How can we determine what colours somebody can see?

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Professor John Barbur

Overview

- **How do we see colour?**
- Why and when is a shared perception of colour is important?
- Anomalous human colour vision?
- How can we determine the colours somebody can see?

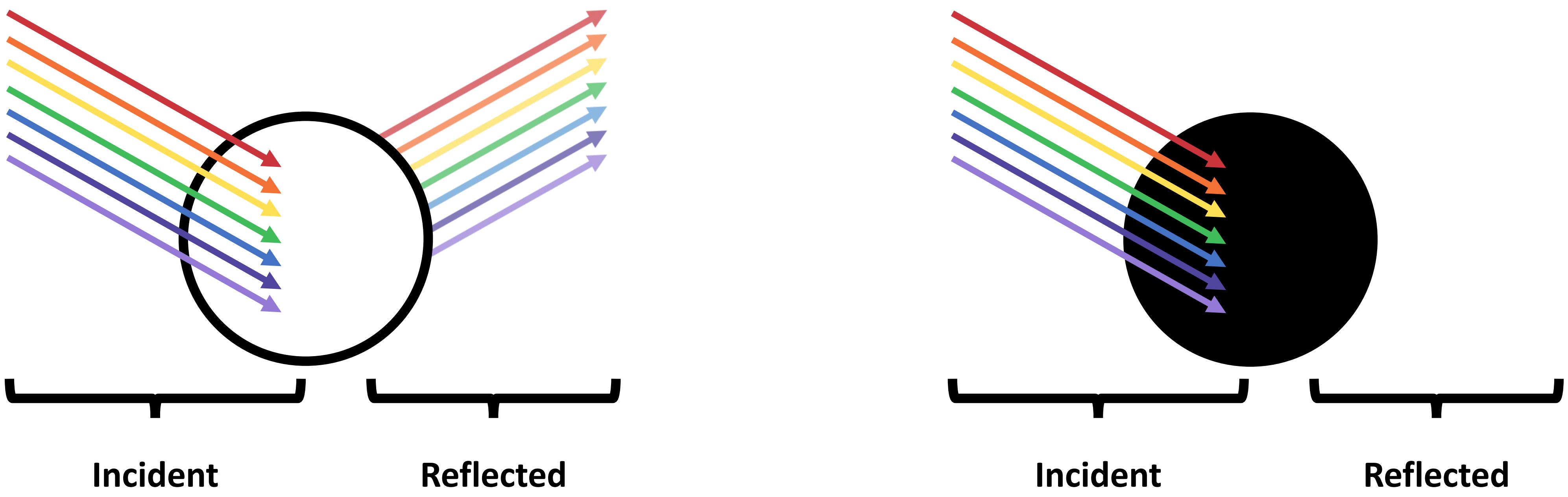
Up front conclusions

I. The ability see and perceive colour is a product of a large number of parallel processes that occur in harmony

II. The use of colour signals can significantly enhance visual performance and, as such, it’s very useful to know if an individual can make use of colour signals

III. There are many methods that have been designed for assessing human colour vision – they vary significantly in efficacy and ease of use!

Colour?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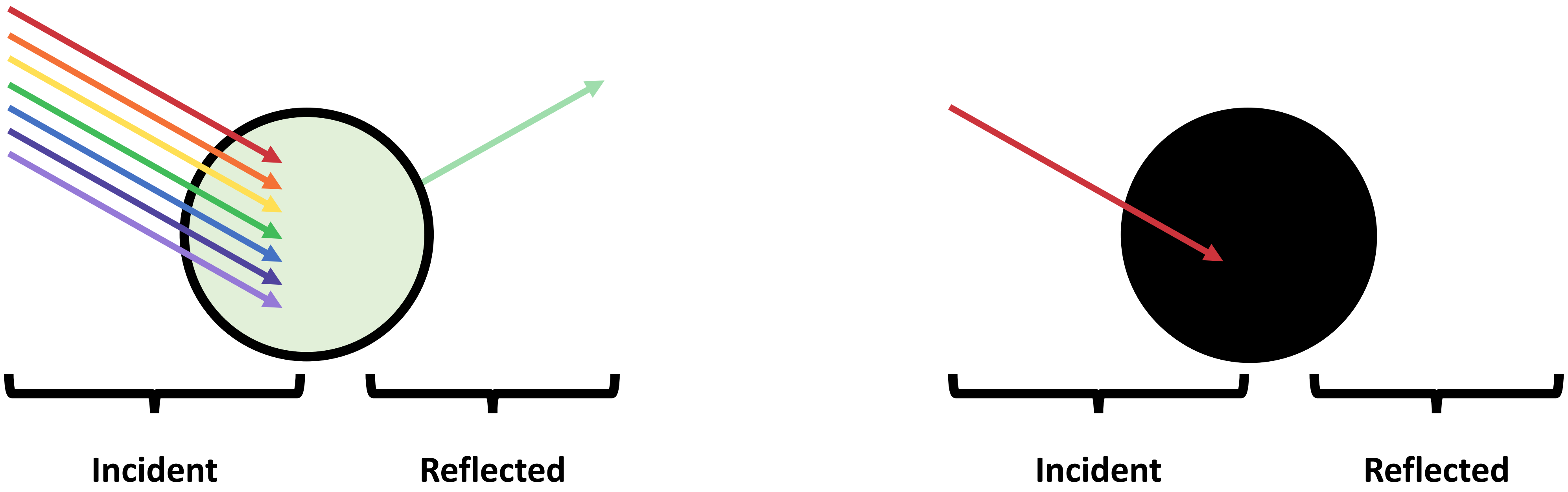
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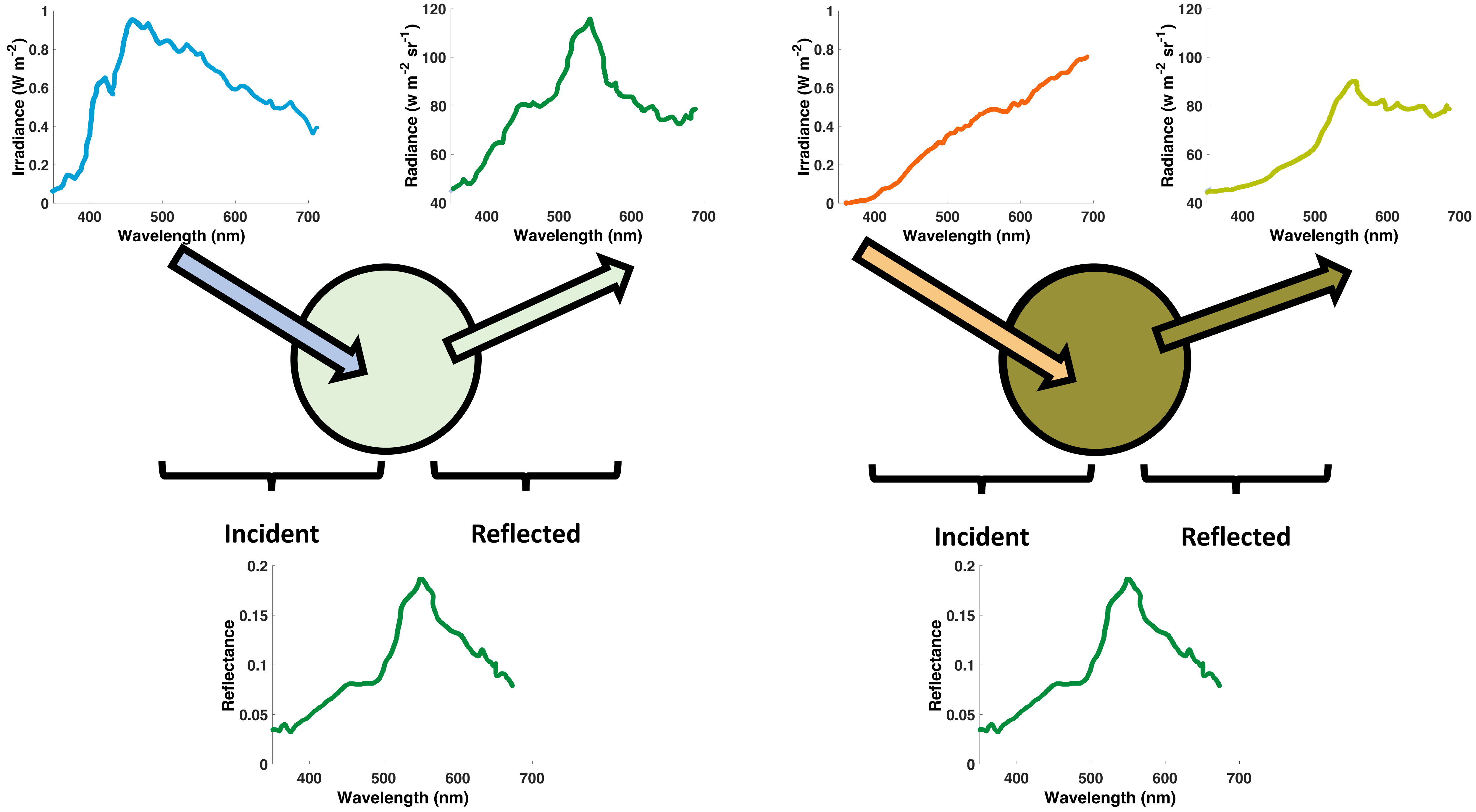

Irradiance (W m-2)
Wavelength (nm)
Radiance (w m-2 sr-1)
Wavelength (nm)
Irradiance (W m-2)
Wavelength (nm)
Radiance (w m-2 sr-1)
Wavelength (nm)
Incident
Reflected
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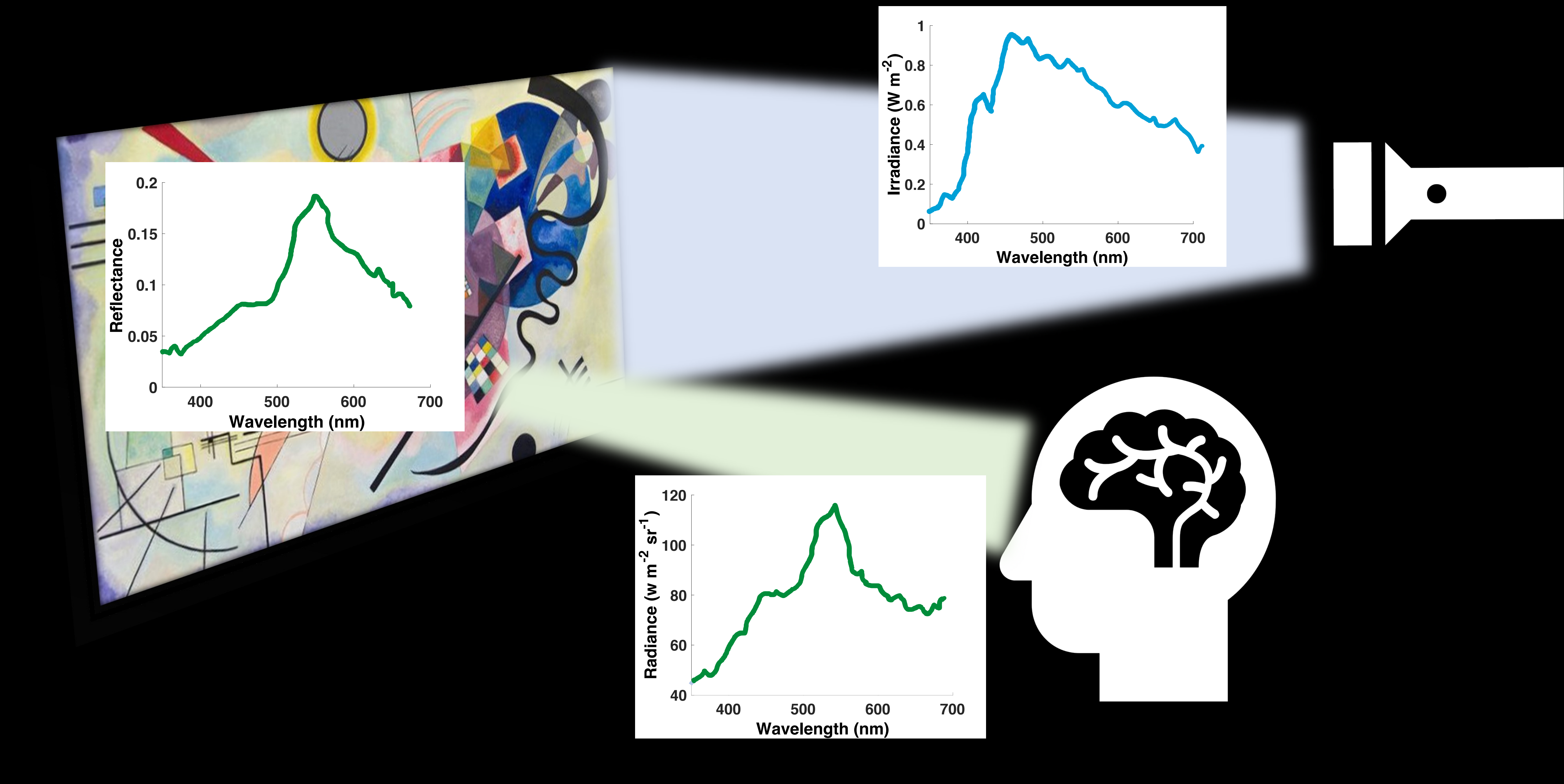
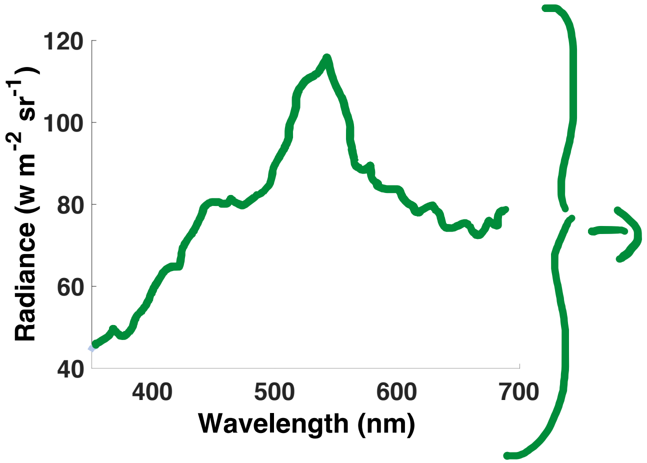
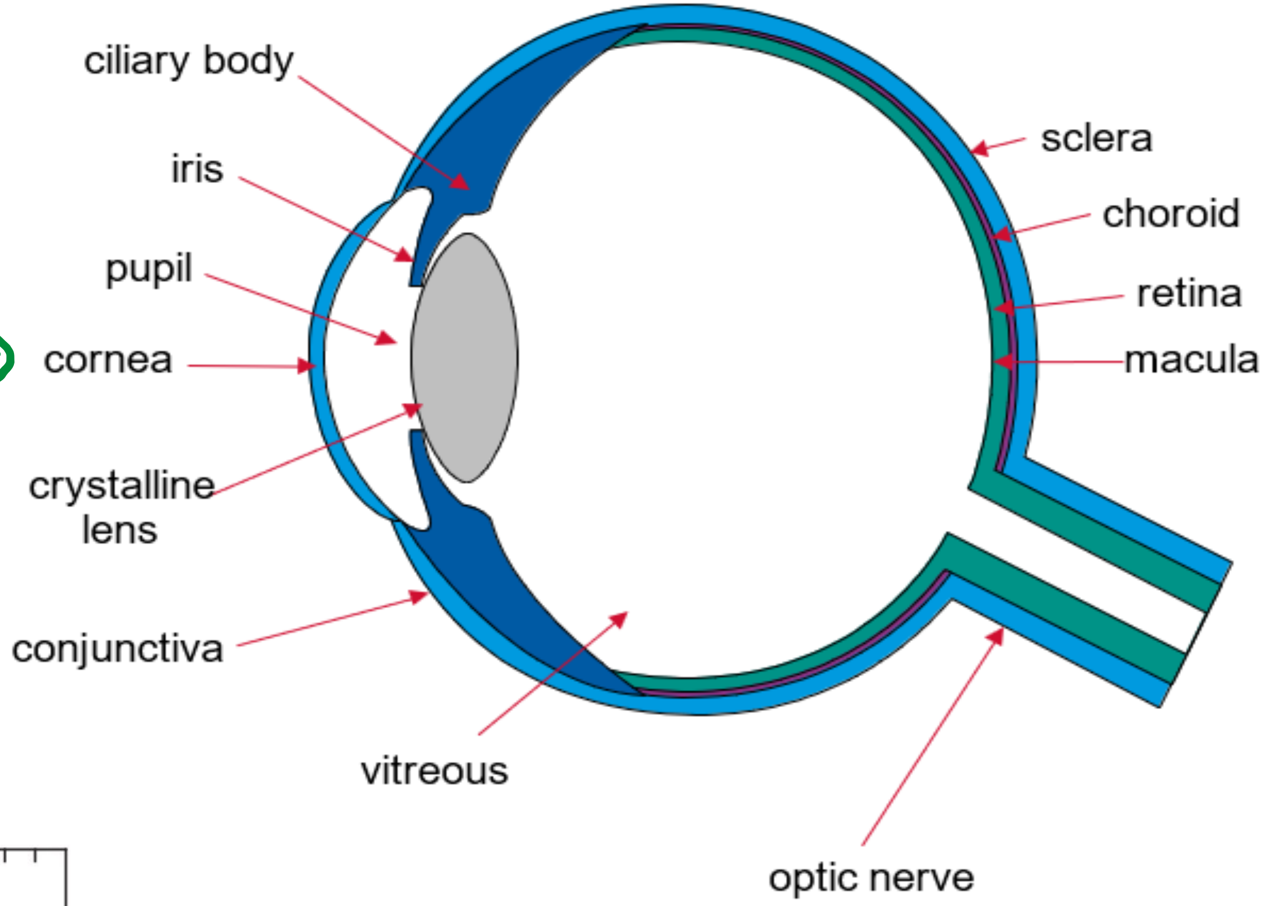
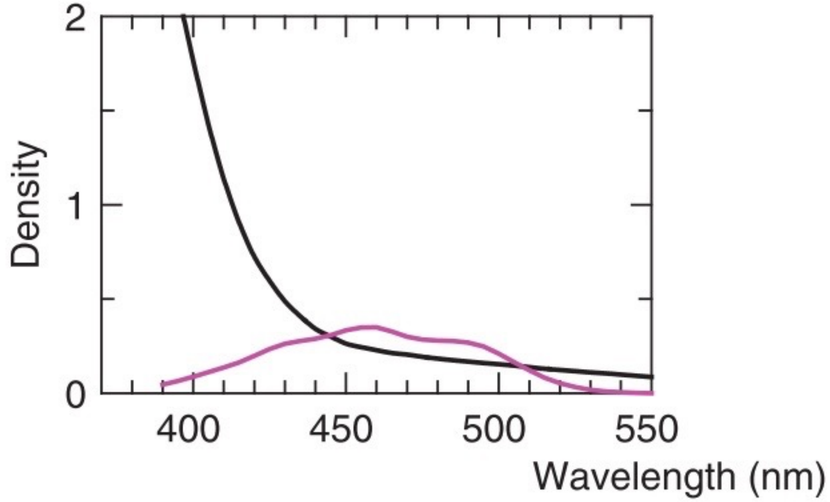
Reflectance
Wavelength (nm)
Reflectance
Wavelength (nm)

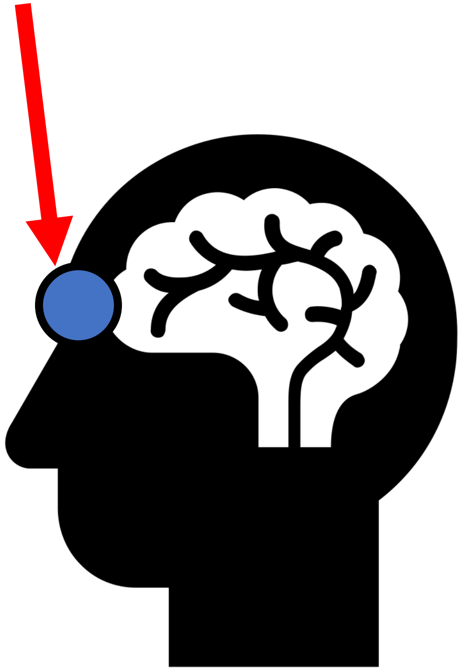


0.2
0.15
0.1
0.05
0
Reflectance
400
500
600
700
Wavelength (nm)
1
0.8
0.6
0.4
0.2
0
Irradiance (W m-2)
400
500
600
700
Wavelength (nm)
120
100
80
60
40
Radiance (w m-2 sr-1)
400
500
600
700
Wavelength (nm)

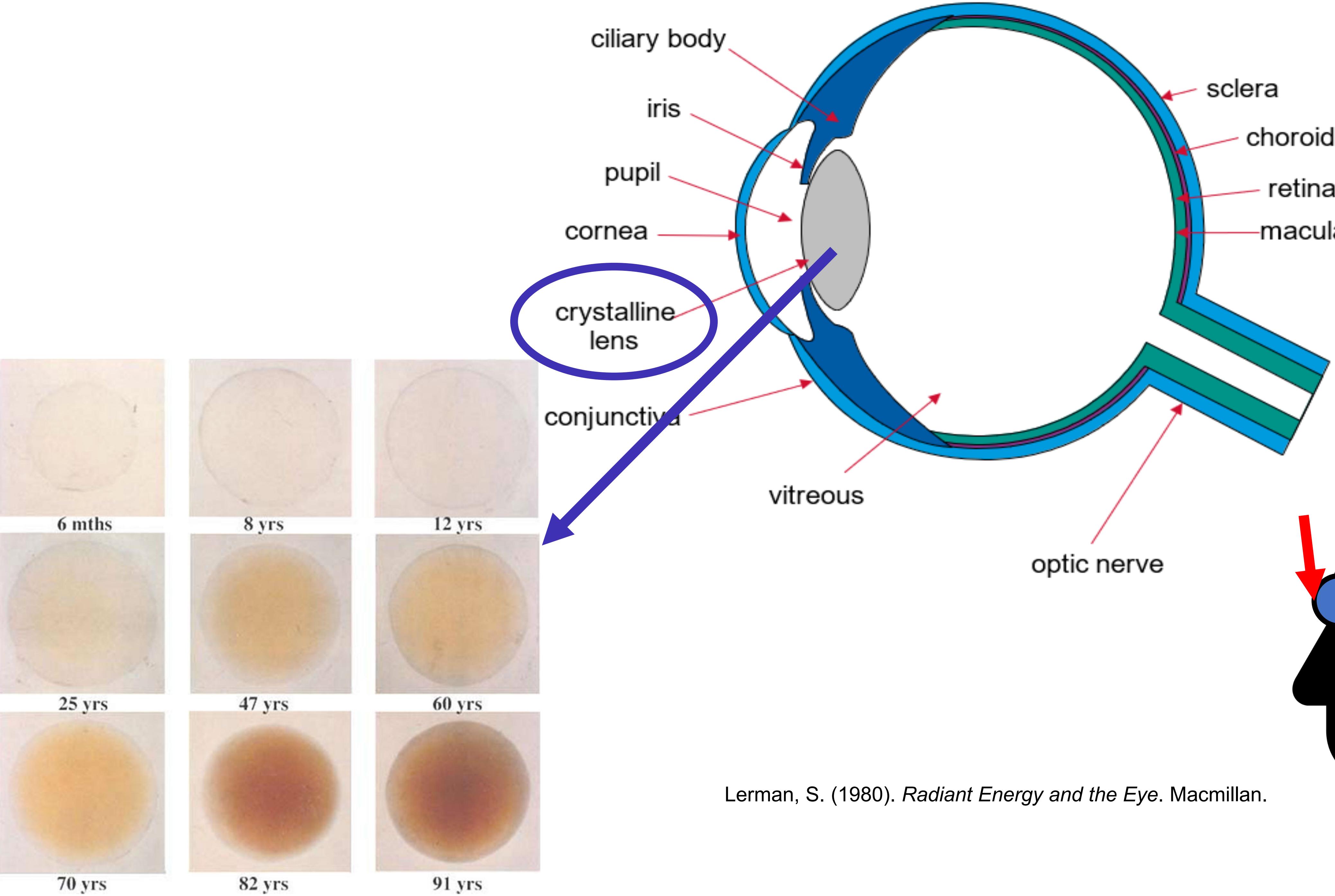


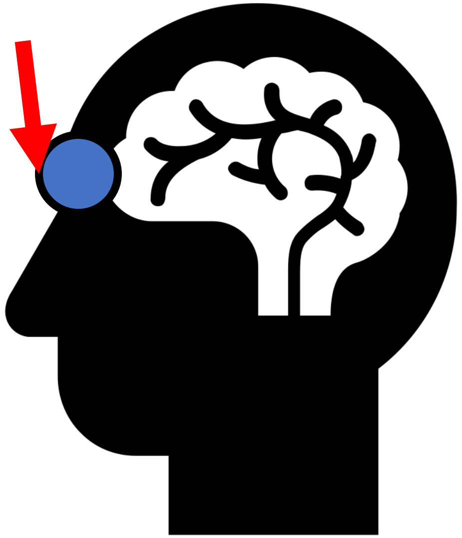




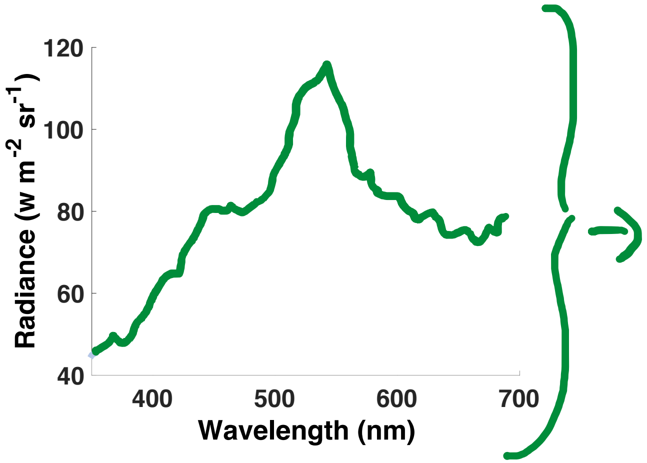


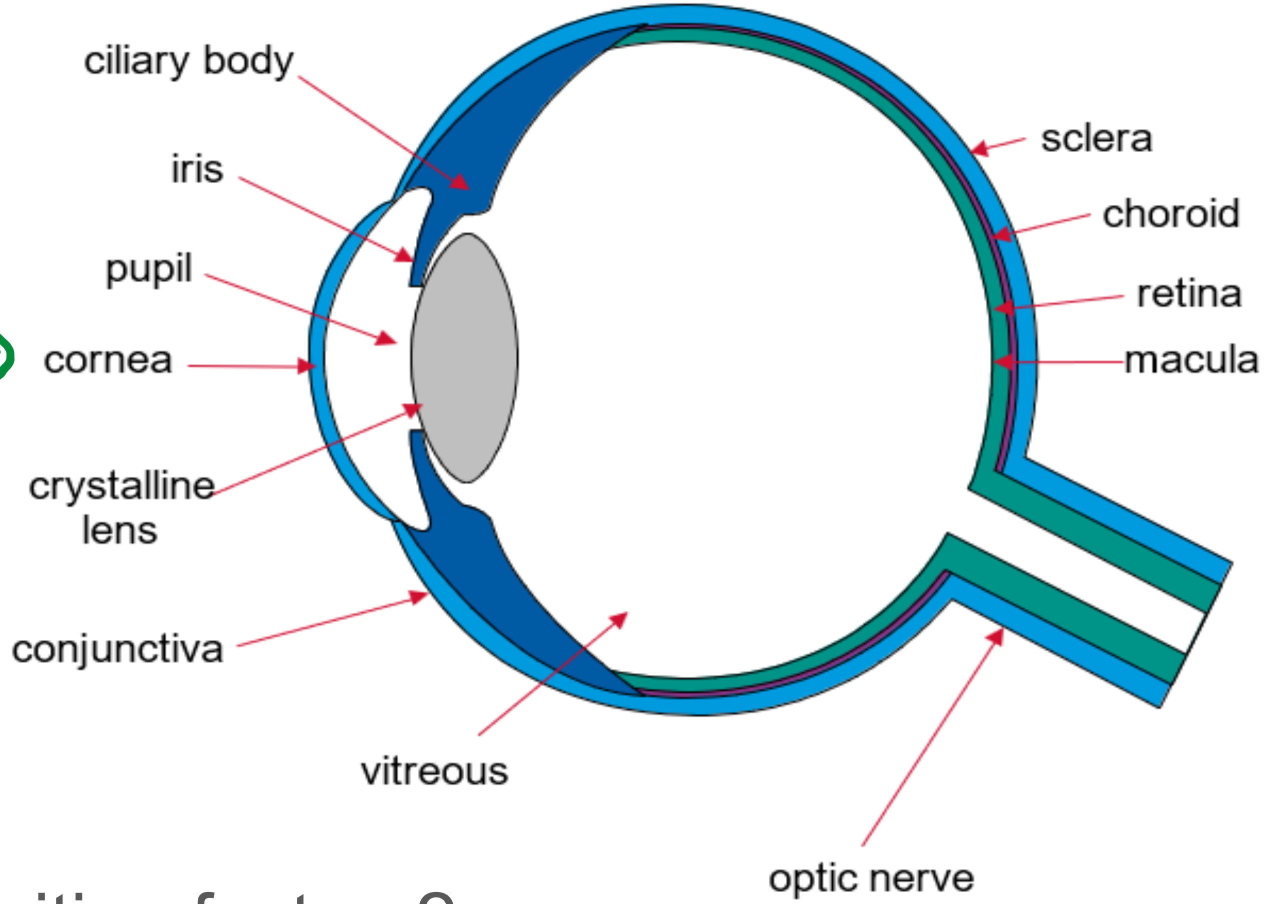
Stockman, A., & Brainard, D. H. (2015). Fundamentals of color vision I: color processing in the eye. In A. J. Elliot, M. D. Fairchild, & A. Franklin (Eds.), *Handbook of Color Psychology* (pp. 27–69). Cambridge University Press. https://doi.org/10.1017/CBO9781107337930.004

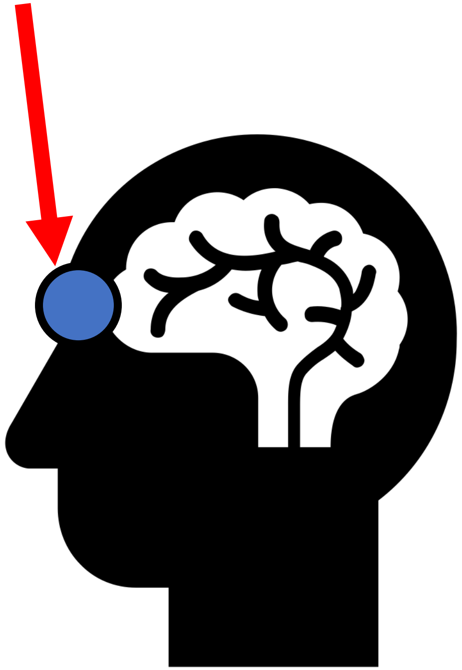




Lerman, S. (1980). *Radiant Energy and the Eye*. Macmillan.







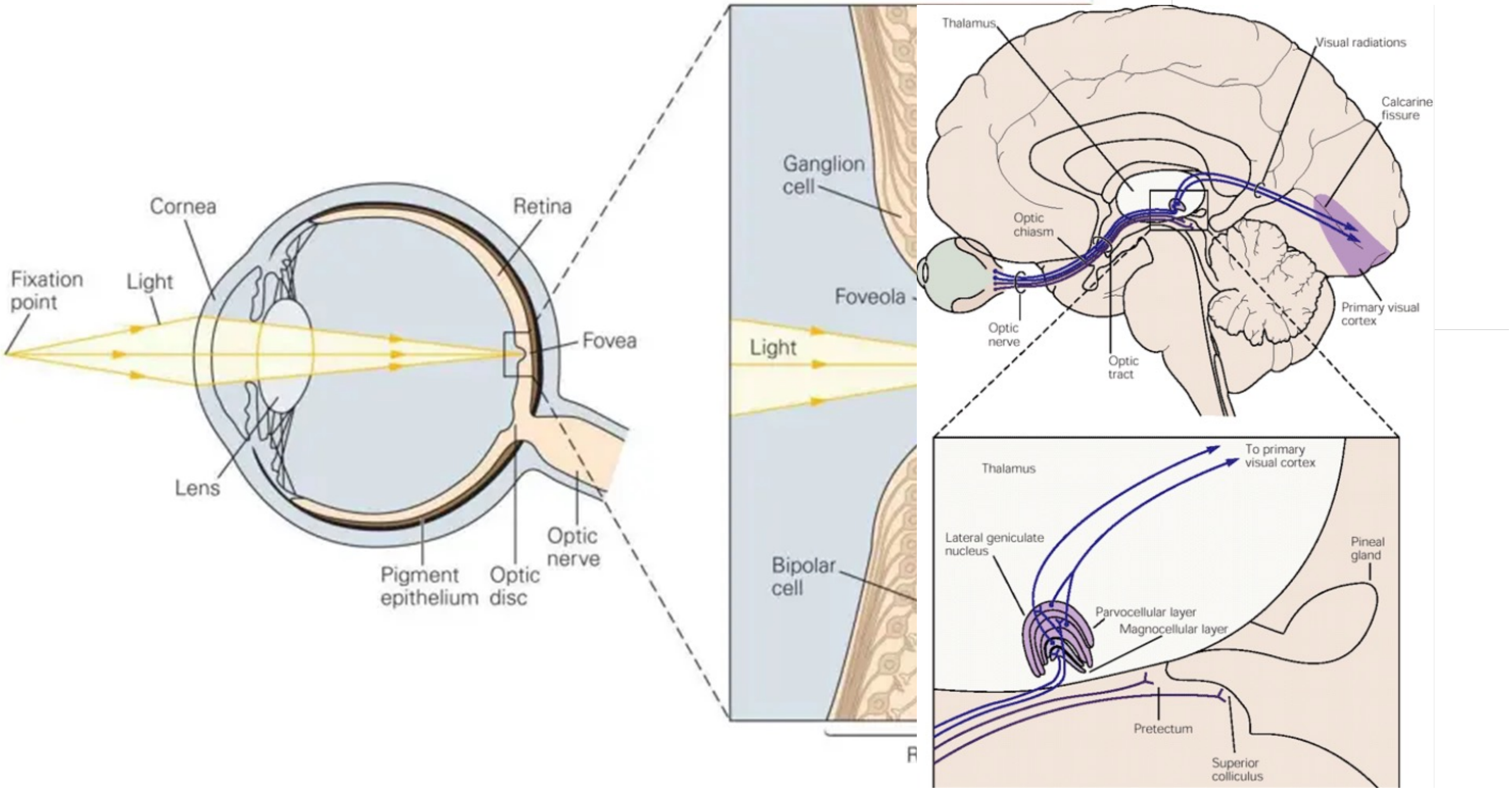
Retinal image limiting factors?

1. Diffraction
2. Aberrations

How do we ‘see’ colour?

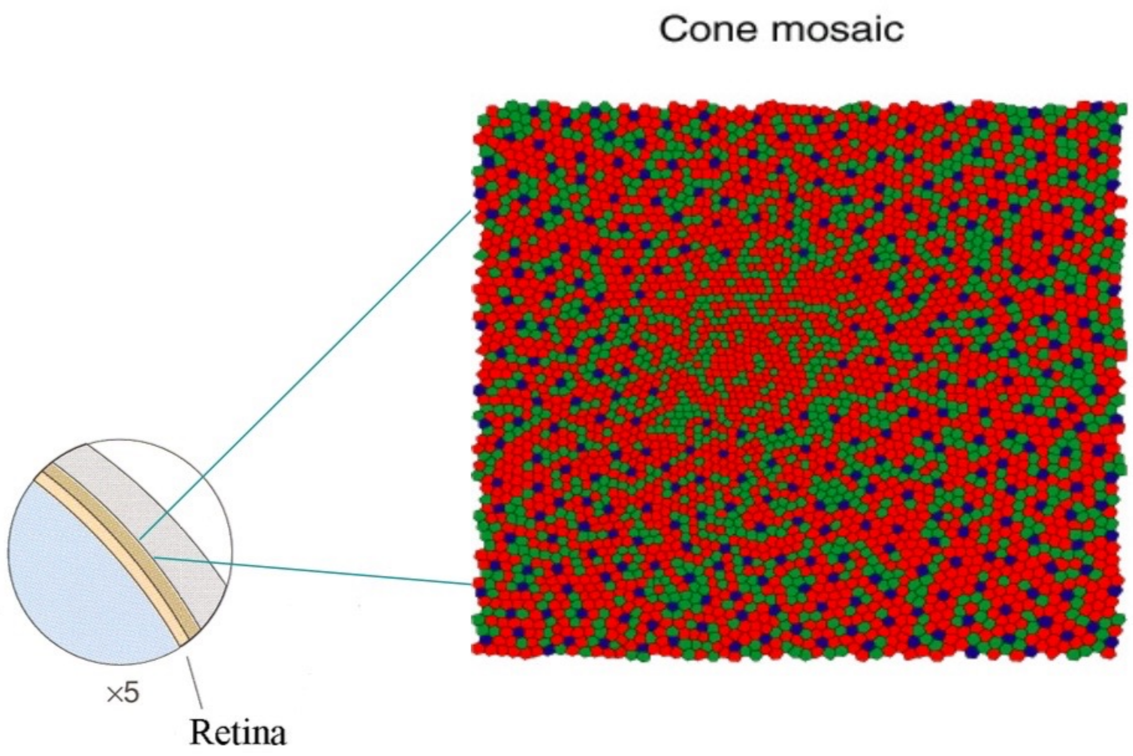
“The Cones of Dunshire.” *Parks and Recreation,* season 6, episode 9, NBC, 21 Nov. 2013.

receptoral colour vision **post receptoral colour vision**

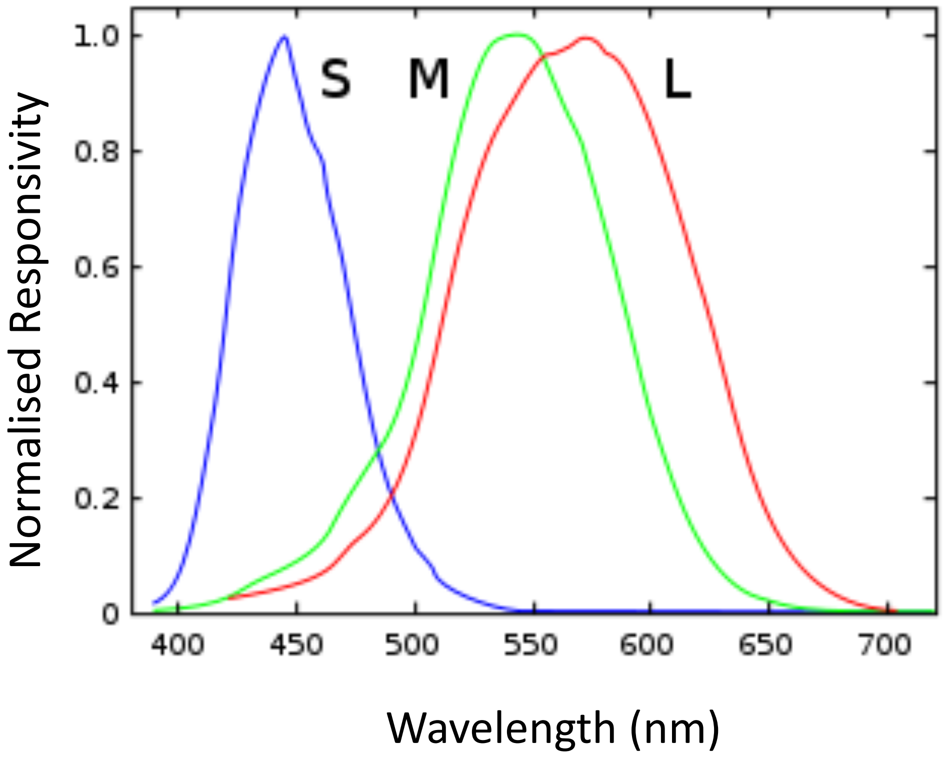


Kandel, Schwartz, and Jessell , Principles of Neural Science (4th Ed.)

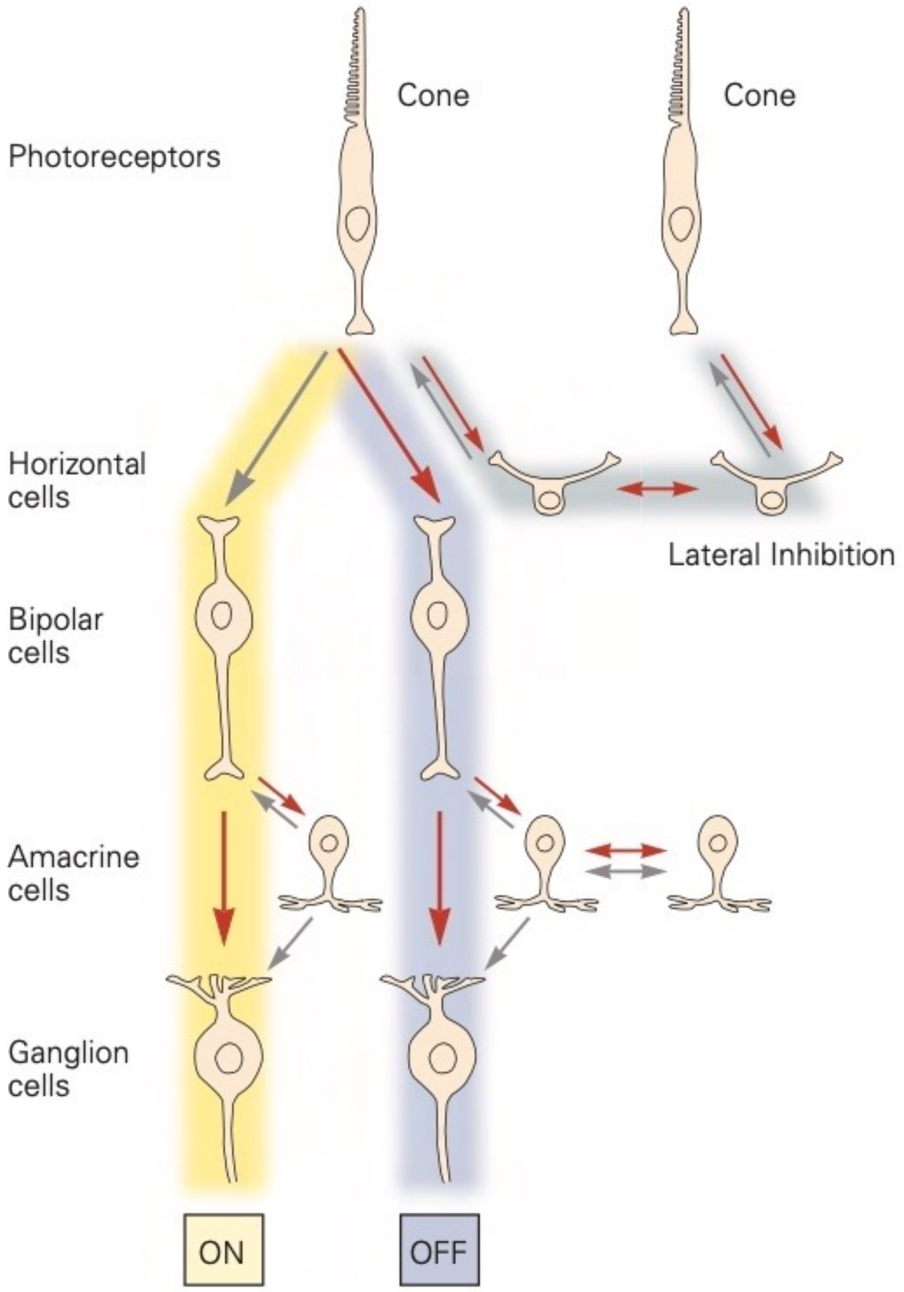
Cone photoreceptors



Andrew Stockman 'Photoreceptors', ICVS Summer School 2020



Normalised S-, M- and L-cone spectral sensitivities from Stockman & Sharpe (2000)



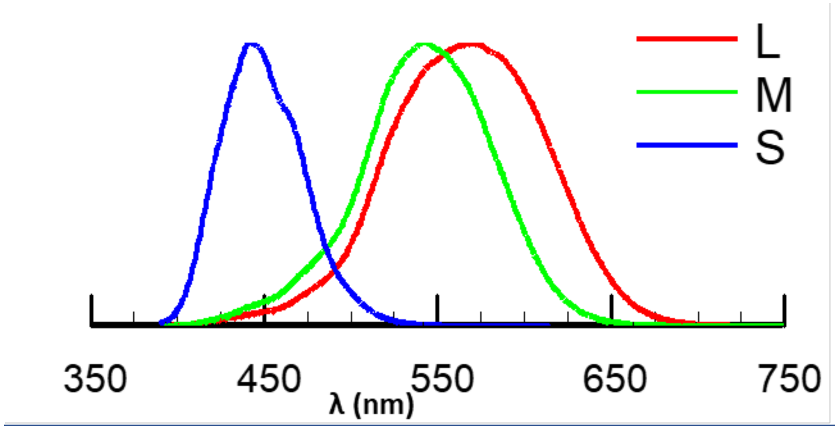
Kandel, Schwartz, and Jessell , Principles of Neural Science (6th Ed.)

The L-, M-, and S-cone signals are processed into opponent channels

1. Red/Green (L vs M)
2. Yellow/Blue (S vs [L+M])
3. Luminance contrast (Black/White)

Visual Information Channels

- Trichromatic at the receptor level + Rods
- Three opponent electrical signals at ganglion cell level
- Horizontal and Muller cells connect receptors and ganglion cells laterally within the plexiform layers and give rise to receptor fields and colour adaptation effects



Spectral Responsivity for a normal trichromat: δλ ~ 28 nm

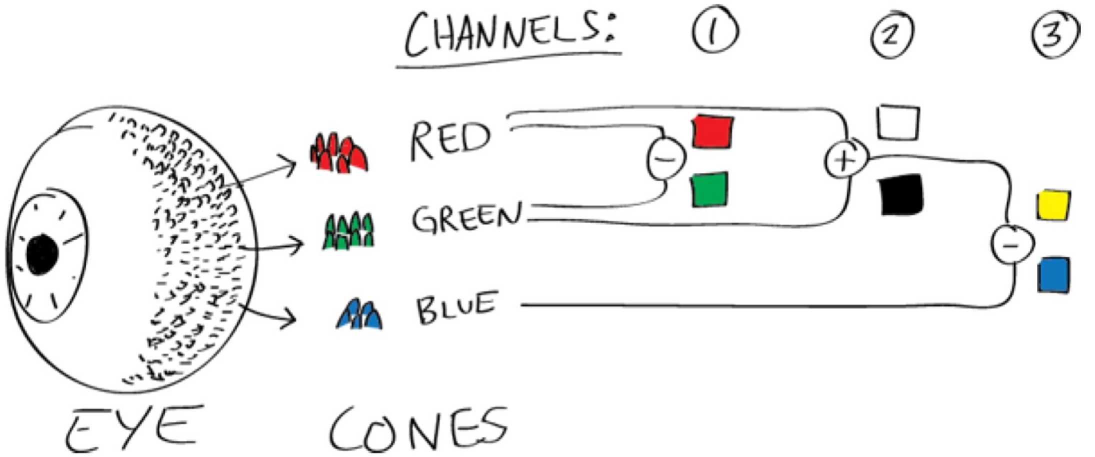


Diagram provided by Dr Marisa Rodriguez-Carmona

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- How do we see colour?
- **Why and when is a shared perception of colour is important?**
- Anomalous human colour vision?
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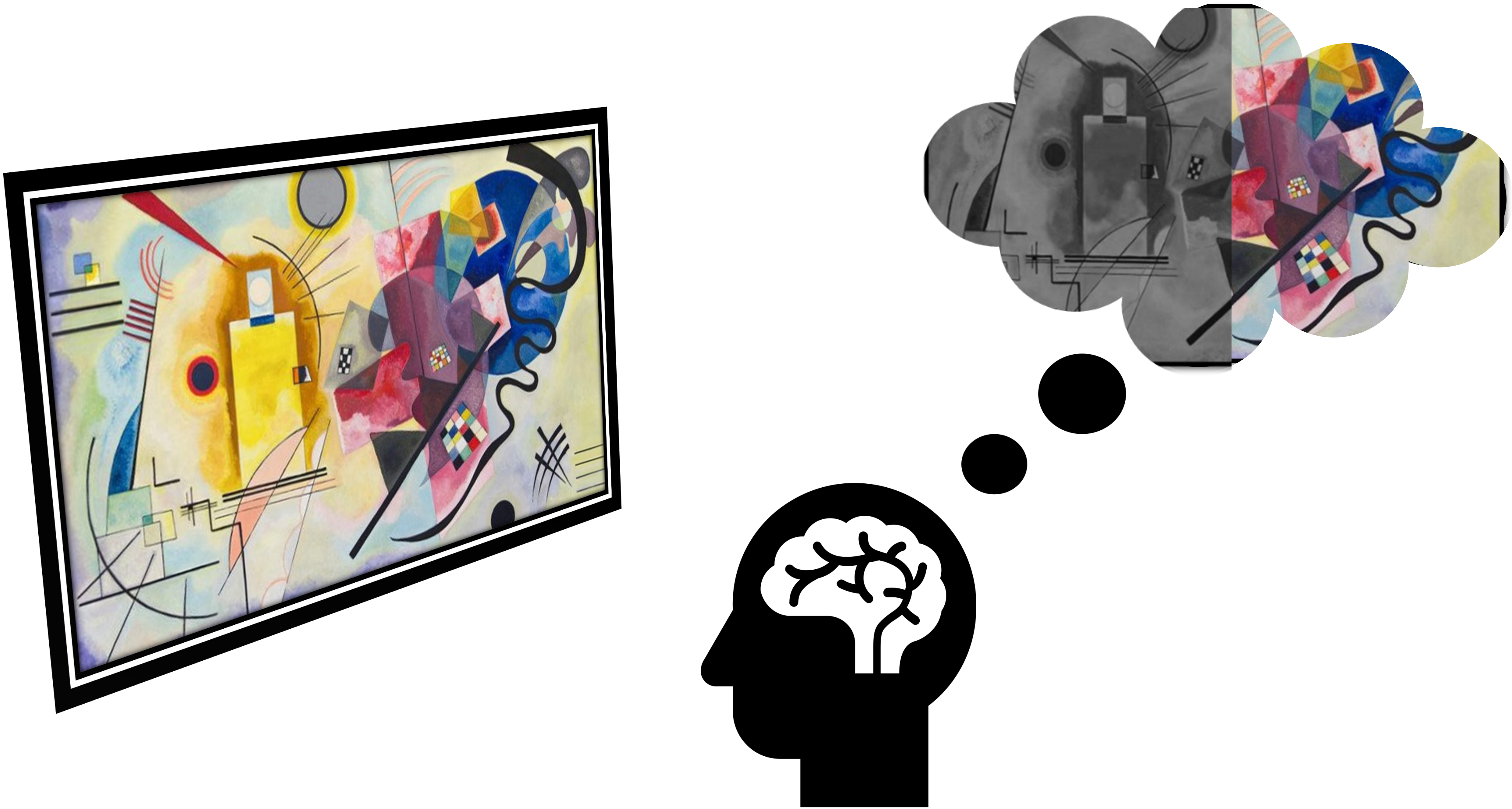
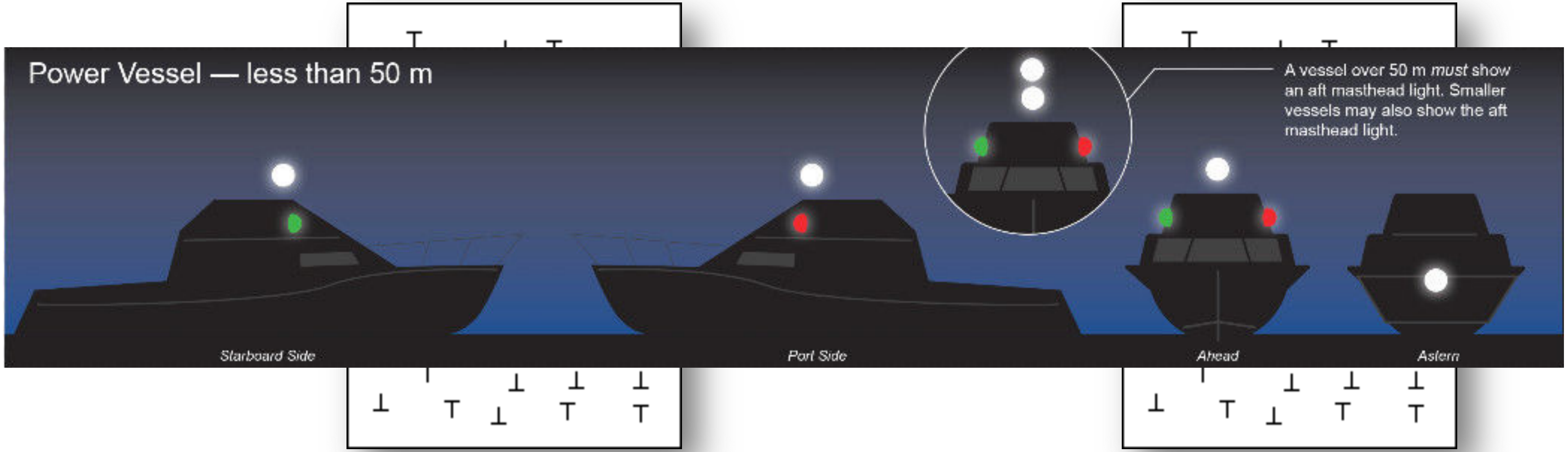


The value of colour

- Colour vision carries useful information that can greatly enhance visual performance
- In some visually demanding occupations, the use of colour signals is safety critical



Colour

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- In some visually demanding occupations, the use of colour signals is safety critical
- Specific occupational requirements
  - Pilots, Air Traffic Controllers & Railways
  - Maritime & Coastguard Agency
  - Electricians
  - Police, Fire Service & Armed Forces

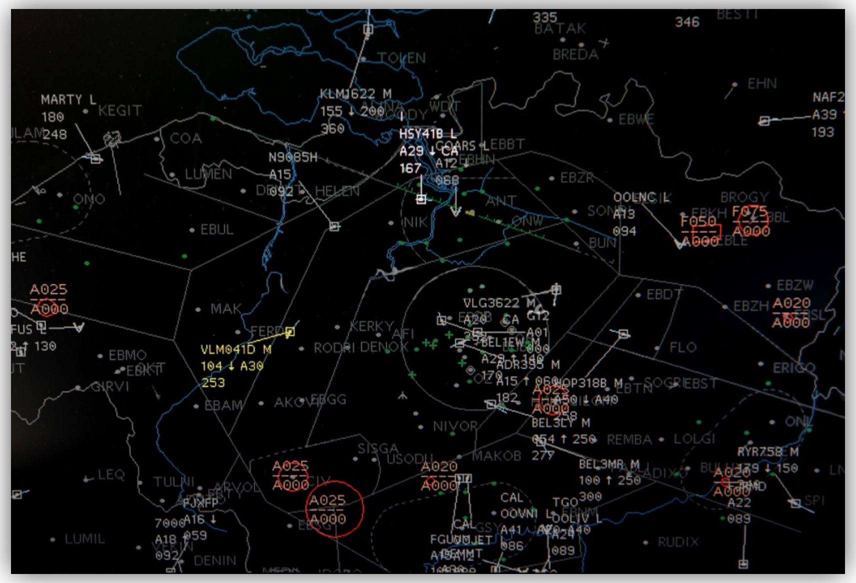

Image provided by Dr Marisa Rodriguez-Carmona

Colour

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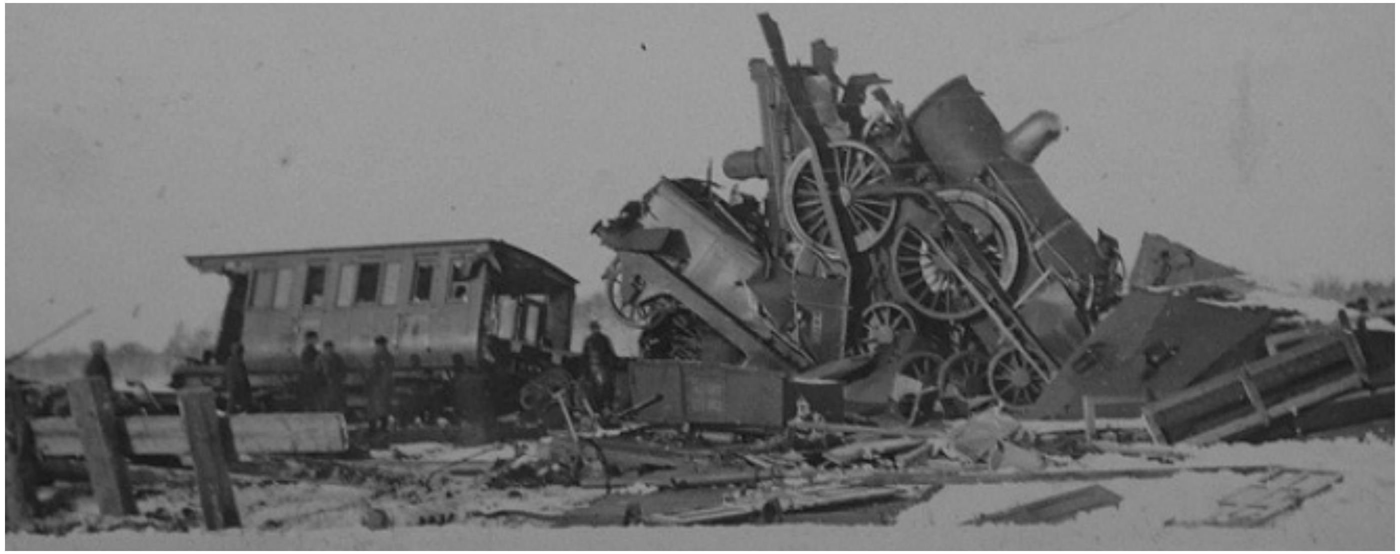
`Colourblind Tube Map' developed as a collaboration between 232 Studios and Ian Hamilton

Why occupational requirements?

- Previous accidents
  - 1875 5th July – Steamship collision with a tug off the coast of Virginia
  - 1875 15th November – Train collision in Sweden near Lagerlunda
- Both attributed to colour ‘blindness’
- Solution? → Screen for normal trichromatic colour vision



Mollon, J. D., & Cavonius, L. R. (2012). The Lagerlunda Collision and the Introduction of Color Vision Testing. Survey of Ophthalmology, 57(2), 178–194. https://doi.org/10.1016/j.survophthal.2011.10.003

Why occupational requirements?

- 2002 FedEx plane crashed short of the runway
  - Prompting the National Transportation Safety Board (NTSB) to review their colour vision requirements for pilots

"The National Transportation Safety Board determines that the probable cause of the accident was the captain's and first officer's failure to establish and maintain a proper glidepath during the night visual approach to landing.
Contributing to the accident was a combination of the captain's and first officer's fatigue, the captain's and first officer's failure to adhere to company flight procedures, the captain's and flight engineer's failure to monitor the approach, **and the first officer's color vision deficiency**."

National Transportation Safety Board. 2004. Collision With Trees on Final Approach, Federal Express Flight 1478, Boeing 727-232, N497FE, Tallahassee, Florida, July 26, 2002. Aircraft Accident Report NTSB/AAR-04/02. Washington, DC.

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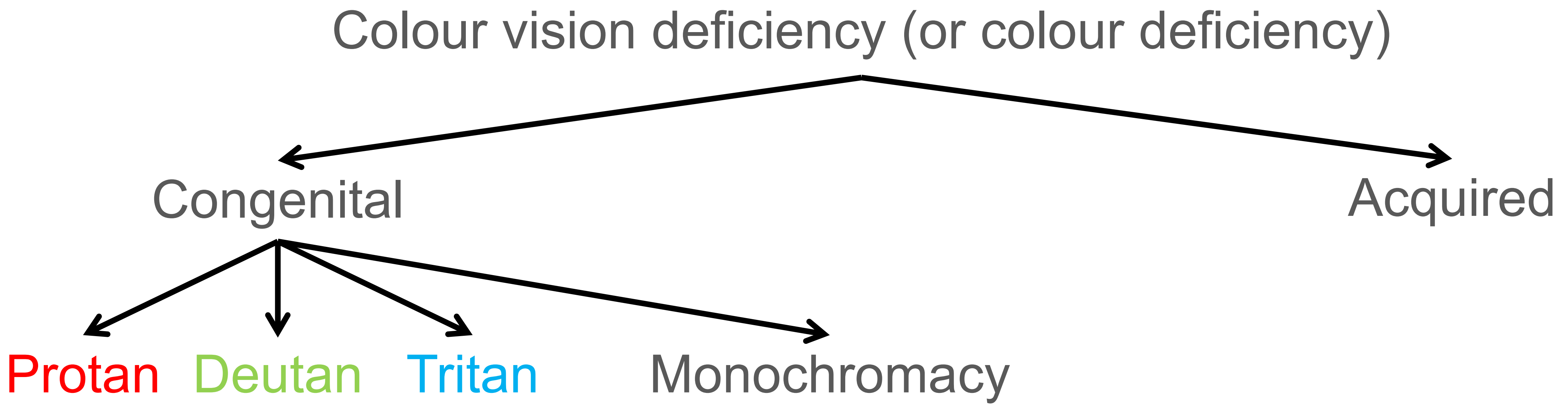
How can human colour vision be abnormal?

Colour & Colour Vision Deficiency

- At the first level of classification
  - Congenital/Acquired
- Congenital
  - Protan/Deutan/Tritan – depending upon the class of cone photoreceptor that is abnormal or absent



Type of colour deficiency	Male (%)	Female (%)
Protanopia	1.01	0.02
Protanomaly	1.08	0.03
Deuteranopia	1.27	0.01
Deuteranomaly	4.63	0.36
Tritanopia	~0.2 (1 in 500)	
Number	45,989	30,711
Total prevalence (%)	7.99	0.42

How risk should be described in healthcare

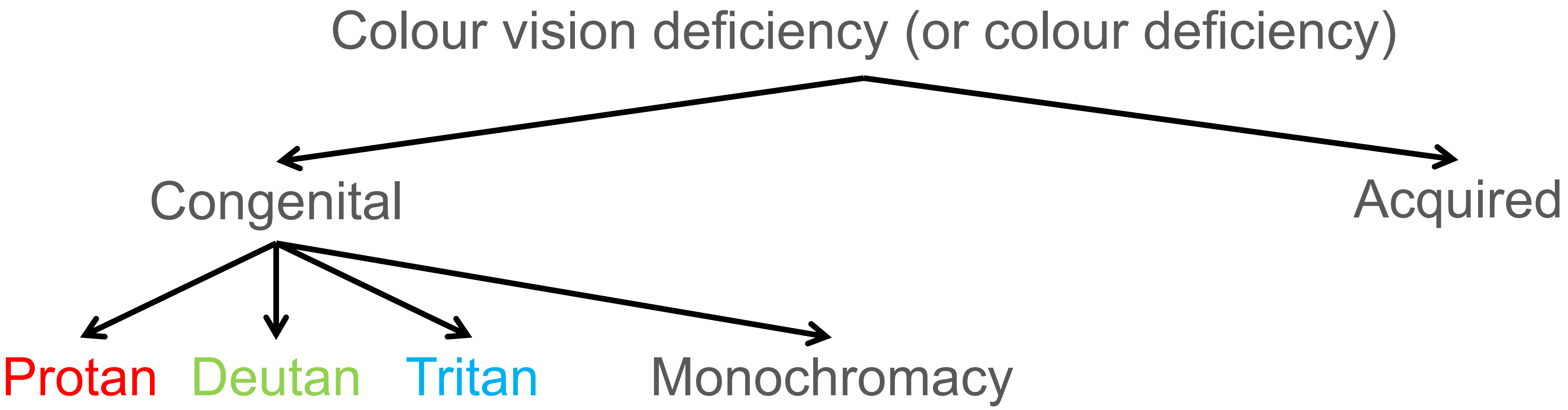
Verbal description[a]	Risk	Risk description[b]
Very common	1 in 1 to 1 in 10	A person in family
Common	1 in 10 to 1 in 100	A person in street
Uncommon	1 in 100 to 1 in 1,000	A person in village
Rare	1 in 1,000 to 1 in 10,000	A person in small town
Very rare	Less than 1 in 10,000	A person in large town

[a] EU-assigned frequency [b] Unit in which one adverse event would be expected

RCOG, 2015

Sharpe L, Stockman A, Jagle H, Nathans J. Opsin genes, cone photopigments, color vision and color blindness, in Gegenfurtner K, Sharpe L (eds) Color Vision. Cambridge, Cambridge University Press; 1999

Simunovic, M. P. (2016). Acquired color vision deficiency. *Survey of Ophthalmology*, *61*(2), 132–155. https://doi.org/10.1016/j.survophthal.2015.11.004



Acquired Colour Vision Deficiency

- Result of ocular or general pathology, intracranial injury or prolonged drug use
- Can originate anywhere in the visual pathway
- Can be an early symptom in some pathological conditions
  - Diabetes
  - Optic neuropathy
- When measured and monitored can be used to assist with medical diagnoses

Roy MS, Gunkel RD, Podgor MJ. Color Vision Defects in Early Diabetic Retinopathy. *Arch Ophthalmol.* 1986;104(2):225–228. doi:10.1001/archopht.1986.01050140079024

Green FD, Ghafour IM, Allan D, Barrie T, McClure E, Foulds WS. Colour vision of diabetics. Br J Ophthalmol. 1985 Jul;69(7):533-6. doi: 10.1136/bjo.69.7.533. PMID: 3874649; PMCID: PMC1040663.

Acquired vs Congenital

Congenital Colour Deficiency	**Acquired colour deficiency**
Present at birth	Onset after birth (after 3 months)
Type and severity the same throughout life	Type and severity changes with time
Visual acuity normal (except in monochromatism)	Reduced visual acuity and/or visual field defects
Easy to classify and diagnose the type of deficiency	Combines the characteristics of more than one type of congenital colour deficiency
Both eyes equally affected	Monocular differences in severity
Higher prevalence in males	Equal prevalence in males and females
Predominantly red-green	

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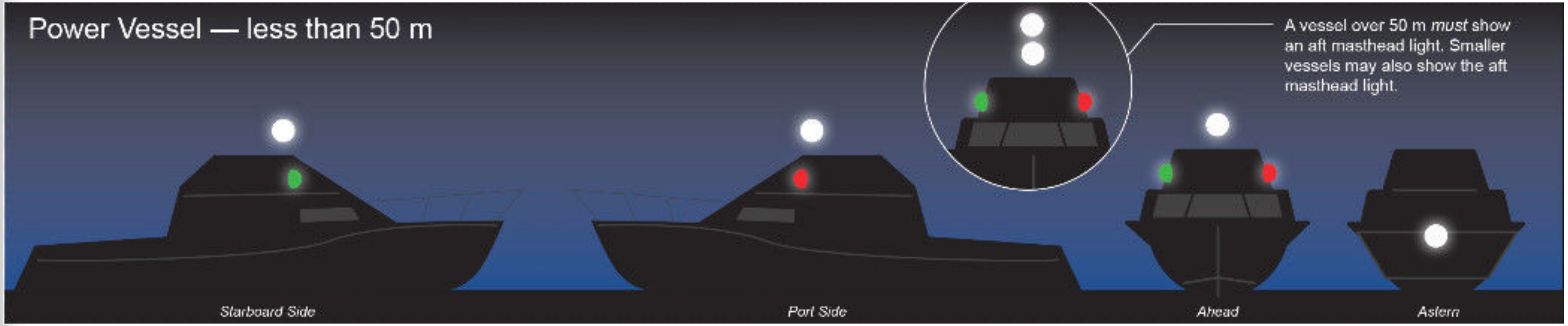
How can we quantify human colour vision?

The ‘first’ colour vision tests

- [1684] Turberville – Colour naming
- [1798] Dalton (& [1837] Seebeck) – Colour ribbons
- [1877] Stilling – First pseudoisochromatic plate test

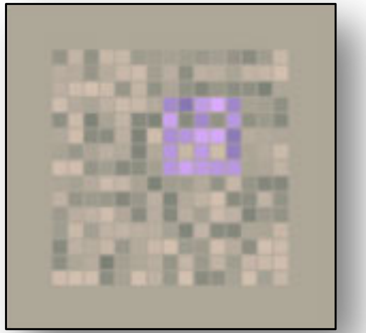
Holmes-Wright Lantern



Assessing Colour Vision

There are 3 stages in assessing an individuals colour vision:

1. Screen for normal red/green and yellow/blue colour vision
2. Classify type of colour vision defect
3. Quantify severity of the red/green and yellow/blue colour vision loss/sensitivity loss



CAD test

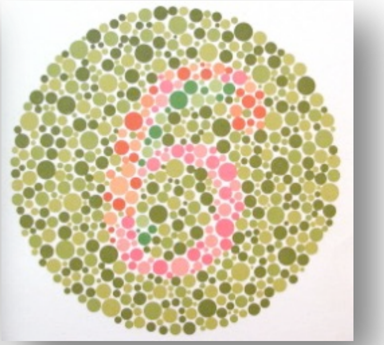
Holmes-Wright Lantern

Nagel Anomaloscope

City University Test (2nd Edition)

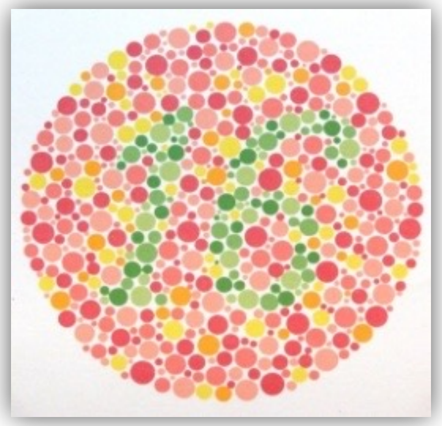
Colour Vision Assessment

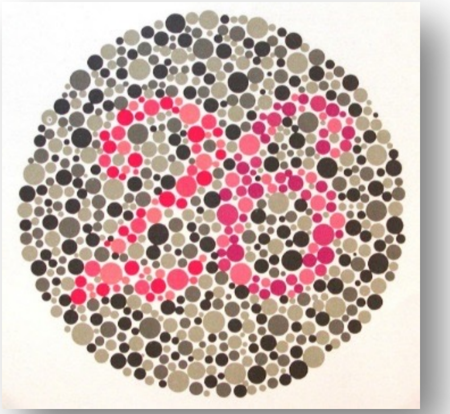
- Pseudoisochromatic plates
  - Ishihara
  - American Optical - Hardy-Rand-Rittler (AO-HRR)



Examples of pseudoisochromatic plates (left: AO-HRR, right: Ishihara)

- Ishihara plate types [38 plate Ed.]
  - Introduction [1]
  - Transformation [2-9]
  - Vanishing [10-17]
  - Hidden digits [18-21]
  - Classification [22-25]





Colour Vision Assessment

- Hue Discrimination
  - Farnsworth D-15
  - Farnsworth-Munsell 100 Hue
  - City University (2nd & 3rd Ed.)

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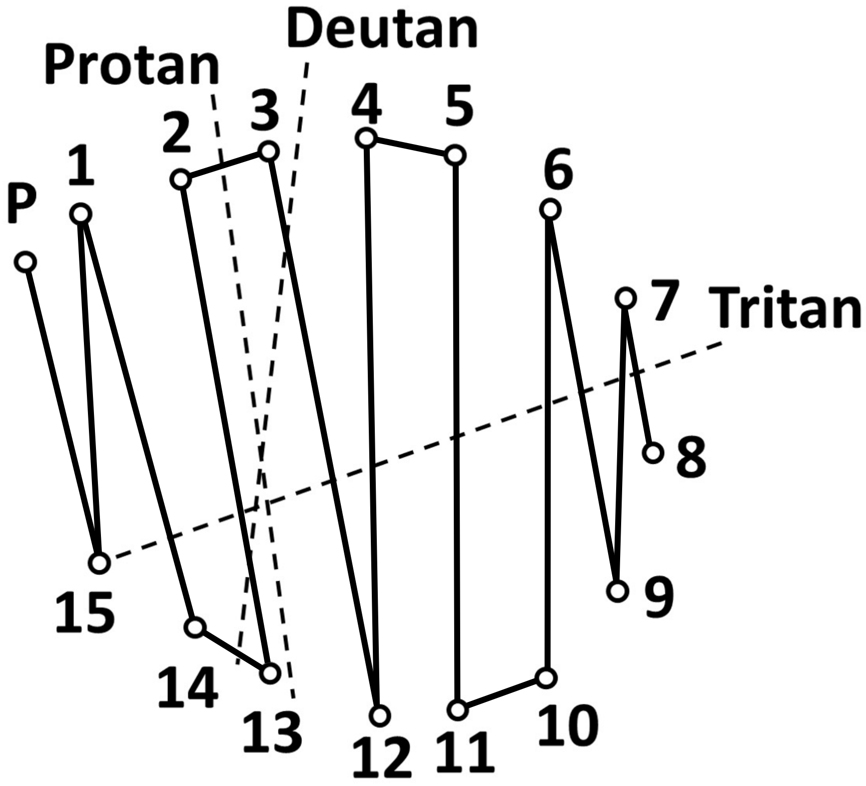
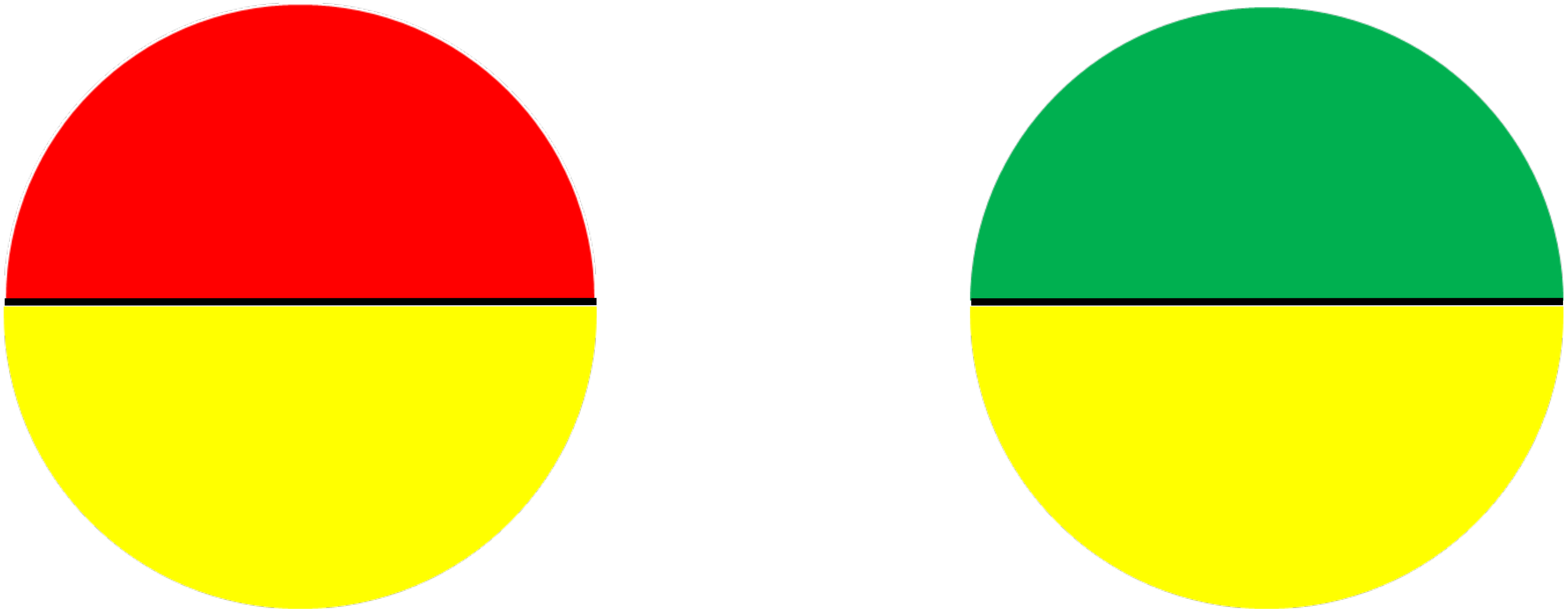
Normal



Farnsworth D-15 Results Diagram

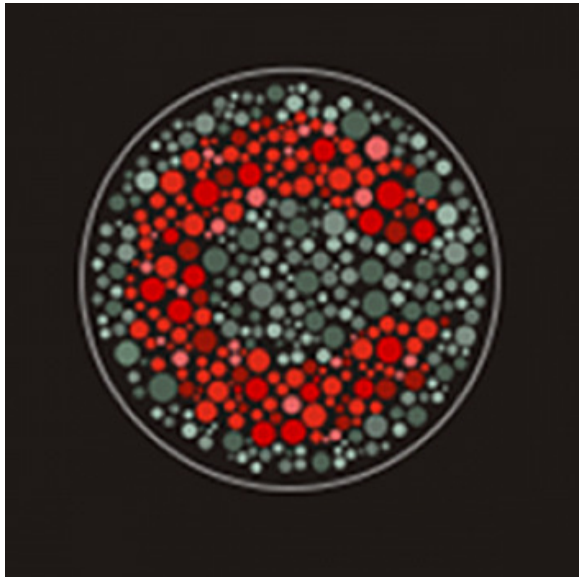
Colour Vision Assessment

- Spectral Anomaloscopes
  - Rayleigh match



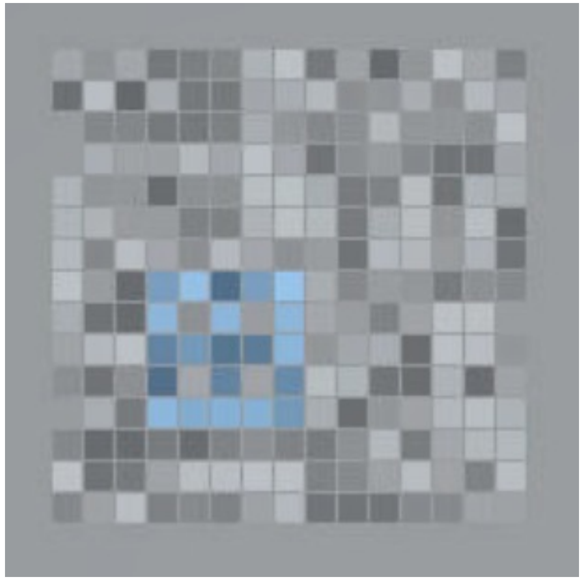
Colour Vision Assessment

- Computerised diagnostic tests
  - Colour Assessment & Diagnosis (CAD)
  - Cambridge Colour Test (CCT)



https://www.crsltd.com/tools-for-vision-science/measuring-visual-functions/cambridge-colour-test/

CCT



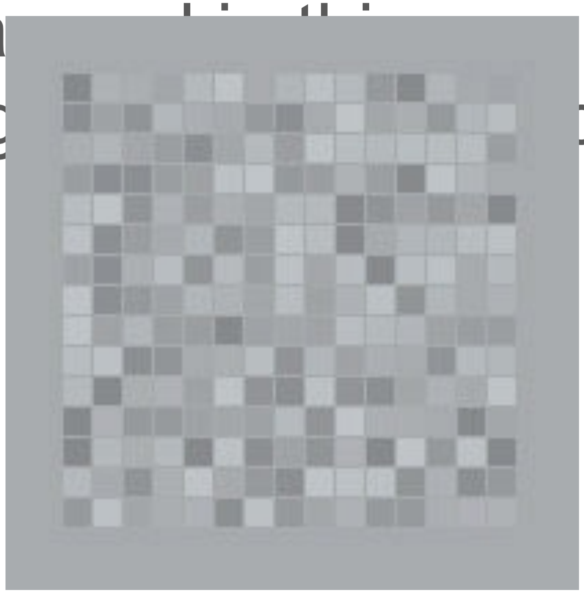
CAD test

Colour Assessment & Diagnosis Test

- Measures both red-green and yellow-blue chromatic sensitivity
- Uses dynamic luminance contrast noise to isolate colour signals
  - Evidence for the independent processing of luminance and colour signals

[Barbur 2004, Barbur et al 1994, Barbur et al 1993]

- Colour thresholds mea are proportional to the cone contrast signals g coloured stimulus

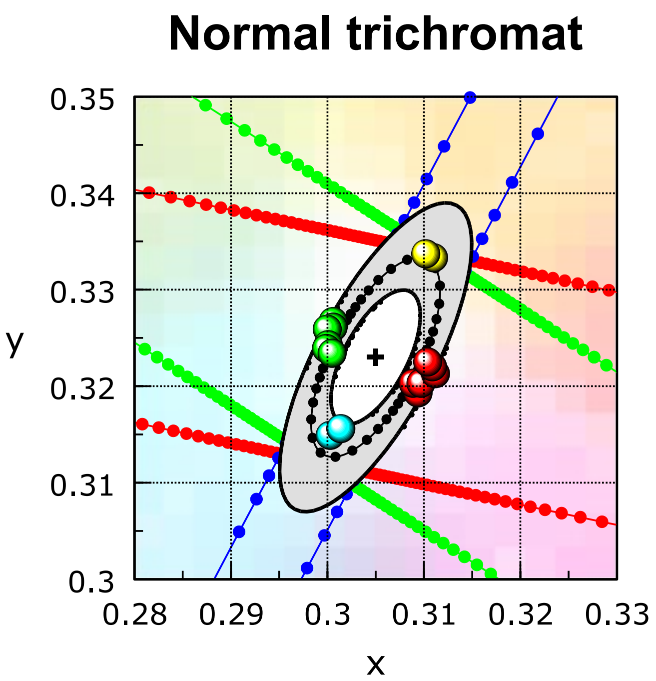


Barbur, J. L. (2004). “Double-blindsight” revealed through the processing of color and luminance contrast defined motion signals. *Progress in Brain Research*, *144*, 243–259. https://doi.org/10.1016/S0079-6123(03)14417-2

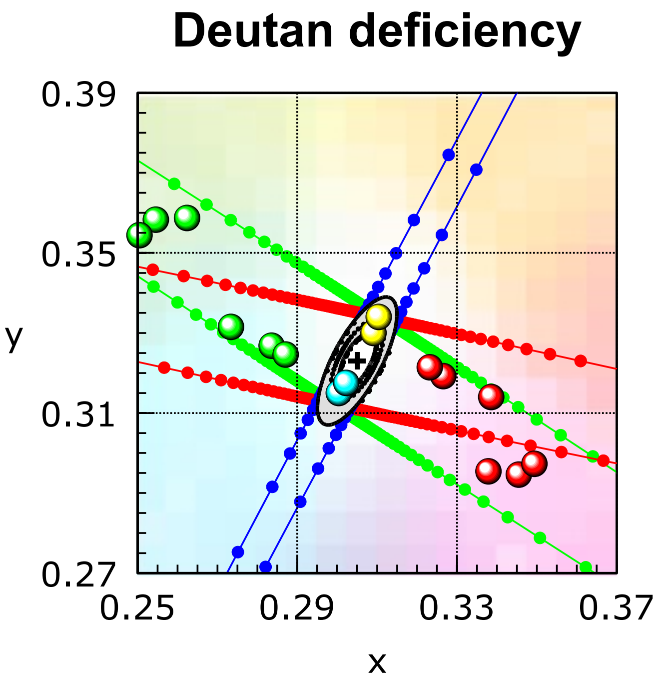
Barbur, J. L., Birch, J., & Harlow, A. J. (1993). Colour vision testing using spatiotemporal luminance masking. In *Colour Vision Deficiencies vol. XI* (pp. 417–426). https://doi.org/10.1007/978-94-011-1856-9_42

Barbur, J. L., Harlow, A. J., & Plant, G. T. (1994). Insights into the Different Exploits of Colour in the Visual Cortex. *Proceedings of the Royal Society B: Biological Sciences*, *258*(1353), 327–334. https://doi.org/10.1098/rspb.1994.0181

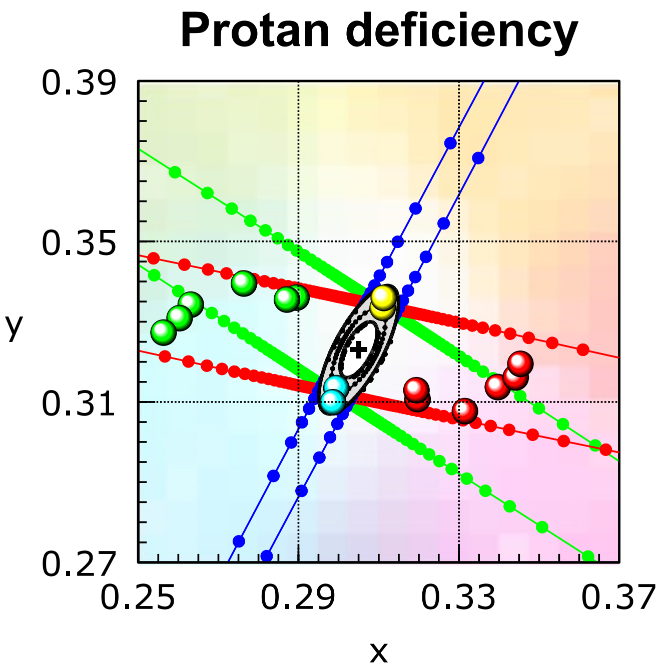
Colour Assessment & Diagnosis Test



CAD Thresholds:
RG = 1.22
YB = 1.09



CAD Thresholds:
RG =11.72
YB = 0.81



CAD Thresholds:
RG = 9.12
YB = 1.17

Conclusions

I. The ability see and perceive colour is a product of a large number of parallel processes that occur in harmony
II. The use of colour signals can significantly enhance visual performance and, as such, it’s very useful to know if an individual can make use of colour signals
III. There are many methods that have been designed for assessing human colour vision – they vary significantly in efficacy and ease of use!