History of colour vision

Anatomists and physiologists discovered the three cone types and their sensitivities, and built the trichromatic theory from this anatomical knowledge.

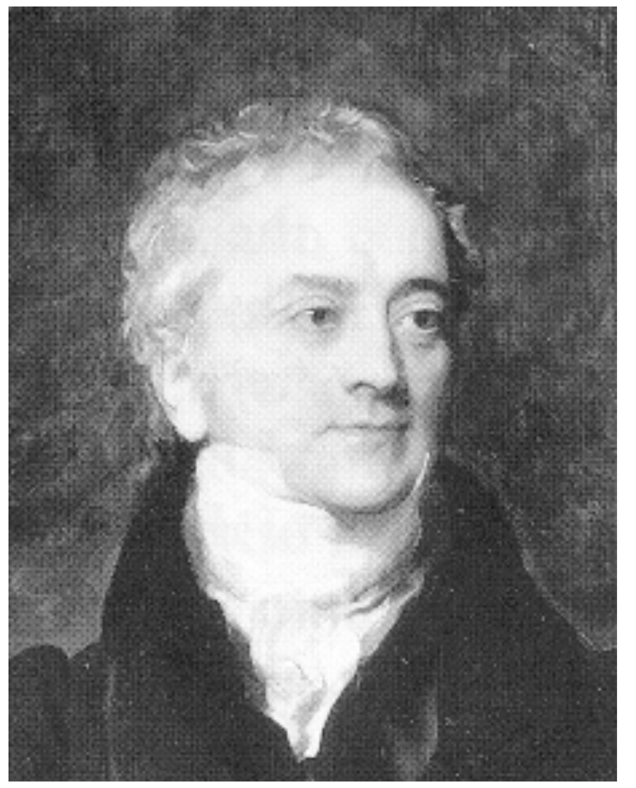
History of colour vision

~~Anatomists and physiologists discovered the three cone types and their sensitivities, and built the trichromatic theory from this anatomical knowledge.~~

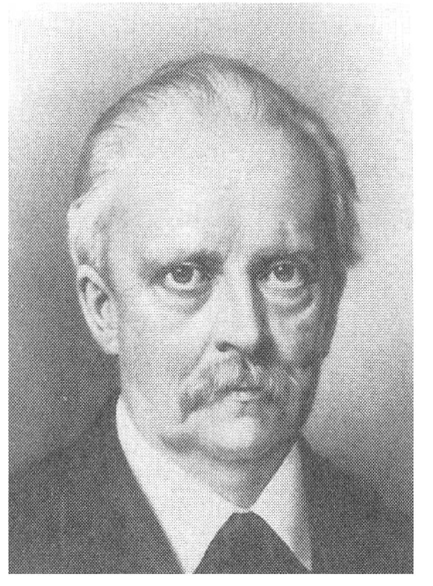
Trichromatic theory was first identified via careful psychophysical observations! It wasn't until the 1990s that the anatomical basis was largely understood.

Thomas Young (1773–1829) and Hermann von Helmholtz (1821–1894) independently discovered the trichromatic nature of color perception. This is why trichromatic theory is sometimes called the "Young-Helmholtz theory"

As it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation, it becomes necessary to suppose the number limited, for instance to the three principles colours, red, yellow and blue. (Young, Bakerian lecture to the Royal Society, 1802)



Thomas Young
1773-1829

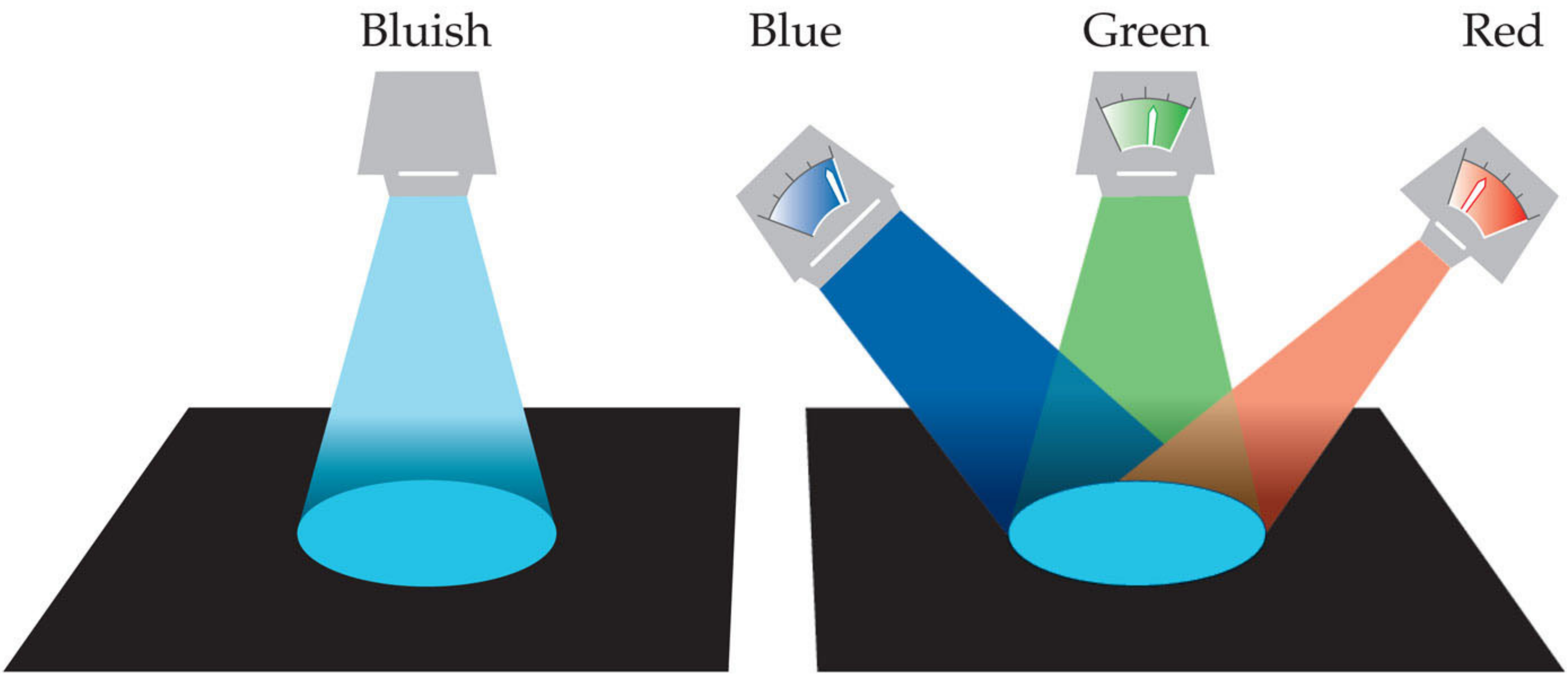


Hermann von Helmholtz
1821-1894

History of colour vision

James Maxwell (1831–1879) developed a color-matching technique that is still being used today.

Modern version of Maxwell's color-matching experiment



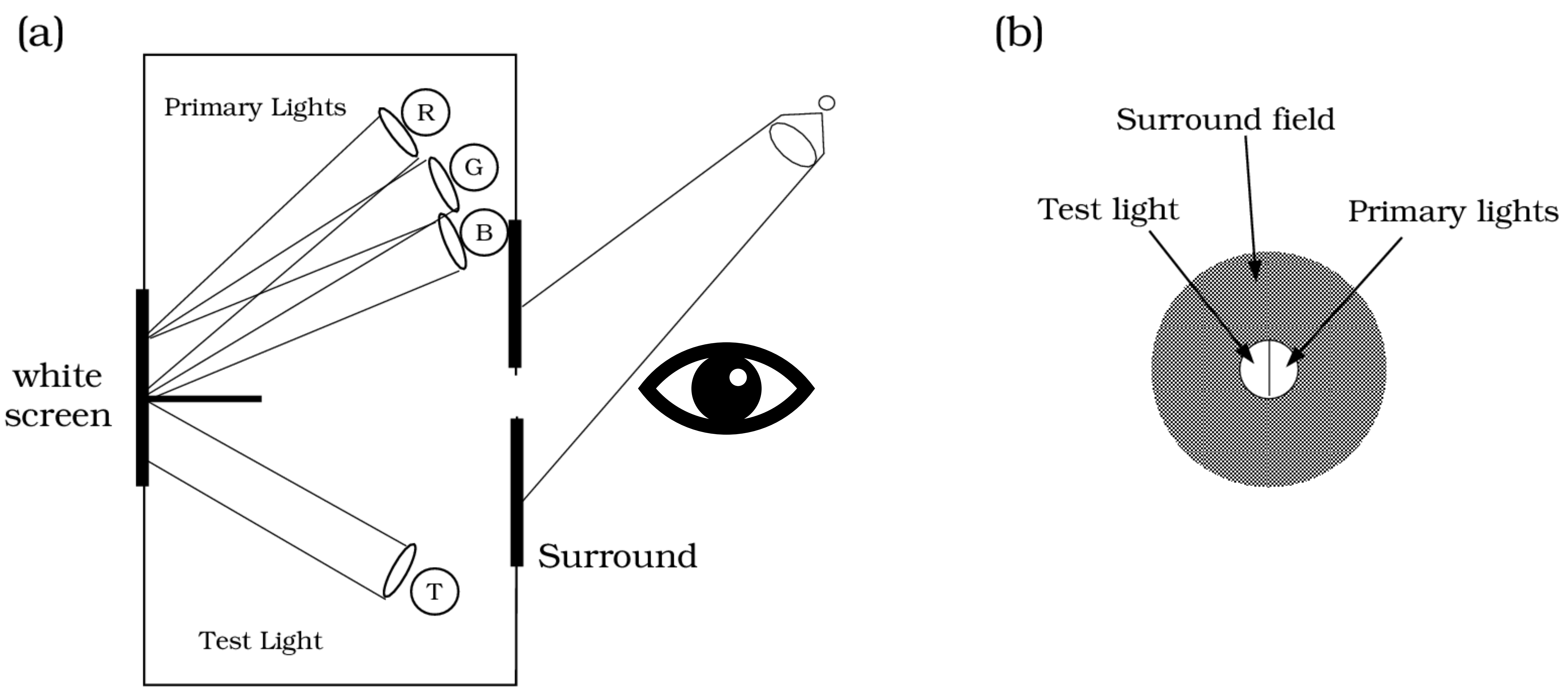
SENSATION & PERCEPTION 4e, Figure 5.8

Modern version of Maxwell's color-matching experiment

The two sides of the bipartite field can be made indistinguishable for every test light using three primary lights if the three primary lights themselves are independent (none of them is a mixture of the other two primary lights).

Two primary lights are not enough. More than three lights are not needed

Young-Helmholtz Theory of Trichromacy: Human colour perception is based on three independent mechanisms ("three-dimensional").



Wandell (2015)

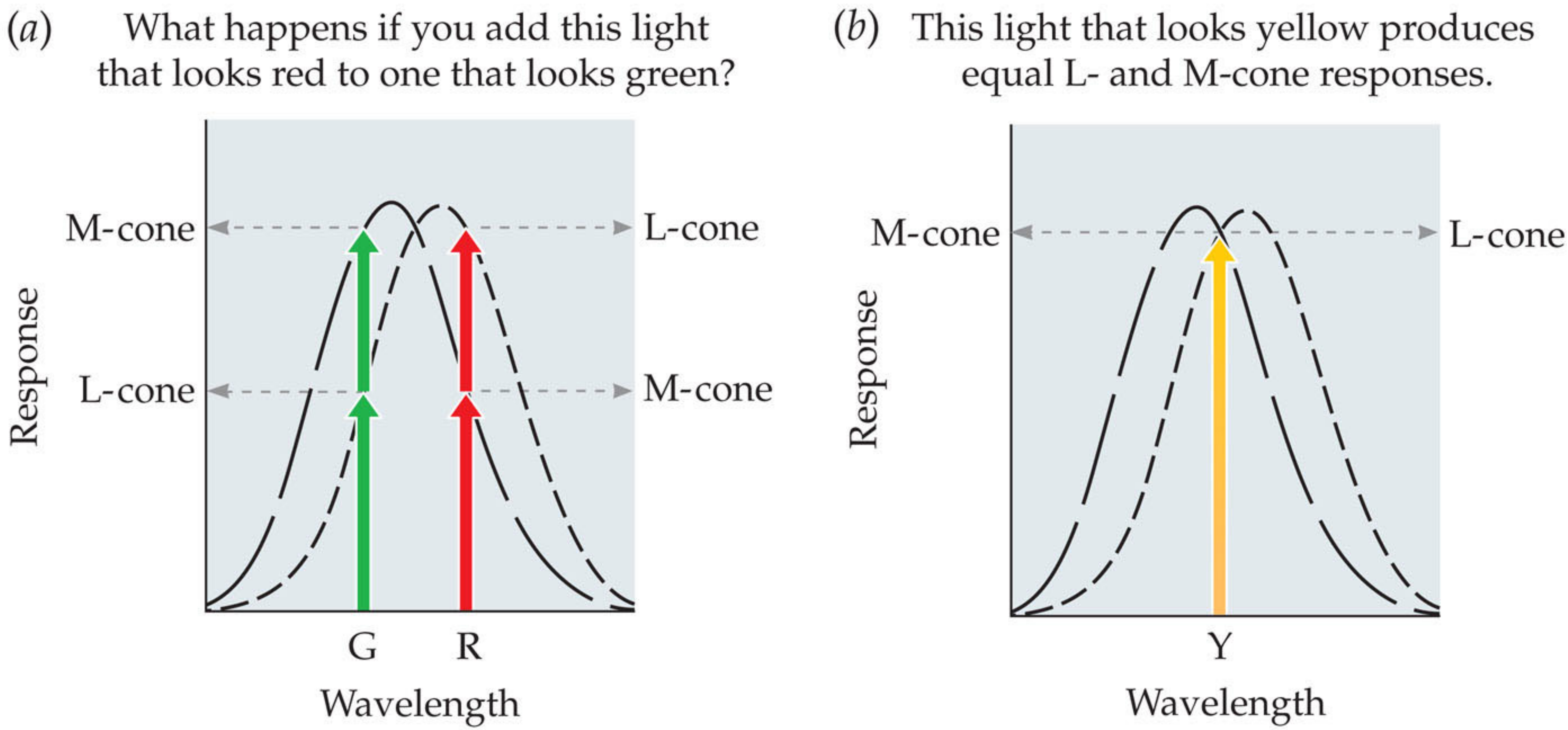
Metamerism

The test light can have any spectral power distribution, whereas the mixture of primaries can only contain spectra given by weighted sums of the three primary lights

Yet a human can set these lights to appear the same!

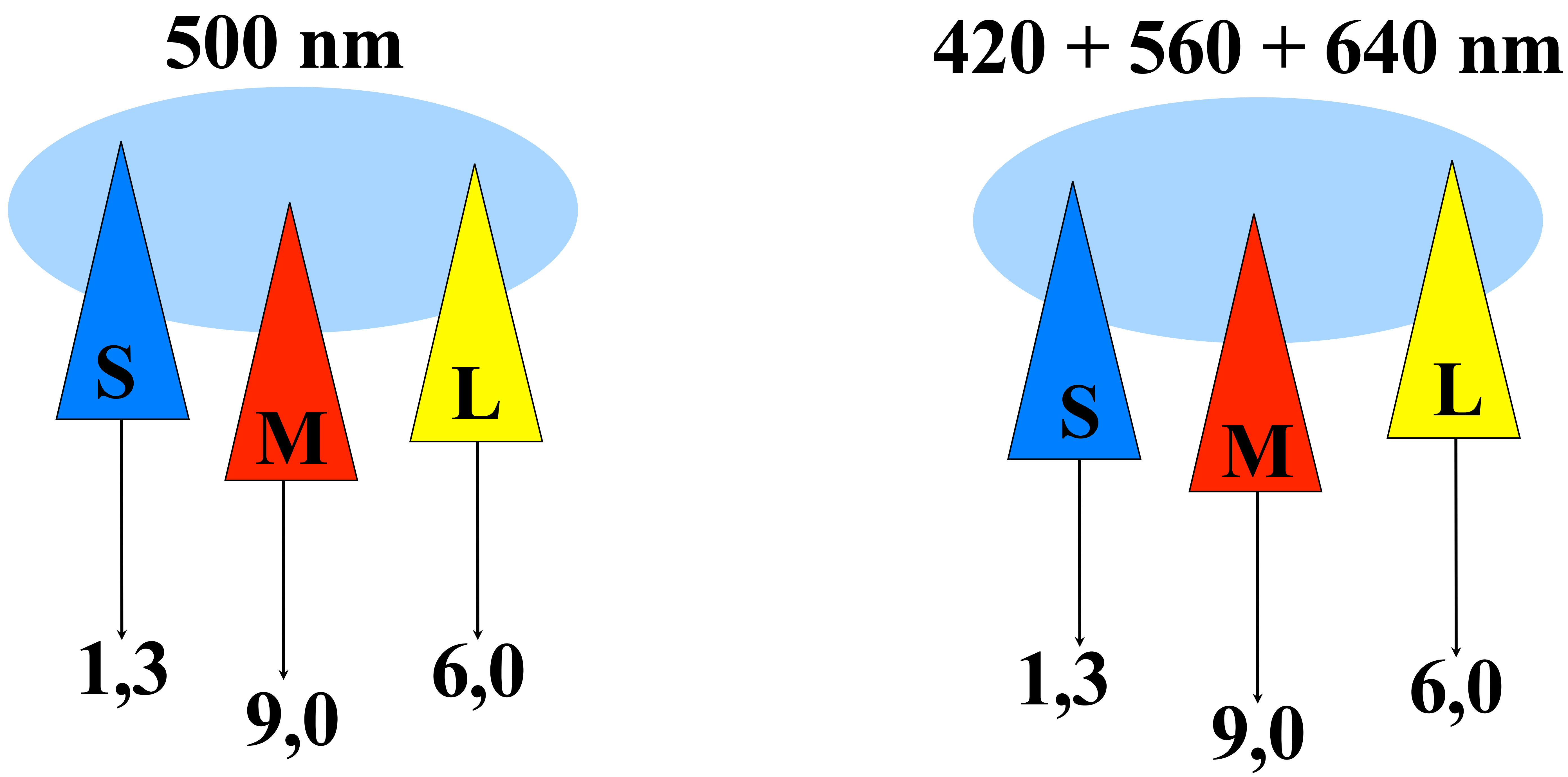
Metamers: physically different stimuli that appear the same. For colour: different mixtures of wavelengths that look identical

(a) The long-wavelength light that looks red and the shorter-wavelength light that looks green mix to produce the same response as does the medium-wavelength light that looks yellow (b)



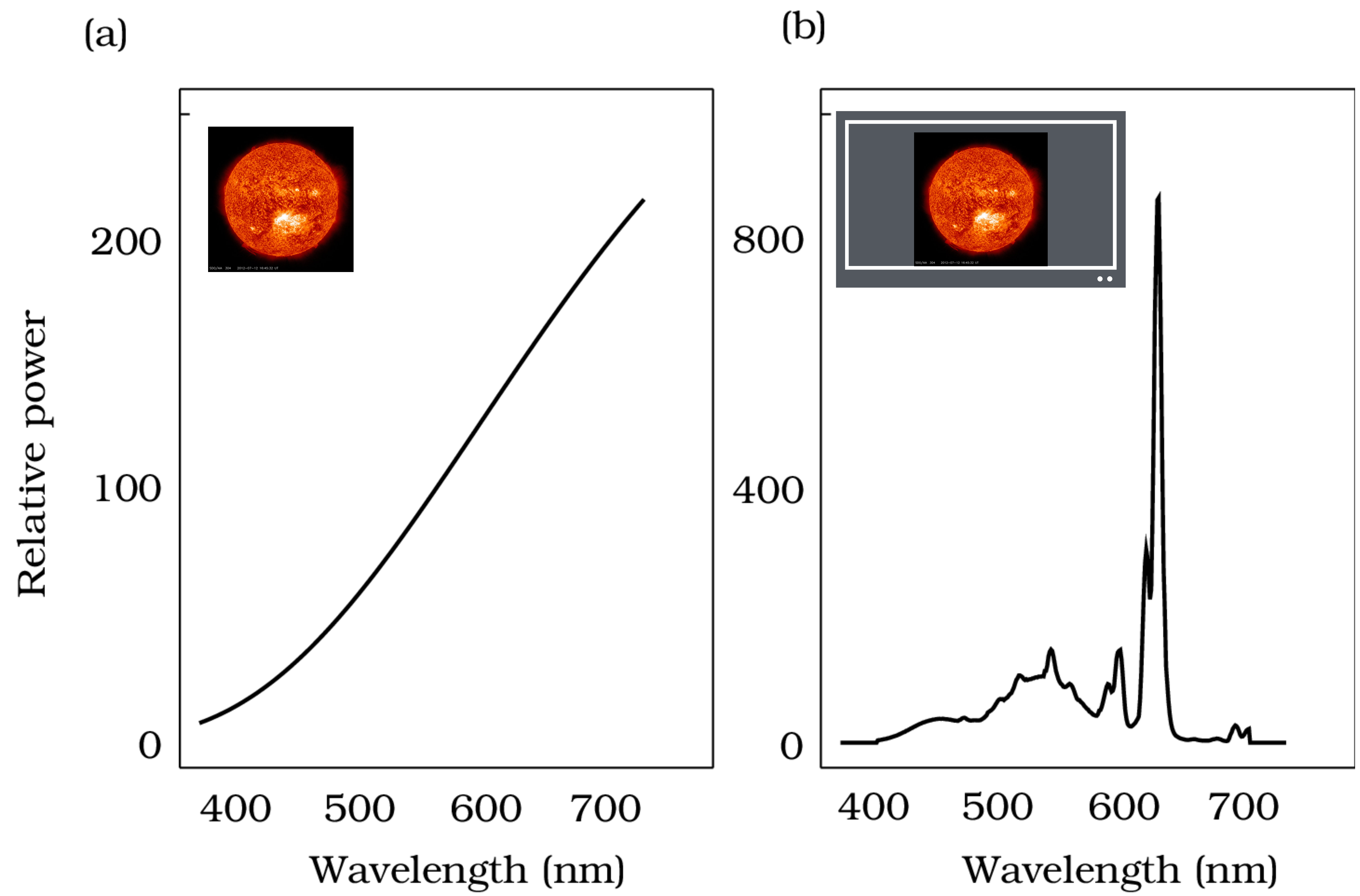
SENSATION & PERCEPTION 4e, **Figure 5.7**

Metamers using monochromatic lights (lasers)



Metamerism

These examples generalise to *any* mixture of lights (or spectral power distributions)!



Wandell (2015)

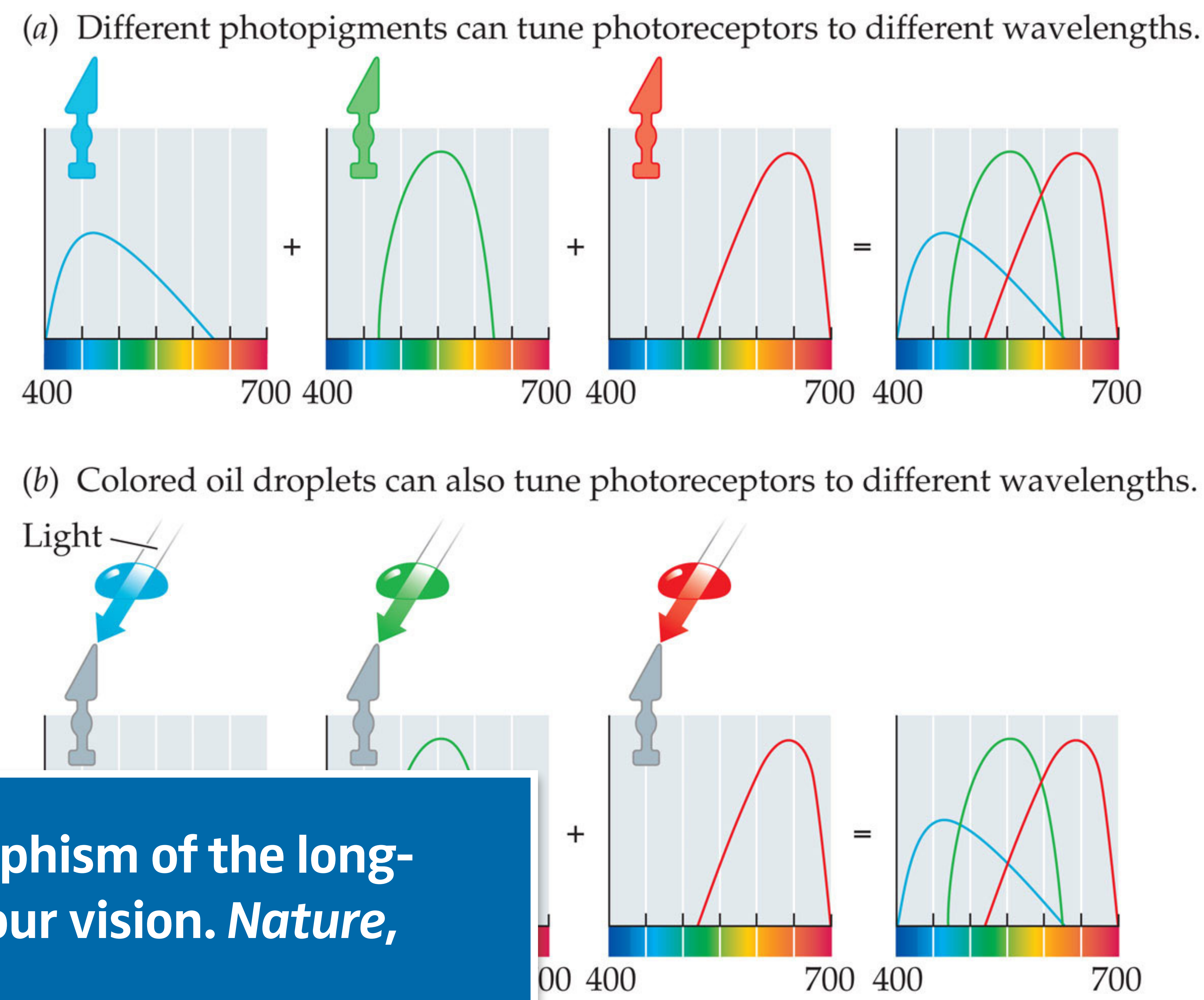
Trichromacy

Trichromacy is a behavioural concept: Our colour space in the colour-matching experiment is three-dimensional, it behaves like a (linear) vector space.

Please note that it does not say anything about photoreceptors—being trichromatic does not logically imply that the species has three photoreceptors:

Digital cameras have only a single photo sensor on their chip, but three (or more) colour filters in front of it.

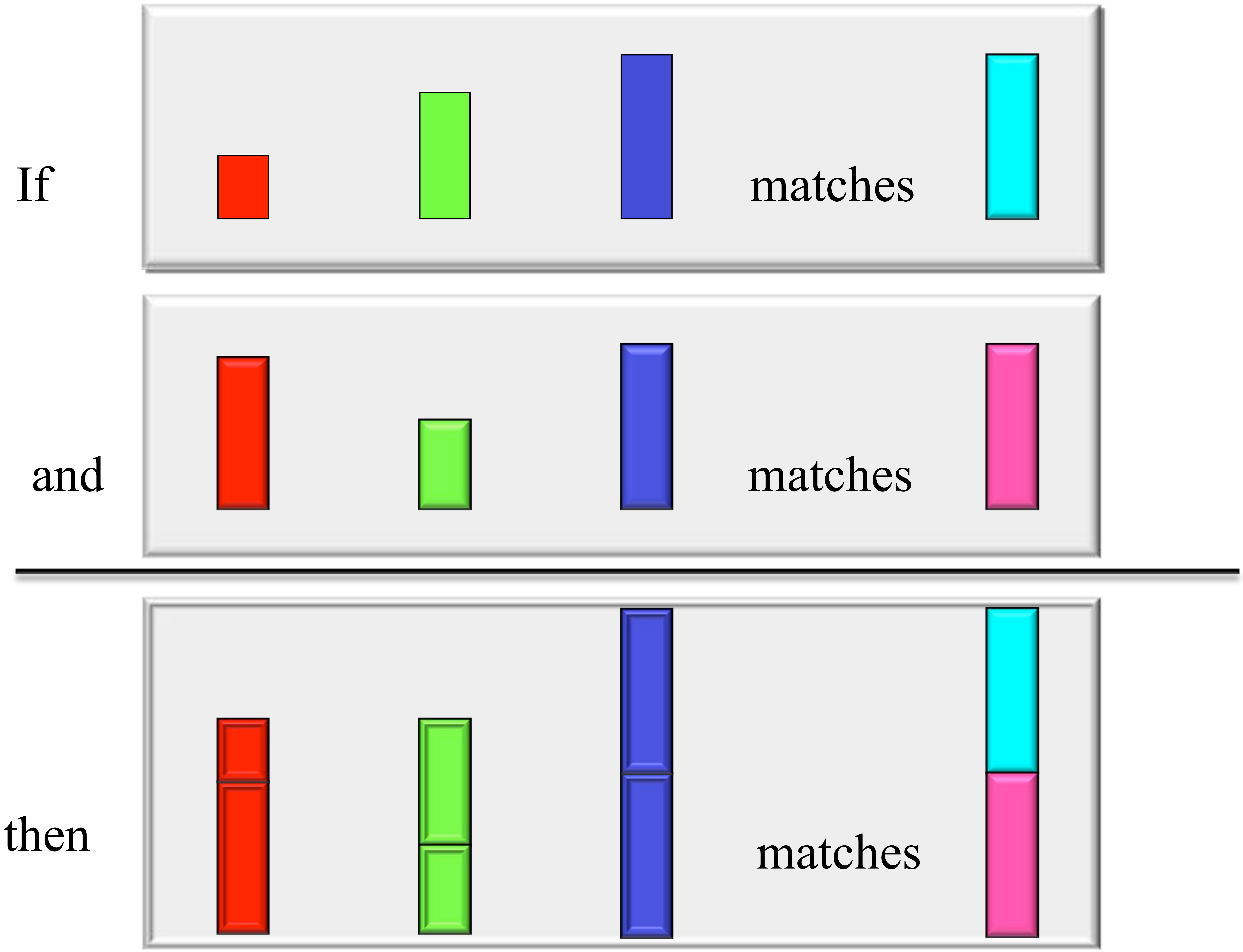
Some birds use coloured oil



Neitz, J. & Jacobs, G. H. (1986). Polymorphism of the long-wavelength cone in normal human colour vision. *Nature*, 323:623–625.

Colour as a linear 3D vector

The colour matching experiment is linear (Grassman’s Law)



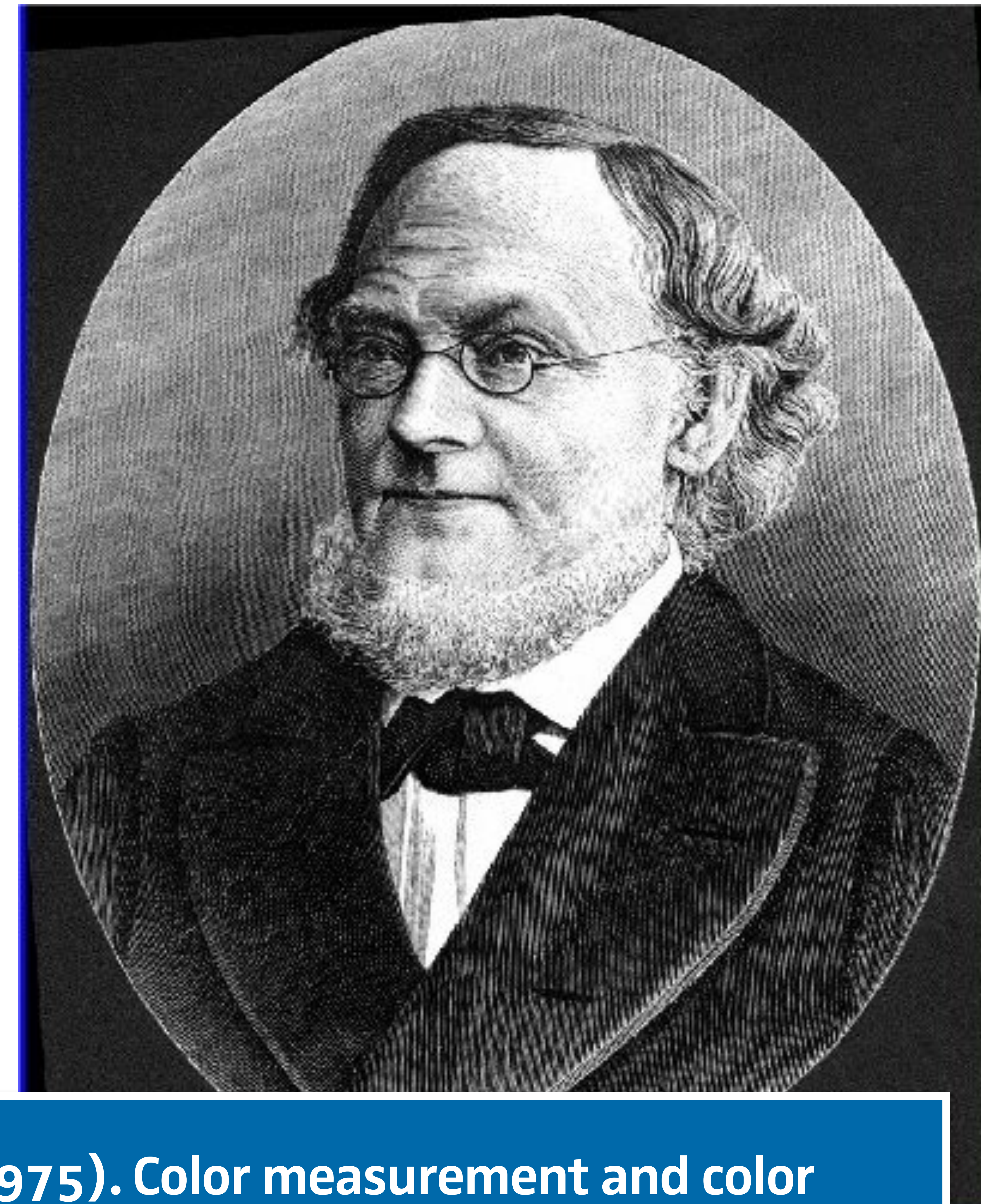
Wandell (2015)

Colour-matching behaves like a 3D vector space

Hermann Günther Grassmann (1809–1877) German mathematician; inventor of vector spaces.

In 1853, Grassmann published a theory of how colors mix, known as **Grassmann's laws**.

Colour-matching: If the three primaries are linearly independent—form a basis in 3D—then any point in the space can be reached (if you have negative coefficients). If not, you have to shine one (or two) primaries to the target to make the the two halves indistinguishable.



KRANTZ, D. H. (1975). Color measurement and color theory: I. representation theorem for Grassmann structures. *Journal of Mathematical Psychology*, 12(3):283–303.

Colour spaces

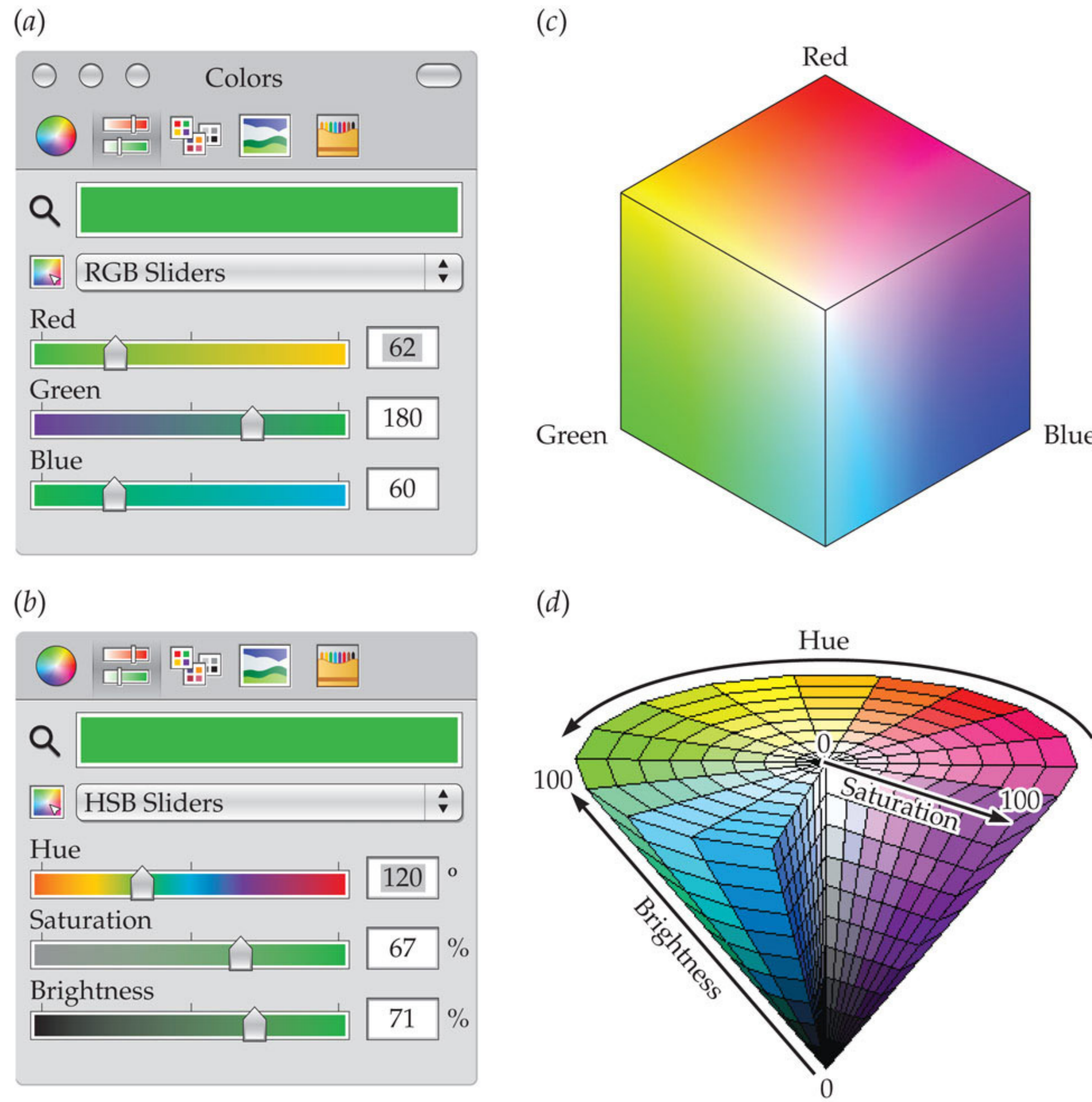
Trichromatic theory: all perceivable colours can be created by mixing three primaries. Colours lie in a 3D vector space (Grassman's laws)

There are many definable colour spaces that describe perceivable colours.

Colour spaces

RGB color space: Defined by the outputs of long, medium, and short wavelength lights (i.e., red, green, and blue).

HSB color space: Defined by hue, saturation, and brightness.
Hue: The chromatic (color) aspect of light.
Saturation: The chromatic strength of a hue.
Brightness: The distance from black in color space.

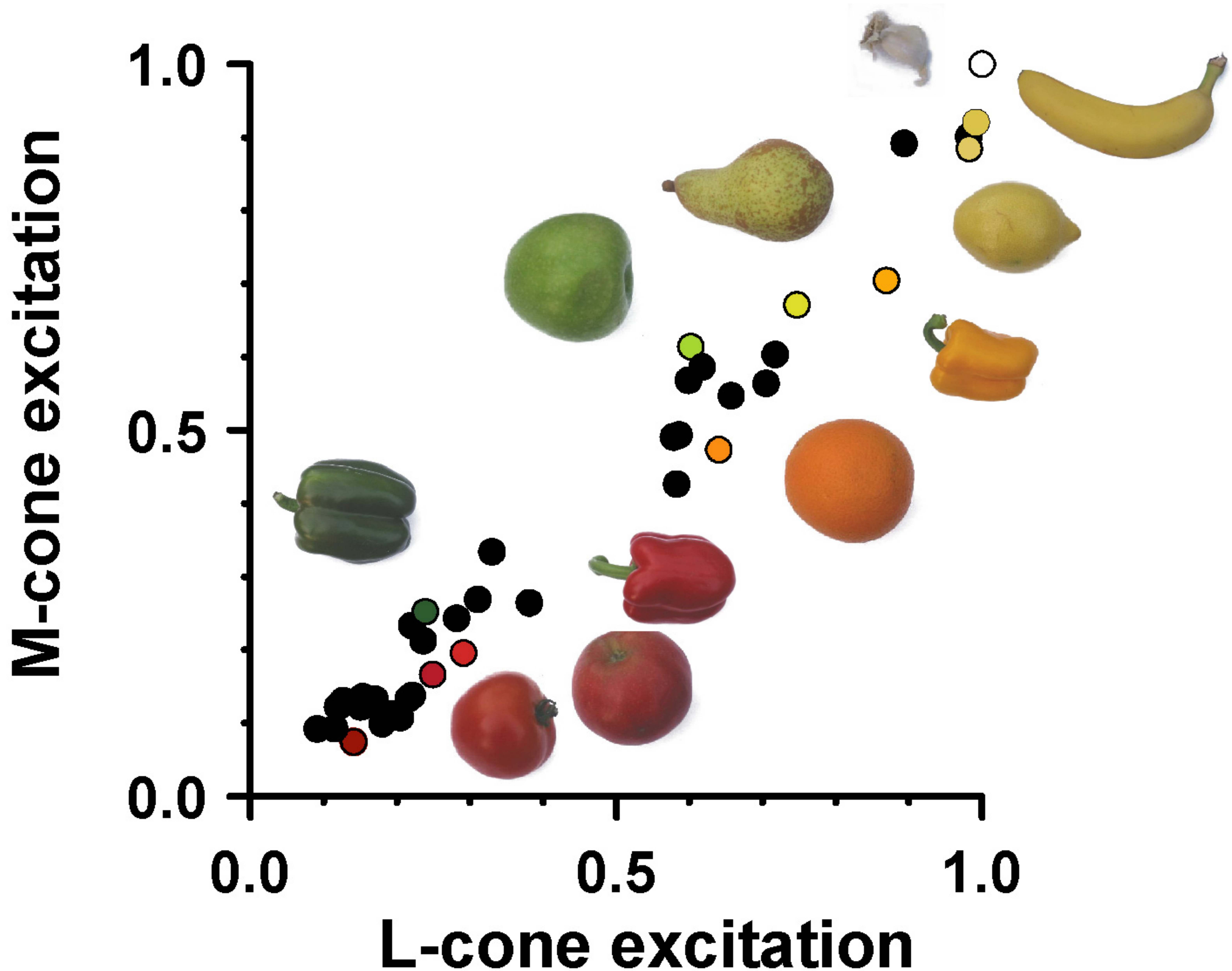


SENSATION & PERCEPTION 4e, **Figure 5.12**

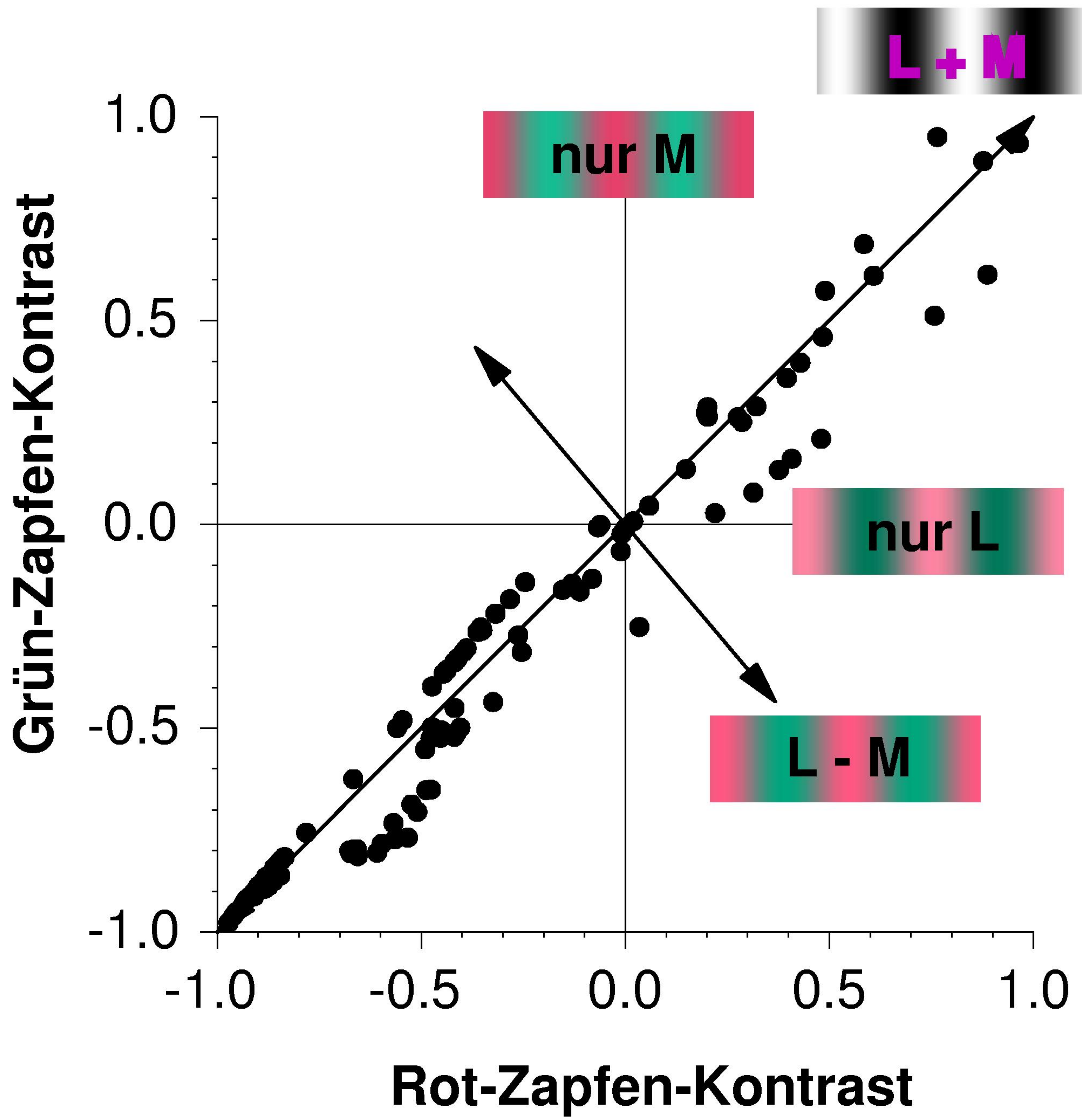
Cone-opponent mechanisms

Colour contrast of natural objects

There is a high correlation between L- and M-cone signals. This is not very efficient!



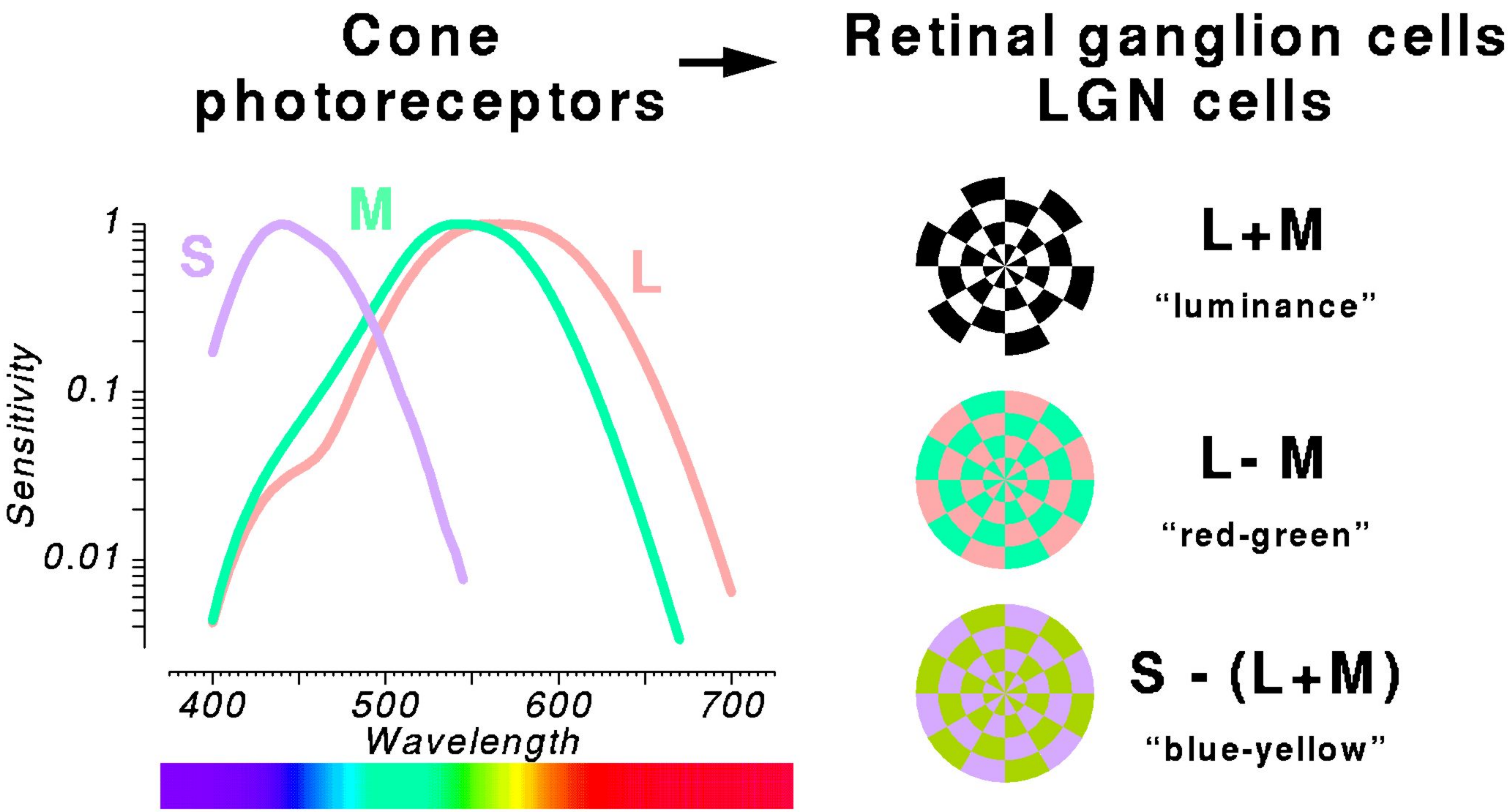
Colour contrast of natural objects



Re-coding makes a lot of sense:

L+M (brightness)
L-M (red-green opponent colours)

Chromatic signal decorrelation via cone-opponent mechanisms

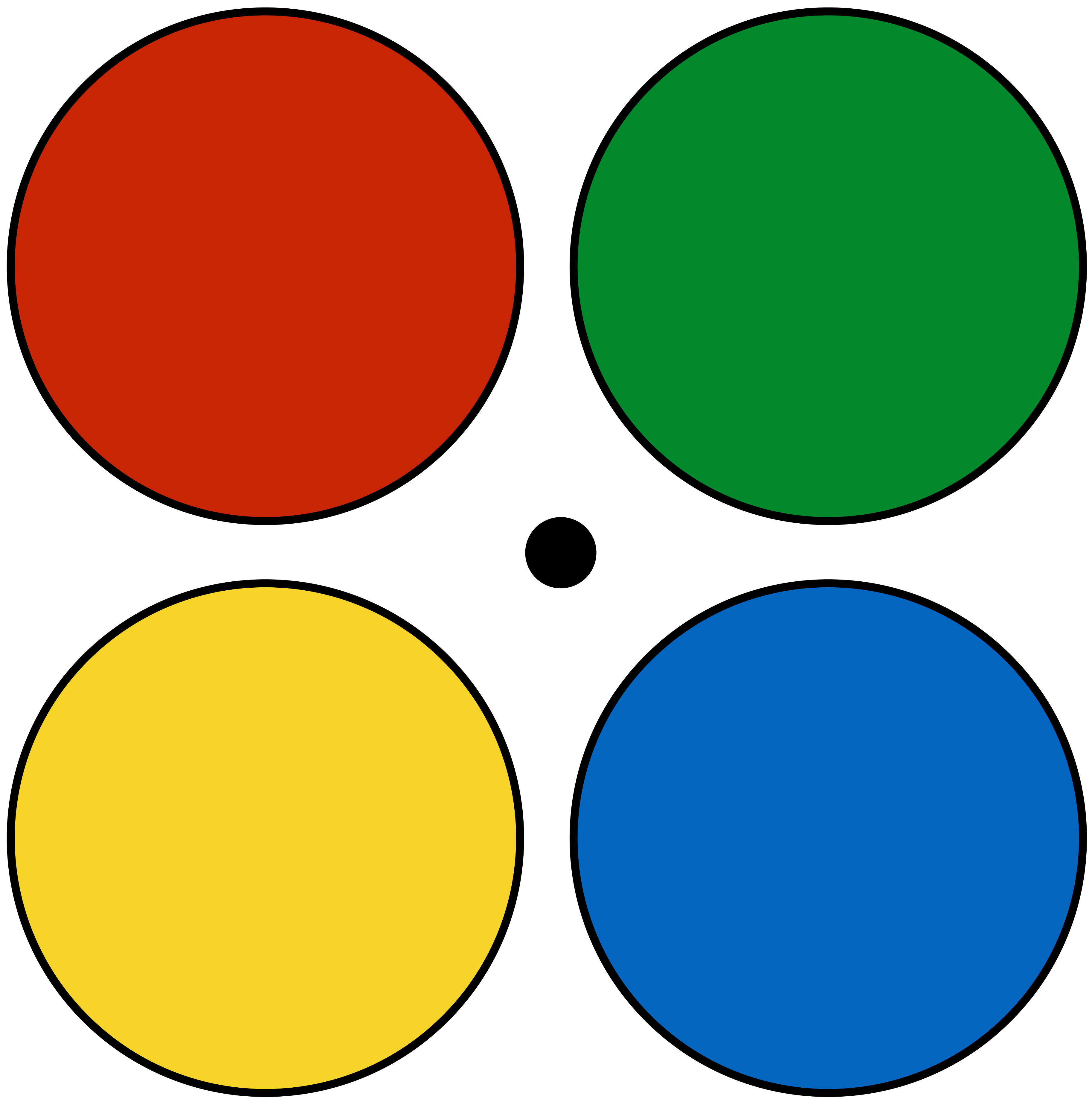


A physiologically-plausible colour space

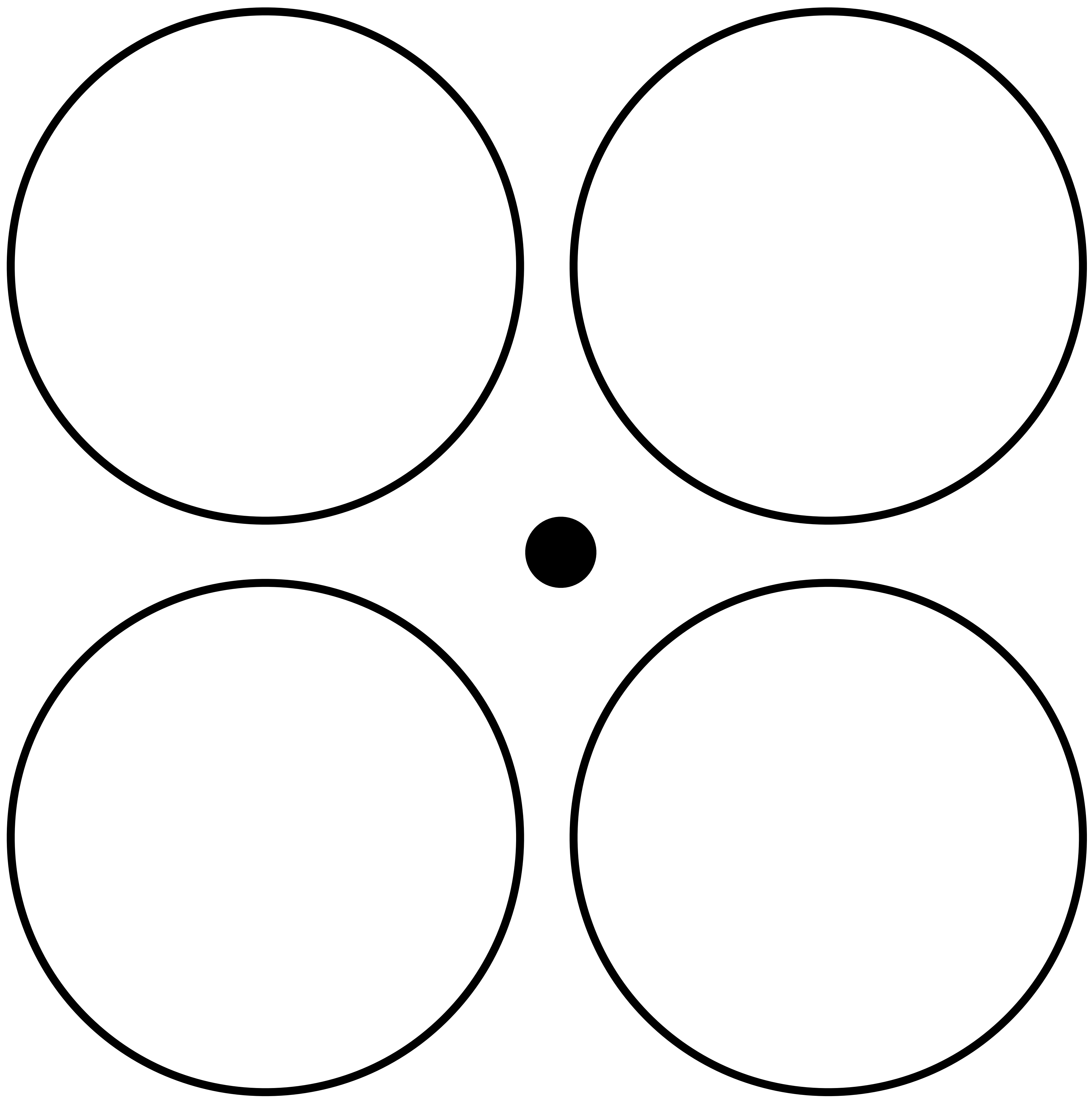
DKL color space: A widely used color space, known as the ''Derrington-Krauskopf-Lennie'' (DKL) space, in which the coordinates represent the purported responses of the three second-site colour discrimination mechanism, L+M, L–M, and S–(L+M). The modulation directions that change the response of one of these mechanisms while leaving the response of the other two fixed are referred to as ''cardinal directions.''

Within the primate retina and LGN, cells that code various types of this opponency in centre-surround organisations have been found: L+M, L-M, M-L, etc...

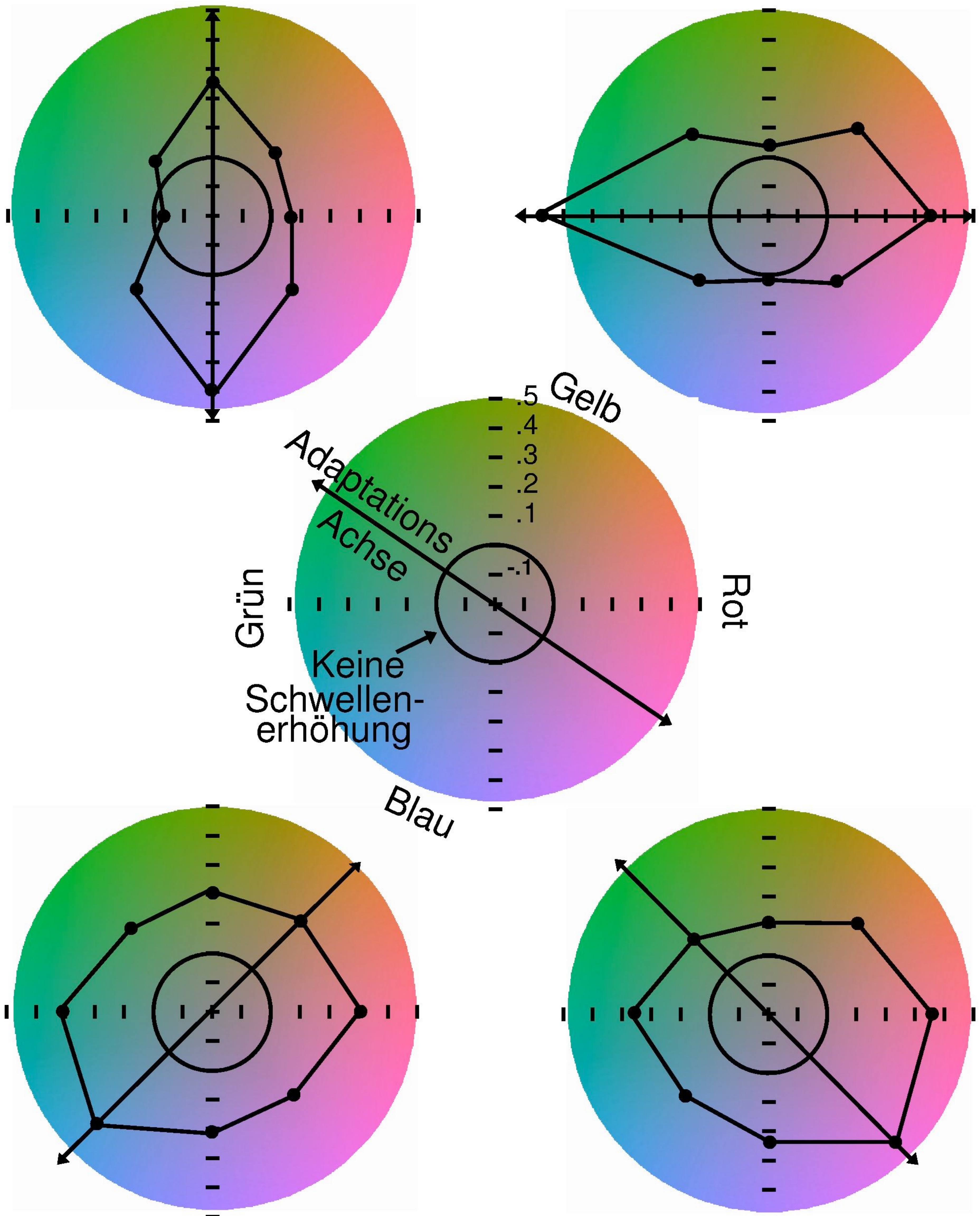
Opponent colours: adaptation



Opponent colours: adaptation



Opponent colours: adaptation



Adaptation along one of the opposing color axes leads to a reduction in the detectability of signals along this axis.

Signals along the other opposing axis are not affected.

The opponent channels are independent of each other and are also referred to as cardinal colour directions.

See Krauskopf, Williams & Heeley (1982)

The End

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