Fundamentals of Imaging
2-Human vision + Photometry + Colorimetry

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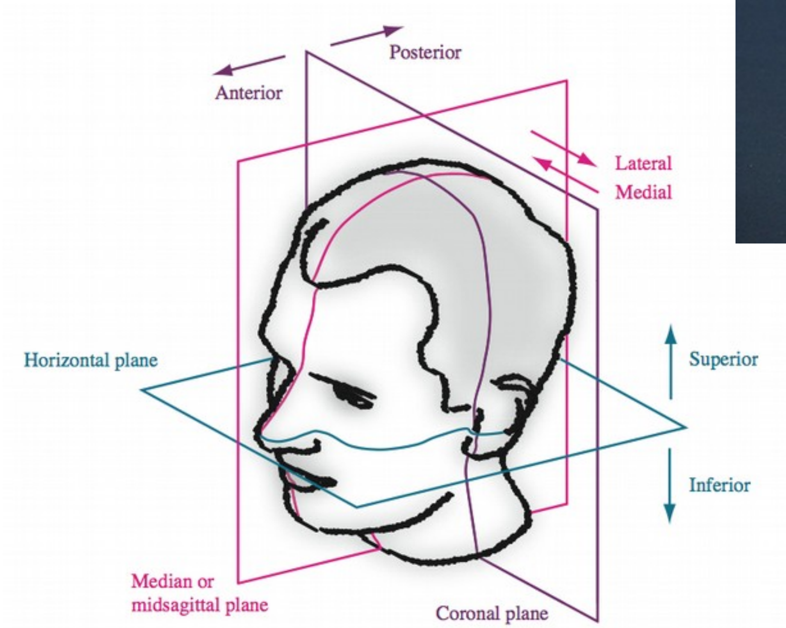
Today's lesson

- The human visual system:
  - Anatomy
  - Nerves and models
- Photometry
- Colorimetry
  - Colour primaries
  - Chromaticity diagrams

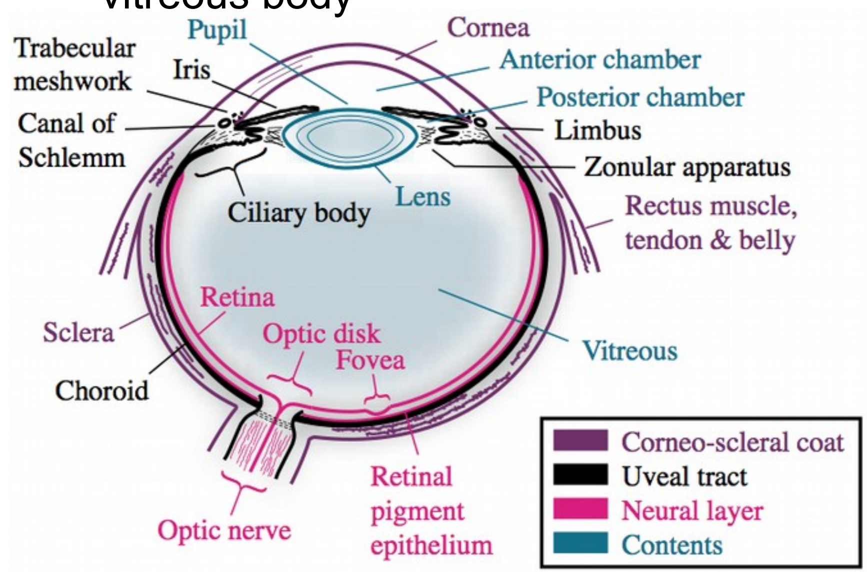
The head

- A skull contains 4 cavities
  - Cranial cavity (houses brain)
  - Nasal cavity
  - Orbits
  - Oral cavity
- The orbits are roughly quadrilateral pyramids, with a
  nerve terminals through
- They house the eyes and their muscles
- Head parts location is named as here right



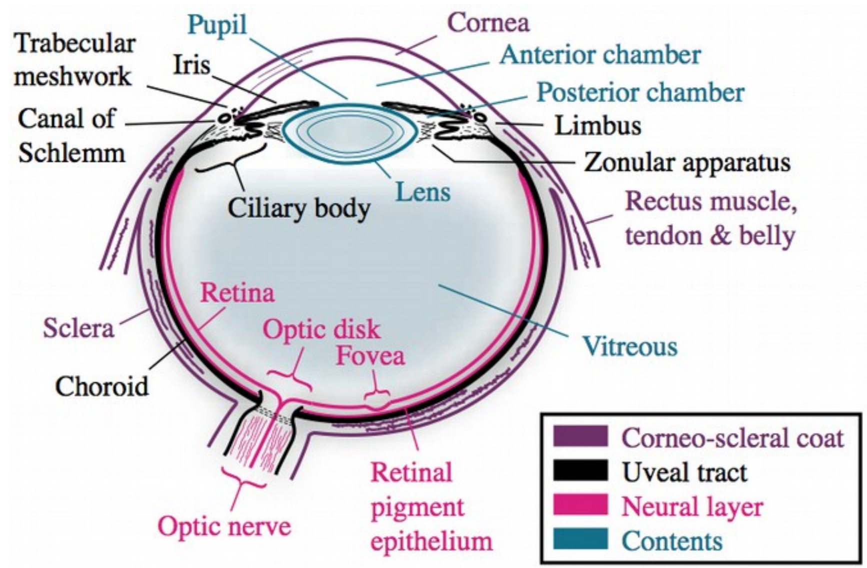
The eye

- Eyes are used for
  - Photoreception
  - Communication of the resulting action potentials to the brain
- Two spheres:
  - Cornea (∅15.6mm)
  - Sclera (∅23mm)
- There are 3 layers:
  - outer corneoscleral envelope
  - uveal tract
  - inner neural layer
- Outer muscles attach to robust corneosclerical envelope
- uveal tract (uvea):
  - Iris + ciliary body + choroid has two openings:
    - In front the the pupil
    - At the back: the optic nerve canal
- Innermost is the retina, which has two layers:
  - *inner neurosensory retina*
  - *retinal pigment epithelium*
- Transparent parts:
  - aqueous humor
  - lens
  - vitreous body



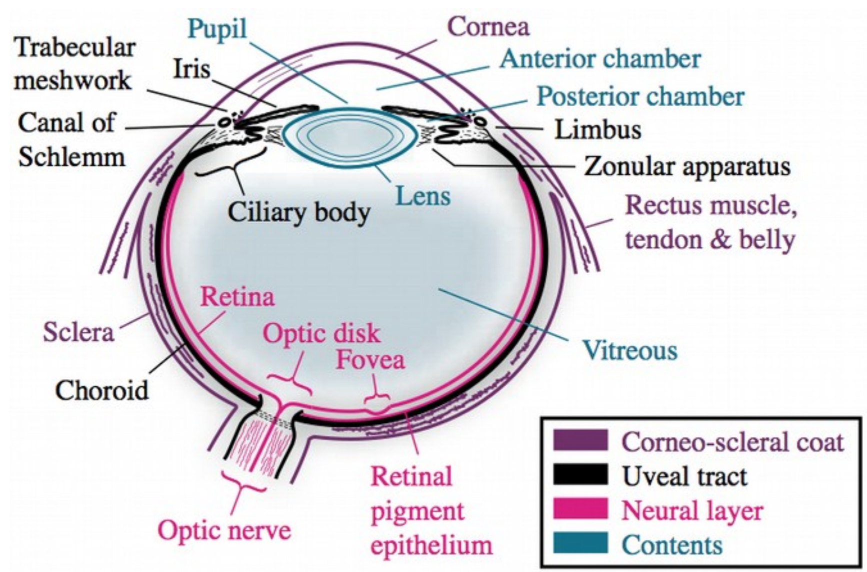
Eye movement

- Visual acuity is best at the fovea:
  - We need to move our eyes so objects of interest project on it (*gaze shifting*).
- Eyes can move 45° in each direction, bust mostly not more than 20°.
- Objects outside of the 20° are tracked by combining head and eye movement.
- Once the object of interest is focused small eye movements focus on its detail



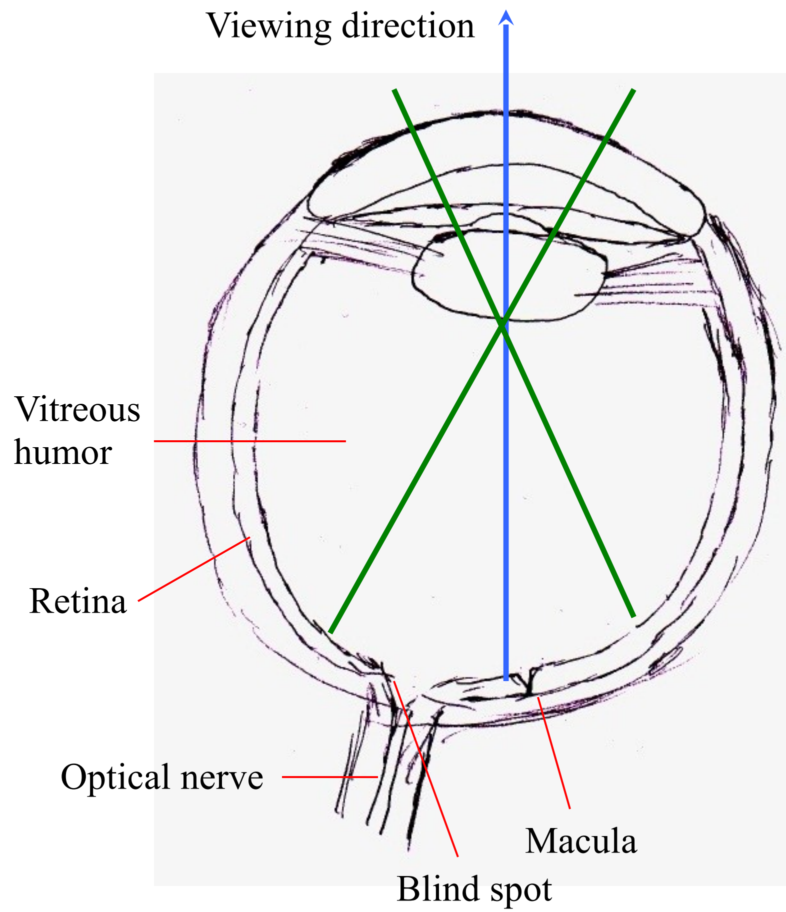
Cornea, iris, lens, vitreous body

- The *cornea* is responsible for eye focusing
- It is composed of fibrils, which are arranged in parallel rows, canceling the diffraction effect
- The *iris* has two muscles, capable of dilating it or shrinking it, from 1 mm to 8 mm.
- This is used to control the pupil, which controls the amount of light entering the eye.
- The pupil size can be adjusted at 4 Hz.
- Behind the pupil there is the lens, which in case it is not regular leads to astigmatismus, and chromatic aberrations
- The lens filters out UV light.
- Behind the lens, the light travels thorugh the vitreous body.



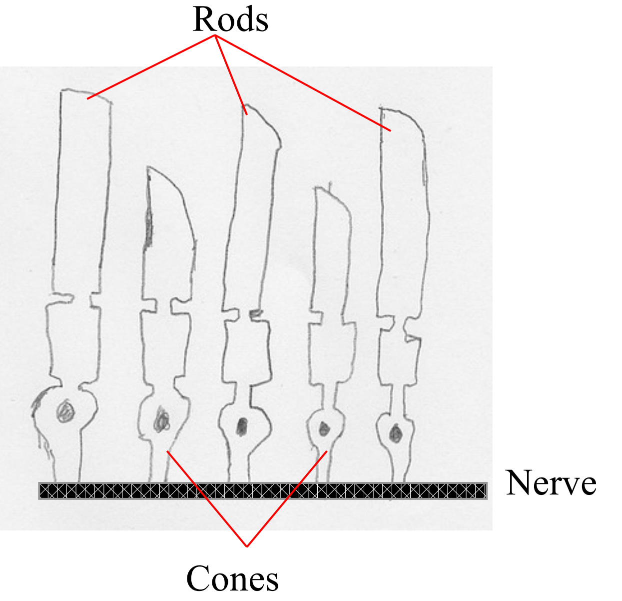
The retina

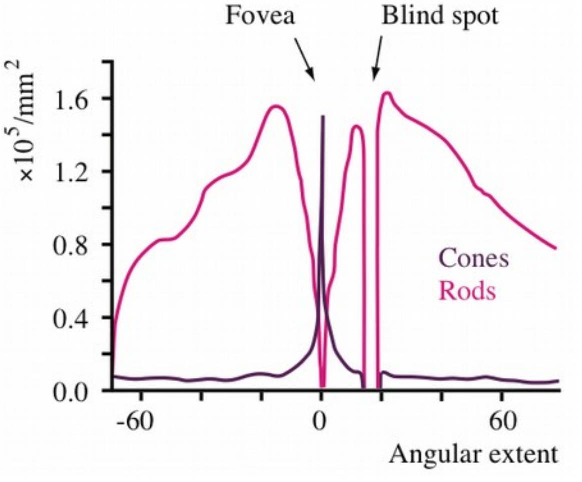
- At the back end of the eye, the photoreceptor parts are on the retina
- In the retina, where the optical nerve is, there is a blind spot for vision
- Photoreceptors are spread on the retina, more densely around the macula, which is the point of maximum visual acuity.
- Eyes sample the environment continously, so that the macula can perceive image detail

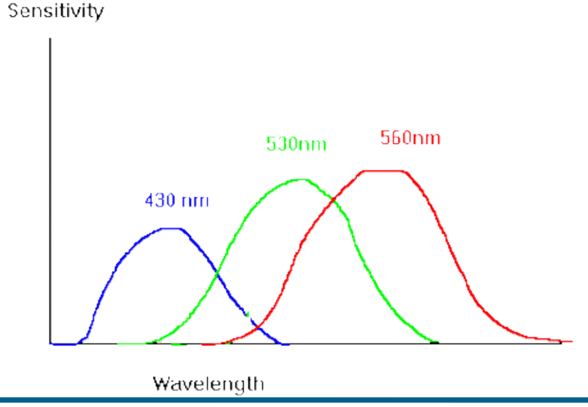


The retina

- At the back end of the eye, the retina has embedded photoreceptors
- The photoreceptors are of two types: *rods* and *cones*
- Rods are responsible for light intensity (500-550nm)
- Cones for colour, with three types of different wavelength sensitivity
- Cones are sensitive to different wavelengths but less sensitive than rods
- Vision works differently from day (cones) to night (rods)

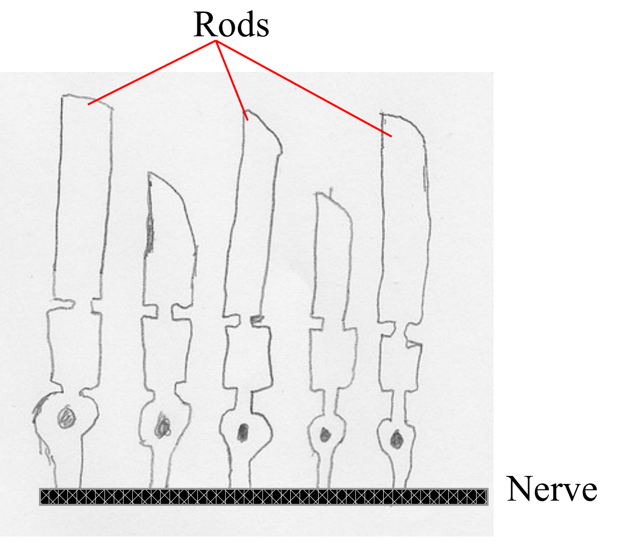


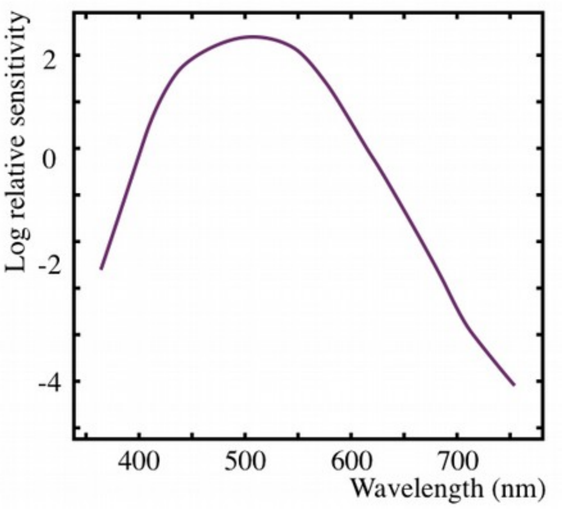




Rods

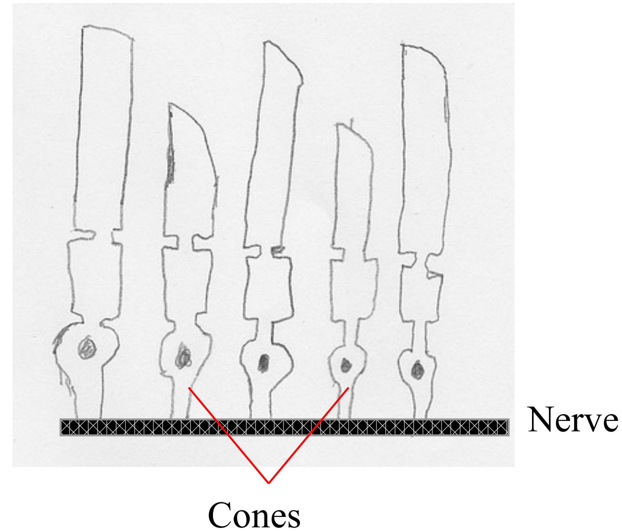
- Rods are packed on a hexagonal pattern
- They contain a visual pigment called *rhodopsin*
- Peak sensitivity at the wavelength of 496nm
- Whenever a molecule of rhodopsin absorbs a photon, a chemical reaction occurs (bleaching), preventing the molecule to absorb other photons.
- After some time, the chemical reaction is reversed, and the rod is ready to sense again
- This reverse operation is quite slow, (ca. 5 minutes) but not as slow as our dark adaptation (time it needs to get used to dark)

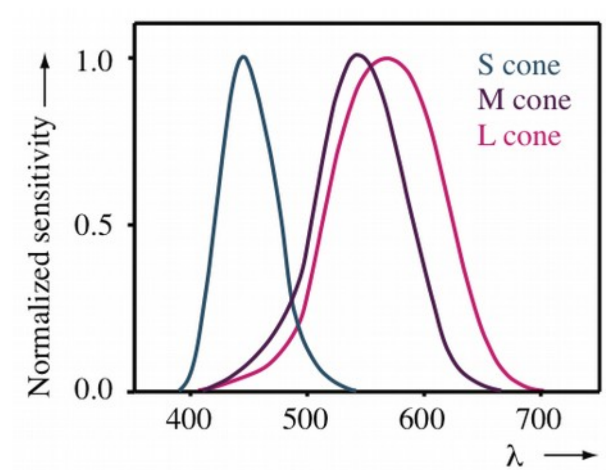




Cones

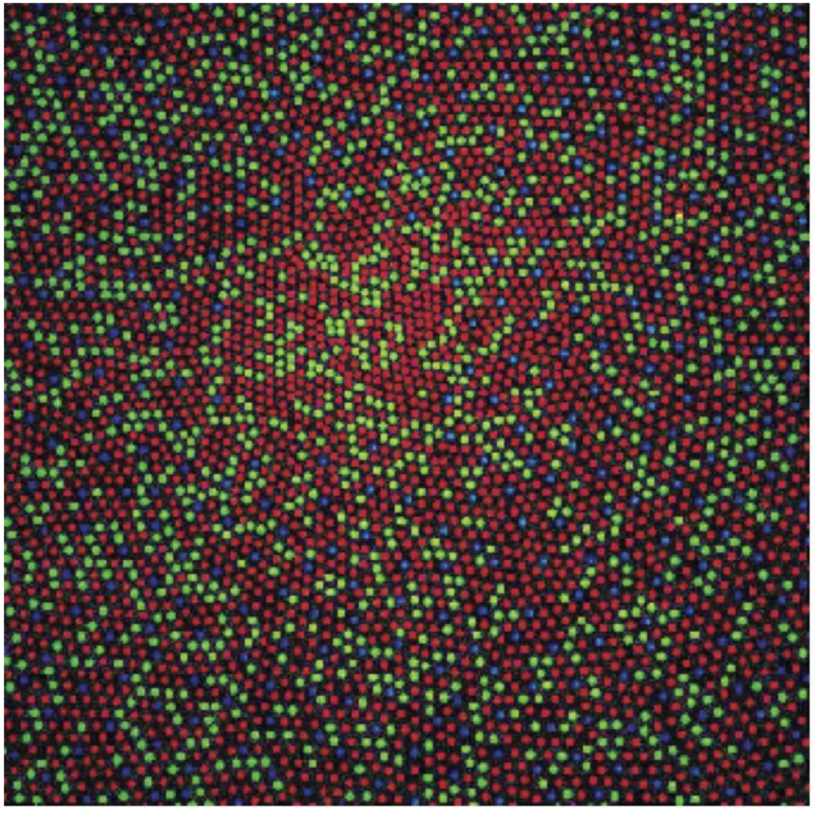
- Also cones have a molecule sensitive to light (*opsine*)
- They are subject to bleaching and regeneration like the rods.
- They are sensitive to different wavelengths, and can be classified as L, M and S cones:
  - S stands for short wavelength
  - M for medium
  - L for long
- Basically, they are responsible for color viewing





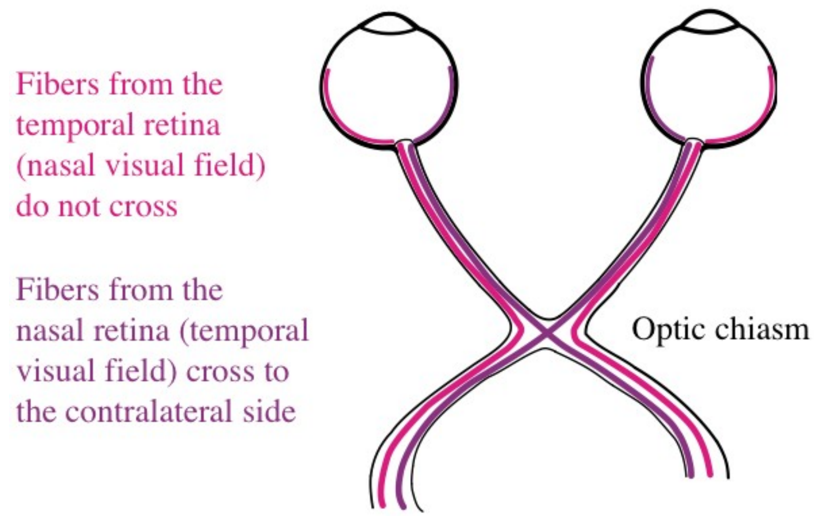
Cones

- S cones are less dense than M and L cones
- They are absent at the fovea, and packed elsewhere in a regular pattern.
- The reason for this probably lies in the much thinner spectral light sensitivity of the S cones: humans need visual acuity where they focus, and this is better in the L and M cones.
- M and L cones are placed more or less at random



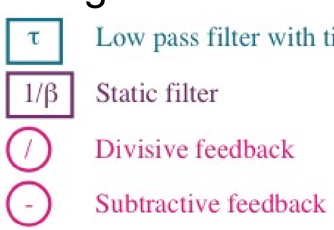
From the sensors to the brain

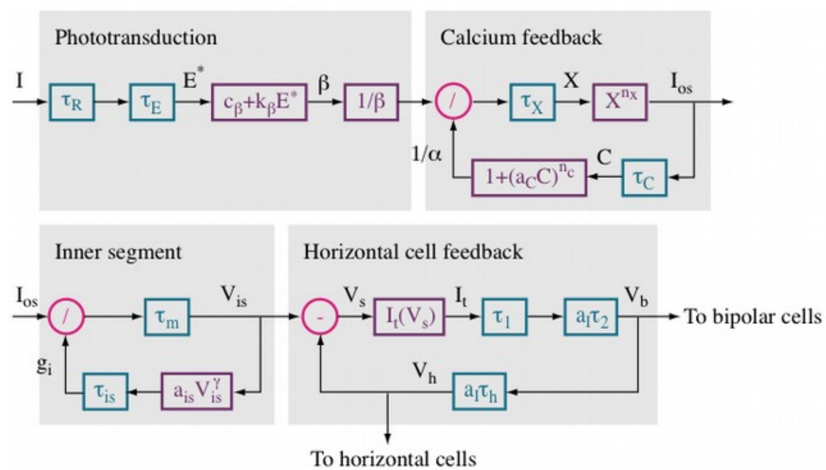
- The signals perceived from the rods and cones are converted into nerve signals and transmitted separately to the visual cortex in the brain
- Parts of the signals are sent to the right hand of the brain, other parts to the left side.
- The study of the physical phenomena in the brain after receiving the nervous visual stimuli is at its infancy
- New technologies, such as MRT and PET scans give the first clues, but the phenomenon is too complex to be understood fast.
- There are a few different theories available, all of them with their advantages and disadvantages.
- Often, results are integrated with psychophysical experiments.



Modeling the human retina

- All displays and rendering methods produce images ultimately perceived by humans.
- A complete model could help building better devices.
- In rendering, such a model could help to point out which parts of an image necessitates more detail.
- Deering presented a model taking into account:
  - Eye optics
  - Photoreceptor mosaic
  - Transduction of photons by the cones
- He presented a new algorithm for synthetizing artificial retinas.
- Van Hateren presented a model for cones capable of predicting a wide range of experimental measurements.
- The model bases on filters:
  - temporal low-pass filters
  - static linear and non-linear filters
  - divisive feedback loops
- Processing functions are cascaded with flow diagrams.





Further readings

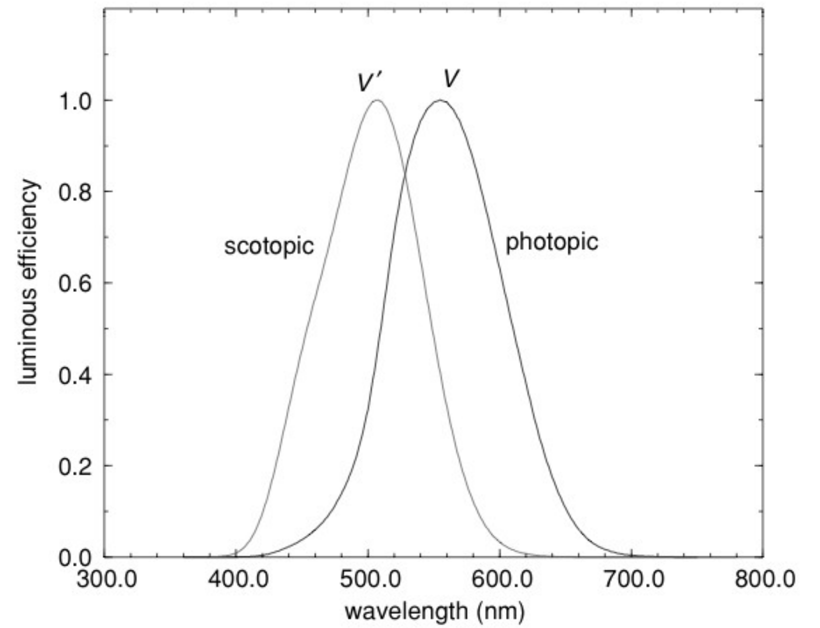
- I hereby skip the psychophysiology of human vision, which you can get taught at the "Wahrnehmungskurs" im Bachelor
- We strongly recommend, if you have interest in this subject, to take a look at the following readings and sites:
  - Hubell's book "Eye, Brain and Vision" http://neuro.harvard.edu/site/dh/
  - Webvision site: http://webvision.med.utah.edu

Photometry

- In the last set of slides we measured light as power or energy (radiometry).
- This does not take into account the perceptual characteristics of our visual system.
  - For example, we are differently sensitive to different wavelengths (= colours).
- Light travel to our eyes, and are transformed in signals and transmitted to the brain, which interprets them.
- The second form of the measuring of radiation is concerned only with energy viewable by the human visual system, and is called *photometry*.
- Photometry deals with measurements of visible light in terms of its effectiveness to produce the brightness sensation in the human visual system.
- Photometry is basically radiometry weighted by the sensitivity of the human eye.
- Measuring visual quantities of light is complicated because light stimuli of different spectral compositions produce complex perceptions of light.
- It is not easy (if not impossible) to order these different color sensations along a single, intensive scale.

Photometry

- As we know, rods and cones are responsible for our vision
- In first approximation, they operate at different illumination levels
- With low light, only rods are responsible: *scotopic vision*.
- With high light, only cones are used: *photopic vision*.
- In the transition between low and high light, both are responsible: *mesotic vision.*
- Peak luminous efficiency frequency changes between scotopic and mesotic vision (Purkinje shift).
- Here a graph of the CIE luminous efficiency function
- The dimmer the light, the more red objects (long wavelength) get darker, and blue objects (short wavelength) get less dark.

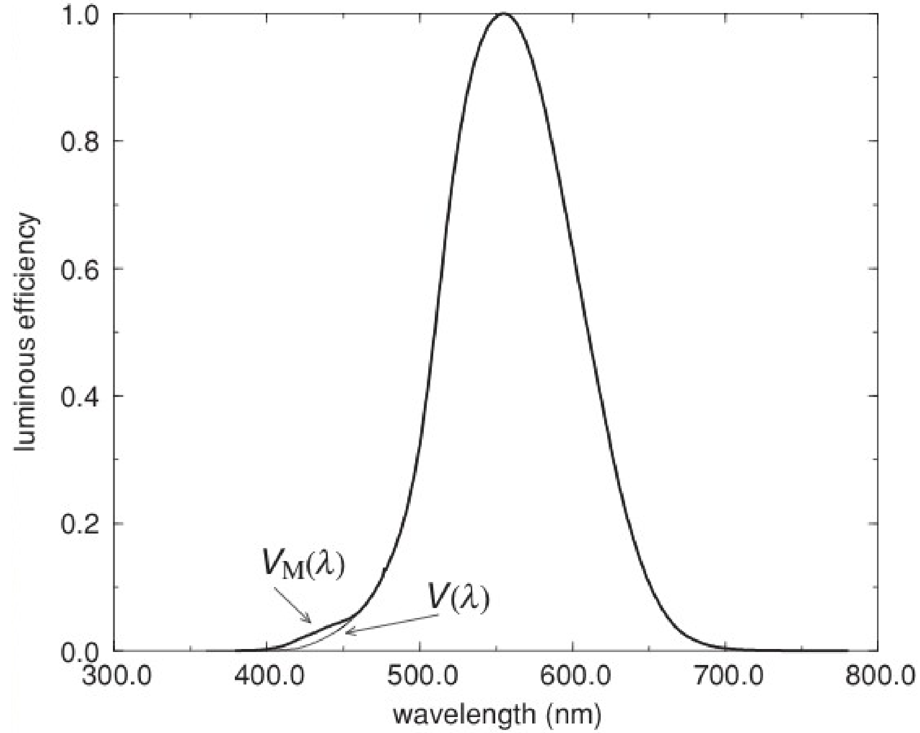


Photometry

- Monochromatic lights of different wavelengths, but the same power, do not produce equal brightness or luminous sensation.
- The problem is that more photoreceptors are responsible for the brightness.
- So matching light quantity for coloured light is a problem.
- How does one do it?
  - Step by step matching: match brightness in small wavelength steps: e.g. 500nm, 505 nm, …
  - Temporal comparison: lights of 2 wavelengths are presented in rapid succession: when flickering is minimum, the intensities match
- Other methods have been used for matching experiments.
- Some laws have been derived too (Grassmann laws):
  - Symmetry law:
    If colour stimulus A matches stimulus B, then stimulus B matches stimulus A
  - Transitivity law:
    If A matches B and B matches C, then A matches C
  - Proportionality law:
    If A matches B, then for a factor α, αA matches αB
  - Additivity law:
    If A matches B and C matches D, then (A ⊕ C) matches (B ⊕ D)
    ⊕ : additive colour mixture

Spectral luminous efficiency function

- Meaures the relative efficiency of light of various wavelengths to produce a luminous sensation
- Works for additive systems
- First proposal: CIE 1924
- Corrected by Judd in 1951 to map better behaviour at law wavelengths



Spectral luminous efficiency function

- The terms radiant flux and radiant power Φ_c (unit in watt, W) are synonyms for power emitted, transferred, or received in the form of radiation
- The spectral version of the radiant flux is called the spectral radiant flux $\Phi_{c,\lambda}$.
- For photopic vision, the luminous flux Φ_v of a radiation whose spectral distribution of radiant flux is $\Phi_{c,\lambda}(\lambda)$, can be expressed by the equation

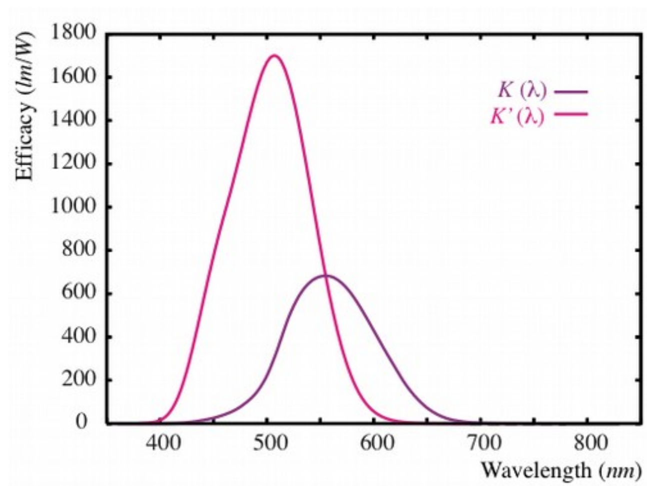
$$\Phi_v = K_m \int_{360nm}^{830nm} \Phi_{c,\lambda}(\lambda) V(\lambda) d\lambda$$

  where K_m = maximum spectral luminous efficacy for photopic vision =683.002 lumens / Watt

- Similarly, for scotopic vision

$$\Phi'_v = K'_m \int_{360nm}^{830nm} \Phi_{c,\lambda}(\lambda) V'(\lambda) d\lambda$$

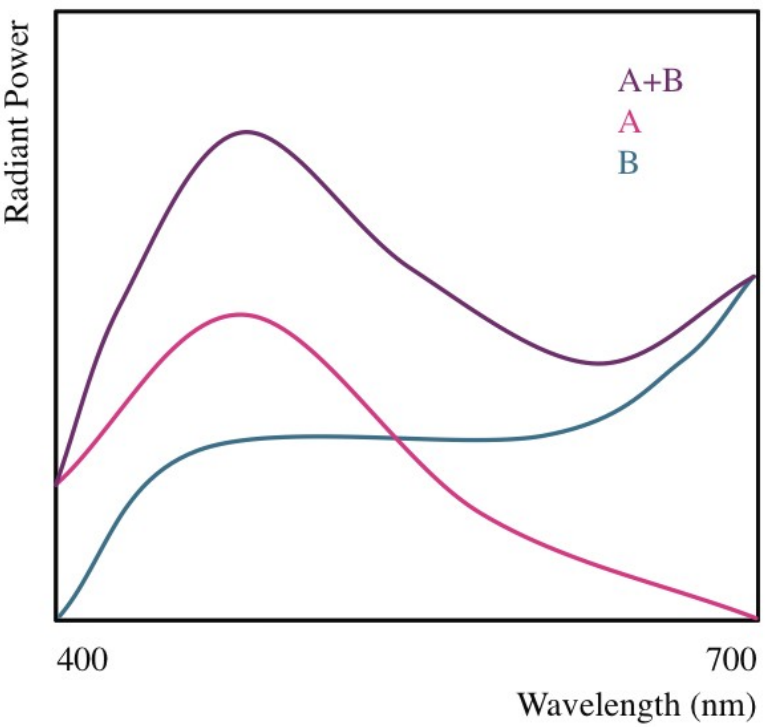
  where the constant K'_m is 1700.06 lumens/Watt
- The K factors are chosen so that the wavelenth 555.016 nm has the same luminous flux for photopic and scotopic vision



Efficiency for photopic (K) and scotopic (K') vision

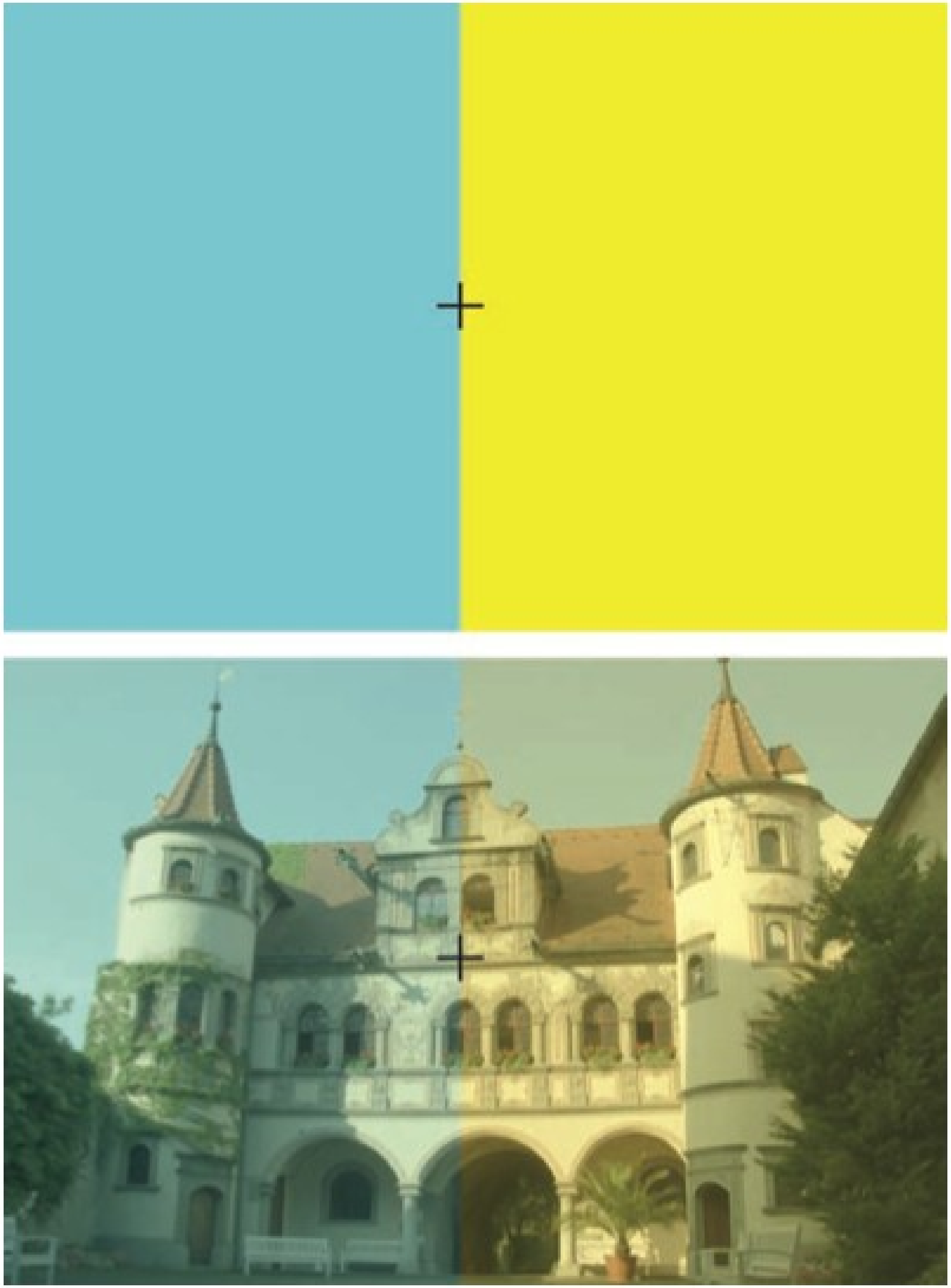
Colorimetry

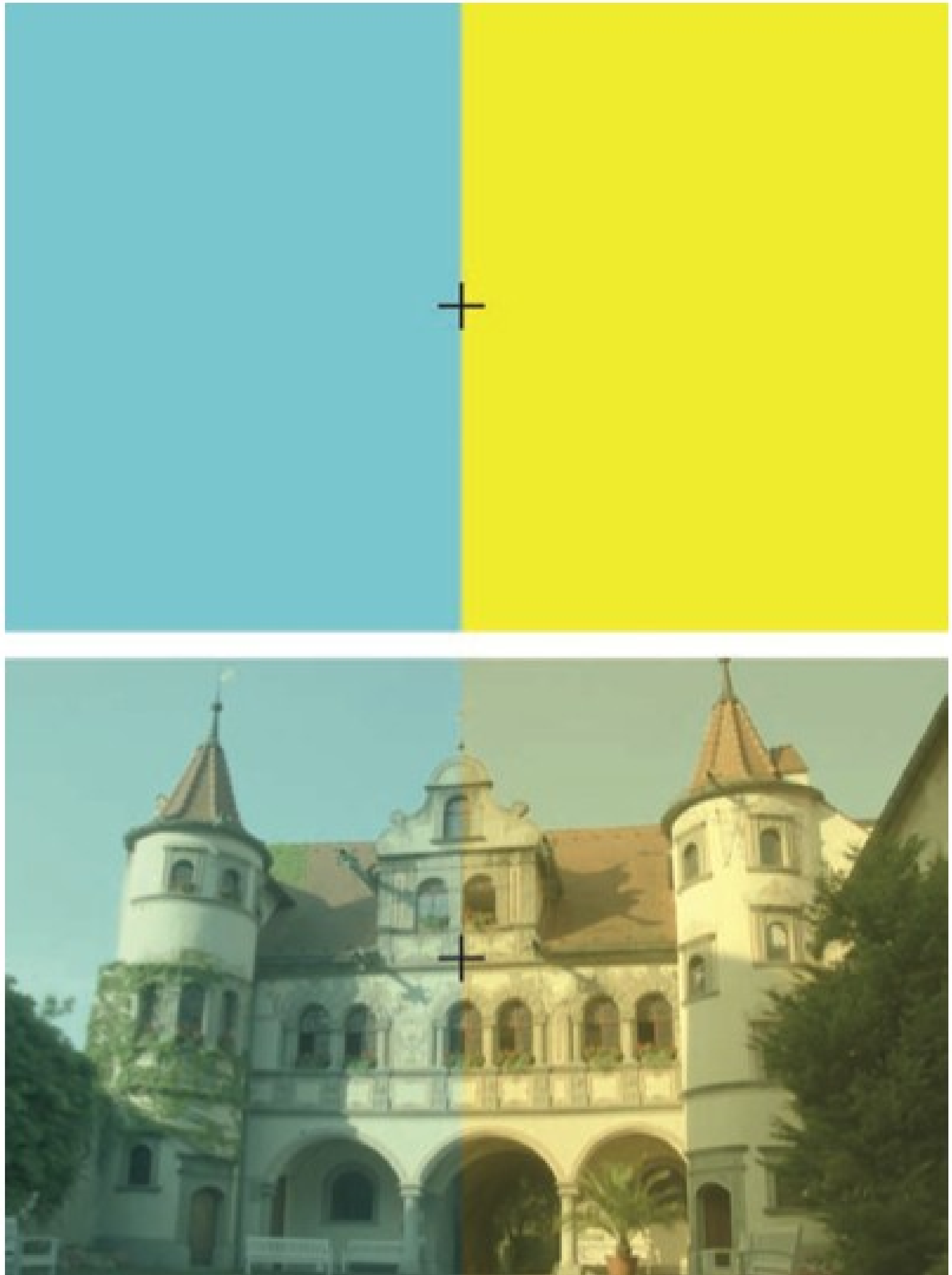
- Colour is a purely psychological phenomenon
- However, it can be measured and quantifed
- *Colorimetry* is the science of colour measurement and description
- We have already seen Grassman's laws for additive colour matching
  - Symmetry law,
  - Transitive law,
  - Proportionality law,
  - Additivity law
- Additive colour mixing means adding the spectral power distributions of radiant light



Colorimetry

- Additive color mixing is only valid for adding light
- They do not take into account the following factors:
  - Dependence of the observational conditions on a match
  - Observer adaptation state: a match might not be one when two stimuli are viewed under different conditions
  - Dependence of a match for a given observer: humans are different. What for one observer is a match, might not be one for another observer.
- Of course it would be nice if one could derive colour perception from the spectral sensitivities of cone photoreceptors
- However, this is difficult to apply because the visual system does more than process pure signals
- A simple example: chromatic adaptation
  - Fix the cross in the upper picture for 20 seconds,
  - then fix the cross on the image below





Colour differences are gone!

Visual colour matching

- If we knew the cone responses, it would be easy to specify color matches in terms of integrated responses to radiant power stimuli.
- For each of the three cone types, the radiant power of the stimulus is multiplied on a wavelength- by-wavelength basis with the cone spectral sensitivity, and then the response is integrated across all wavelengths.

$$L_1 = \int_\lambda \Phi(\lambda) L(\lambda) d\lambda$$

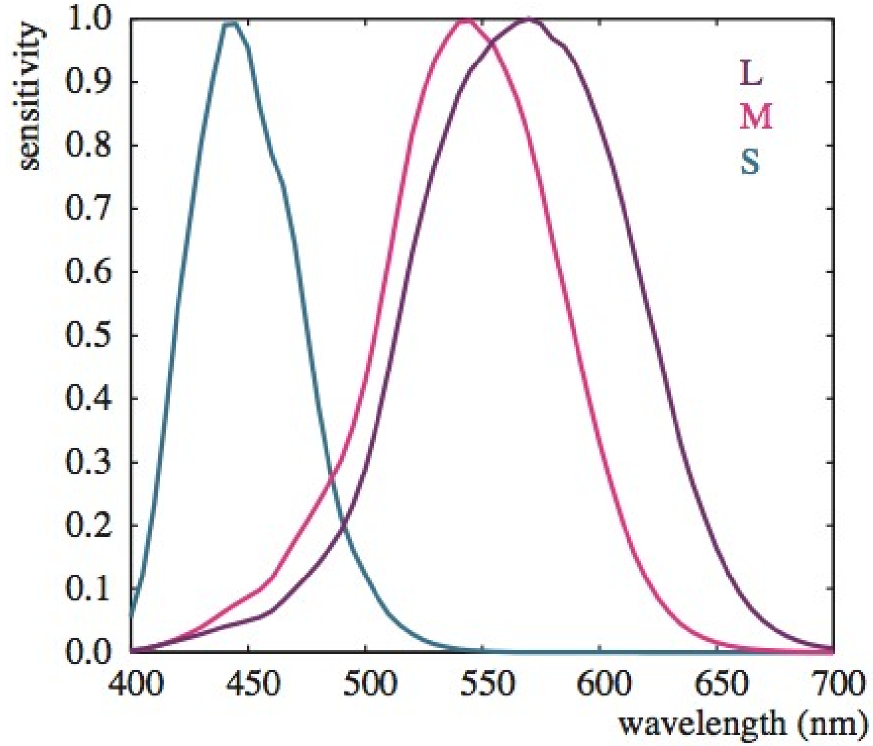
$$M_1 = \int_\lambda \Phi(\lambda) M(\lambda) d\lambda$$

$$S_1 = \int_\lambda \Phi(\lambda) S(\lambda) d\lambda$$

- Where
  - L,M and S are the relative cone spectral sensitivities,
  - Φ the power distribution of the stimulus
- These integrals can be seen as *tristimulus values*

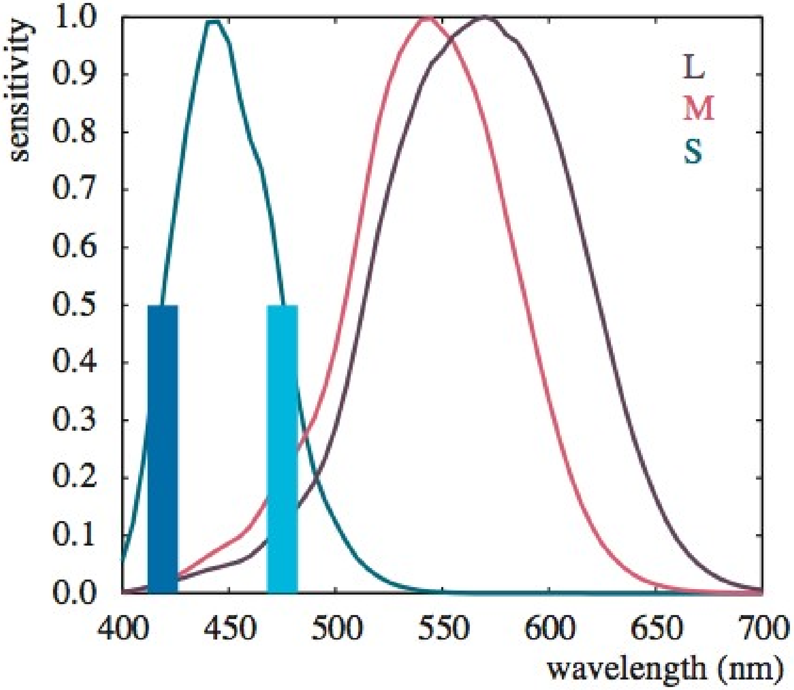
Visual colour matching

- Cone sensitivity curves show that our visual system is optimized for perceiving colour differences
- This is why the sensitivity curves overlap
- If they did not overlap, we would not have two or three types of cone sensing light and we would not be able to perceive colors well



Visual colour matching

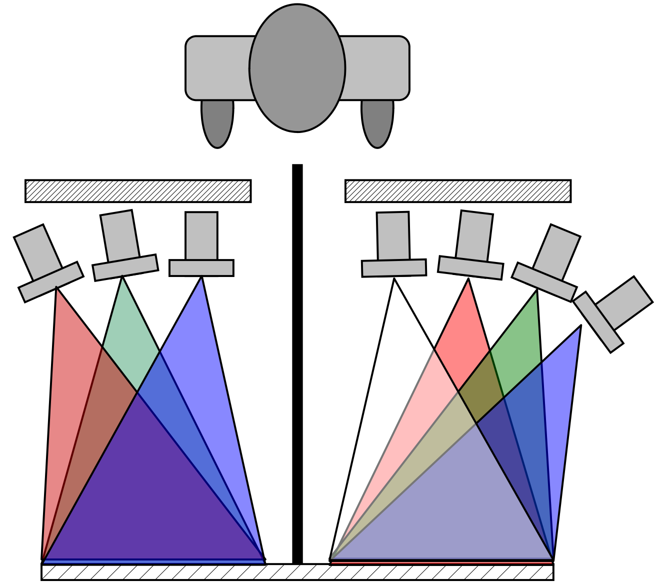
- In fact, cones work as if they would compute the integral of the light signal
- This principle, called *univariance*, is visible in the picture
- Two monochrome light sources achieve same stimulus on S cones
- However, M and L cones have different responses on the two signals
- However, due to the fact that only three sensors are present, signals with very different spectral distribution can be still perceived as the same colour (*metamerism*)
  - This when their integral is the same
- We use this principle it every day when we reproduce colour
  - Print
  - Display
  - Photography

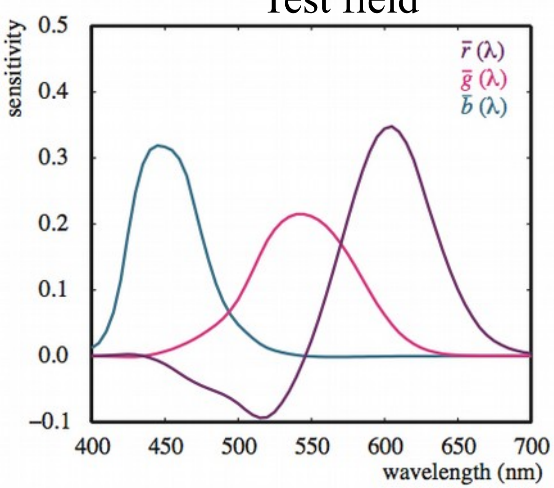


Colour matching functions

- In a simple experiment, it is possible to perform colour matching experiments by comparing side by side two different projections of colour
- The user can then tweak projector intensities to match the colour
- In the reference side, light is added to unsaturate the colors

- R(r)+G(g)+B(b)=
  λ-R(r_2)-G(g_2) -B(b_2)
- Similar experiments were performed by Wright and Guild in the 20s.
- They led to the spectral tristimulus values known as CIE color matching functions $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$



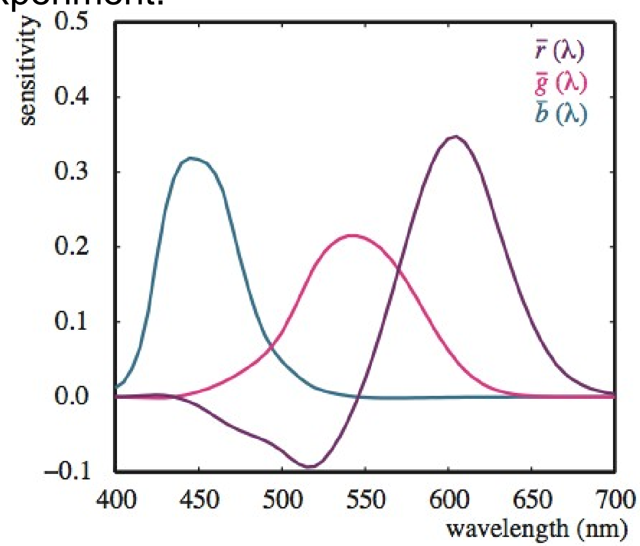


Colour matching functions

- In 1931 the international standard committee CIE
  - took the data of two independent experiments performed by Wight and Guild
  - found them in agreement, and
  - averaged them to obtain the spectral tristimulus values for the three monocromatic primaries in the picture.
- The curves have to be read wavelength wise: amount of primaries that generates colour match.
  - Can be therefore seen as colour matching functions
  - Colour matches can be computed by integrating on each of the functions for R,G and B, e.g.

$$R = \int_\lambda \Phi(\lambda)\bar{r}(\lambda)d\lambda \quad G = \int_\lambda \Phi(\lambda)\bar{g}(\lambda)d\lambda \quad B = \int_\lambda \Phi(\lambda)\bar{b}(\lambda)d\lambda$$

- Notice that one of the curves has negative values.
- Of course, it is impossble to have negative colour sources.
- However, by adding a fourth source to decrease saturation, one can do this
- Another way to think about the negative tristimulus values, is that the particular monochromatic illumination is outside the gamut of the primaries used in the matching experiment.



A second standard

- With the ability to compute the RGB values with the integral functions one can eliminate the need to do experiments.
- Colors are the same if

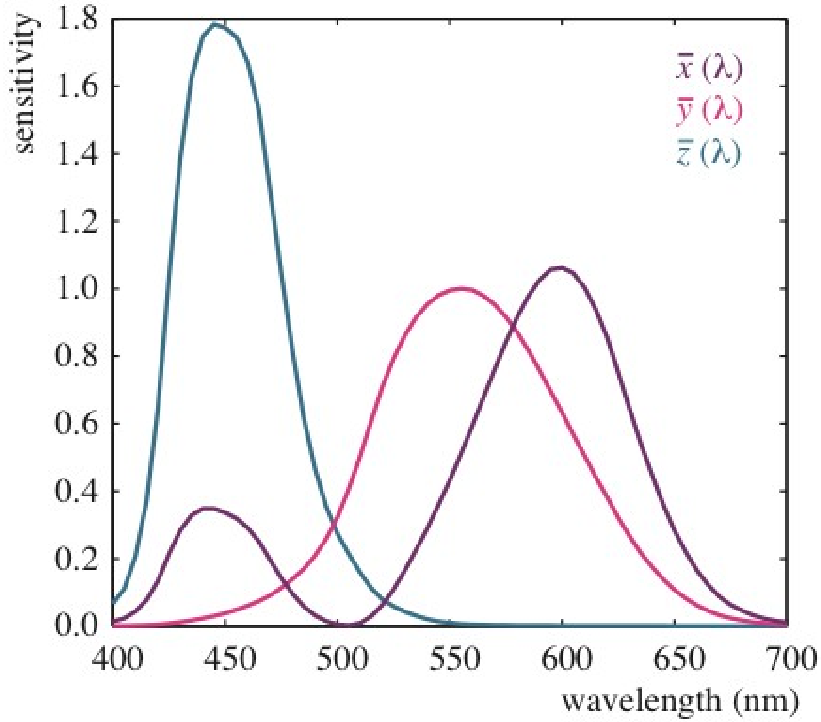
$$\int_\lambda \Phi_1(\lambda)\bar{r}(\lambda)d\lambda = \int_\lambda \Phi_2(\lambda)\bar{r}(\lambda)d\lambda$$
$$\int_\lambda \Phi_1(\lambda)\bar{g}(\lambda)d\lambda = \int_\lambda \Phi_2(\lambda)\bar{g}(\lambda)d\lambda$$
$$\int_\lambda \Phi_1(\lambda)\bar{b}(\lambda)d\lambda = \int_\lambda \Phi_2(\lambda)\bar{b}(\lambda)d\lambda$$

- Through this we can match colors
- In 1964 the CIE decided to modify the functional basis with two objectives:
  - having an all positive response
  - having one of the primaries be the photopic luminance response function
- They introduced three new abstract primaries, called

$$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$$

- The middle of these (y) is the photopic response
- Passing from RGB to XYZ can be done like this:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.4900 & 0.3100 & 0.2000 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.0000 & 0.0100 & 0.9900 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

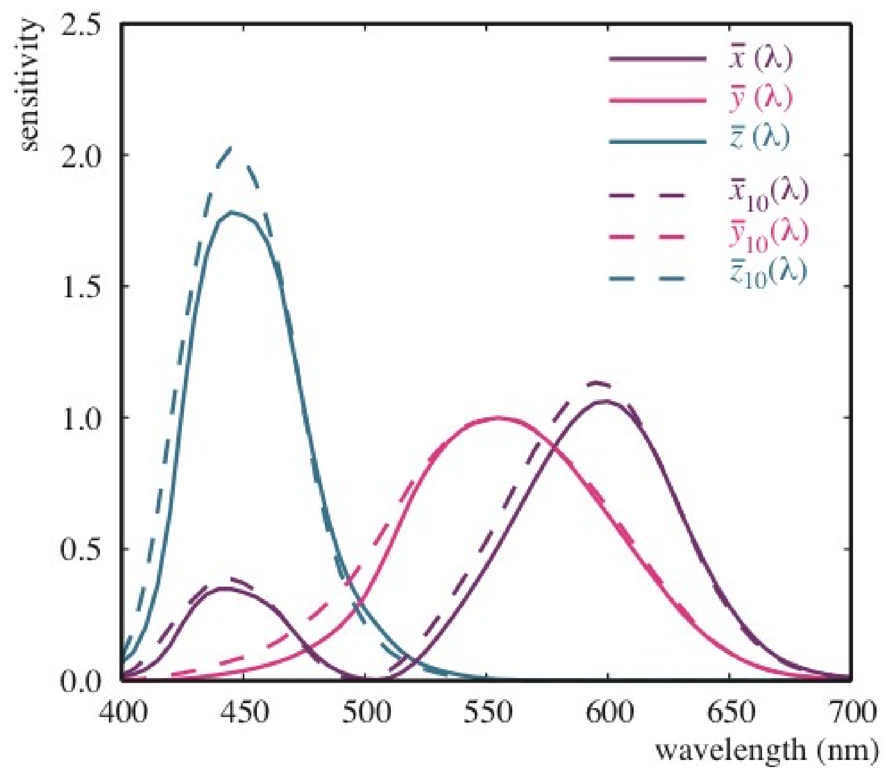


Correcting with modern experiments

- The color matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ were based on experiments done on humans in 1931
- The CIE ordered new colour matching experiments, measuring small field colour matches at 2° and 10°.
- Experiments showed that the 1931 measurings were adequate for smaller fields (2°) but that this should be corrected for larger fields (10°)
- These new experiments are defined the 1964 standard observer,and the corresponding curves are called

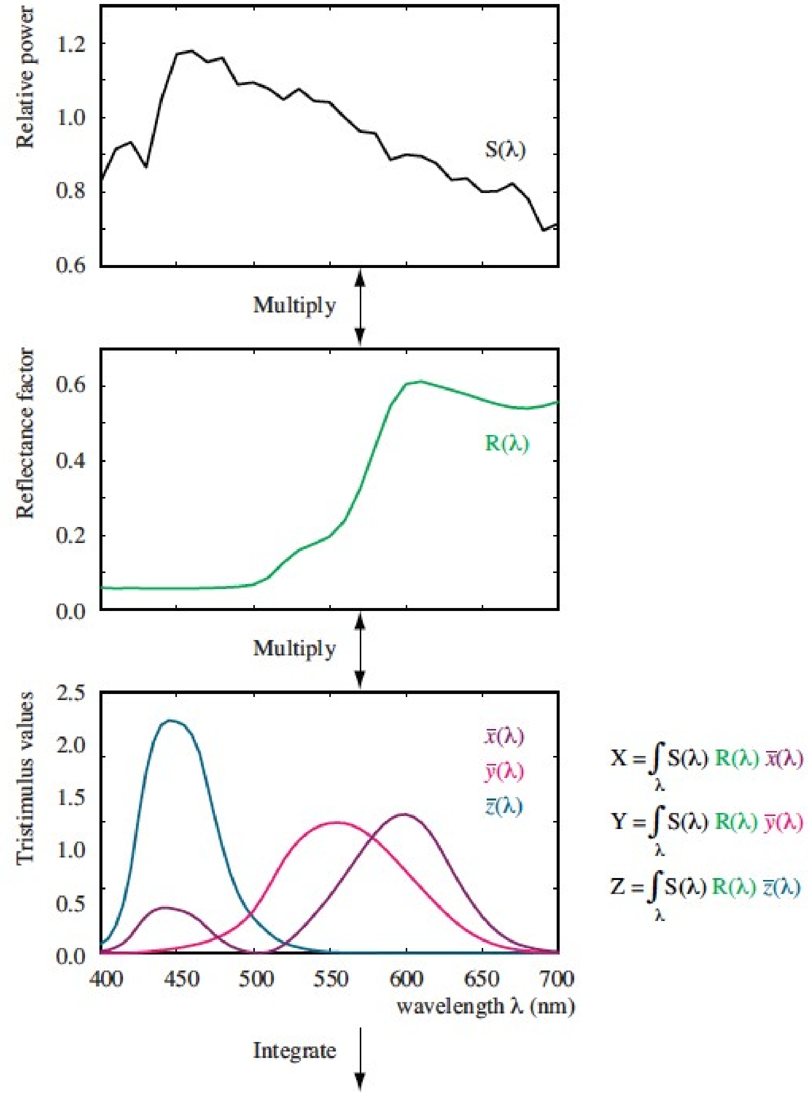
$$\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$$

- Just as before with RGB, we can compute X,Y,Z matches by integrating over the visible spectrum



Computing what we see

- In real life, the colour stimulis $\Phi(\lambda)$ is obtained by multiplying
  - Power distribution of the light source
  - Spectral reflectance of the object (normalized to [0,1])
  - Standard observer values
- …and integrating over the visible wavelengths



Visible light in XYZ space

- We can treat now x,y,z as coordinates in a colour space
- If we draw the visible spectrum in such space, we get a pretty curve in 3D space.
- The shape of it, however, is pretty complicated as shown below
- However, we can remember that the Y coordinate was photopic response, which is dependent on luminosity, not colour.
- This means that the colour information is not on the Y axis but on the other two axes

Visible light in XYZ space

- If colour does not have anything to do with Y, then let us project onto 2D, i.e. onto the XZ axes.
- This new space contains colour information, but no magnitude information (= luminosity) and is called a chromaticity diagram.
- Chromaticity coordinates are ratios of tristimulus values not containing any magnitude information, and are usually marked in non capital letters:

  $x=X/(X+Y+Z)$

  $y=Y/(X+Y+Z)$

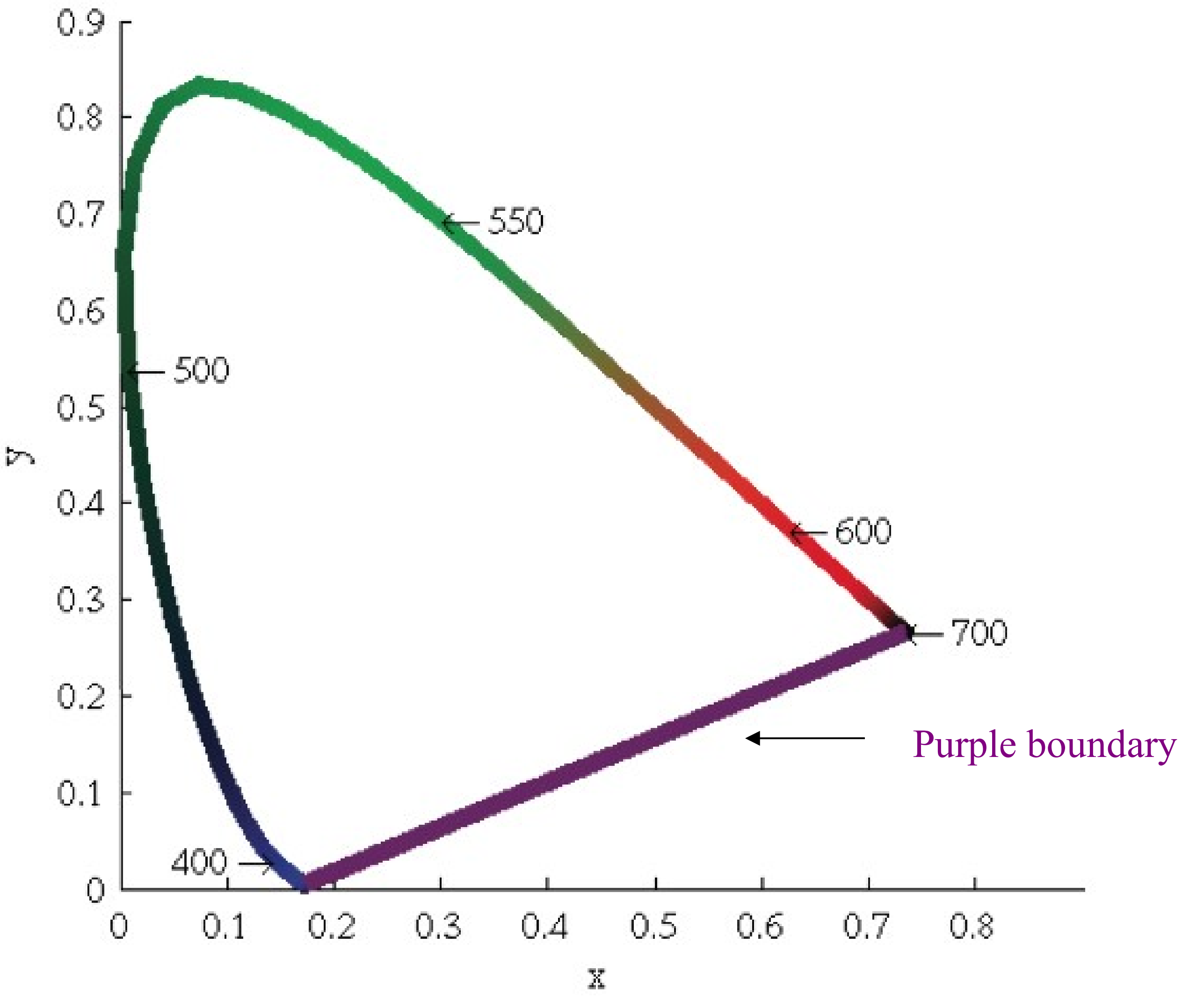
  $z=Z/(X+Y+Z)$

  with $x+y+z=1$
- Projection means loss of info, however, it is always possible to describe a full color (not projected) by giving Y and the 2 remaining projection coordinates.
- To add to confusion, the two remaining projection coordinates are called x and y (without bar on top).
- Despite notation, from the 3 variables Yxy one can compute all colour information:

  $X=(x/y)Y$

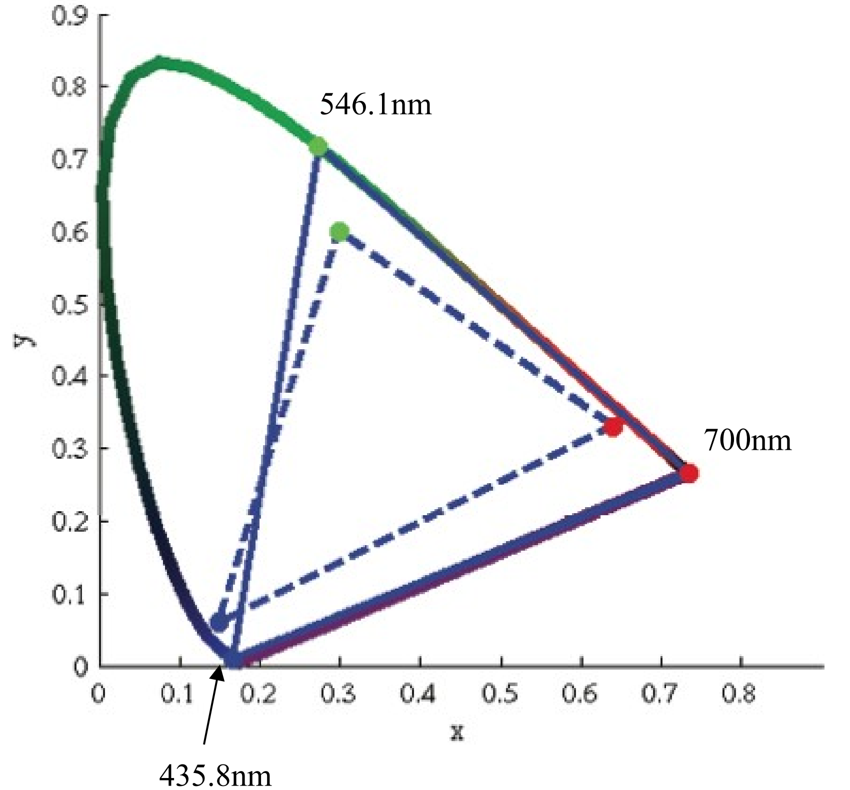
  $Z=(z/y)Y$
- Plotting the colours in the xy space results in the shape of the next page

CIE chromaticity diagram



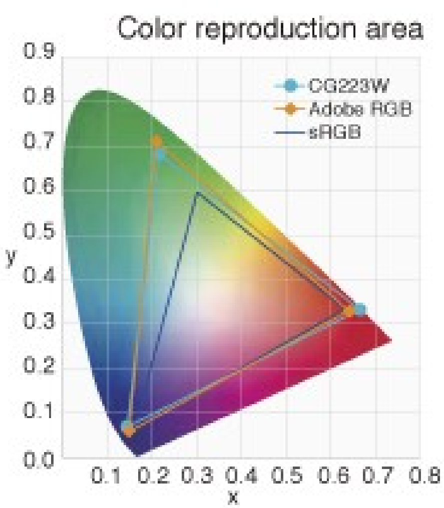
CIE chromaticity diagram

- The purple line does not indicate a color, but just the linear combination of the short and high wavelegth stimuli
- Colors represent points inside (or at the border) of the horseshoe.
- Mixing two colors means moving on the interpolating line between these two colors
- Mixing 3 colors means interpolating in the triangle between these three colors: *gamut projection onto xy*.
- Picture displays:
  - gamut of 1931 CIE RGB
  - Gamut of typical HDTV (dashed)

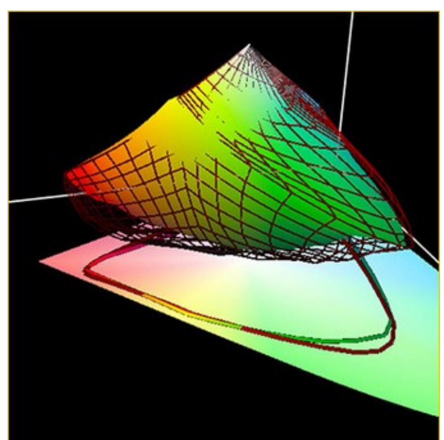


CIE chromaticity diagram

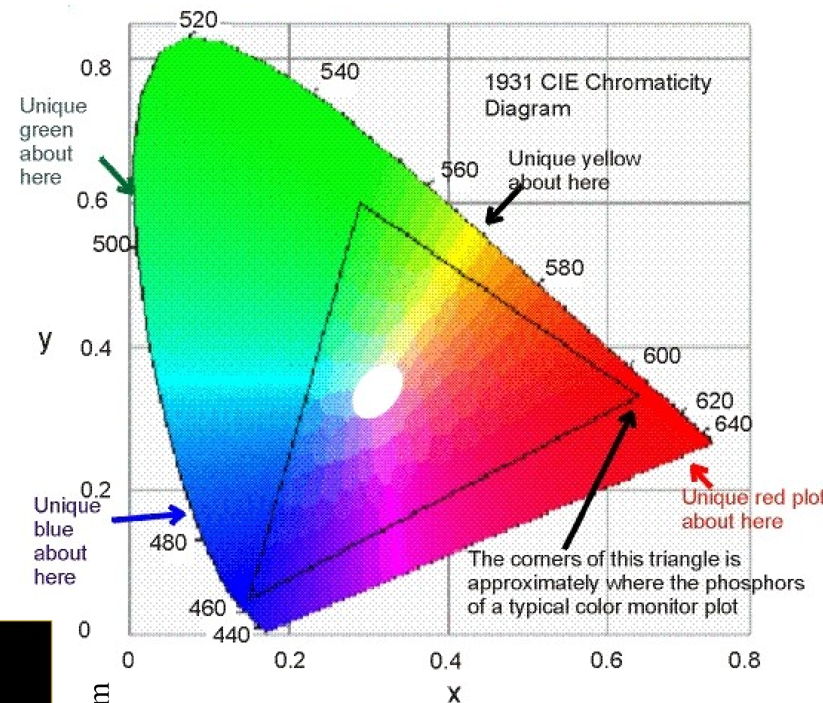
- A typical quality display/printer will have in selling prospect a picture of the gamut of the device.
- Gamut might be not only a triangle, but also a convex polygon, in case more than 3 colours are mixed
- For example, this is the case in high end printers



© Eizo CG223W brochure

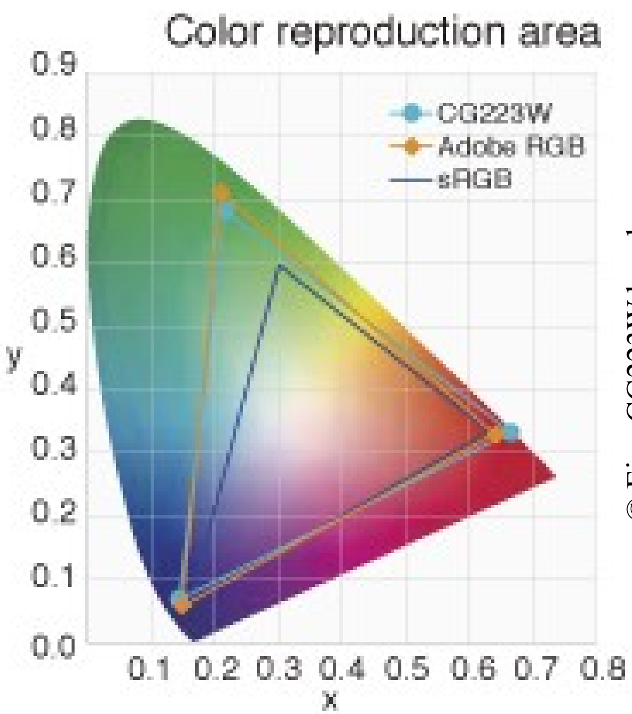


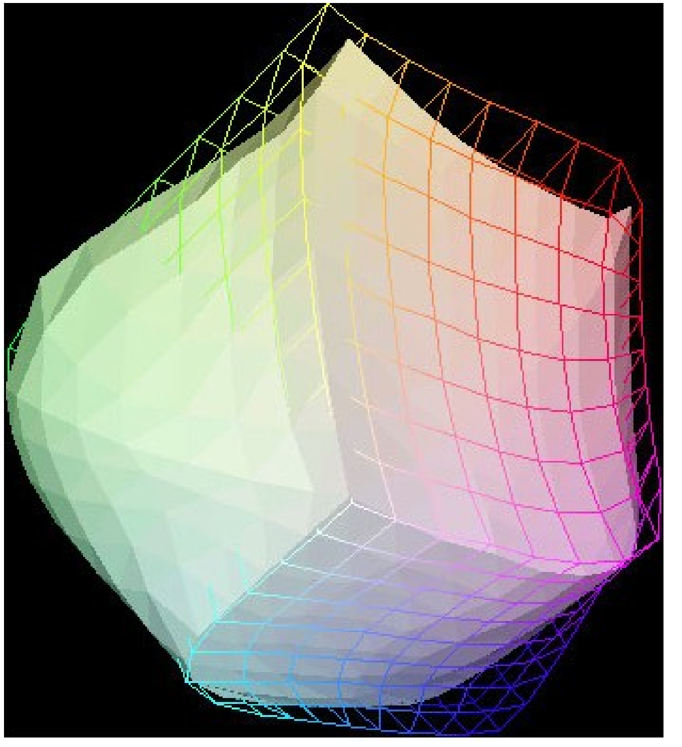
© luminous landscape.com
Canon IPF500
(6 basic colours)



Gamut diagrams

- Notice that gamut really makes sense if it is viewed in 3D
- This due to the absence of the luminance component in the 2D graph





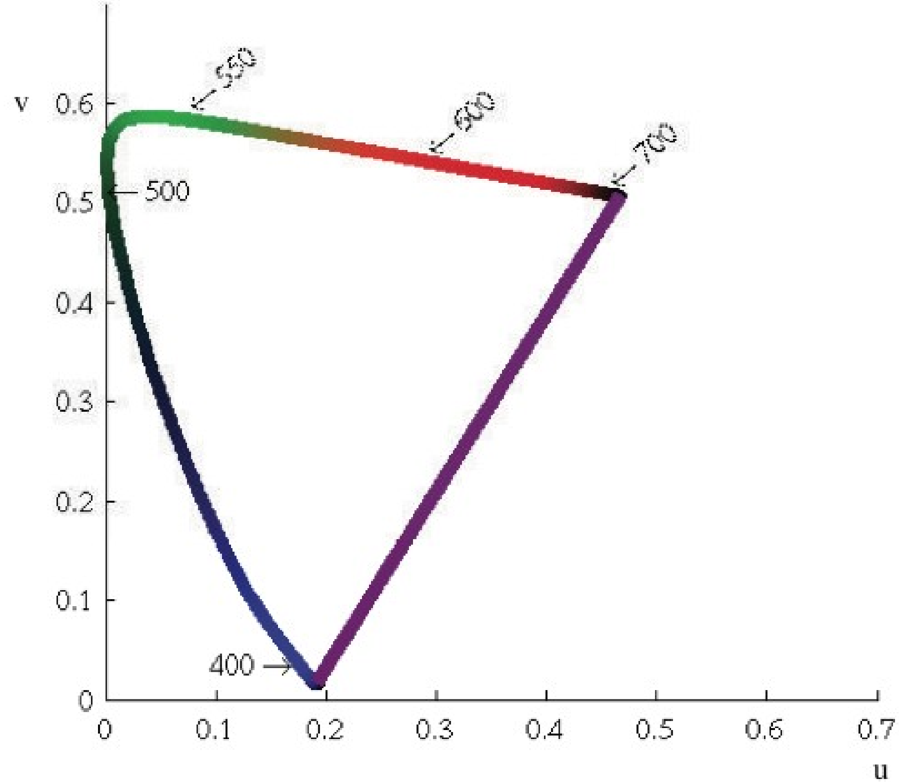
Uniform chromaticity scale

- One problem in the CIE is the fact that equal distances on the graph do not imply perceptual distances
- In 1976 the CIE proposed to use the *u',v'* *Uniform Chromaticity Scale* chromaticity diagram
- Its purpose is to have more uniformly spaced colors
- Areas and distances correspond more to perceptual distances
- Again, it does not contain luminance info
- Mathematically

$$u' = 4X/(X+15Y+3Z)$$
$$v' = 9Y/(X+15Y+3Z)$$

- Or

$$u' = 4x/(-2x+12y+3)$$
$$v' = 9y/(-2x+12y+3)$$

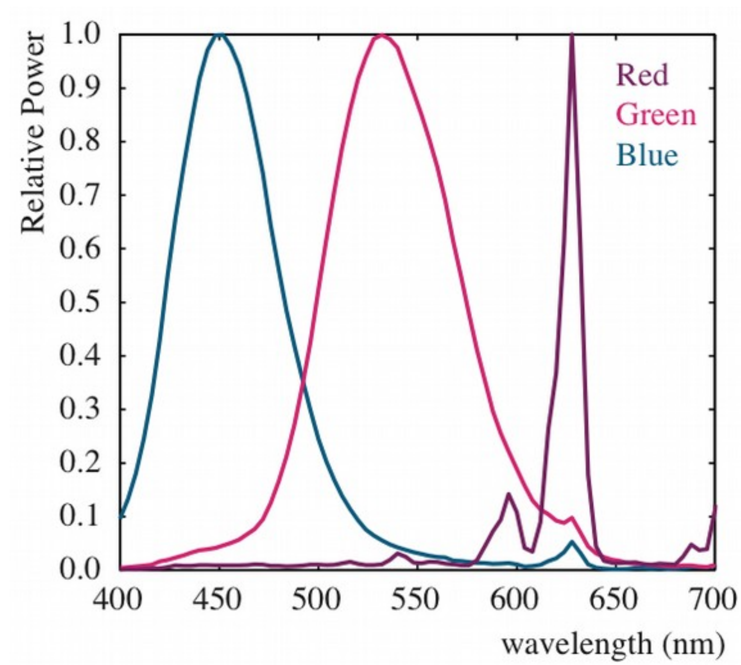


Applicatons

- Colorimetry forms the basis for colour management systems
- It provides a method for describing color as *device independent*
- Everyone of you will have experienced that different devices display the same colours differently
- But the original image was device independent!
- In Computer Graphics, sometimes rendering is performed spectral space, according to wavelength

$$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$$

- Then this is integrated
- The result is a perceptually accurate image on the file
- But the device does not display this!
- One has to apply a transformation of primaries
- For example, a computer screen (CRT) has 3 basic additive colours, as in the picture.



Applicatons

- Grassman's law work only with linear colour scales
- Unfortunately, displays are rather logarithmic mediated by a gamma function to linearize them (gamma correction)
- Depending on the characteristics of the additive components (e.g. the phosphors) one can establish a relation for the display

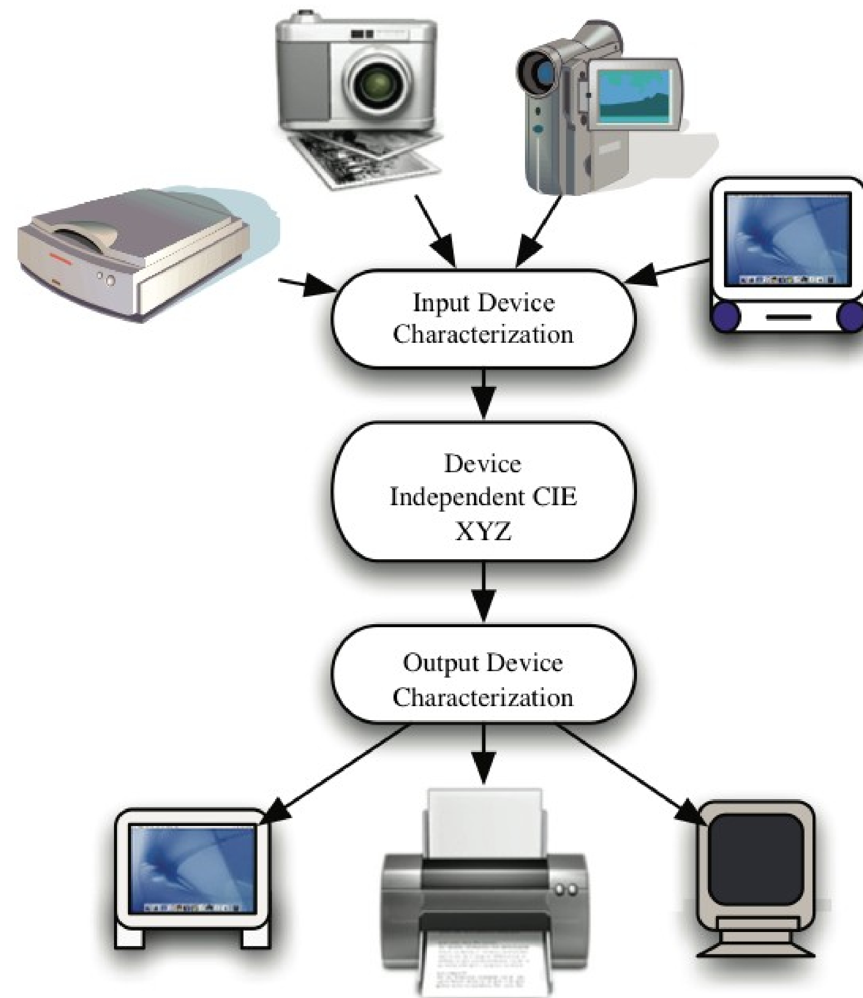
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{\text{red}} & X_{\text{green}} & X_{\text{blue}} \\ Y_{\text{red}} & Y_{\text{green}} & Y_{\text{blue}} \\ Z_{\text{red}} & Z_{\text{green}} & Z_{\text{blue}} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- By inverting it, one can obtain the correct RGB to be displayed onto the display

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} X_{\text{red}} & X_{\text{green}} & X_{\text{blue}} \\ Y_{\text{red}} & Y_{\text{green}} & Y_{\text{blue}} \\ Z_{\text{red}} & Z_{\text{green}} & Z_{\text{blue}} \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Applicatons

- Since both input and output have to be normed, we would have to do similar computations for
  - Input devices
  - Output devices
- This to obtain a perceptually sound image…
- … and correct colour processing



Thank you!

- Thank you for your attention!
- Web pages
  http://www.uni-weimar.de/medien/cg