IBTM6010J Lighting Engineering

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Principles of Vision & Colour

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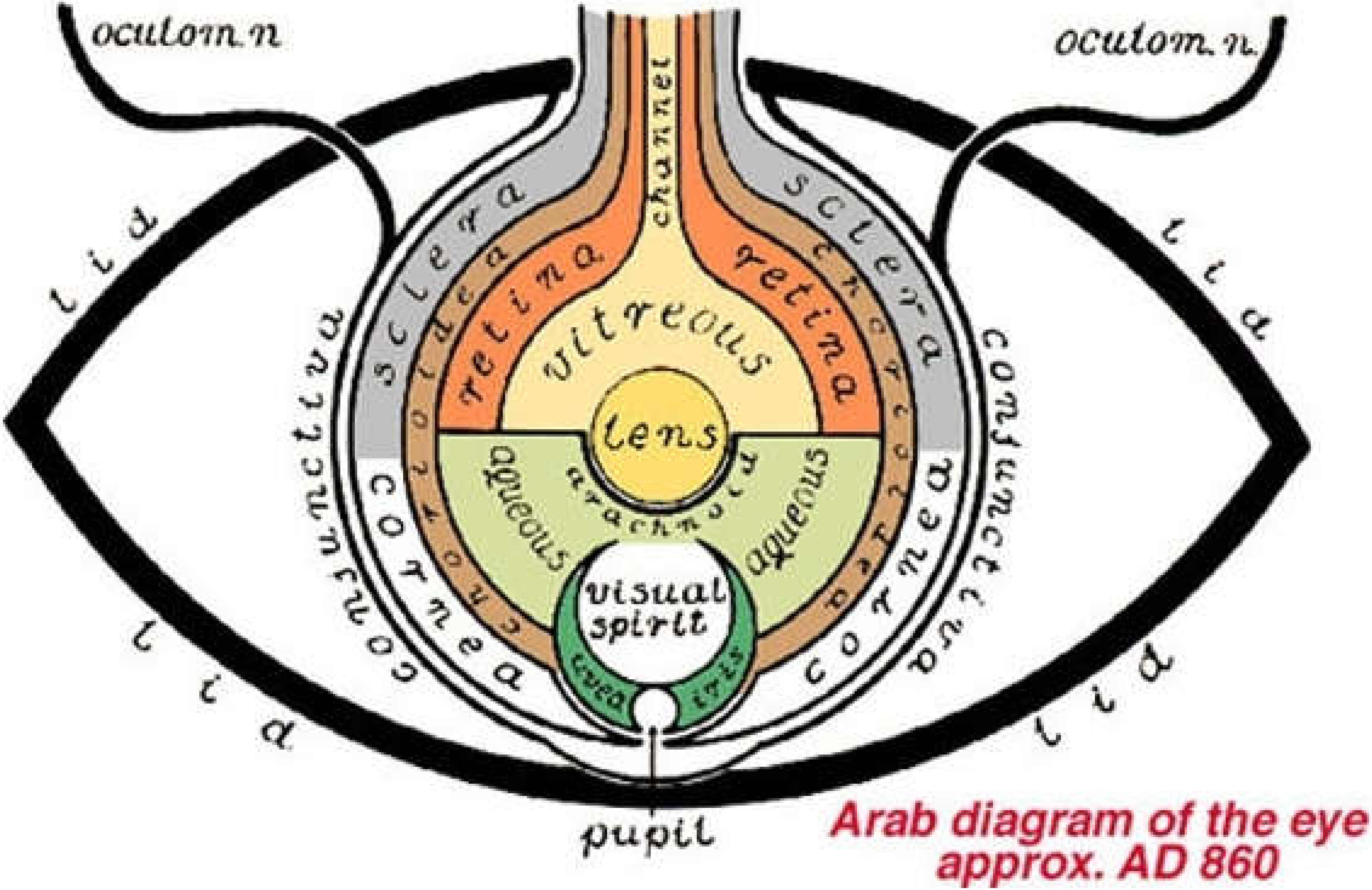
Human vision

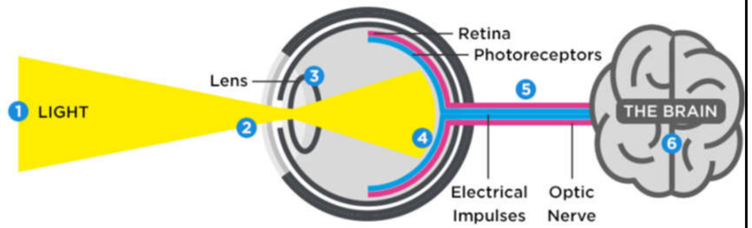
- Vision involves the nearly simultaneous interaction of the two eyes & the brain through a network of neurons, receptors, and other specialized cells
  - Human stereo colour vision is a very complex process that is not completely understood
  - Human visual system not only detects light & colour, but as an optical system, must be able to discern differences among objects, or an object & its background (contrast discrimination)

The earliest Arabic drawing of the structure of the eye



(Source: Principles of Vision https://www.ncbi.nlm.nih.gov/books/NBK11513/)

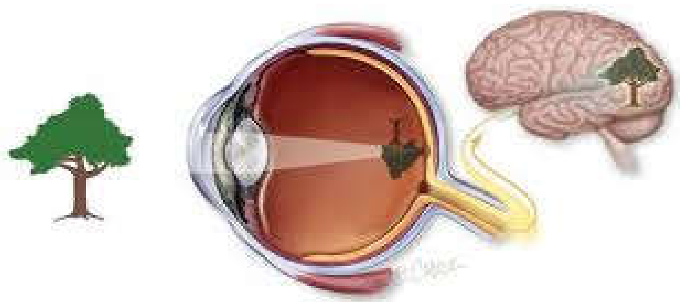
Human vision



- Normal human vision
  - 1. Light enters the eye through the cornea
  - 2. The light passes through the pupil. The iris controls the amount of light passing through
  - 3. From there, it then hits the lens
  - 4. Next, light passes through the vitreous humour
  - 5. Finally, the light reaches the retina
  - 6. The optic nerve carries the signals to the visual cortex of the brain & turns the signals into images

Human vision

- Principle of VISION
  - Light energy → retina (photo-chemical) → optic nerve (electrical signal) → brain (sight centre)
  - Initial information: brightness + colour
  - *Stereoscopic effect* of two eyes (size & position)
  - The brain selects items in the *field of view*
  - The *sense of vision* depends on interpretations from previous experience

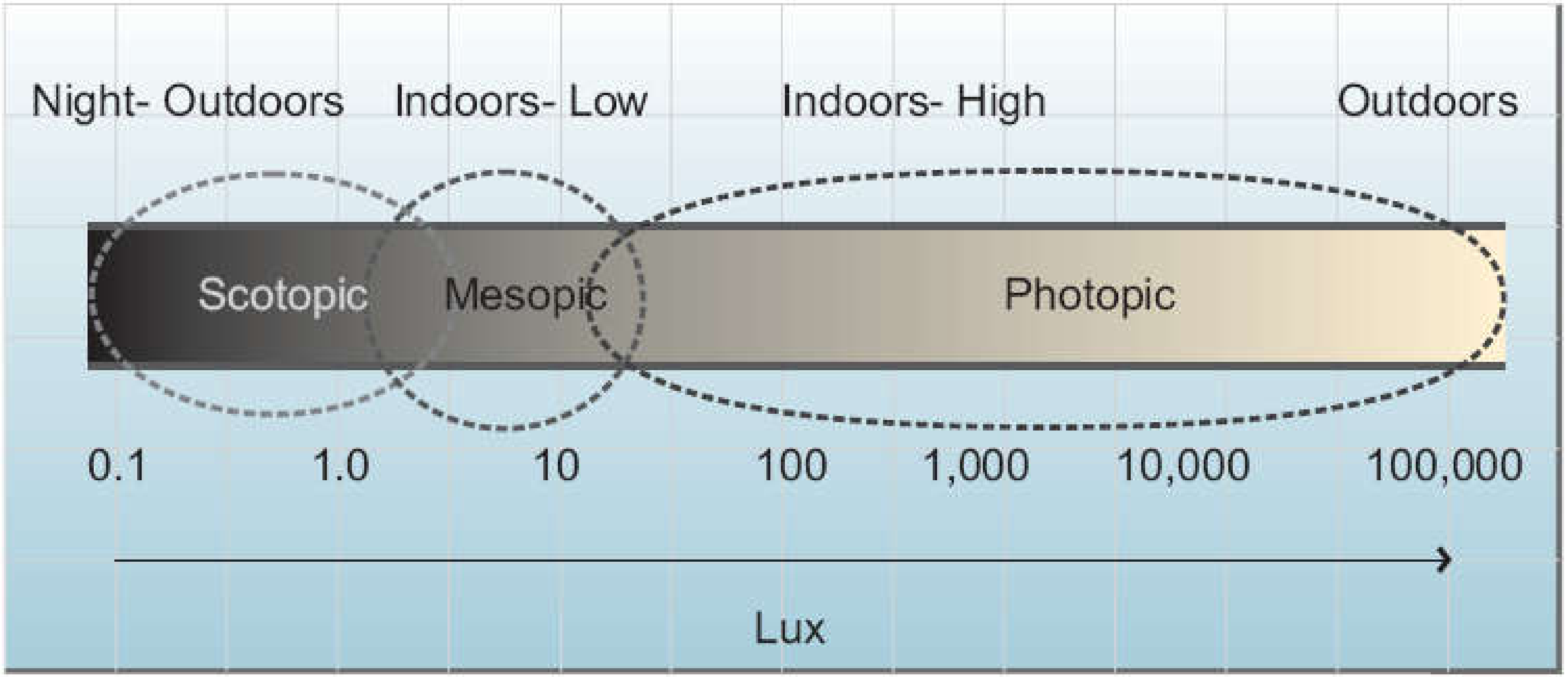


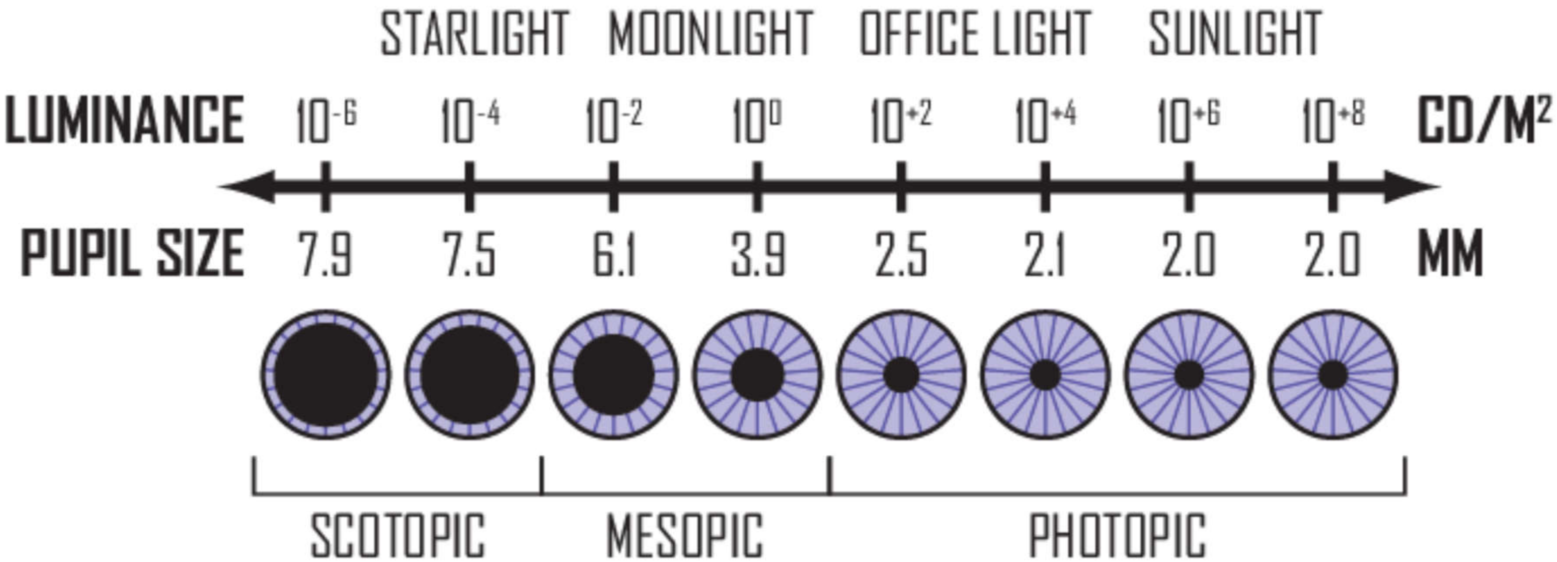
Human vision

- Characteristics/Regimes of VISION
  - *Scotopic vision* 暗視 - in the dark by the rods
    - Luminance 10^{-6} to 10^{-2} cd/m^2 (dark adapted, by rods)
    - Low ambient light; only see in shades of grey
  - *Mesopic vision* 暮視 - between 10^{-2} and 10 cd/m^2
    - Sense of brightness & colour; foval detection
  - *Photopic vision* 適光 - above 10^{-2} cd/m^2
    - By cone mechanism (light adapted); in colour
    - High ambient light; enables details to be seen

Ranges of scotopic, mesopic and photopic visions

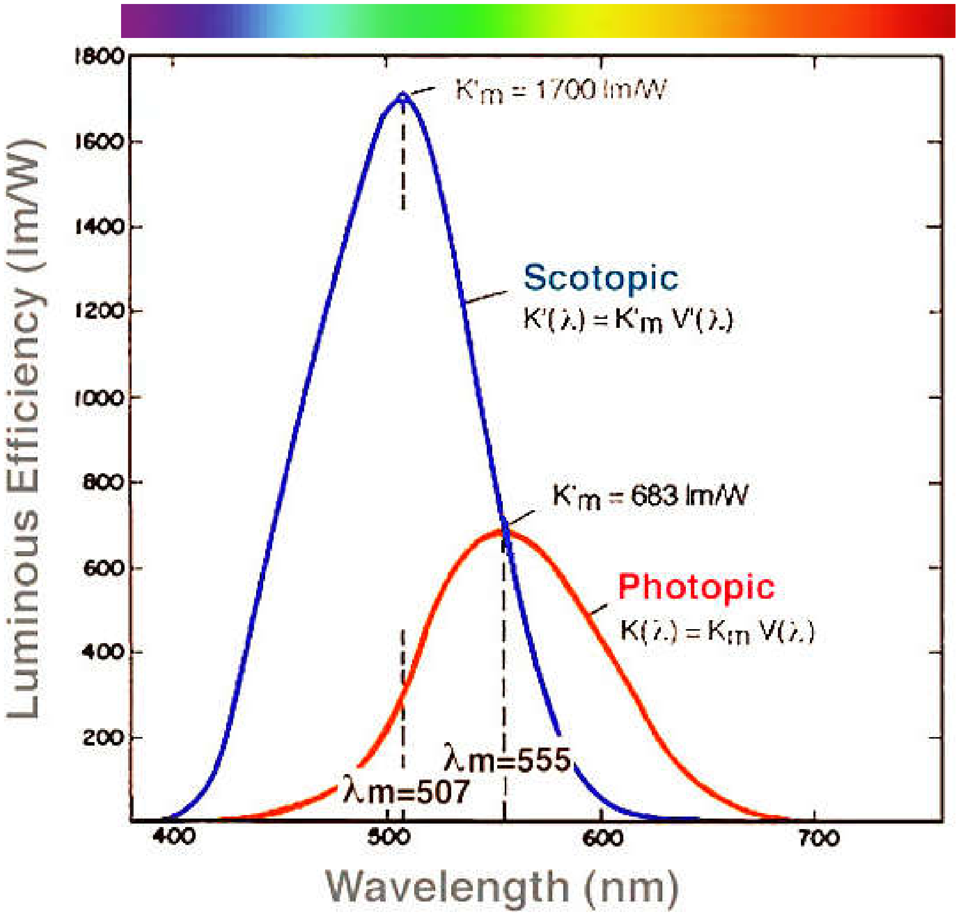
(Source: Advanced Lighting Guidelines 2001 and www.ecse.rpi.edu)



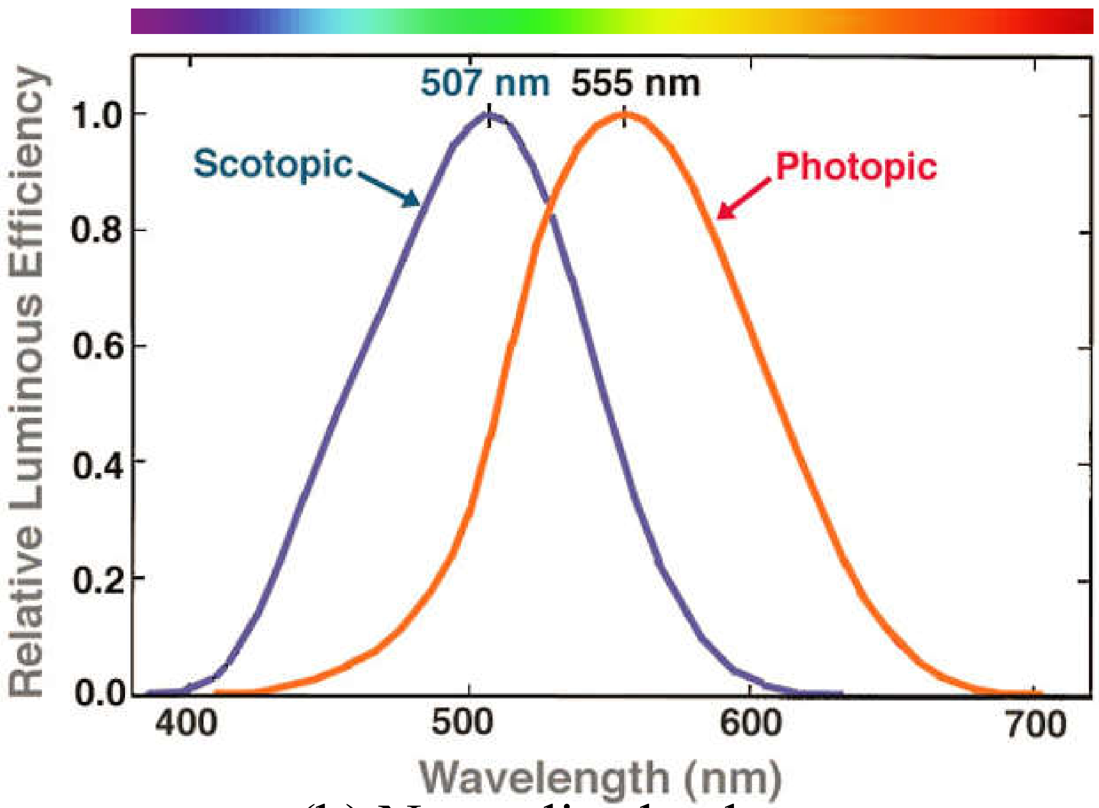


(Source: Advanced Lighting Guidelines 2001)

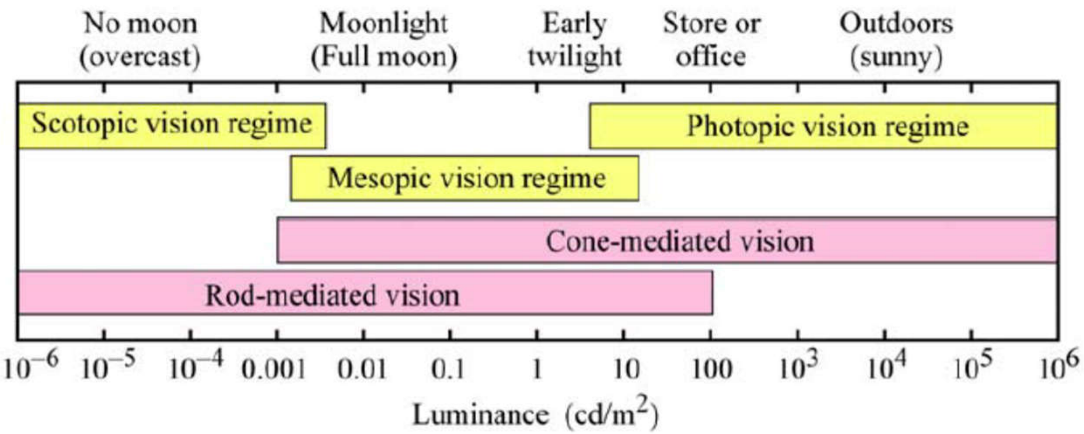
Scotopic & photopic curves of spectral luminous efficiency



(a) Non-normalised values



(b) Normalised values



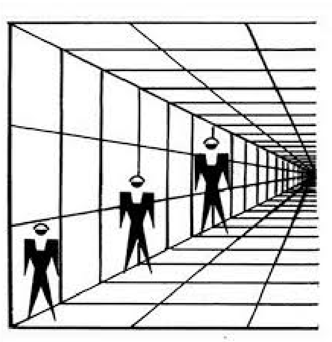
(Source: http://retina.umh.es/webvision/psych1.html; www.ecse.rpi.edu)

Human vision

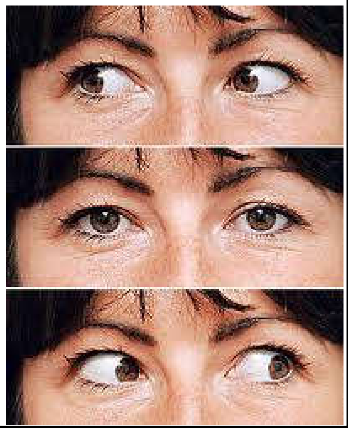
- Purpose of vision
  - The primary goal of any lighting system is to provide a proper stimulus for the human visual system
- Processing of visual information
  - 1. Depth perception
  - 2. Motion detection
  - 3. Brightness perception
  - 4. Colour deficiencies in the visual system

Human vision

- 1. <u>Depth perception</u>
  - Pictorial cues



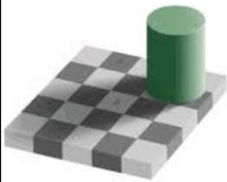
    - Relative image size due to distance or scale of known objects
    - Interposition or layering
    - Shadowing, perspective, or surface texture
    - Motion parallax – relative movement between any two objects at different distances
  - Binocular cues
    - Eye convergence – “cross-eyedness”
    - Binocular disparity or parallax – “stereo” vision



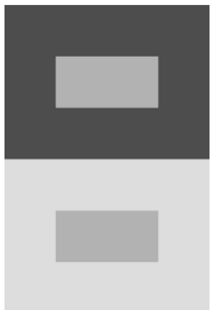
Human vision

- 2. Motion detection
  - Stroboscopic integration – perceived motion from stills

- 3. Brightness perception*
  - Vision in darkness & lightness
  - Luminance is measurable quantity of light reflected from objects



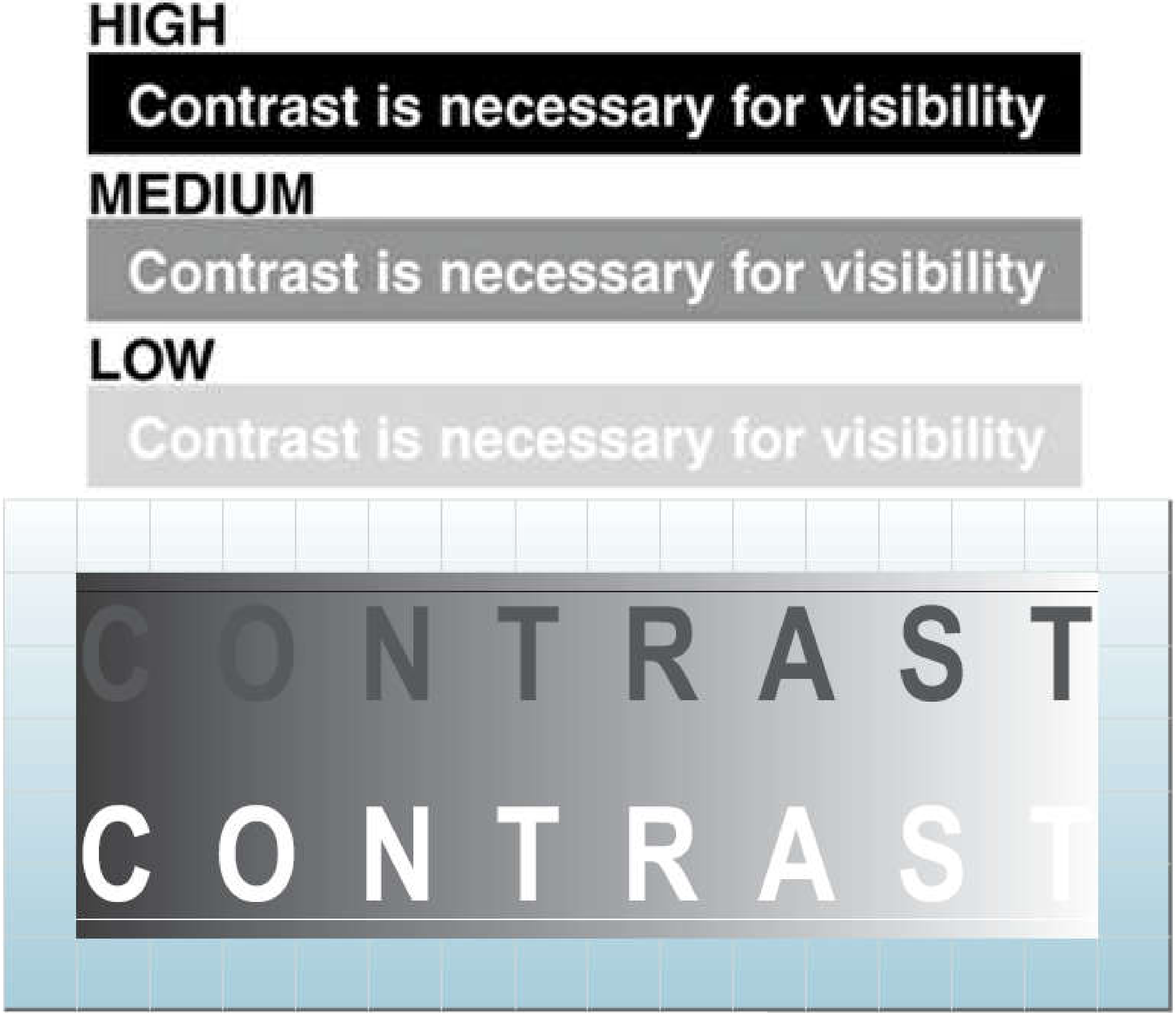
  - Brightness is the perceived difference in light reflected from objects



  - Simultaneous contrast – the perceived difference in brightness of two objects of the same luminance when viewed against different backgrounds

(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/bright.html)

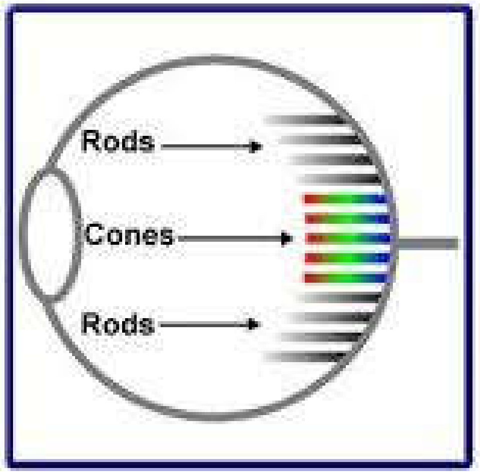
Visual contrast – lack of contrast can reduce visibility

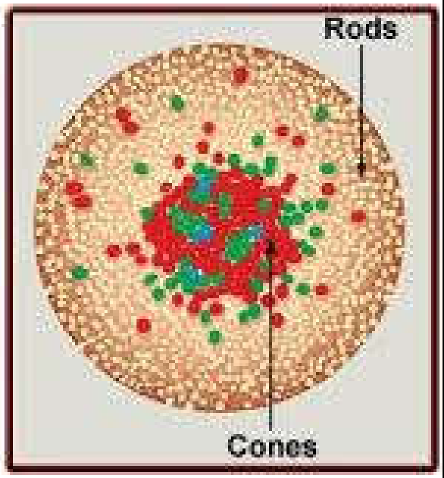


(Source: Advanced Lighting Guidelines 2001)

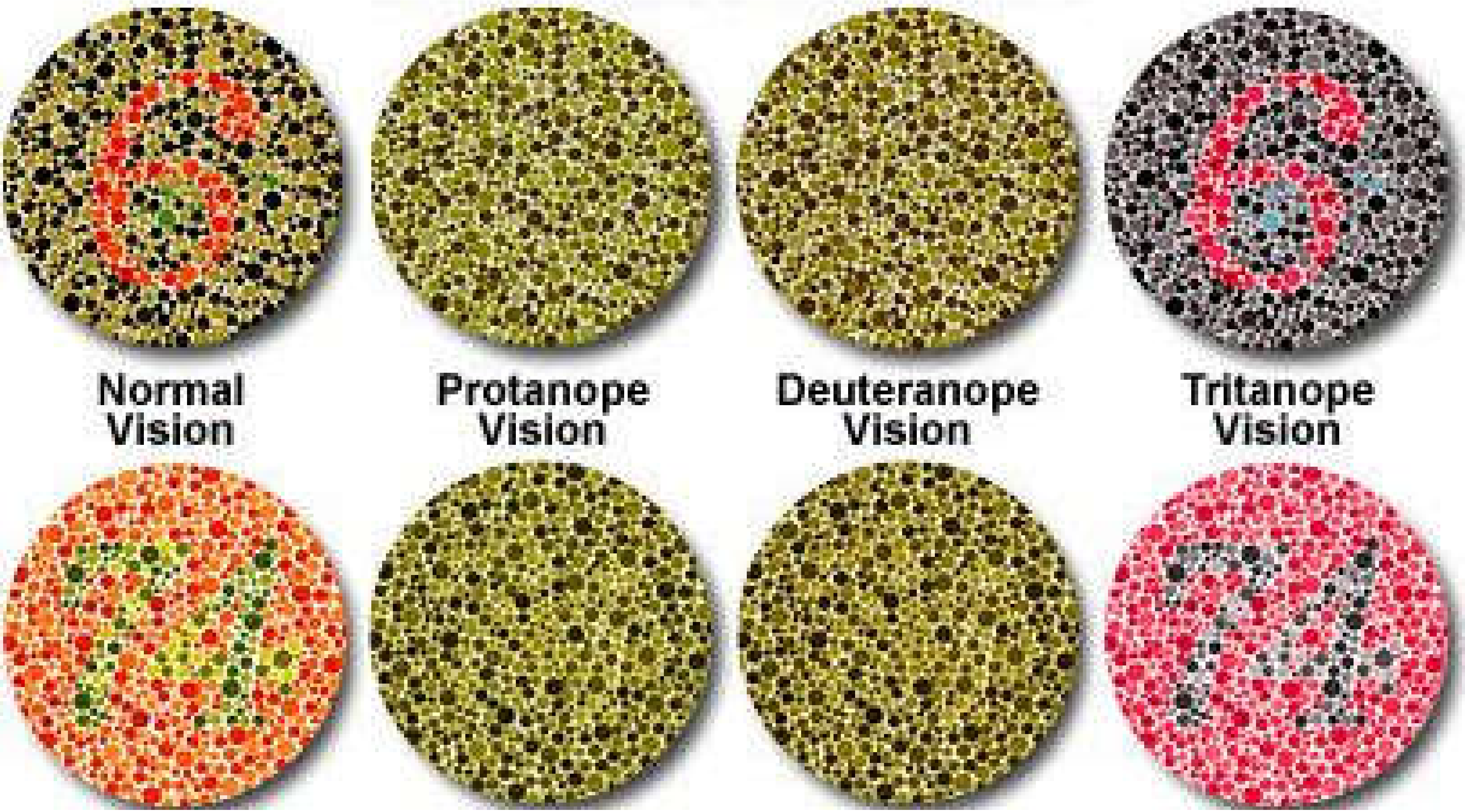
Human vision

- 4. Colour deficiencies in the visual system
  - Inability to distinguish certain shades of colour under normal lighting conditions
  - The “cones” lack one or more light-sensitive pigments
    - Such as particular shades of reds & greens
  - 色盲 Colour-blindness – deficiencies in or lack of cone sensitivity (affects males much more often than females)
    - 8% of males
    - 0.5% of females
  - Can range from mild to severe





Ishihara colour blindness test

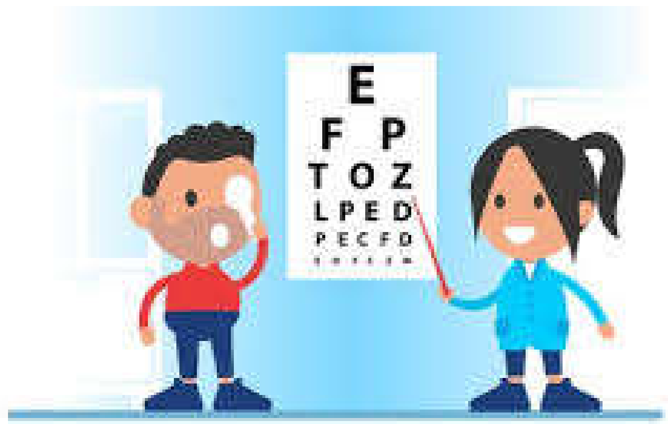


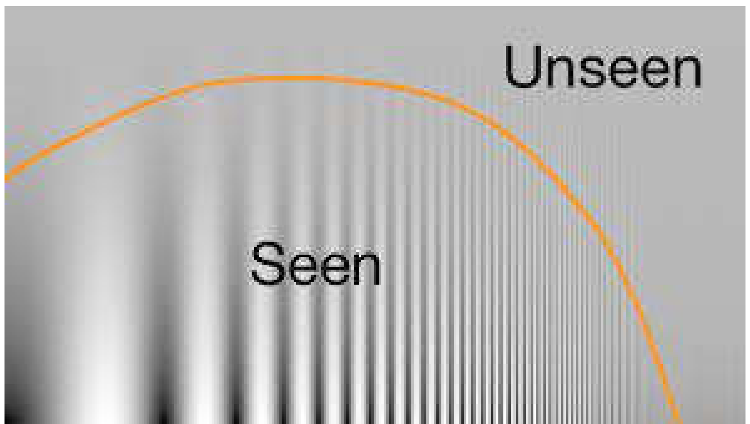
Ishihara Colorblindness Test:
https://www.colorlitelens.com/ishihara-test
https://www.olympus-lifescience.com/en/microscope-resource/primer/java/humanvision/colorblindness/

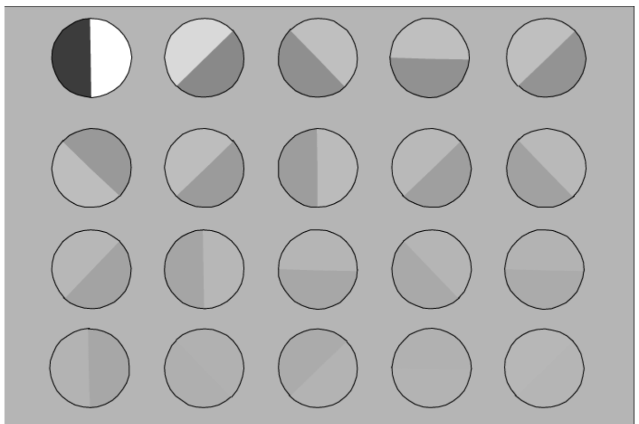
(Source: https://www.olympus-lifescience.com/en/microscope-resource/primer/lightandcolor/humanvisionintro/)

Human vision

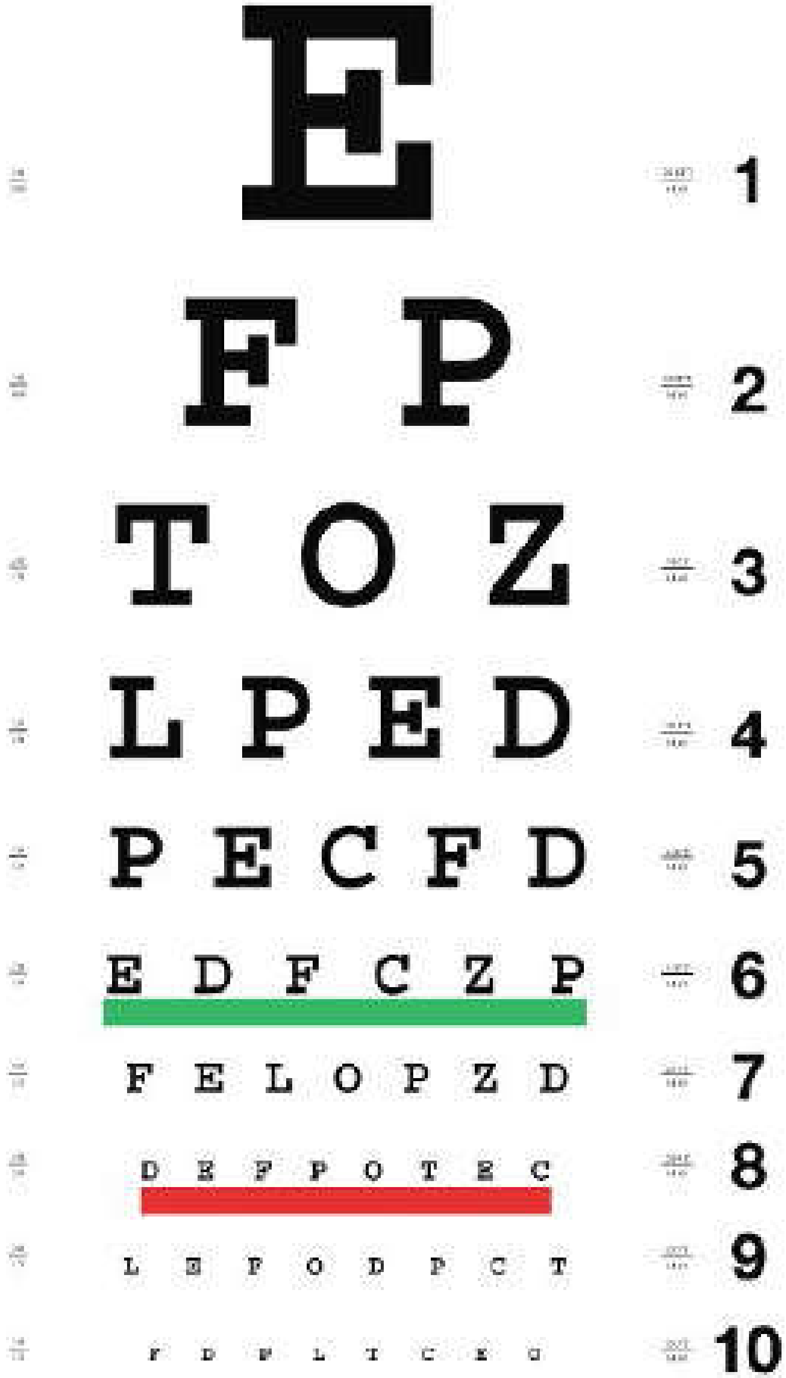
- Measuring vision
  - Visual acuity – measure of the smallest detail a person’s visual system can resolve
  - Contrast sensitivity – the ability to detect the presence of luminance differences
  - Contrast detection – the contrast at which an object is just visible

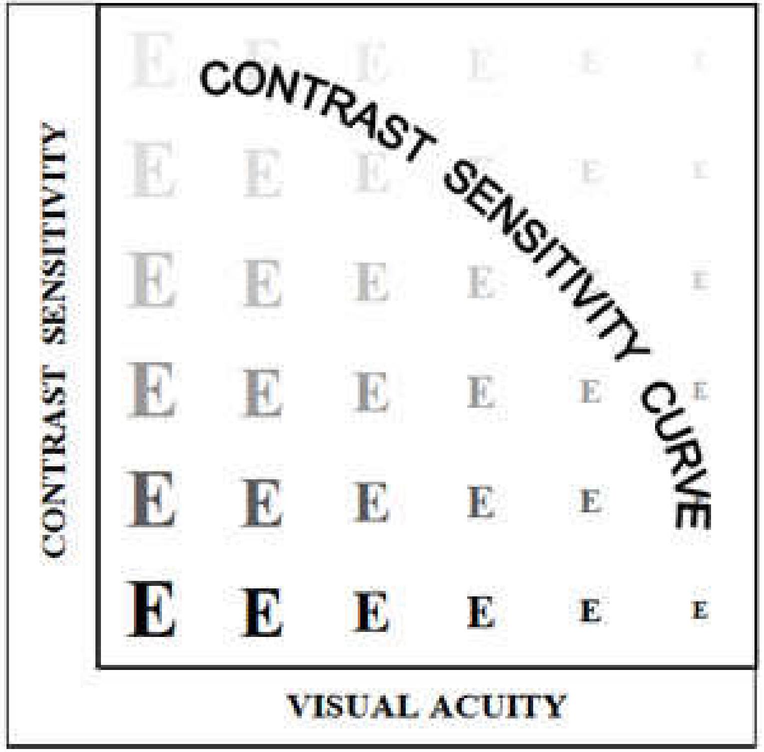


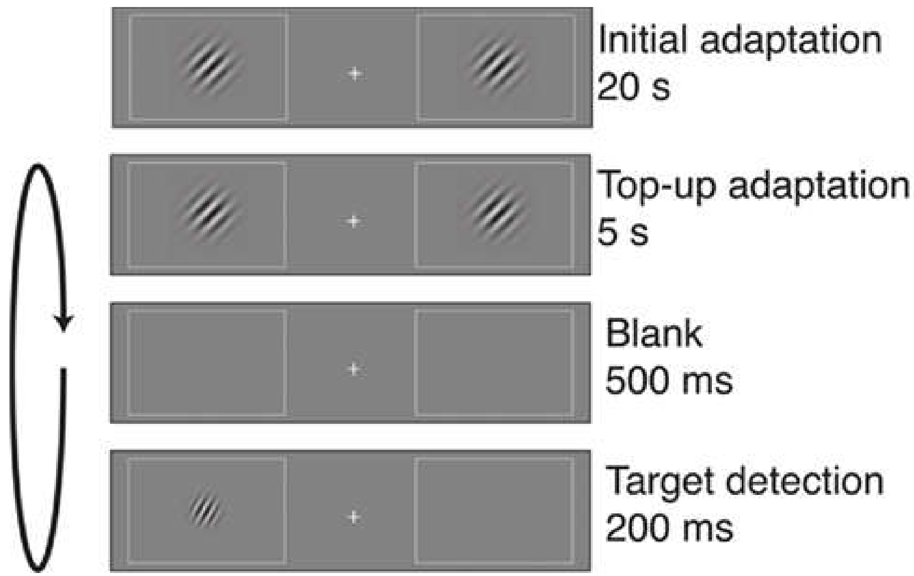




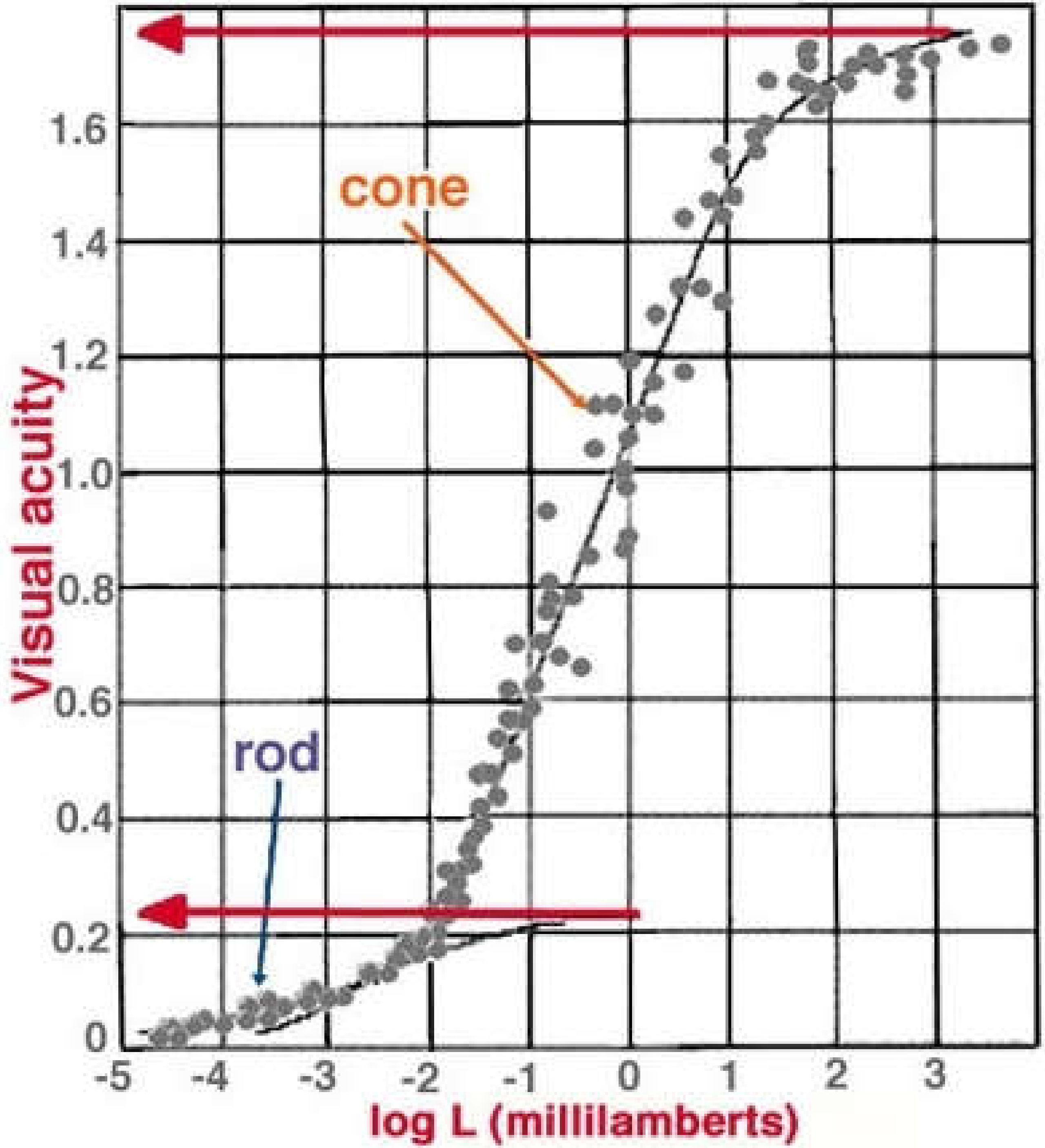
Methods for measuring vision







Relationship between visual acuity and background luminance



(Source: https://www.ncbi.nlm.nih.gov/books/NBK11509/figure/ch25kallspatial.F18/)

Design considerations

- Task parameters affecting visual performance
  - Contrast (C) – relationship between object and background luminances (L)
    - $C = (L_{task} - L_{background}) / L_{background}$
  - Size – visual angle subtended by an object from an observer
  - Luminance – quantity and quality of light reflected from an object
  - Time – viewing time necessary to process vision

Design considerations

- Building design considerations

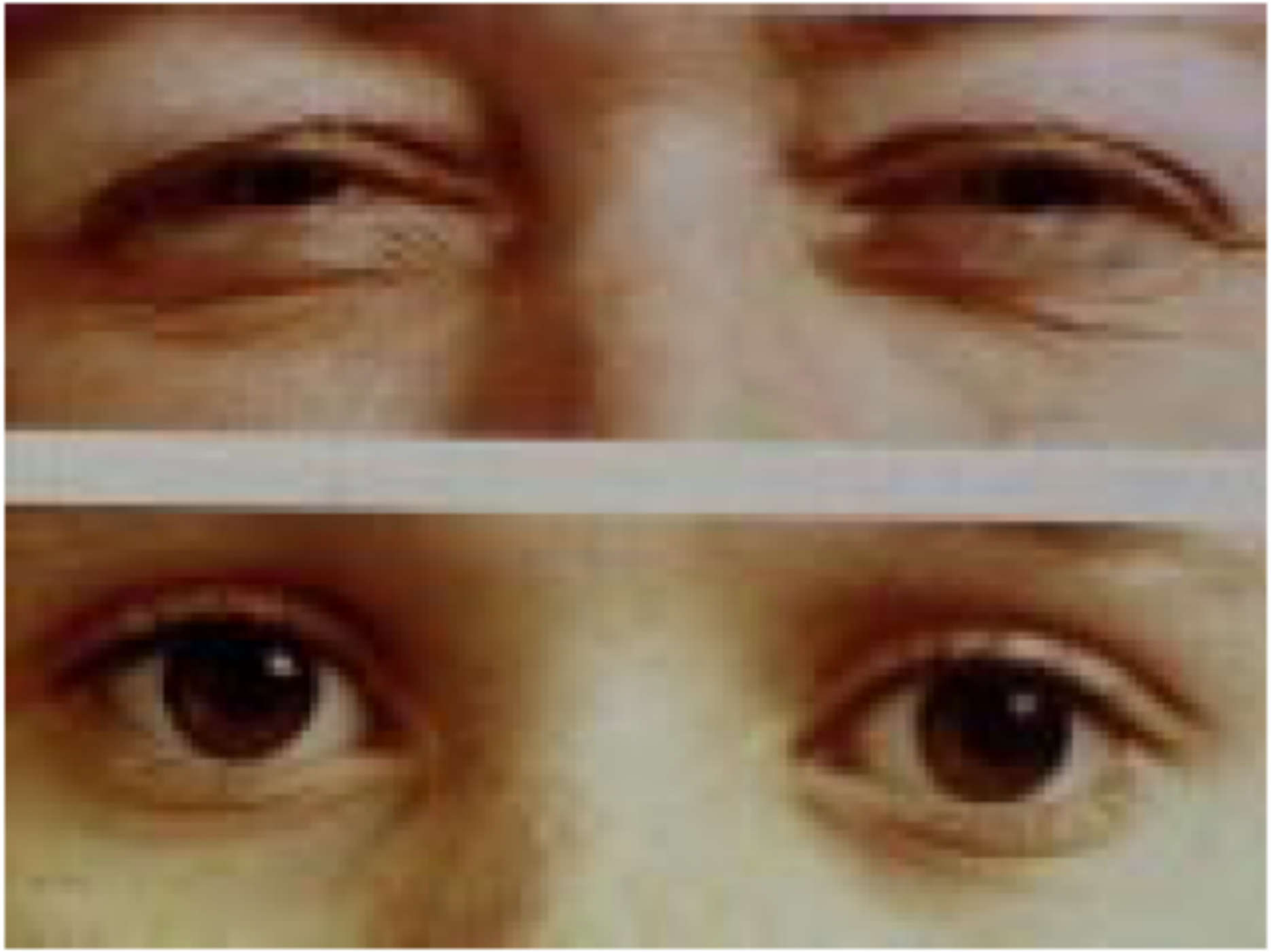
眩光
  - Discomfort glare
    - Luminance which causes visual discomfort
      - Source luminance, position, size, number of sources, field luminance
  - Disability glare
    - Luminance which adversely affects visual performance
  - Veiling reflections

    - Reflected luminance which prevents visual performance
      - Tasks viewed at a mirror angle to a source

Examples of glare and veiling reflection

Bright light entering from a window

Veiling reflection from overhead light source



It is critical that lamps and luminaires be selected to mitigate the problem of discomfort glare.

Design considerations

- Unified glare rating (UGR) 統一眩光指數
  - A method of calculating glare from luminaires, light through windows & bright light sources
  - Helps to determine how likely a luminaire is to cause discomfort to those around it
  - UGR values range from 40 (extremely high glare) to 5 (very low glare)
  - International standards e.g. EN12464 recommend maximum UGRs for different situations
  - UGR < 19 is recommended for many office & classroom settings

(Source: What is UGR? https://www.nvcuk.com/technical/what-is-ugr/529.htm)

How to calculate unified glare rating (UGR)

Σ means the sum take into account all the luminaires in the room

Luminance of the luminous parts of each luminaire in the direction of the observer's eye

The solid angle of each luminaire at the observer's eye

$$UGR = 8 \log_{10} \left(\frac{0,25}{L_B} \sum \frac{L^2 \omega}{p^2} \right)$$

Background luminance, at the observers eye's

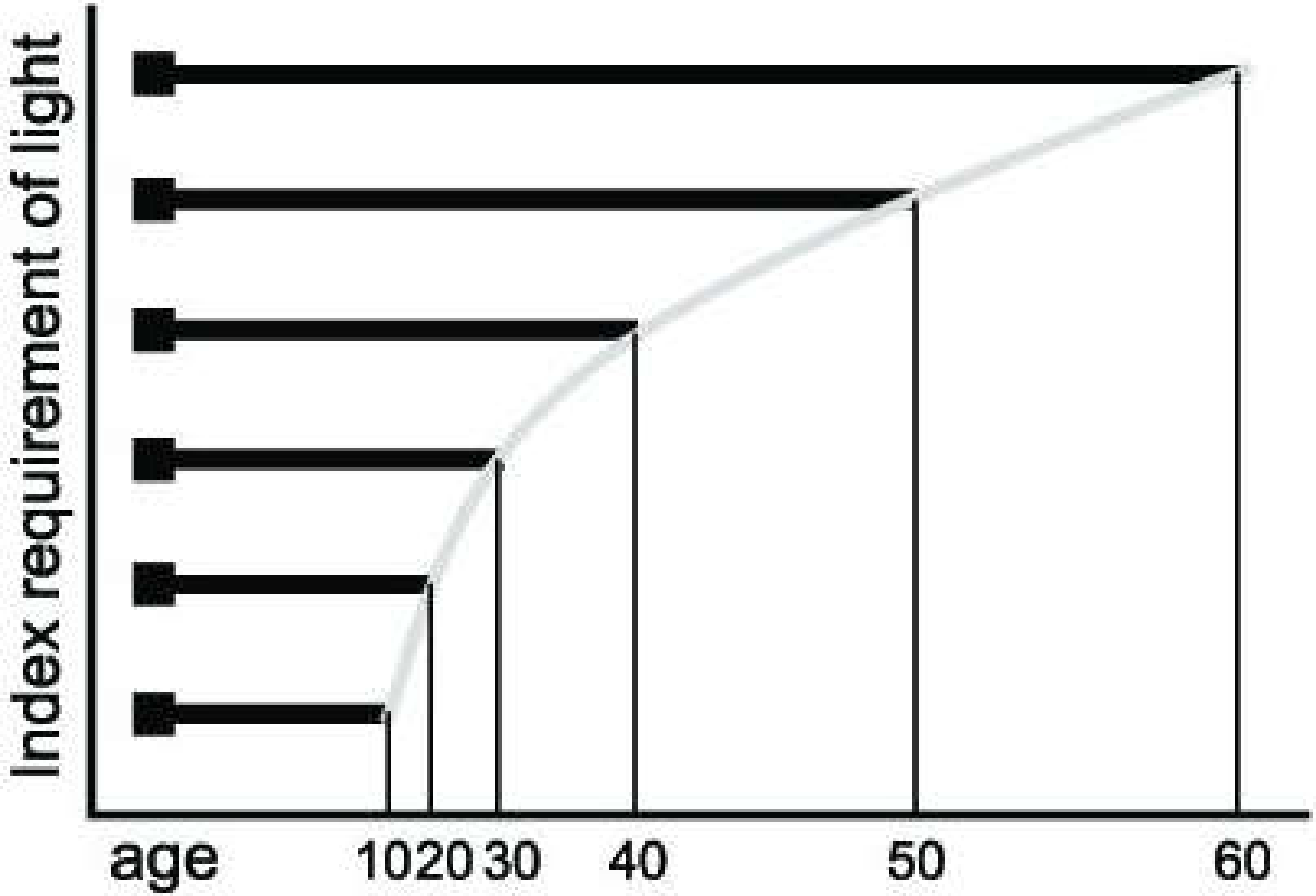
The Guth position index Each luminaires position from the line of sight of the observer

(Source: https://www.hidealite.com/en/knowledge/concept/ugr)

Design considerations

- Effects of aging
  - Increased lens opacity – light scattering within the eye flare
  - Crystalline lens yellowing – reduced blue vision
  - Presbyopia – loss of lens elasticity and near vision
  - Reduced pupil size – less light reaching retina – more light required
  - Increased visual processing and adaptation time – reduced performance
  - Decreased acuity and contrast sensitivity – due to decreased nerve function

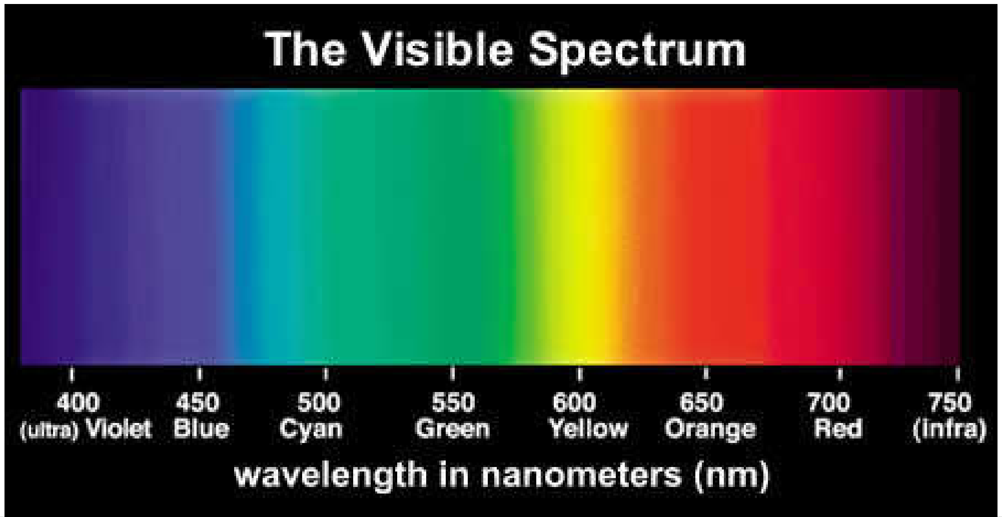
Requirement of light in relation to human age

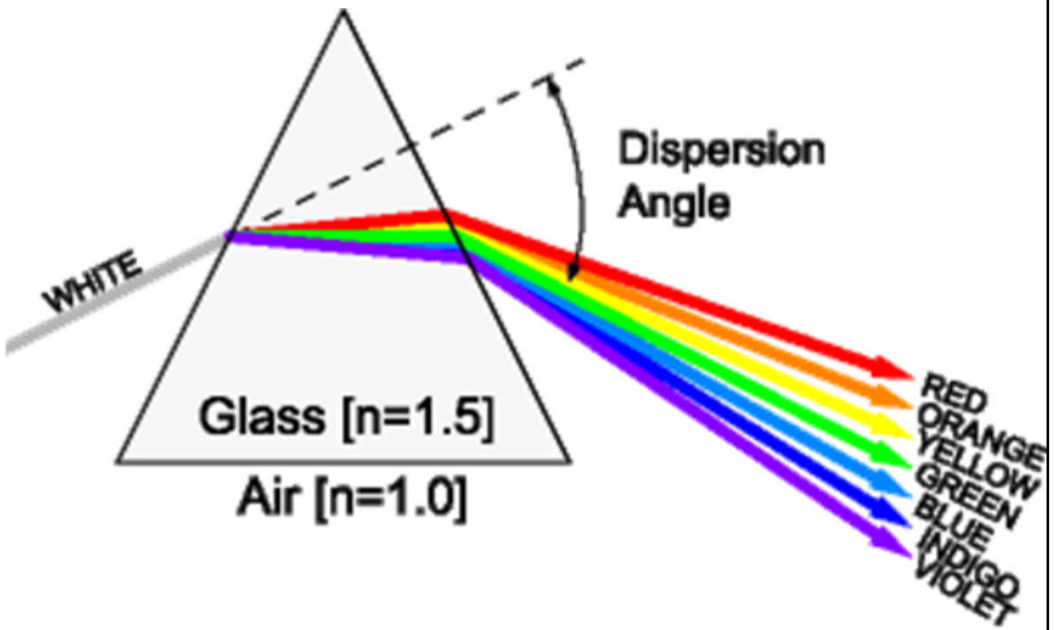


(Source: https://www.researchgate.net/publication/268326391_Visibility_Estimation_of_Textile_Warning_Materials_in_the_Pedestrian-Vehicle_Arrangement_n_Introduction/)

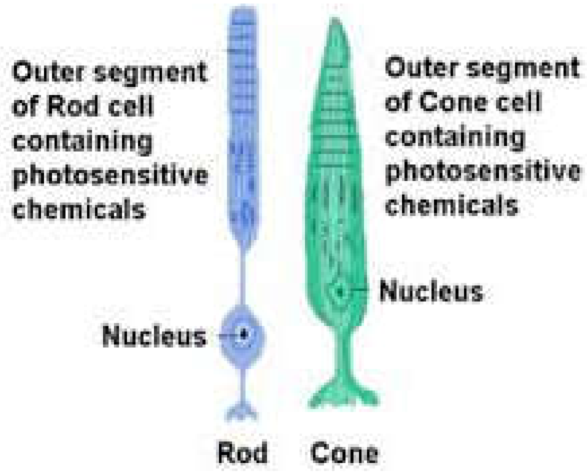
Colour theory

- Creation & perception of colour
- How colours are specified & quantified
- White light
  - All wavelengths combined at approximately equal power levels



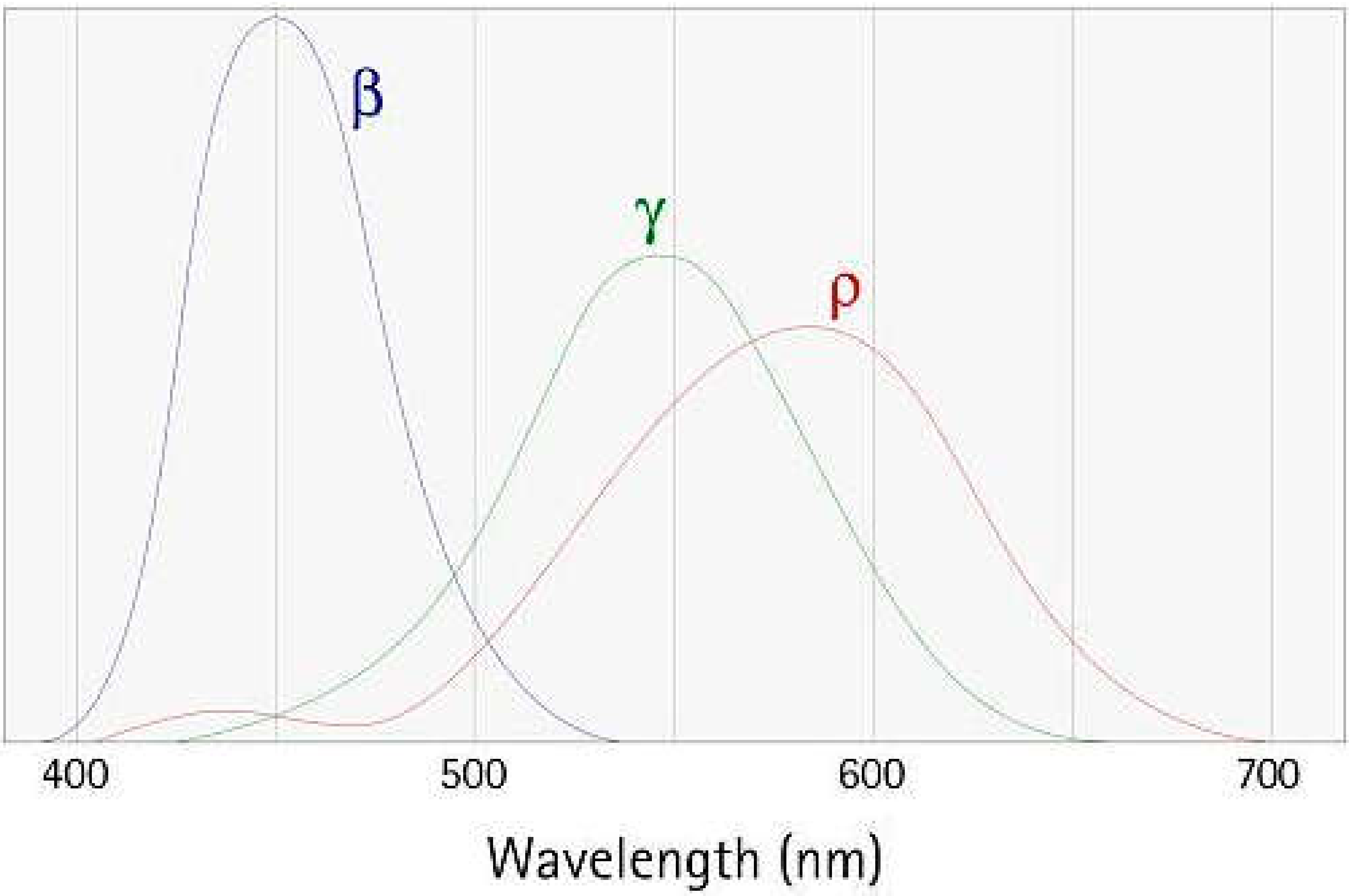


Colour theory



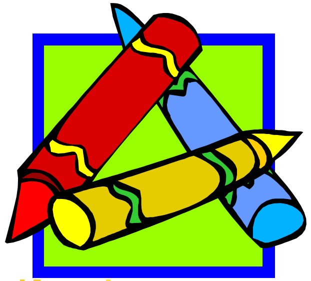
- The two types of receptor cells
  - Rods – *scotopic vision*
    - Night and peripheral vision
    - See very low luminance levels
    - Surfaces appear as shades of gray or blue/gray – difficult to distinguish between colours
  - Cones – *photopic vision*
    - Responsible for colour vision at normal interior and exterior lighting levels
    - Colour experience determined by relative strength of the signal from each of three types of cones (R, G, B)

Spectral colour sensitivity of the cones in relation to the wavelength



(Source: https://www.erco.com/en/guide/basics/physiology-of-the-eye-2225/)

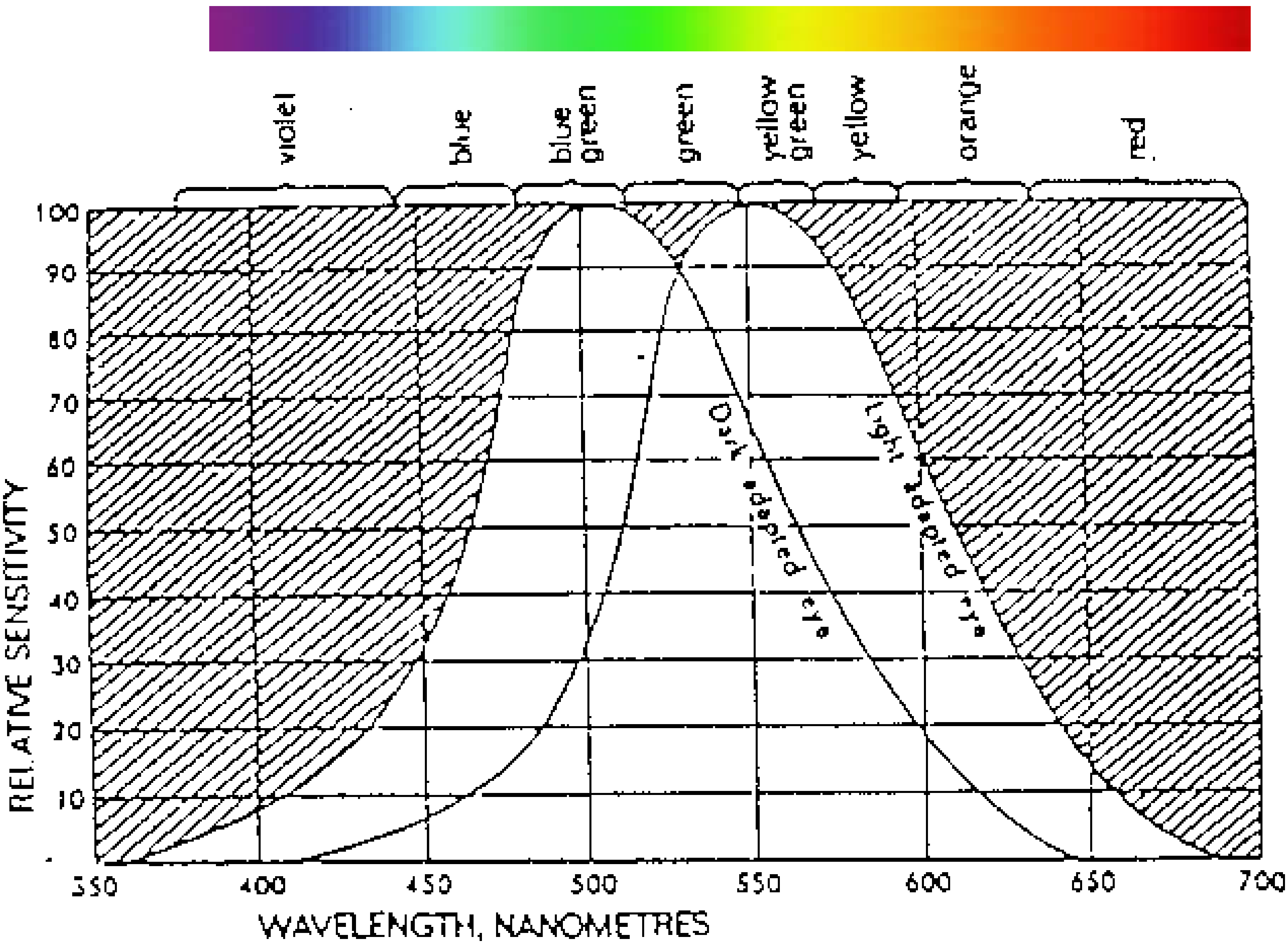
Colour theory



- Photopic vs. scotopic sensitivity
  - Spectral luminous efficiency curve or the V-lambda curve
  - Peak sensitivity shifts to lower wavelengths under scotopic (rod) vision – Purkinje shift*
  - Surface colour that appears lighter under photopic vision may appear darker under scotopic

(* See also http://en.wikipedia.org/wiki/Purkinje_effect)

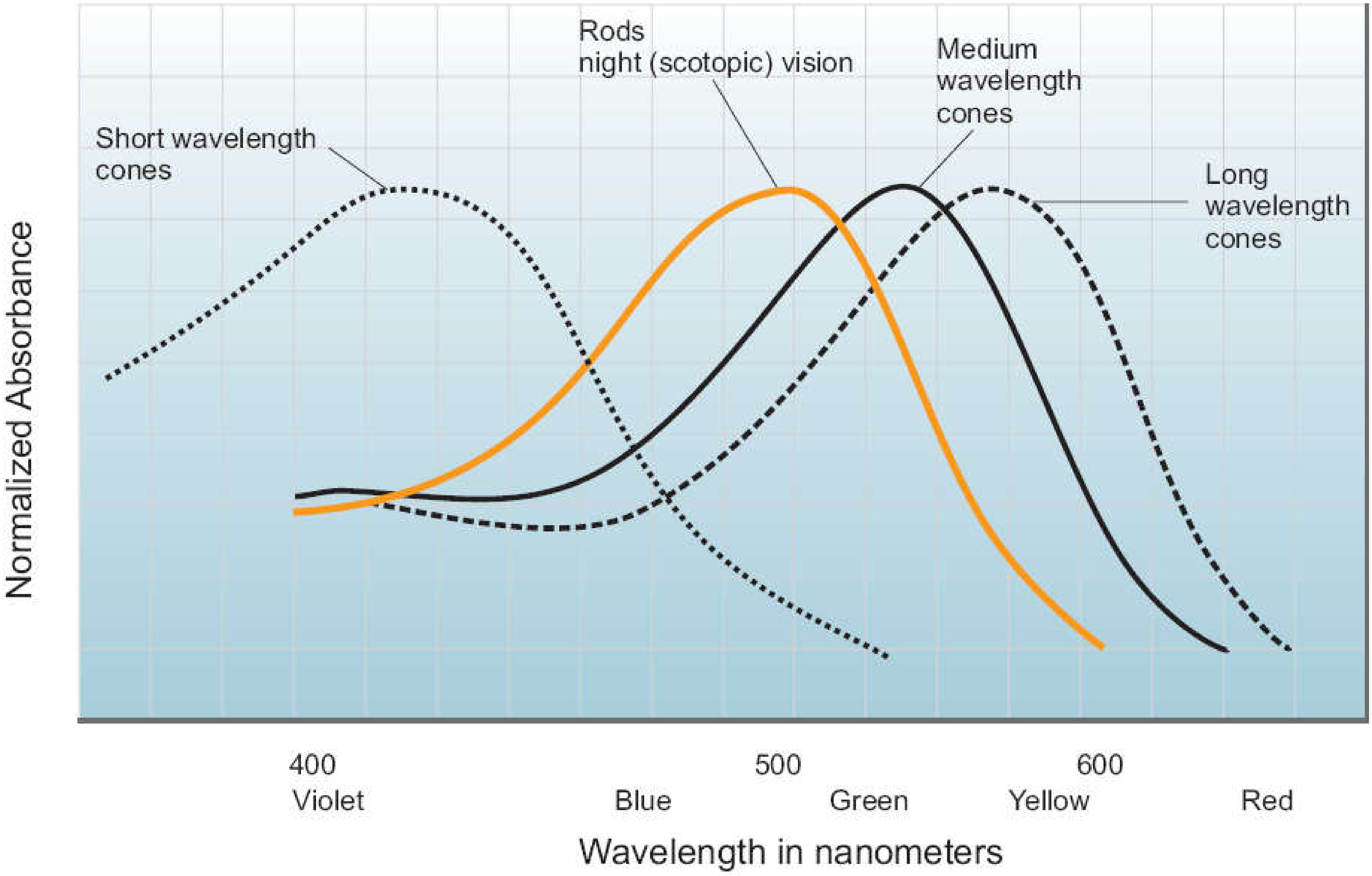
The eye's response to equal energy of radiation



Colour theory

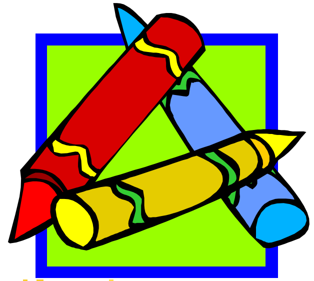
- Photopic curve
  - Used to determine the nos. of lumens present in a light source, given the spectral power distribution for a lamp
  - Trade-off between colour rendering & efficacy
- Mesopic vision
  - Rods & cones are nearly equal in sensitivity
  - Both photopic & scotopic systems contribute to response to object colour of different luminance
  - Luminance level is low so that rods & cones function at similar sensitivities, e.g. twilight

Spectral sensitivity of rods and cones



(Source: Advanced Lighting Guidelines 2001)

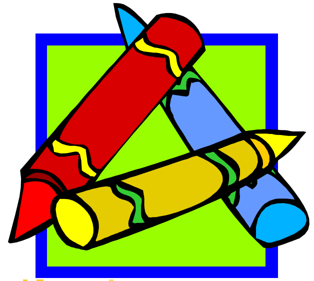
Colour theory



- Perceived object colour (colour perception)*
  - Visual experience
  - Based on relative proportions of different wavelengths of light reflected from a surface
  - Function of both surface characteristics & illuminant
  - Defined using three designations
    - Hue, Value and Chrome
    - Using Munsell colour system

(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/colper.html)

Colour theory

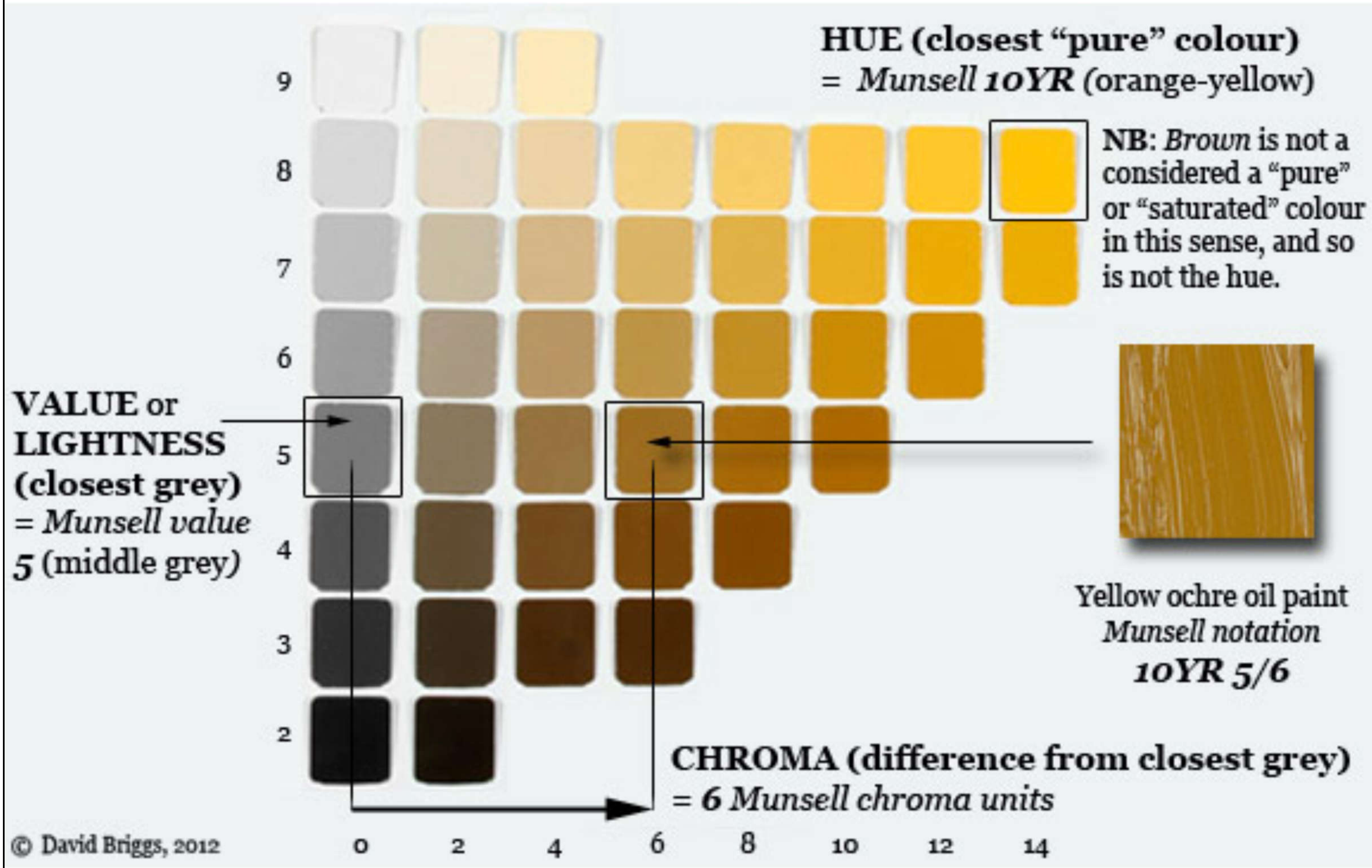


- Hue
  - General description of the perceived colour of an object
  - Single colour name or combination of two adjacent colour names (red, yellow, green, blue)
- Value
  - Indicates the relative lightness or darkness of a colour – e.g. sky blue and navy blue
  - Value is related to gray scale – from black to white
  - The value of a particular colour is the value of the gray that is of the same relative lightness

Colour theory

- Chroma
  - Indicates how saturated a colour appears
  - Two colours may be of the same hue and value, but one more rich in hue – e.g. a gray blue and a rich blue
- Metameric match
  - A condition where a different source/reflectance producing the same relative signal from the three types of cones will be perceived as being equal in colour
  - (Note that it is possible that two materials which appear to match under one illuminant will not match under a second)

Hue, Value and Chrome in the Munsell colour system



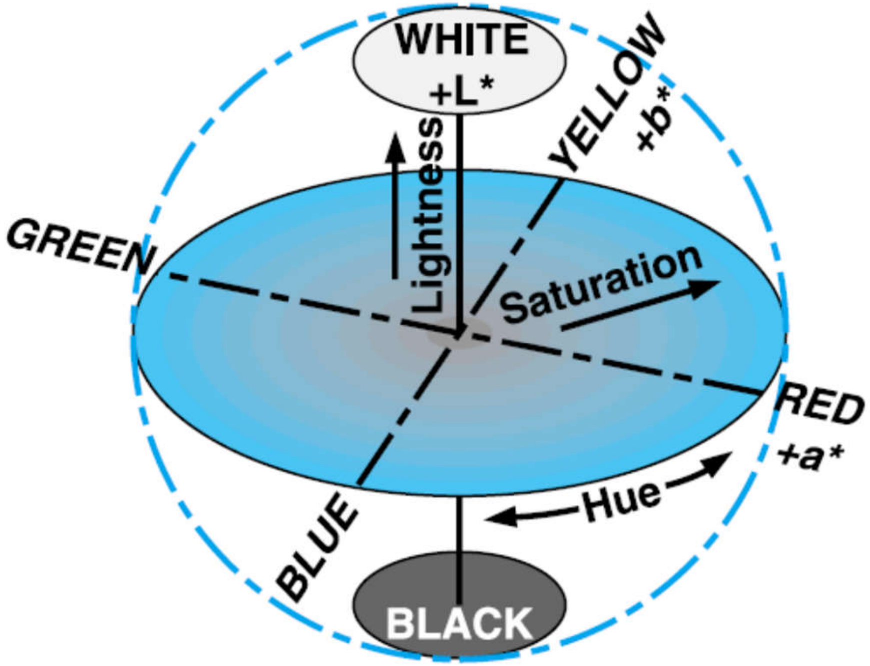
(Source: http://www.huevaluechroma.com/011.php)

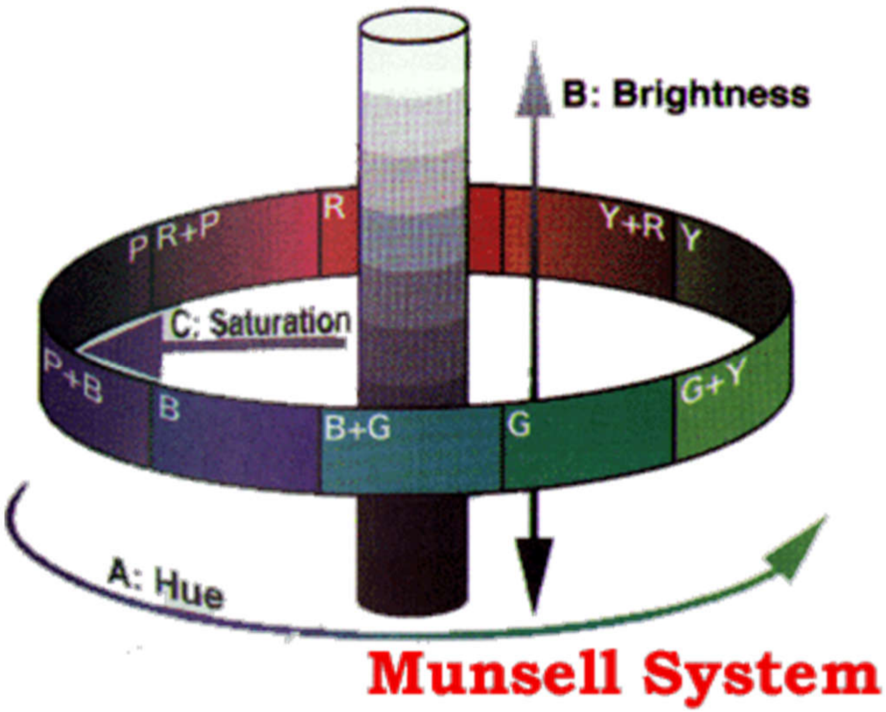
Colour theory

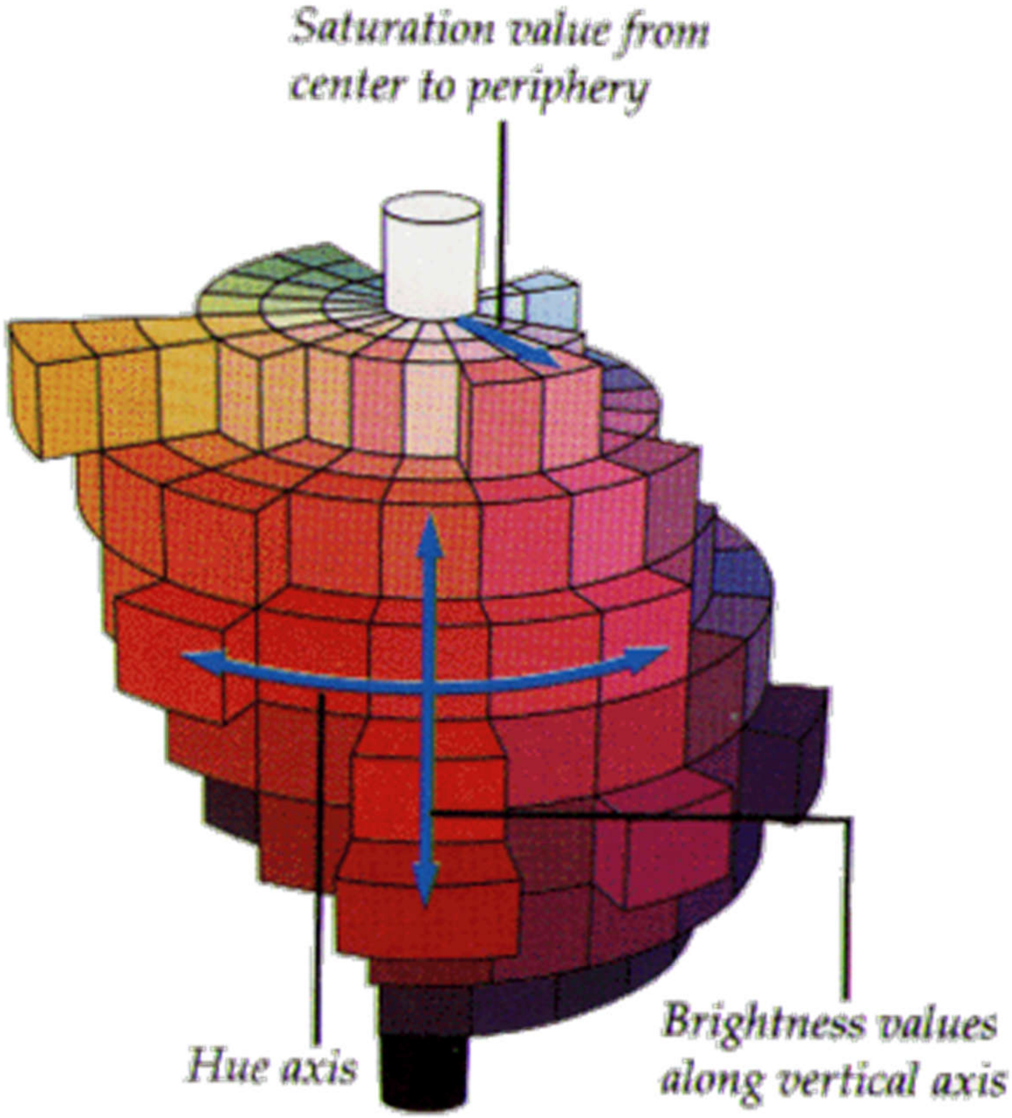
- Specification of colours*
  - Munsell colour system
    - Hue scale – 5 principal hues (red, yellow, green, blue, and purple)
    - Value scale – 10 equal visual steps from black to white
    - Chrome scale – 6-14 equal steps from no colour (white, gray, or black) to the strongest chroma for that level
  - Colour discrimination functions
    - Hue discrimination (change in wavelength)
    - Saturation discrimination (degree of colour paleness)

(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/colsys.html)

Munsell colour system



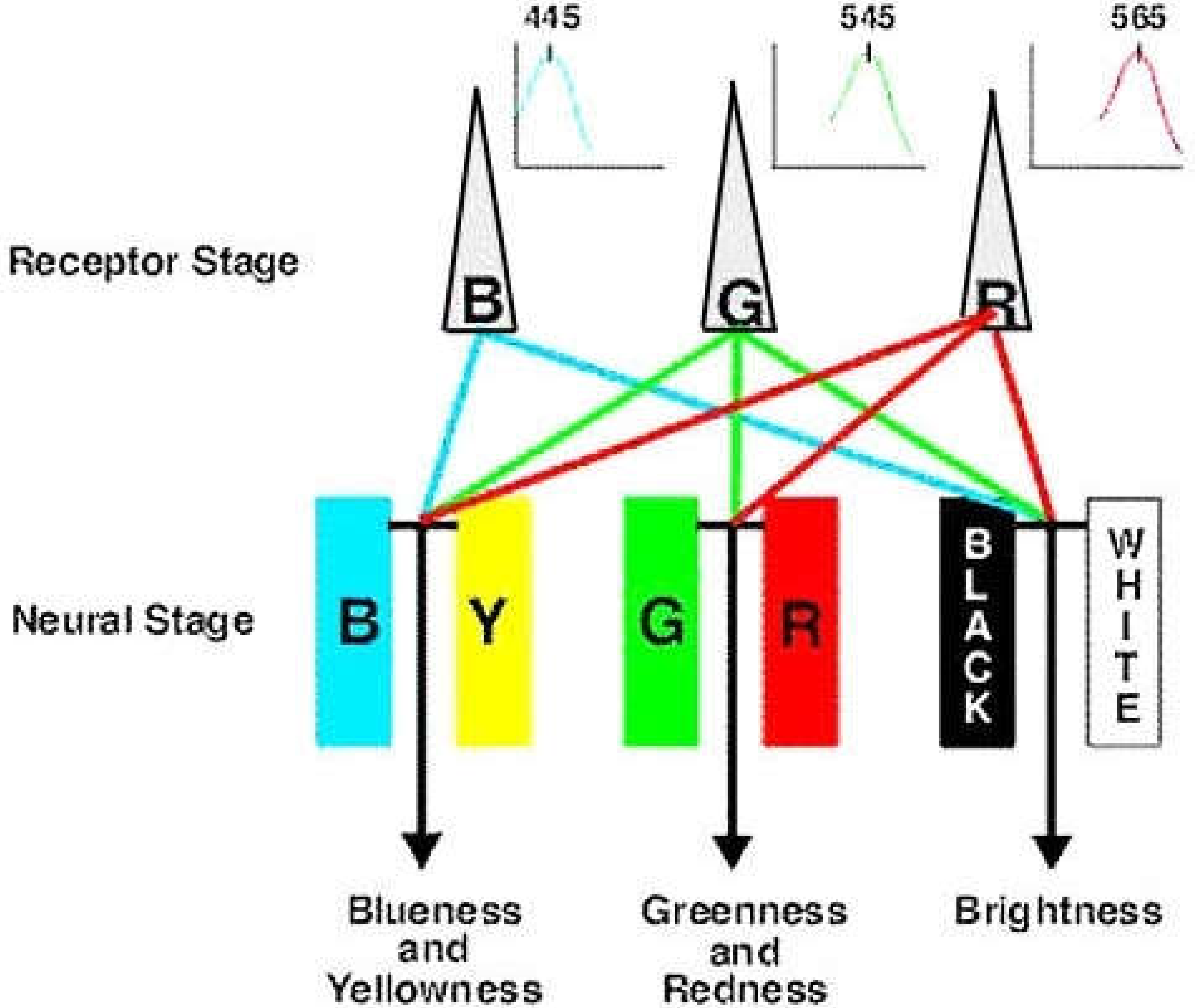




Colour vision

- Colour vision processes:
  - 1. Trichromatic input: recorded by the responses of the cone cells in the retina
  - 2. Opponent output: responses from the cones are compared with each other
  - 3. Processing for colour constancy: information from throughout the visual field is rapidly, automatically & seemingly effortlessly analysed and resolved into an interpretation of object, lighting & atmospheric properties

Stage theory and model for normal human colour vision



(Source: https://www.ncbi.nlm.nih.gov/books/NBK11538/)

Colour vision

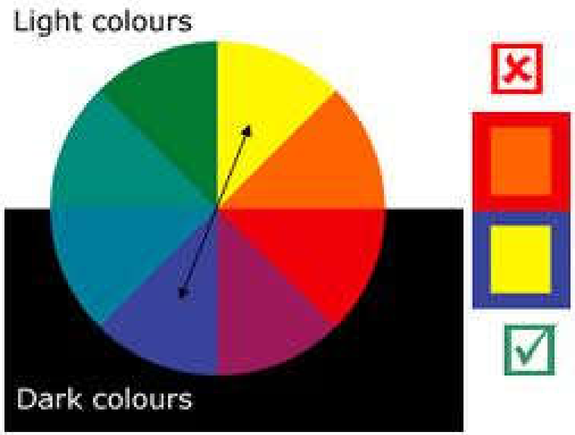
- Perceived colour of light source
  - Spectral content of emitted light determines source appearance
  - Two sources that appear to be the same colour may have different spectral compositions
  - Two sources that have the same colour appearance may have different colour rendering qualities

High CRI

Low CRI

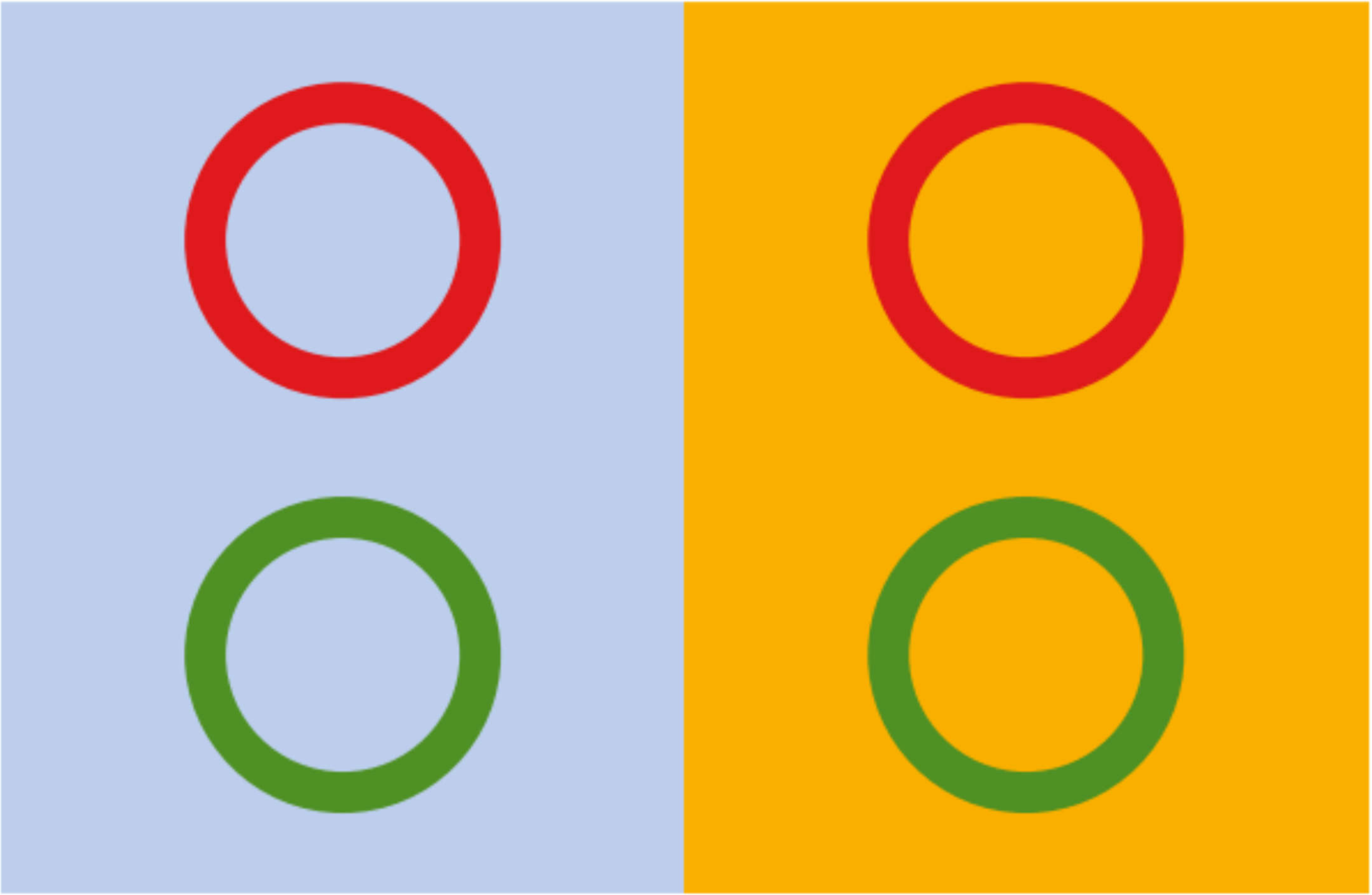
Colour vision

- Function of the surround
  - Simultaneous contrast
    - Appearance of a colour is affected by the colour against which it is viewed



  - Colour adaptation
    - An after image, the compliment of the colour to which the visual system was adapted, appears over the region of the visual field that was exposed to that colour
- Colour preference
  - Colour fidelity, saturation, naturalness & vividness

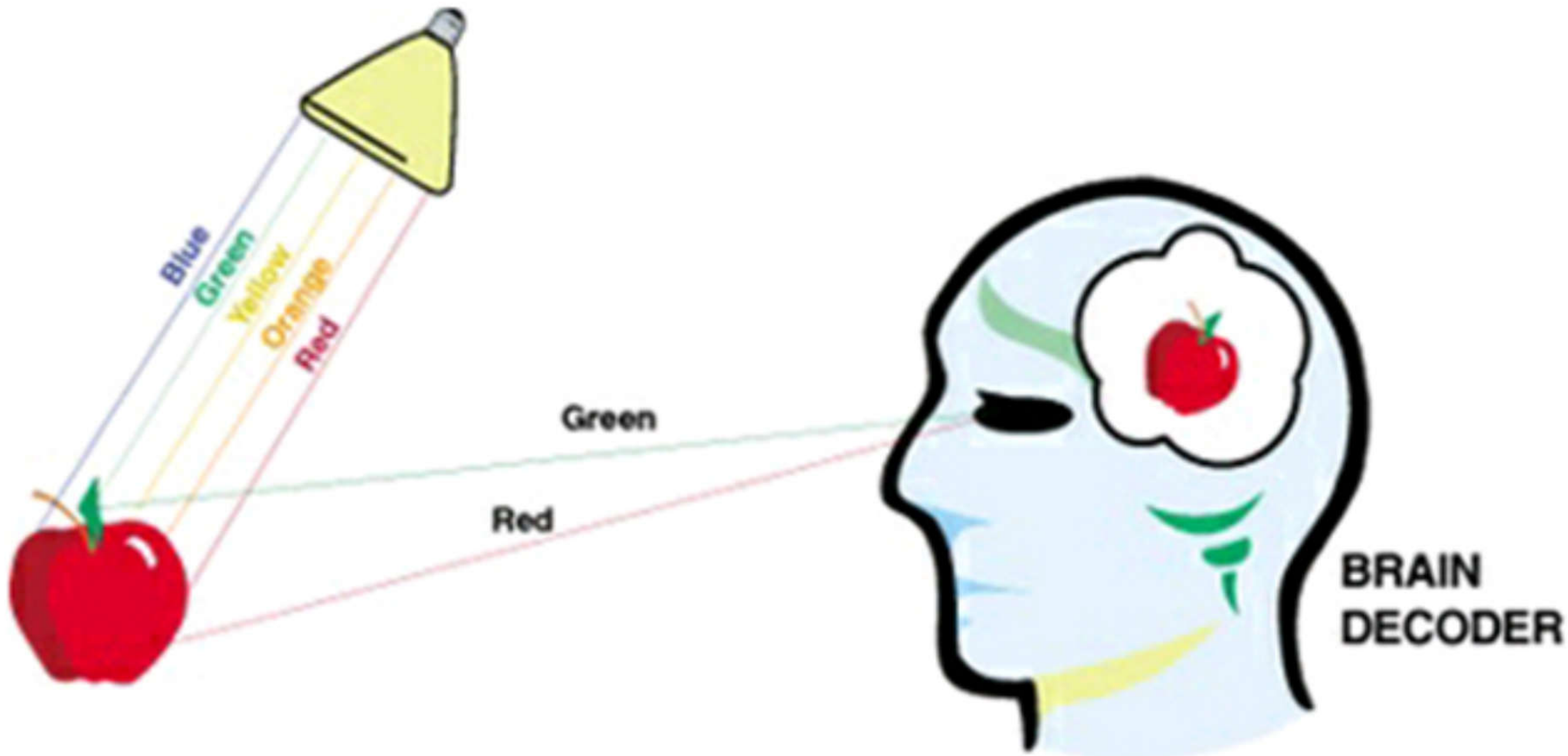
Colour contrast: the circles have a different apparent brightness with a different coloured background



(Source: The Science of Lighting, Signify)

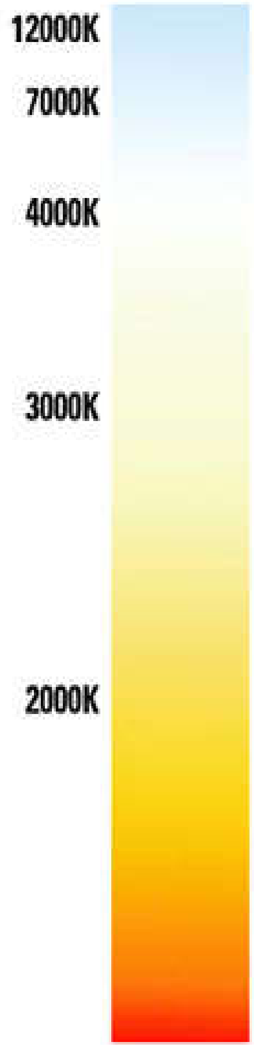
Colour vision

- Light source characteristics
  - Colour temperature
  - Colour rendering ability



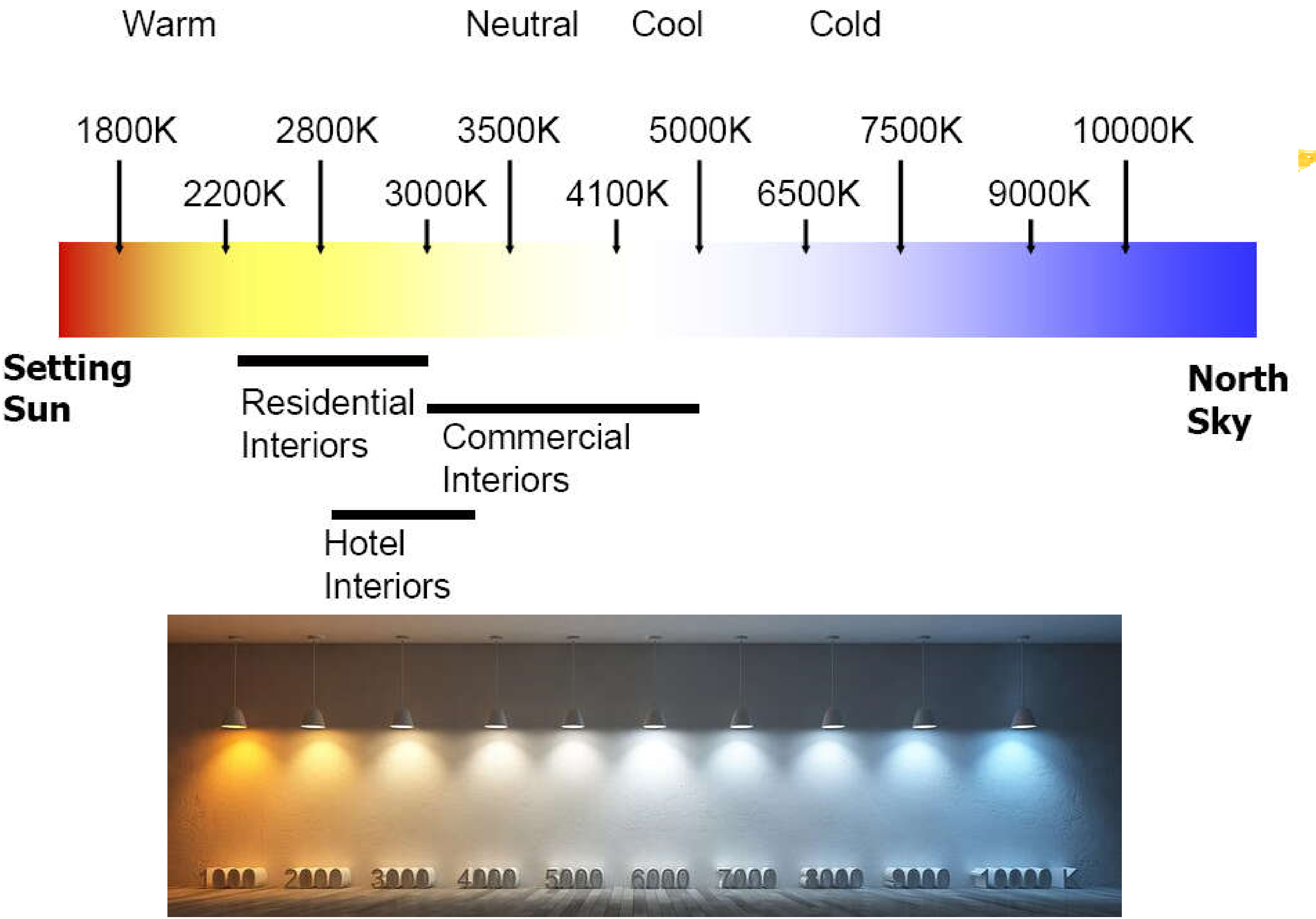
Colour vision

- Correlated colour temperature (CCT)
  - Used to specify source appearance
  - CCT equates the appearance of a source to a blackbody radiator operating at the same temp.
  - Expressed using Kelvin temp. scale
  - A lower CCT means longer wavelengths and warmer colour
  - Typical light source – 2,100 to 6,500 Kelvin

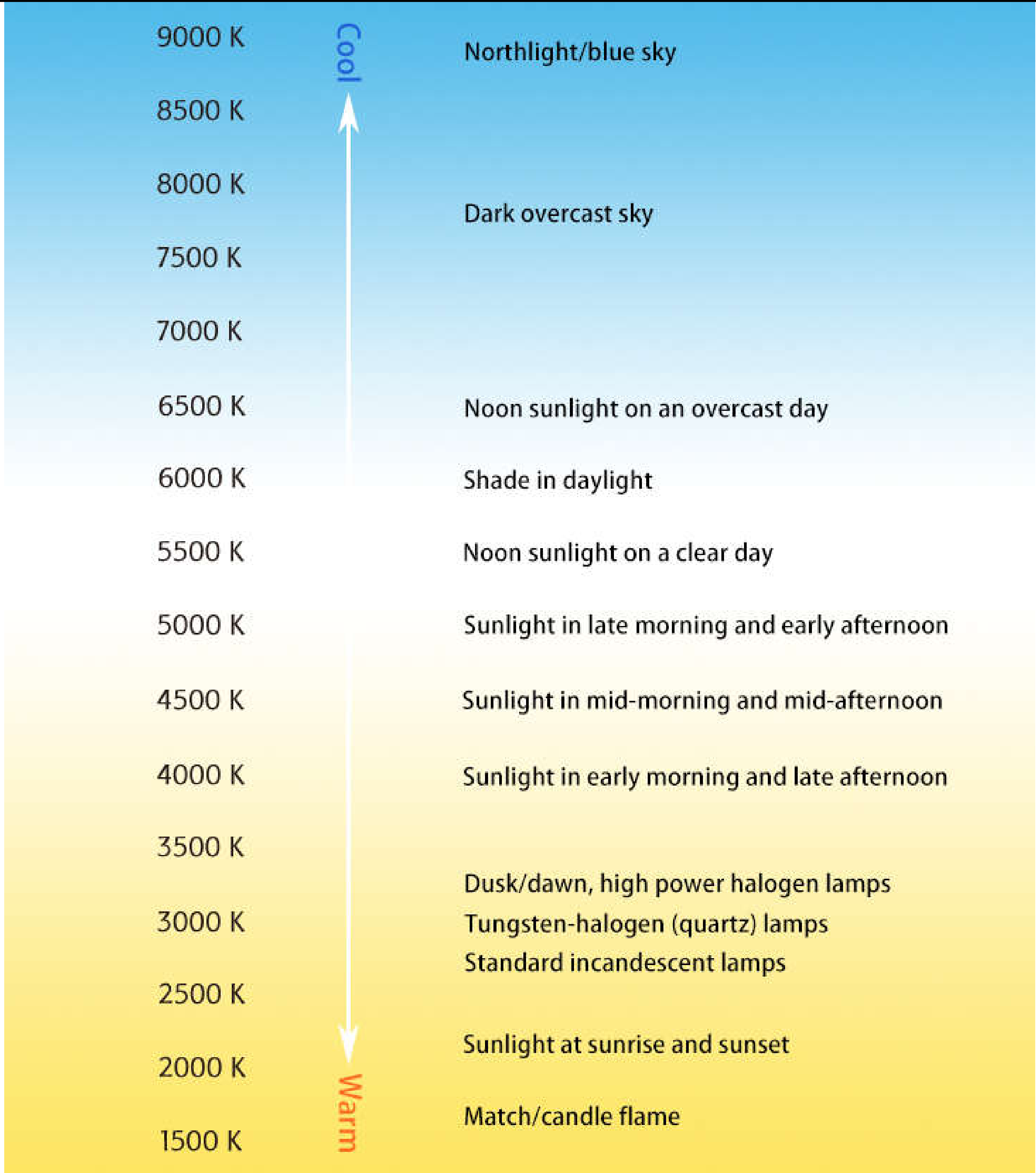


(* See also http://en.wikipedia.org/wiki/Color_temperature)

Correlated colour temperature (CCT) of lamps



[Source: www.benyalighting.com]



Colour temperature and appearance

(Source: https://www.manufacturer.lighting/info/245/)

Colour vision

- Colour rendering index (CRI)
  - Used to evaluate light sources based on how well particular sample colours are rendered relative to a standard source at the same CCT
  - CRI index is a value from 0 to 100 that is a measure of the deviation in colour appearance that occurs when test colours are illuminated by the test source and the standard source
    - (A greater deviation results in a lower CRI value)

(* See also http://en.wikipedia.org/wiki/Color_rendering_index)

red-rich source *blue-rich source*

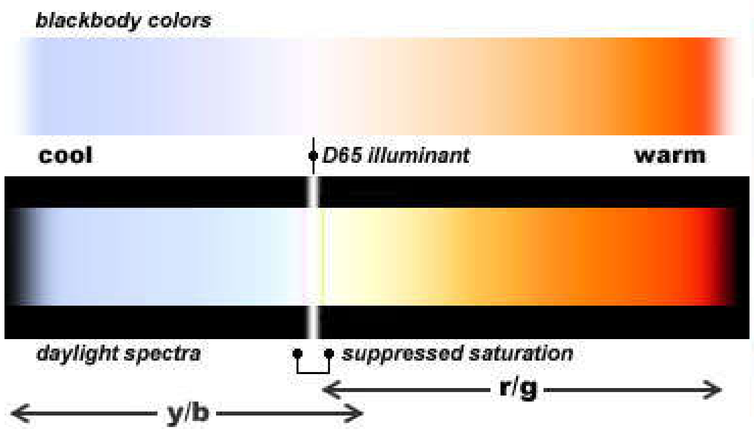
Colour rendering index (CRI or Ra) of common lamp types

Lamp type	Ra
Incandescent	100
Fluorescent	
Colour / 33	65
Colour / 54	72
Colour / 82/ 83/ 84	86
Colour / 93/ 94/96	93
Low pressure sodium (SOX)	(- 44)
High pressure sodium (SON)	26
High pressure mercury (HPL – N)	45
Blended light (ML)	60
Metal Halide (HPI)	70

(Source: Philips Lighting, http://www.lighting.philips.co.in)

Colour vision

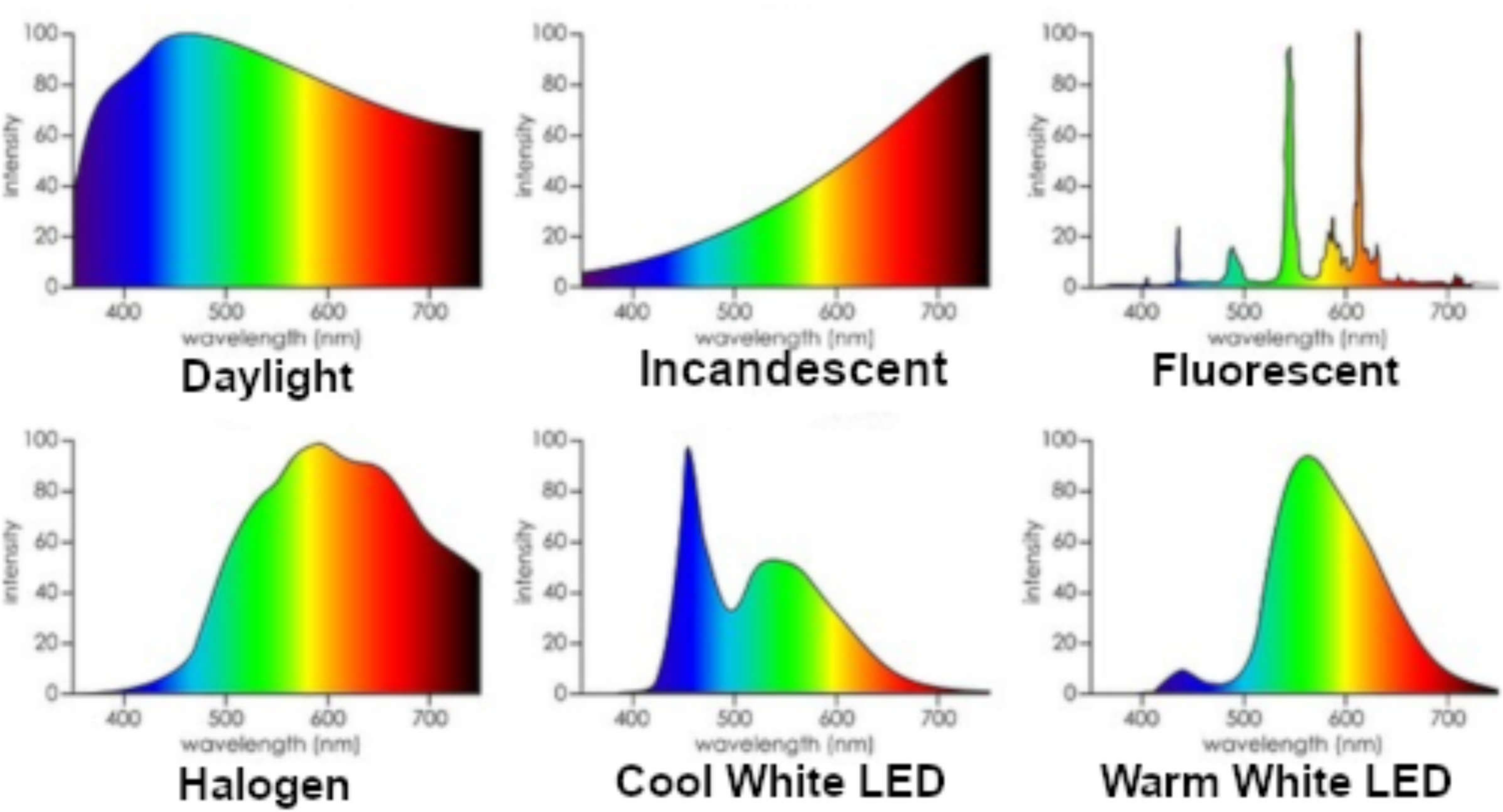
- Daylight and colour
  - Daylight has excellent colour rendering quality with a CRI of 100
  - Colour temperature is high – cool or bluish-white
  - If electric light sources are used in a daylighted area, those of high colour temperature are preferred



Colour vision

- Electric light sources
  - Colour quality & spectral power distribution (SPD)
    - Incandescent – good colour rendering (halogen has a higher colour temperature)
    - Fluorescent – range of colour temperature & colour rendering ability
    - High intensity discharge (HID) – mercury, metal halide & high pressure sodium provide a range of colour temperature & colour rendering ability
    - Light emitting diode (LED) – various colour temperatures & colour rendering ability

Spectral power distribution (SPD) of common light sources



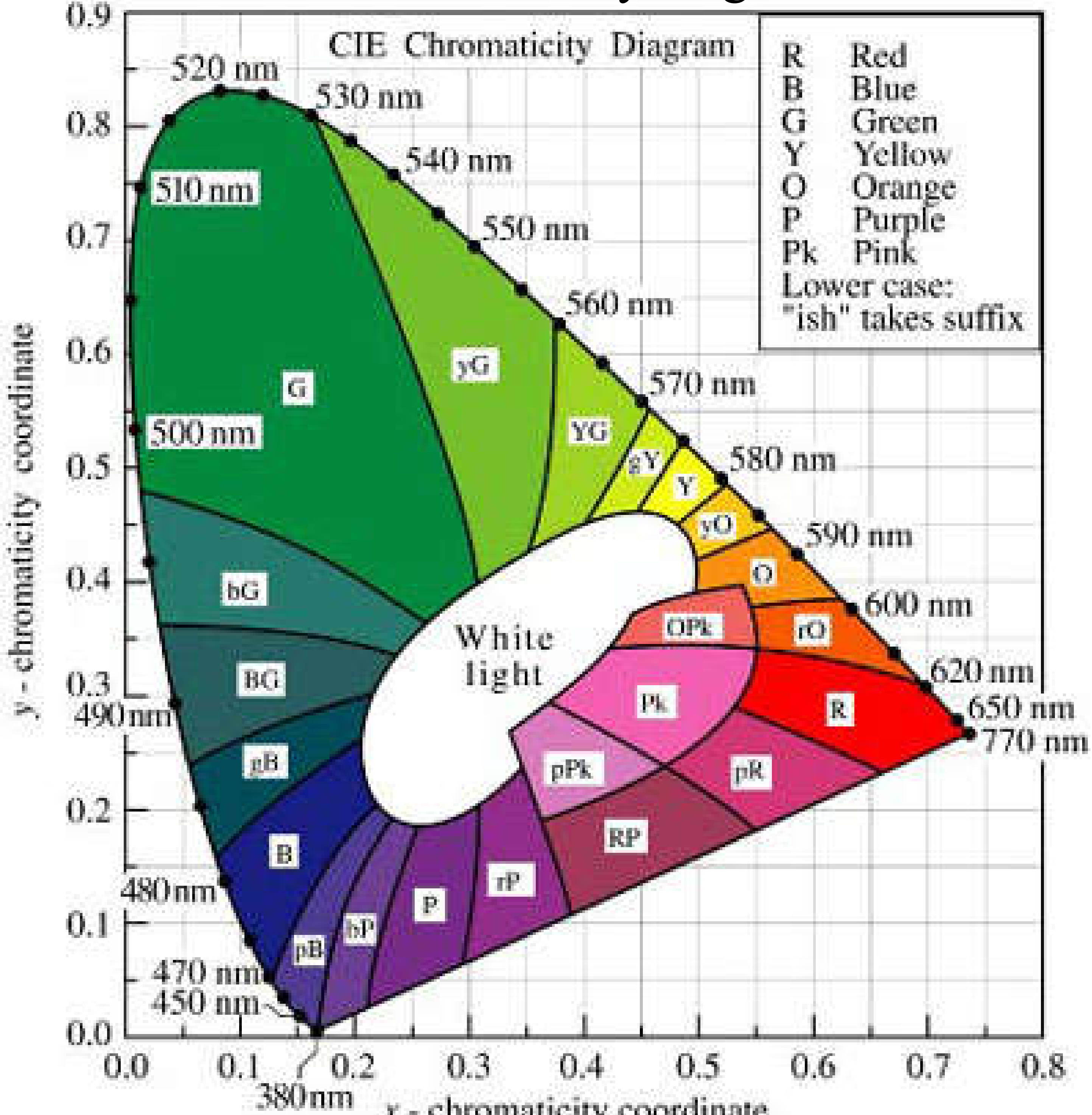
(Source: https://www.paintingframesplus.com/painting-frames-plus-website-colors.php)

Colour vision

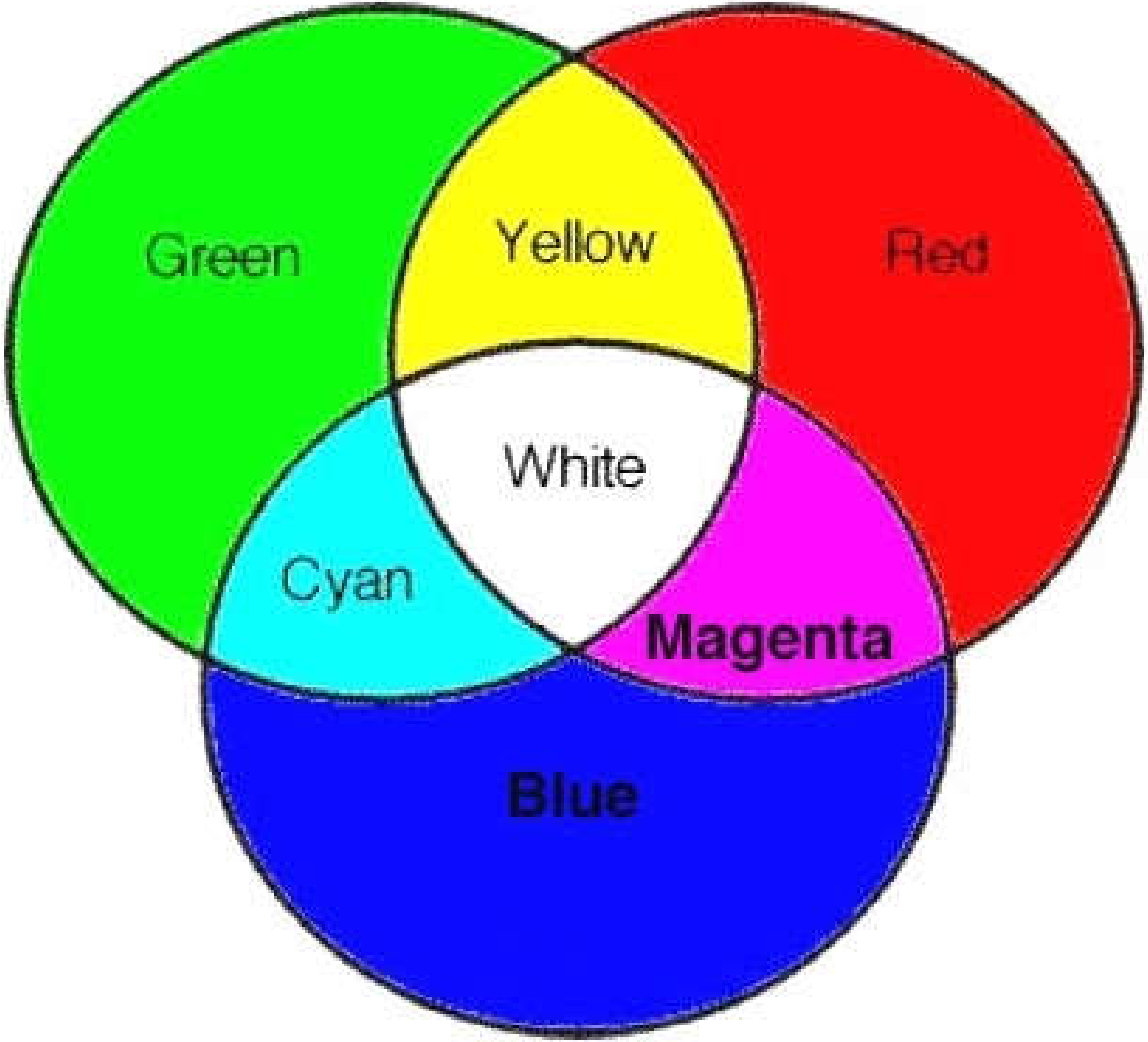
- CIE Chromaticity Coordinates*
  - The system used for the specification of CCT
  - Based on three coordinates (x, y, z)
  - CIE chromaticity diagram describes how colours can be mixed (trichromatic colour matches)
- Additive colour mixing
  - Primary colours – Red, Green, Blue
  - Other colours of the spectrum are achieved by mixing the primaries
  - White light = equal concentration of the primaries

(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/ciecon.html)

CIE chromaticity diagram

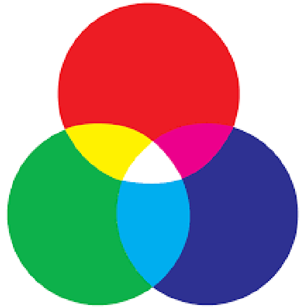


Additive colour mixture

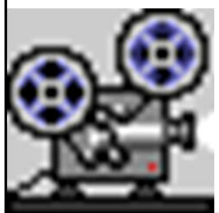


(Source: https://www.ncbi.nlm.nih.gov/books/NBK11538/)

Colour vision

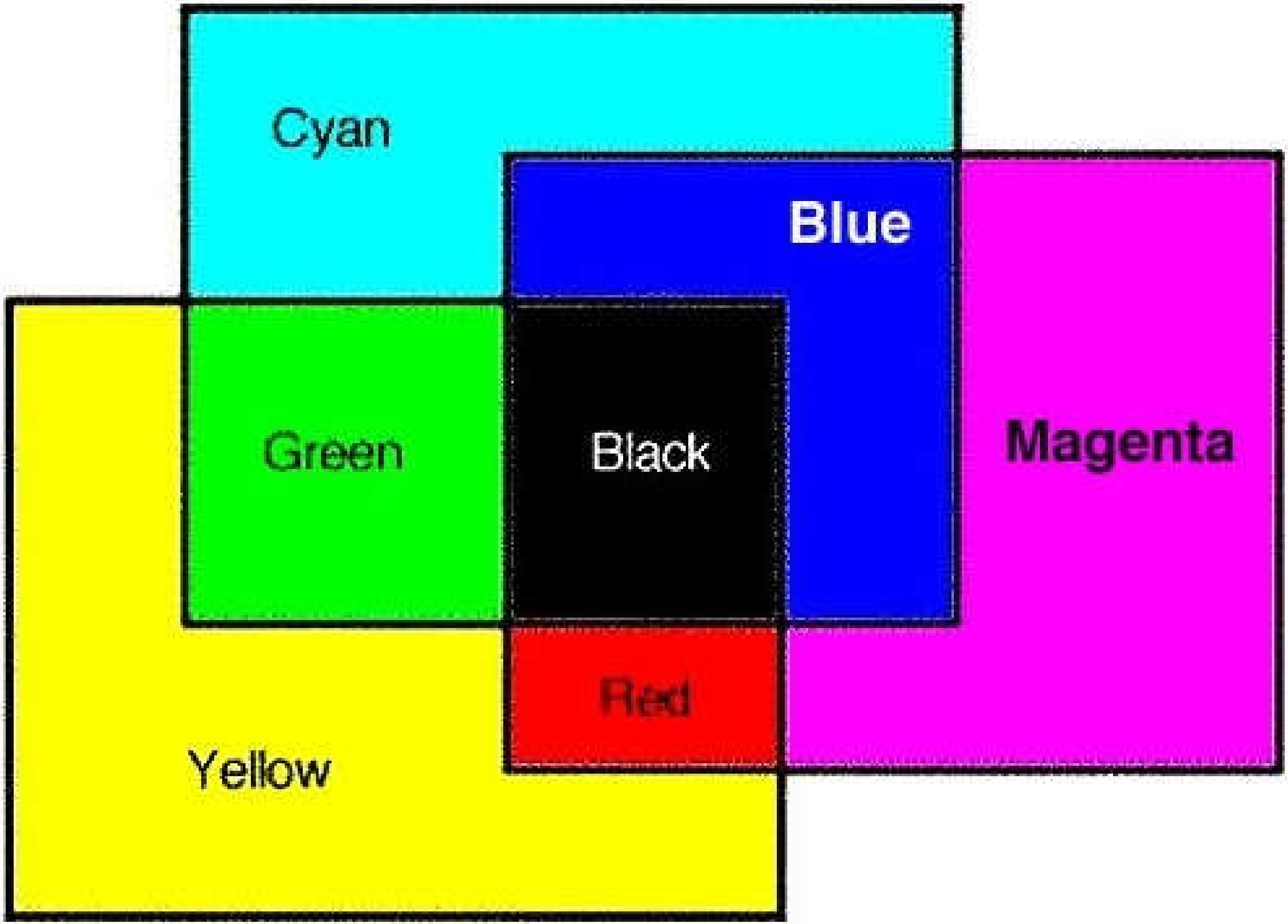


- Subtractive colour mixing
  - Involves one source (broadband)
  - Selective reduction/elimination of certain wavelengths
  - Subtractive primaries – Red, Blue, Yellow
  - Adding these three primaries results in no colour experience



Video: Color Vision 1: Color Basics (15:10) https://youtu.be/iDsrzKDB_tA

Subtractive colour mixture



(Source: https://www.ncbi.nlm.nih.gov/books/NBK11538/)

Further Reading

- Principles of Vision
  https://www.ncbi.nlm.nih.gov/books/NBK11513/
- Color vision - Wikipedia
  https://en.wikipedia.org/wiki/Color_vision
- Human Vision and Color Perception
  https://www.olympus-lifescience.com/en/microscope-resource/primer/lightandcolor/humanvisionintro/