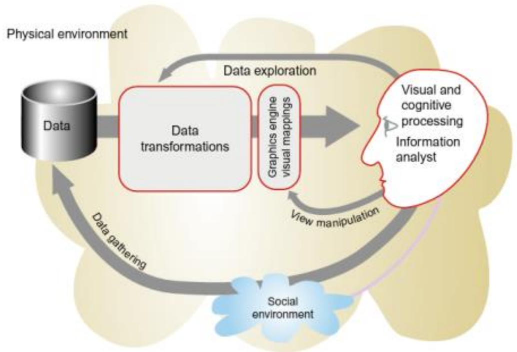
CS-E4840
Information Visualization
Lecture 6: Human perception

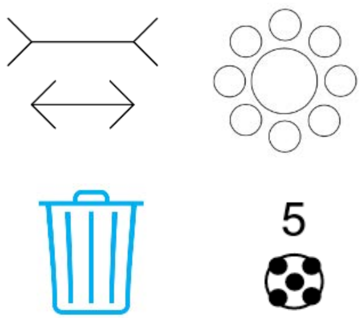
Tassu Takala <tapio.takala@aalto.fi>
18 March 2021

Recap of last lecture

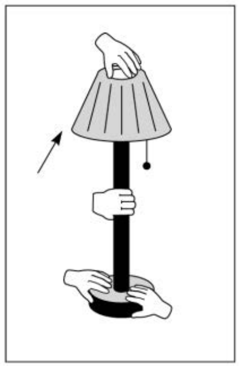
visualization process



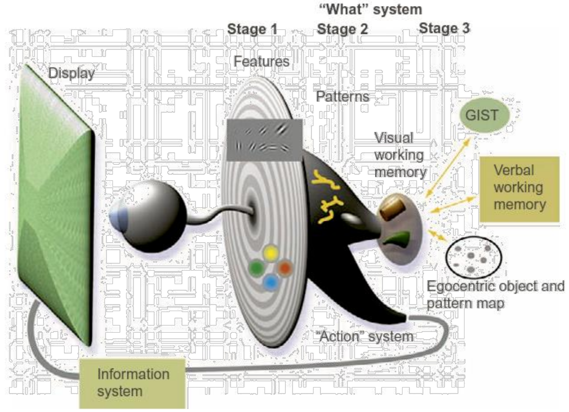
semiotics
sensory & arbitrary symbols

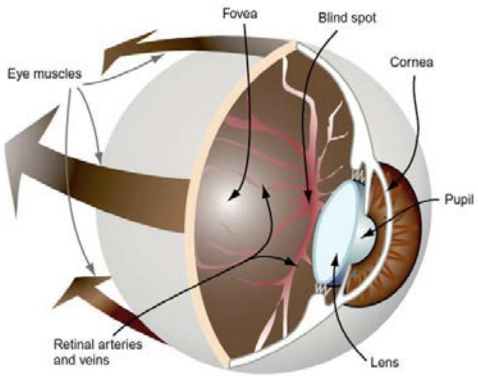


affordance theory

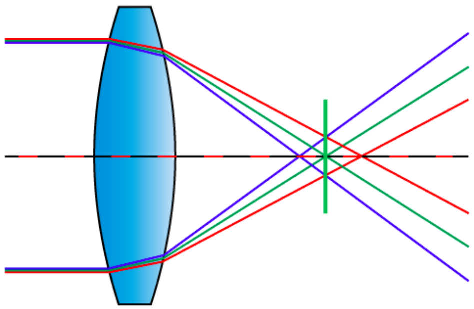


model of perceptual processing

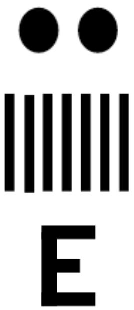




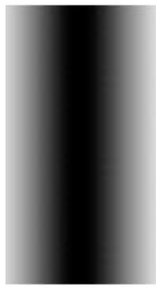
human eye



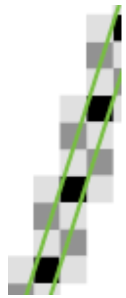
optics



visual acuity



contrast sensitivity
visual stress



displays

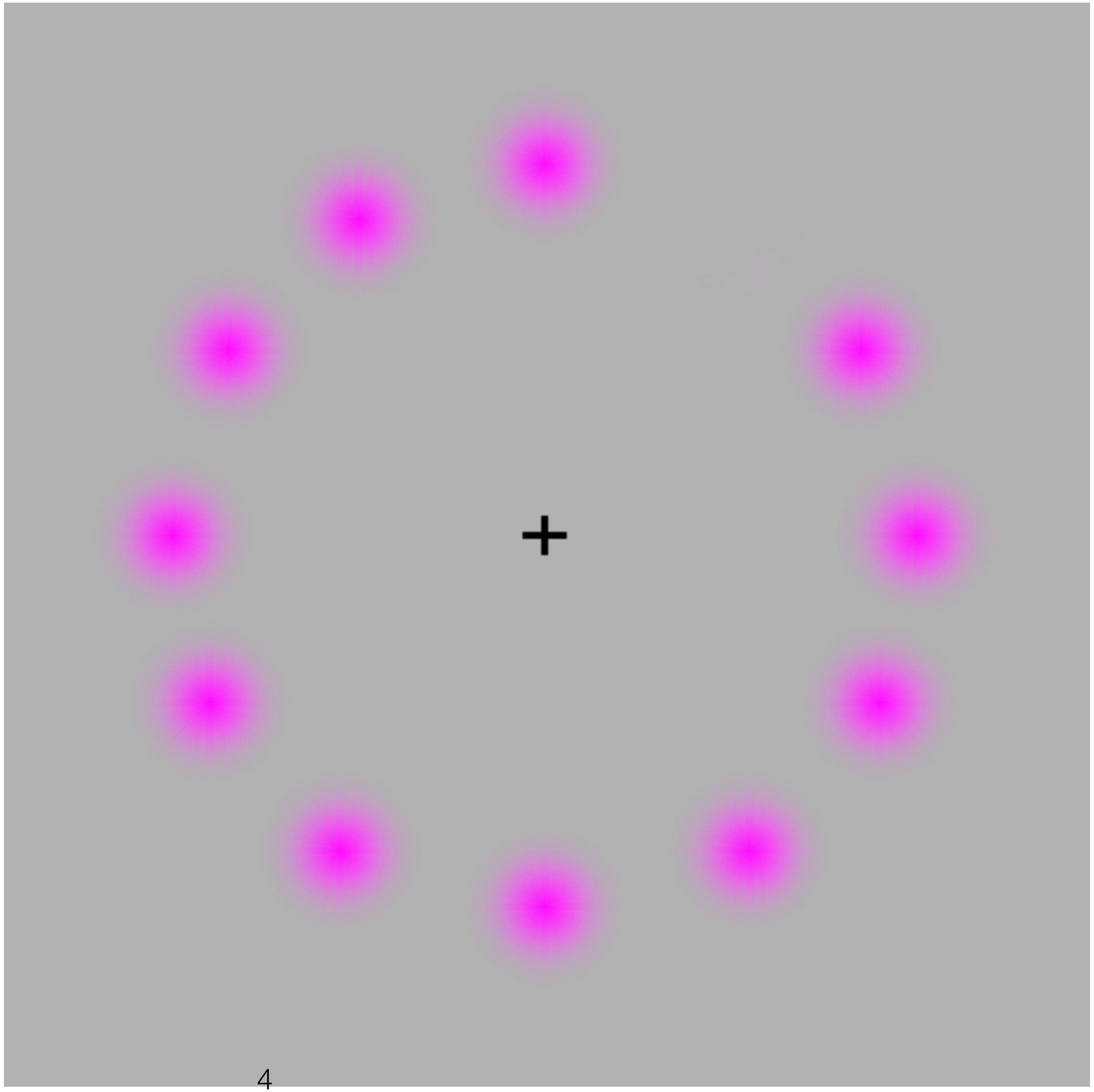
Eye is a lot like a camera

- Eye has a lens (obeys laws of physics, no flexibility left at age of c. 60) and retina is like a film

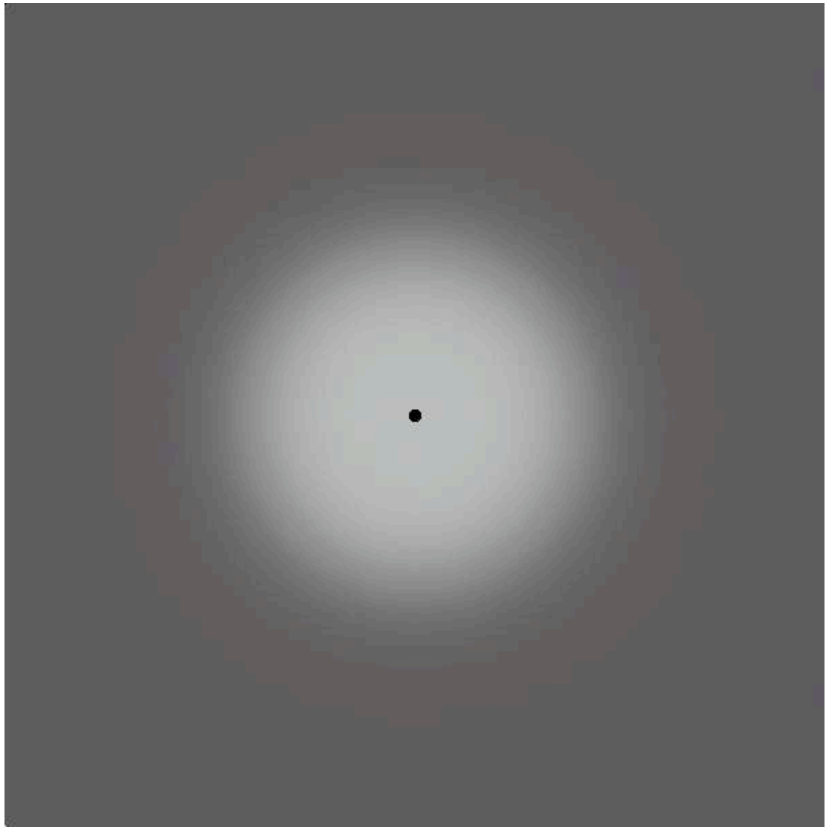
- Acuity and contrast sensitivity:
  - simple acuity (maximal at fovea, c. 1')
  - super-acuities (achieved by integrating the output of several retinal receptors, 10")
  - contrast sensitivity

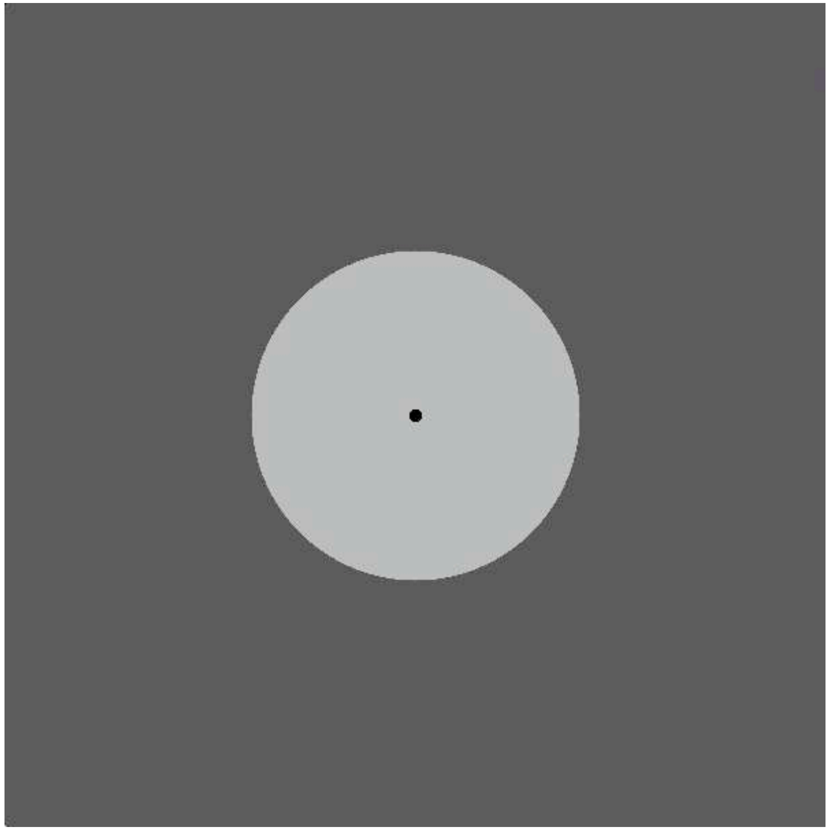
Eye is not like a camera

- Close one eye. Follow the rotating pink dot with your eye for at least 30 seconds.
- Keep the other eye closed. Now, keep your eye fixed on the black cross (+) at the center of the picture for at least 30 seconds.
- You should see at least two strange phenomena



Eye is not like a camera

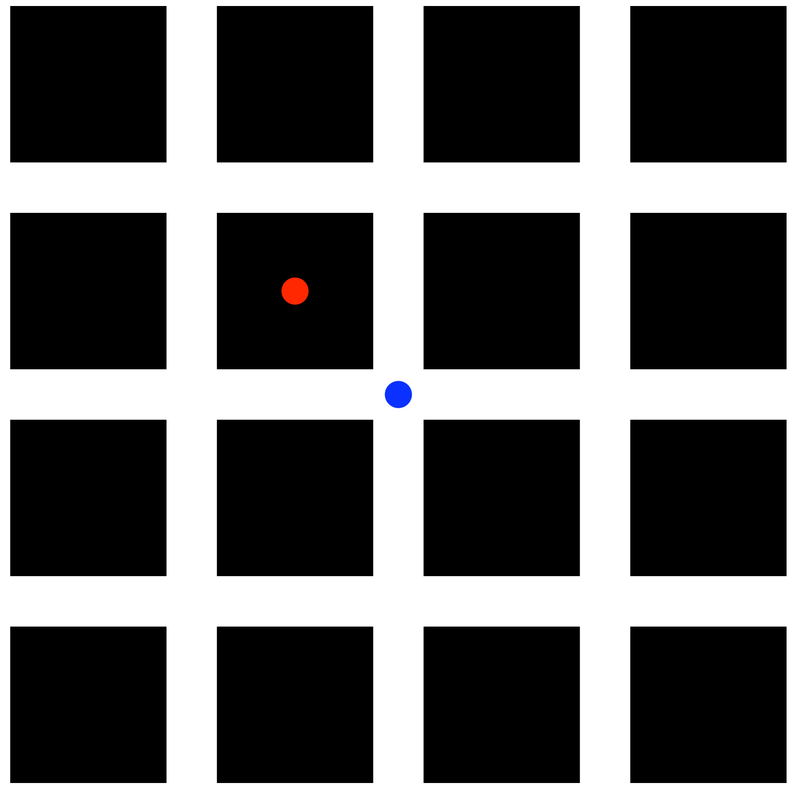




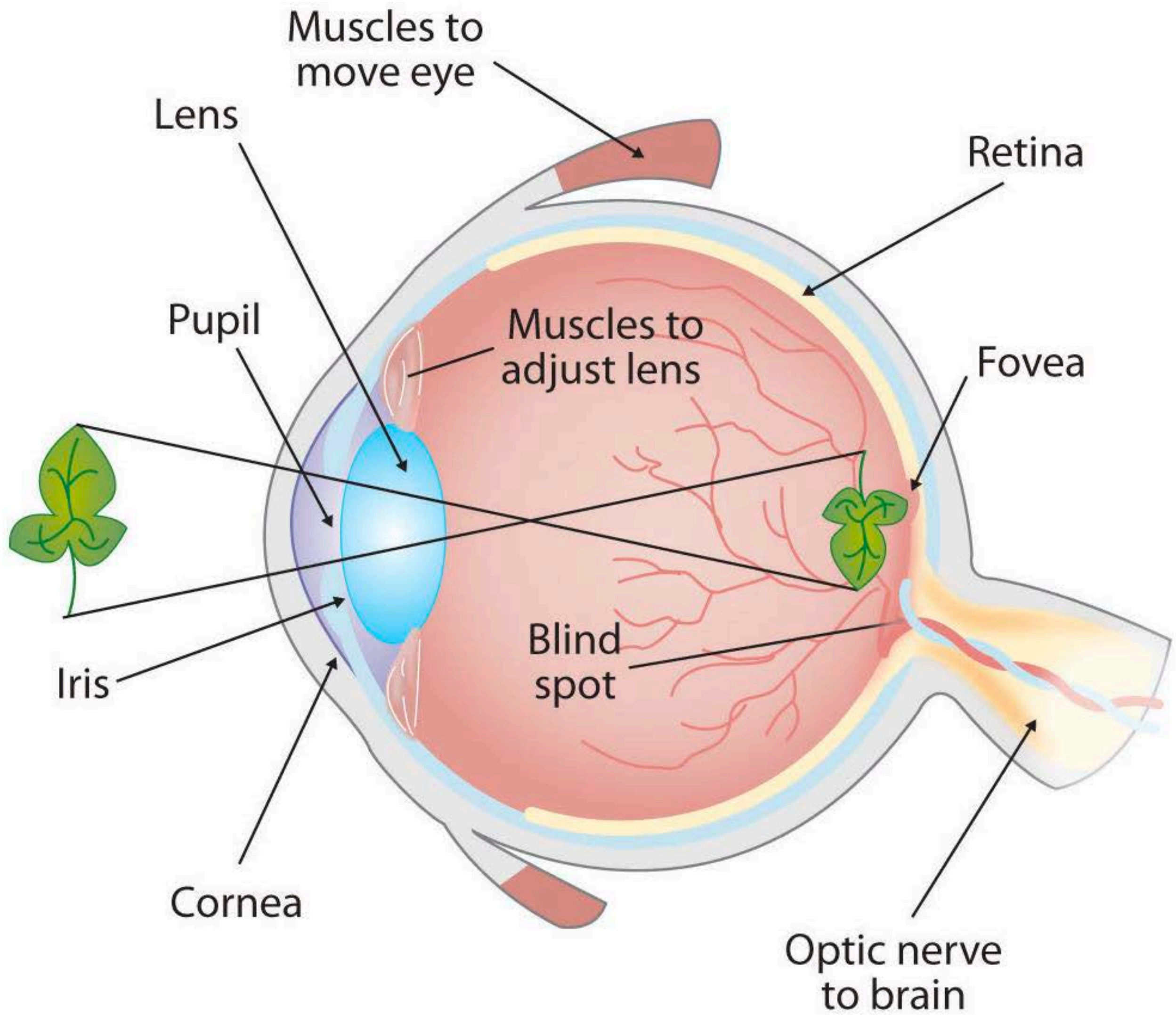
Close one eye. Look at the black dot at the center of the fuzzy disc for at least 30 seconds. Then look at the center of the sharp disc. Is there any difference?

Eye is not like a camera

- Close on eye and look at the blue dot for 60 seconds. Then look at the red dot. You should see the white afterimage jiggle.
- The disc with sharp contours does not (start to) disappear because the eye jiggles involuntarily. The amount of light to the receptors near to the contour is thus constantly changing.
- Jiggling of the fuzzy contours (previous slide) induces only slight changes to the receptors.
- Summary: retina responds poorly, if at all, to constant stimulus.



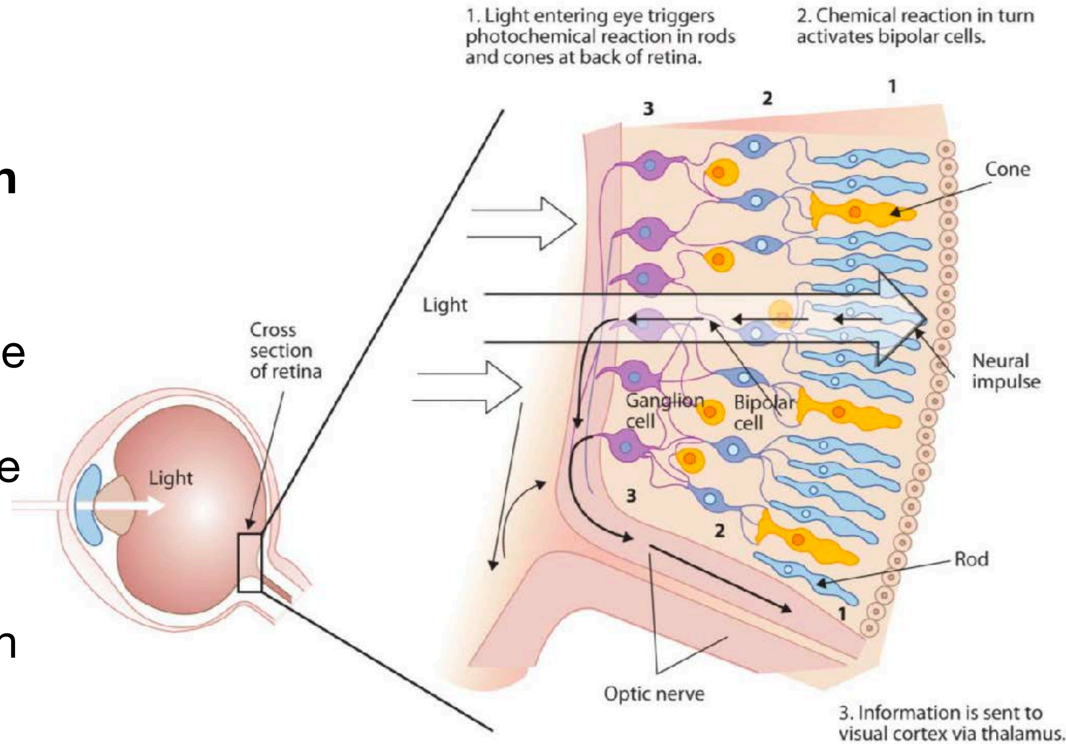
The human eye



http://2012books.lardbucket.org/books/beginning-psychology/s08-02-seeing.html

The human eye

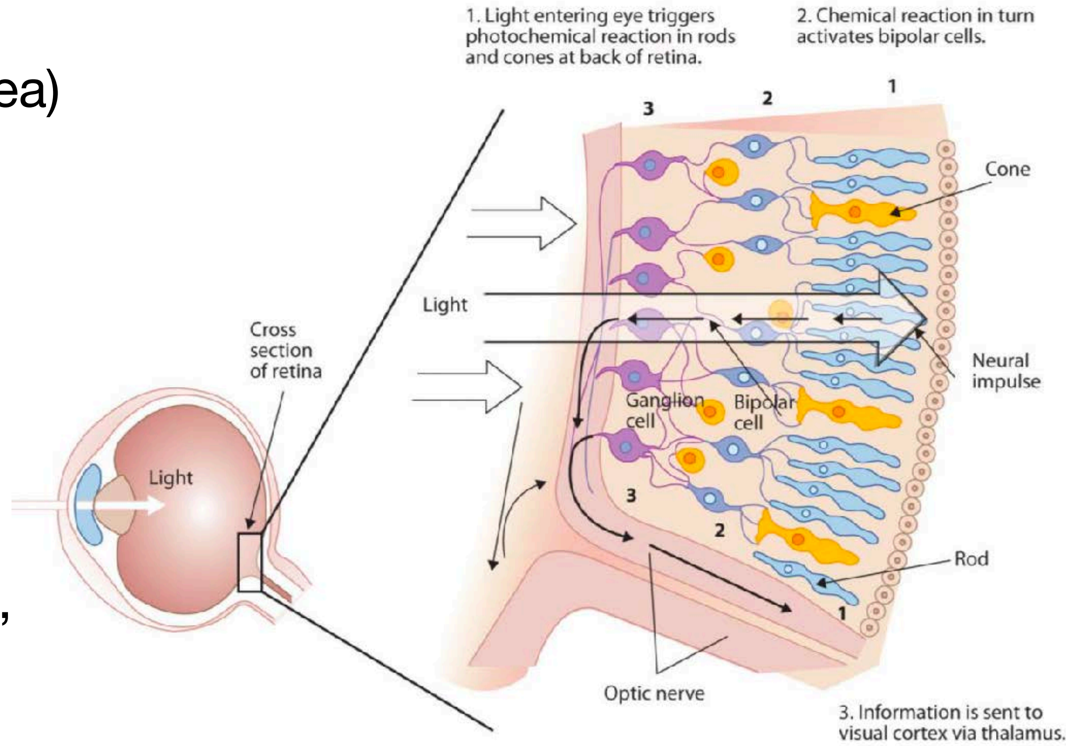
- The retina is made up of layers of neurons that respond to light
- Light falling on retina activates (1) **receptor cells** (i.e., rods and cones) which in turn activate (2) **bipolar cells** and then (3) **ganglion cells** through cascading photochemical reactions that transform the light into neural impulses, which carry visual information via the optic nerve to the visual processing areas in the visual cortex at the back of the brain where meaningful images are composed
- **optic nerve** = a collection of ganglion cells
- **ganglion** = a cluster of nerve cells (also known as neurons) existing outside the central nervous system
- **ganglion cell** = a cell (or neuron) in a ganglion



http://2012books.lardbucket.org/books/beginning-psychology/s08-02-seeing.html

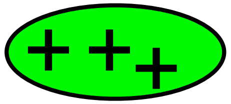
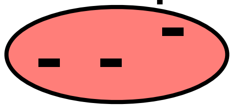
The human eye

- **fovea:** centre of retina
- **rods:** detect black/white/grey colours but not much detail
  - function best in dim light
  - located all over the retina (except fovea)
  - c. 120 million in each eye
- **cones:** detect fine detail and colours
  - function best in bright light
  - densely packed in fovea
  - c. 5 million in each eye
- When focusing on 1 word in the text, neighbouring words seem blurred as the word in focus is mapped onto the cones, while others are mapped onto the rods which detect much less detail than the cones (remember that acuity is maximum at fovea!)



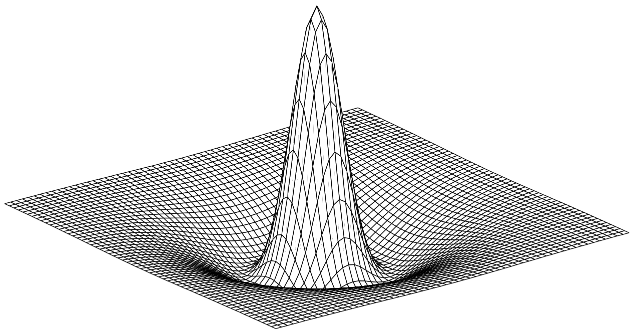
http://2012books.lardbucket.org/books/beginning-psychology/s08-02-seeing.html

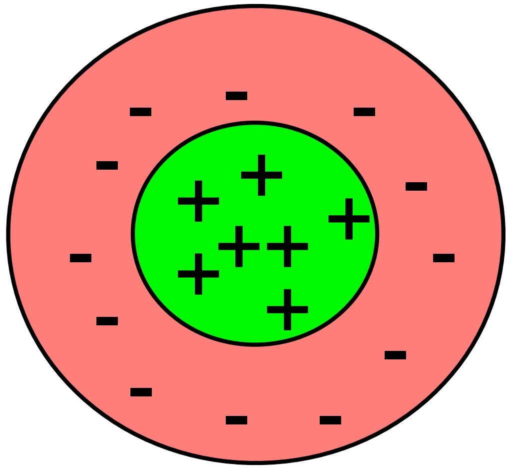
Lateral inhibition

- Retinal ganglion cells are organised with circular receptive fields
- When light falls at the center of receptive field it emits pulses at increased rate (*excitation*) 
- When light falls off center of receptive field it emits pulses at lower rate (*lateral inhibition*) 
- The receptive fields can be modelled with **Difference of Gaussians** (DOG) model

$$\text{Response} = K_e e^{-\left(\frac{2r}{a}\right)^2} - K_i e^{-\left(\frac{2r}{b}\right)^2}$$

Lateral inhibition



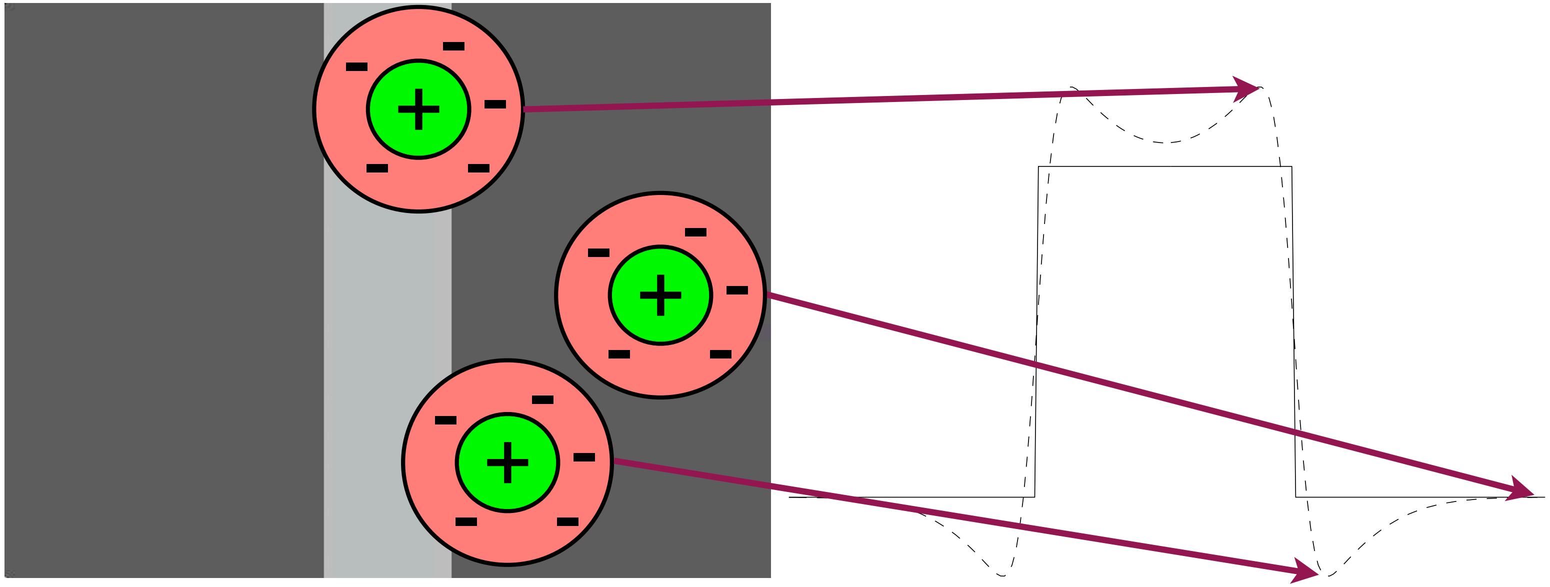


Local context affects brightness

- The DOG model can be used to explain the difference between physical **luminance** and perceived **brightness**
- Discontinuous lightness profiles generate dark and light bands near the discontinuities (*Chevreul illusion*)
- *Mach bands* appear if there are discontinuities in the first derivative of the lightness profile
- A gray patch placed on a dark background looks brighter than the same patch on a light background

Discontinuous lightness profiles

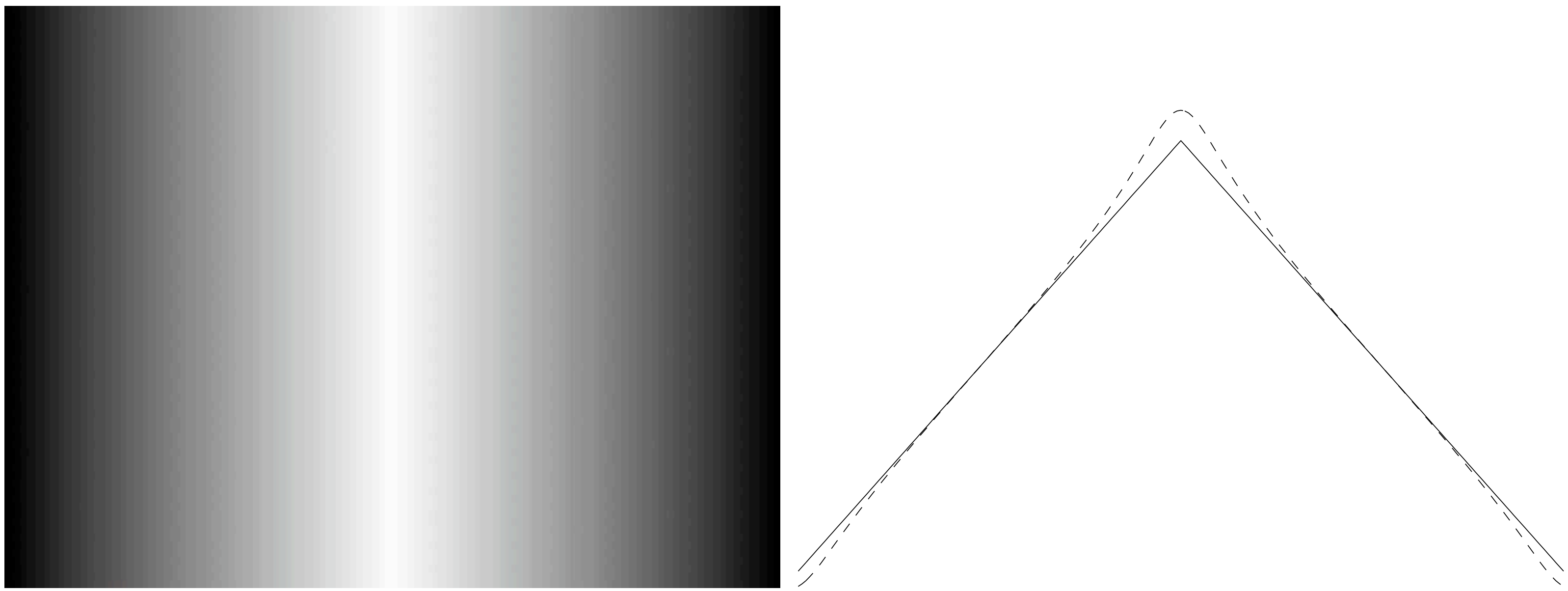
Discontinuous lightness profiles generate dark and light bands near the discontinuities (*Chevreul illusion*)



Solid lines describe (physical) *luminance* and dashed lines (perceived) *brightness*.

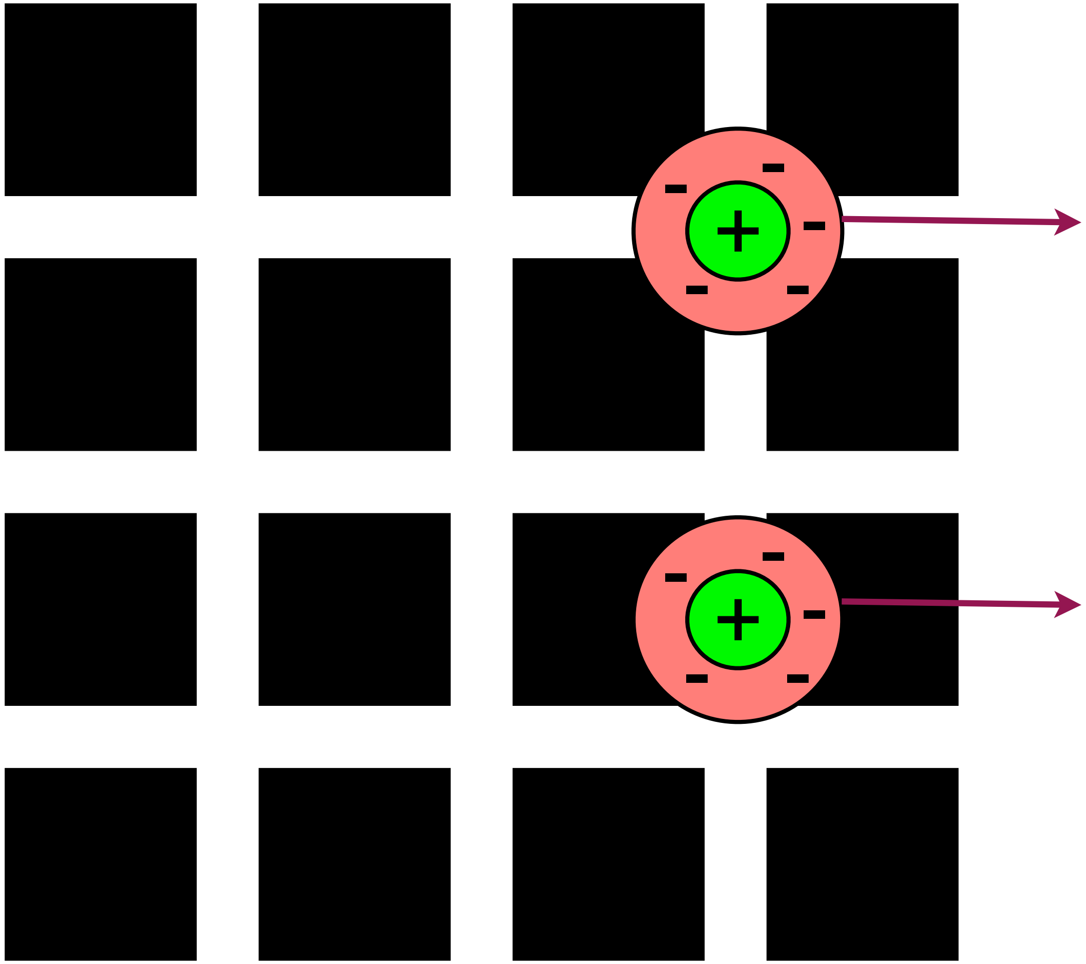
Mach bands

Mach bands appear at the discontinuities of the continuous brightness profile.



Solid lines describe physical *luminance* and dashed lines perceived *brightness*.

Hermann grid illusion

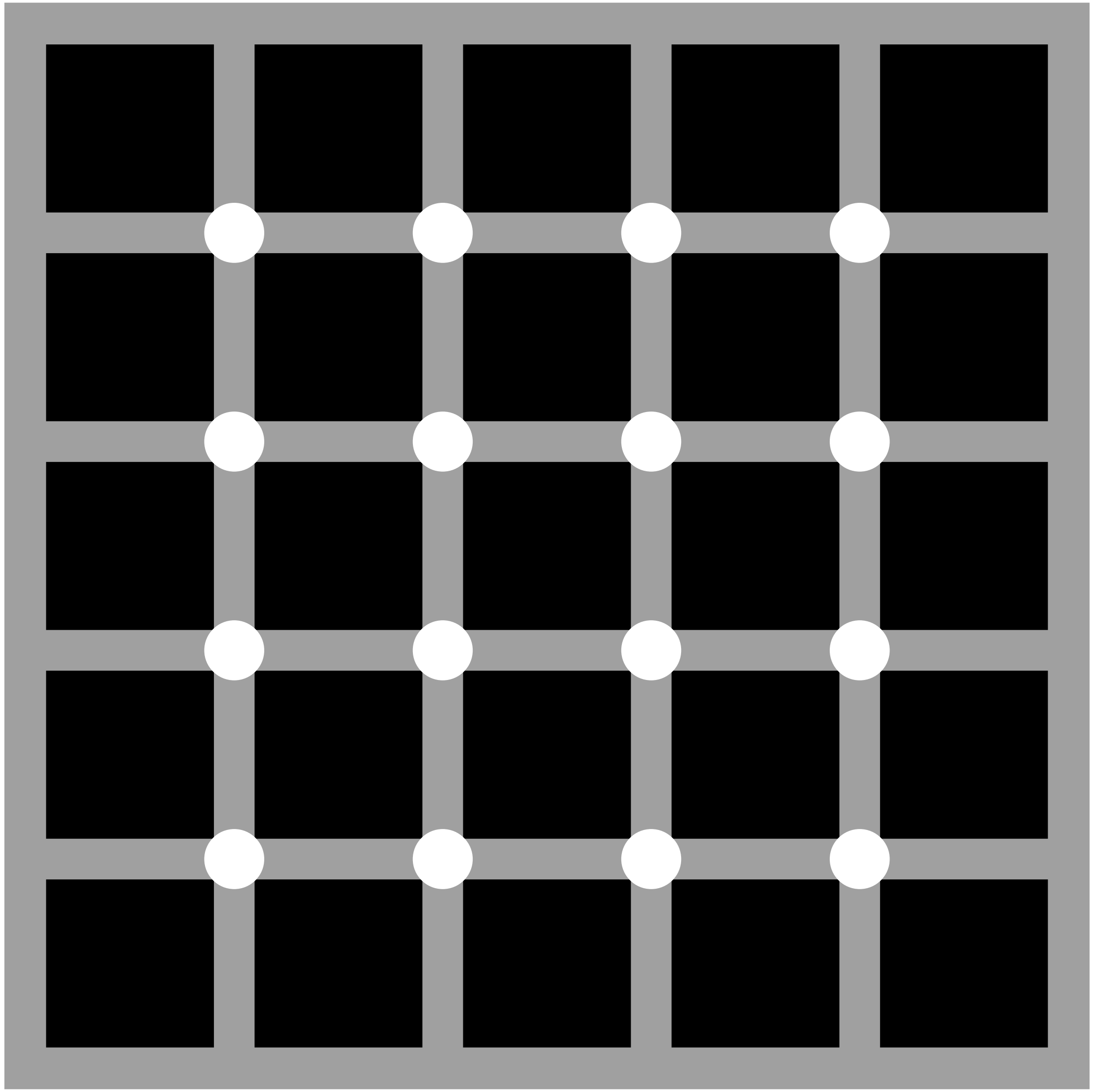


More inhibited rate
➜ darker spot

Less inhibited rate
➜ lighter spot

Hermann Grid illusion

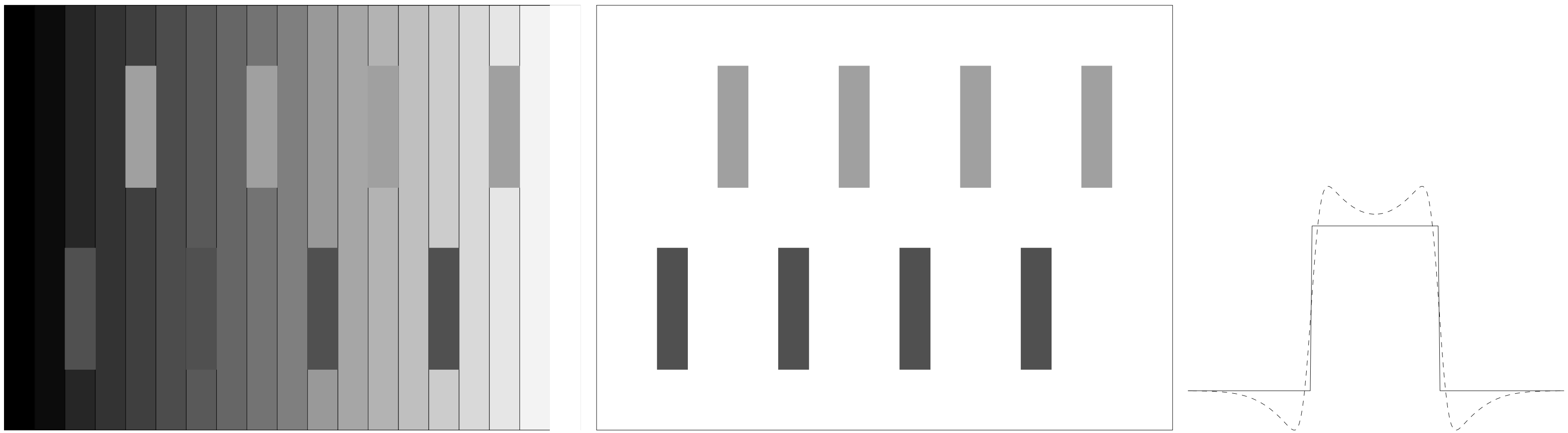
Hermann grid illusion



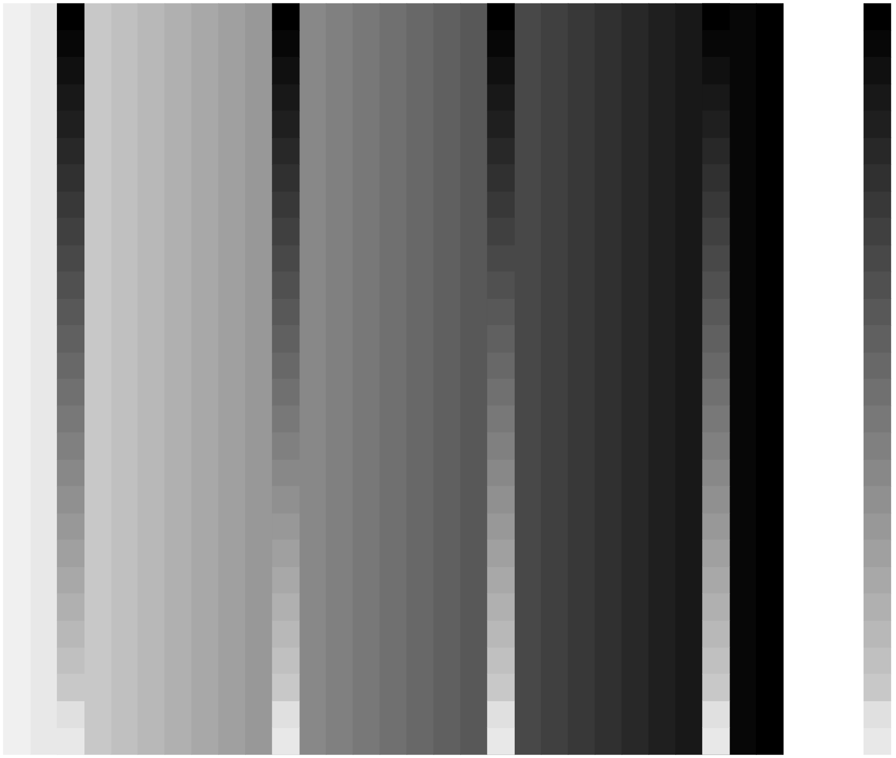
Modified Hermann grid illusion

Simultaneous brightness contrast

A gray patch placed on a dark background looks brighter than the same patch on a light background.



Crispening



- The variations in perceived gray scale brightness are enhanced when the luminance values are close to the background (**crispening**)
  - If **outline of the shapes** of objects is important, then background should have maximal contrast with foreground objects
  - If it is important to see **variations in grayscale**, then background should have minimal contrast with foreground objects

Sensitivity to wavelengths

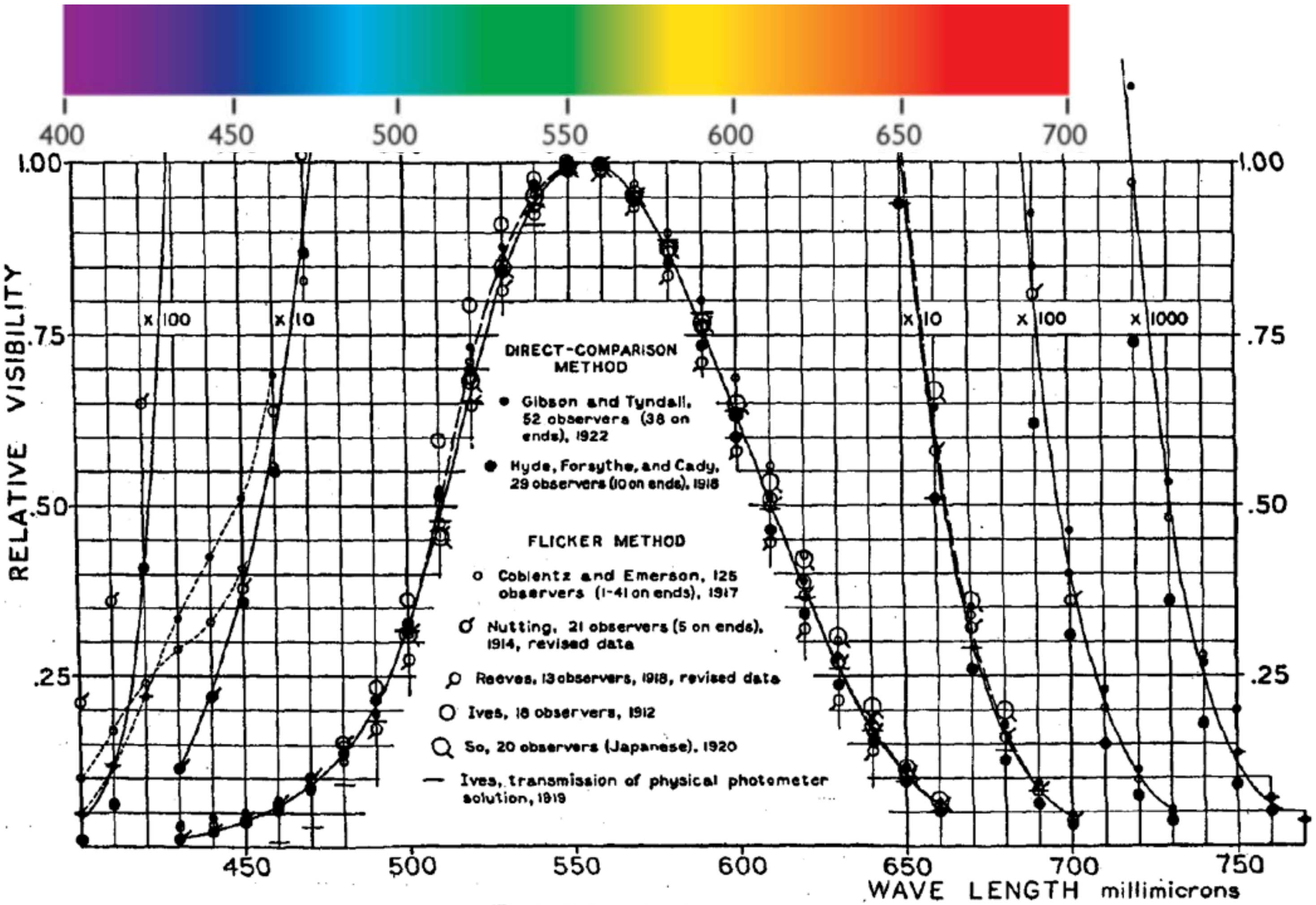


Fig. 1. Values of Relative Visibility.

From CIE 1924 proceedings

Luminance vs. brightness

- **Luminance** (L) is the **physical** amount of light energy coming from a region of space (candelas per square meter).

- **Brightness** (S) refers usually to the **perceived** amount of light from a self-luminous source.

  - The overall luminosity of a scene is essentially ignored by the visual system.

  - The relation between luminance and brightness is not linear but can be described by a power law $S=L^n$, where n=0.33 for large patches of lights, and n=0.5 for point sources (Stevens 1961)

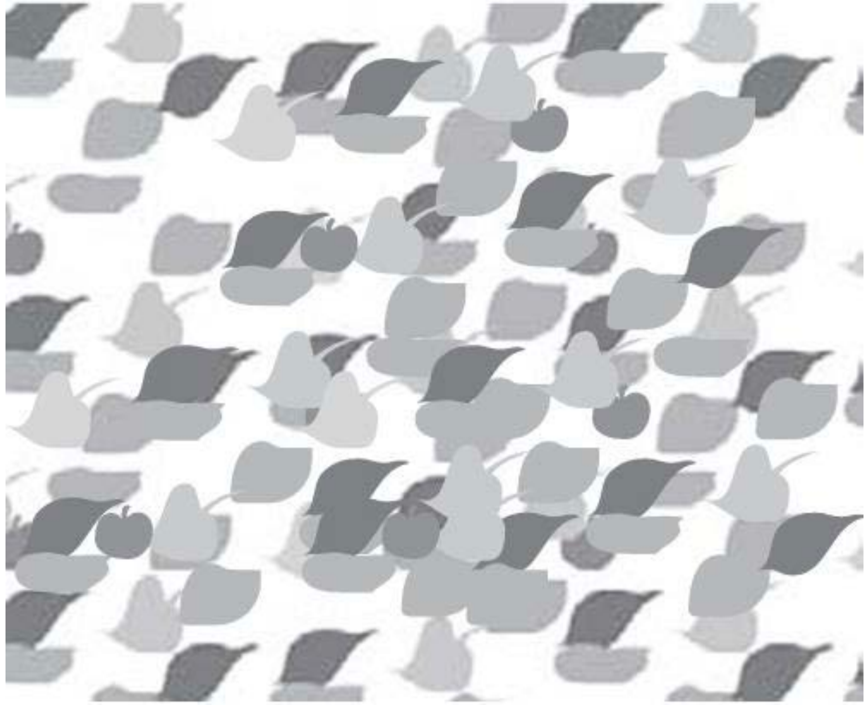
Eye is a lot *not* like a camera

- Human visual system is adapted to illumination levels of six orders of magnitude. The absolute illumination levels are essentially ignored.
- The lightness **perception is extremely relative.**
  - …due to adaptation & lateral inhibition
  - physical luminance and perceived brightness can be quite different

- Some design principles:
  - gray scale is bad at encoding absolute values, good at encoding relative values and shapes
  - if **outline of the shapes** of objects is important:
    - background should have maximal contrast with foreground objects
  - if it is important to see **variations** in grayscale:
    - background should have minimal contrast with foreground objects

NEW TOPIC

spot the cherries



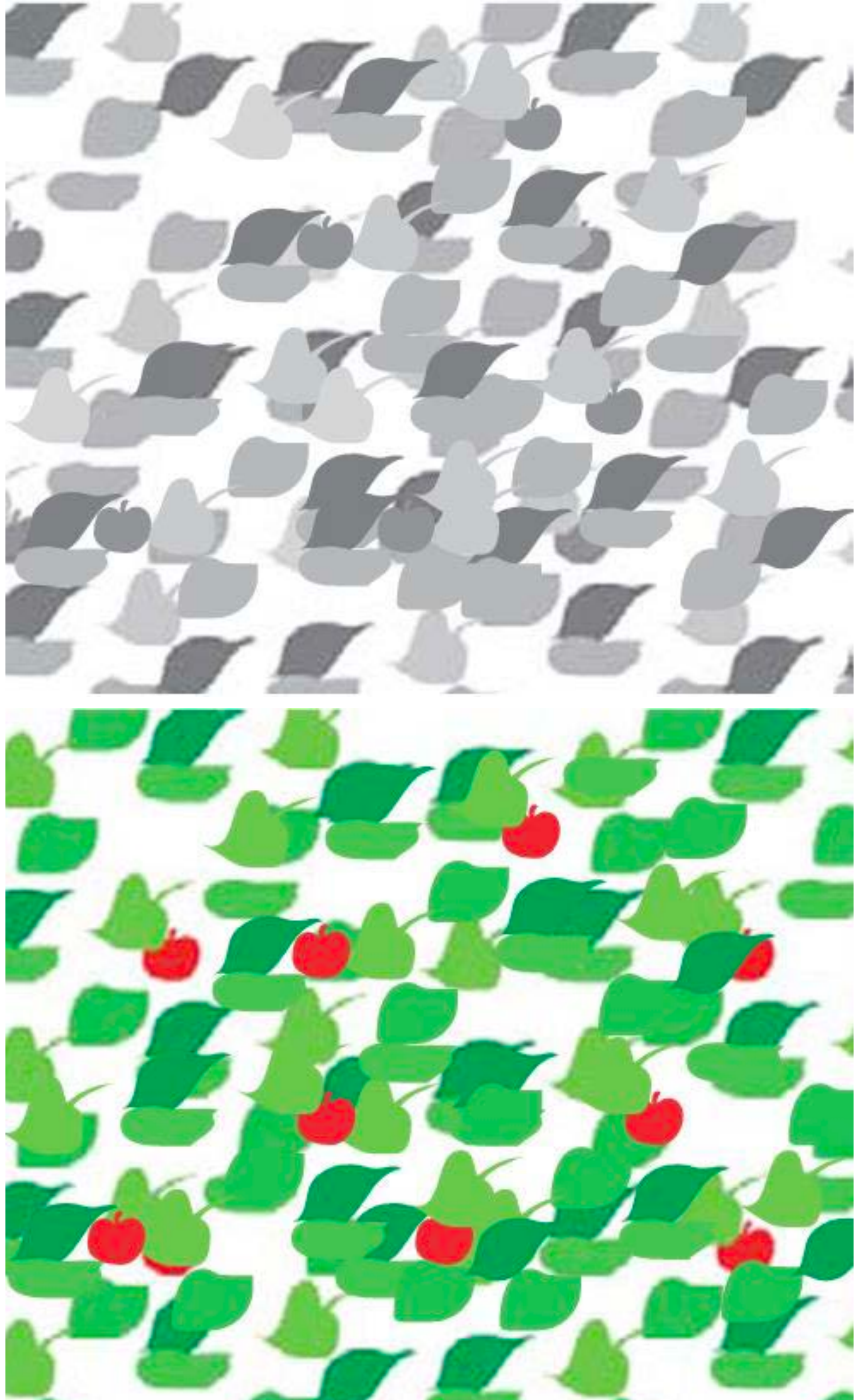
Why colours?

- Colour breaks camouflage
  - some things differ visually from their surroundings only by their colour
  - e.g., with colour we can easily see the cherries hidden in the leaves

- Colour tells us about material properties of objects
  - e.g., which fruit are ripe? Which food has gone bad?

- Colour is an attribute of an object that helps us distinguish it from others
  - good for labelling and categorising, but poor for displaying shape, detail or spatial layout

spot the cherries

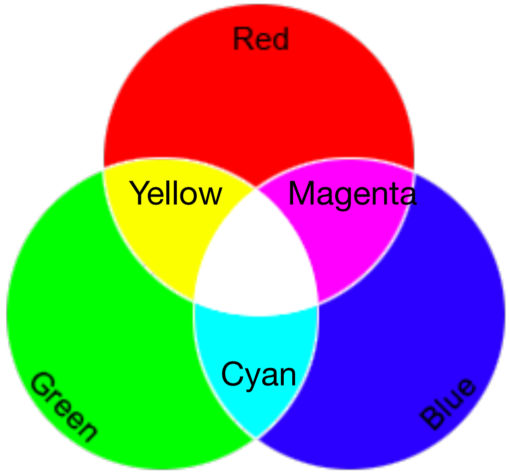


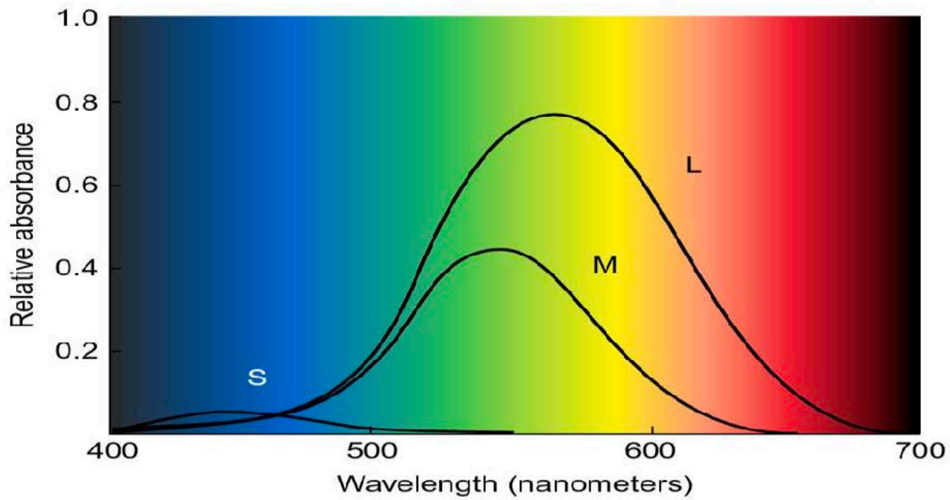
Colour in visualisation

- One of the most (academically) studied topics
- Practical implications in visualisation:
  - basics of colour perception
    - opponent process theory
    - two chromatic channels (red-green & yellow-blue) and luminance channel (colour is a 2D thing!)
  - how to design colour scales to encode information
    - only limited number of identifiable colors
    - perceived difference of colors
  - contrast effects etc. apply also in colour perception
  - no physical device can reproduce all perceived colours (gamut)

Trichromacy theory

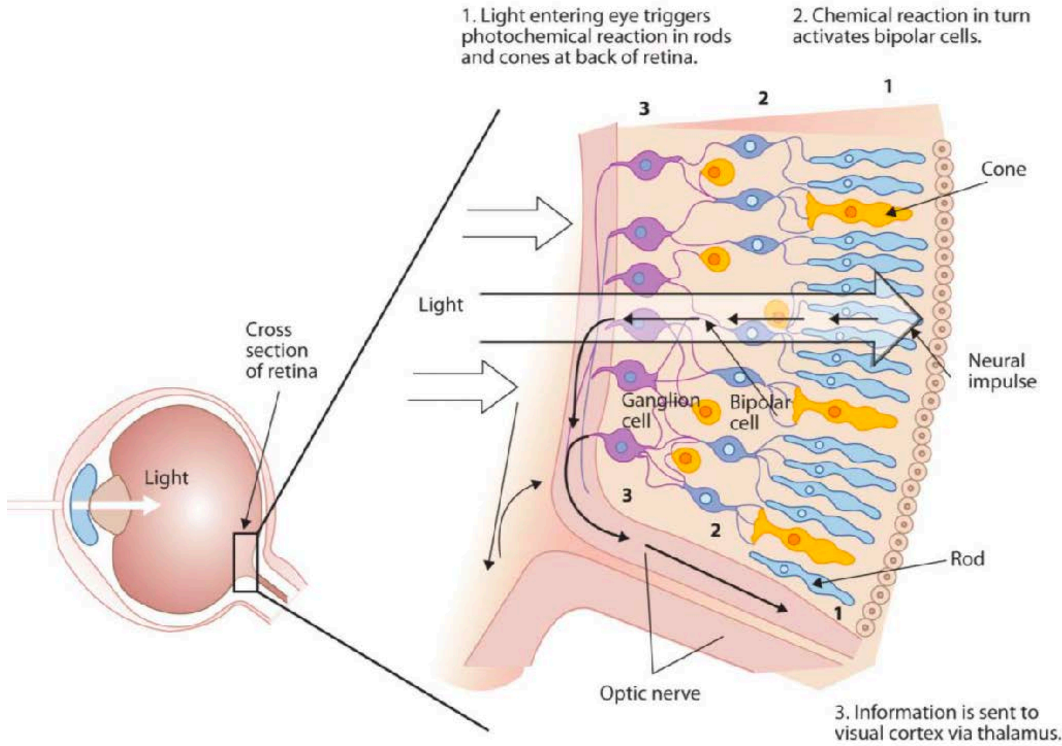
- The human eye has 3 distinct colour receptors, called cones (chicken have 12!)
  - Red (sensitive to long-wavelength light) L
  - Green (sensitive to medium-wavelength light) M
  - Blue (sensitive to short-wavelength light) S
- Red, green, blue = primary colours of light (light primaries, additive primaries)
- Cyan, magenta, yellow = secondary colours (light secondaries, subtractive primaries),
  - produced as equal mixtures of two additive primaries
  - print: absorbing a primary color from white
- Human colour vision is fundamentally 3-dimensional
  - colour space is an arrangement of colours in a 3d space and
  - any colour we perceive can be represented as a mixture of the 3 primaries





Reminder: the human eye

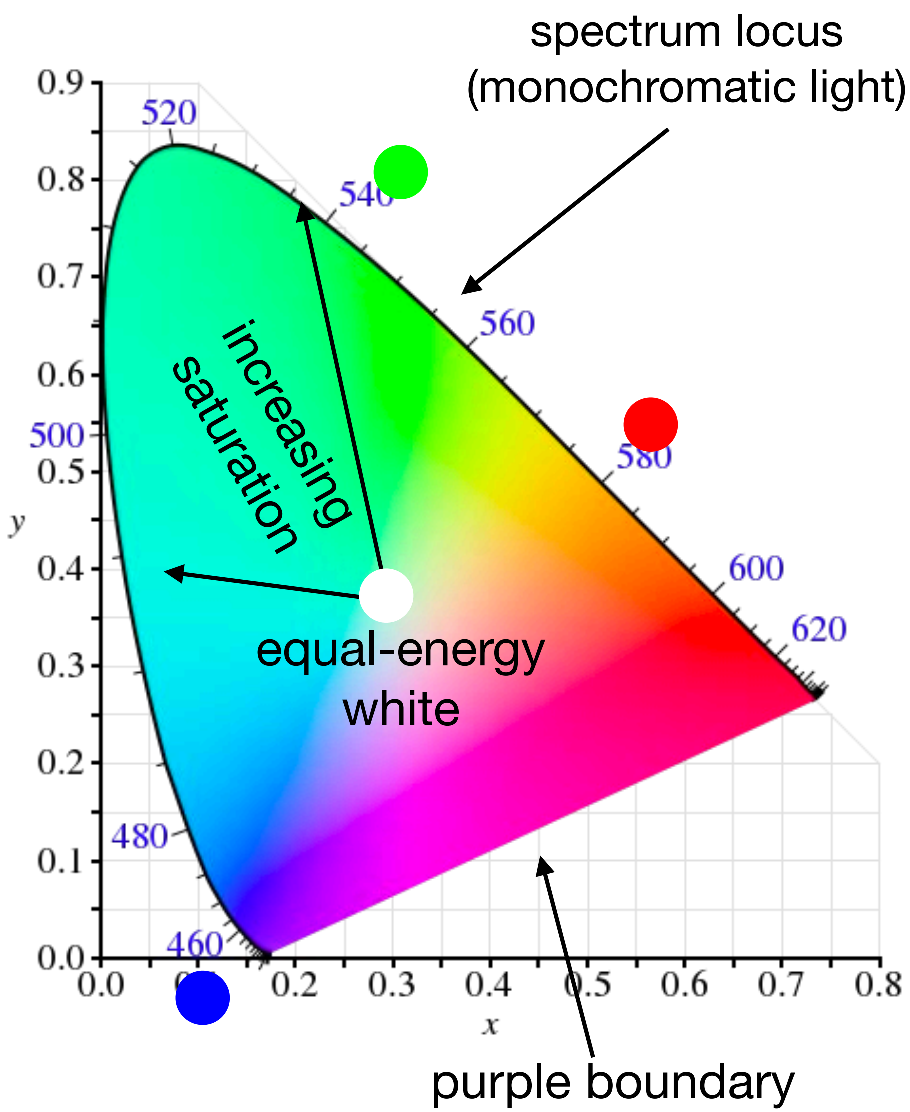
- **rods:** detect black/white/grey colours but not much detail
  - function best in dim light
  - located around the edges of the retina
  - c. 120 million in each eye
- **cones:** detect fine detail and colours
  - function best in bright light
  - densely packed in fovea (centre of retina)
  - c. 5 million in each eye



http://2012books.lardbucket.org/books/beginning-psychology/s08-02-seeing.html

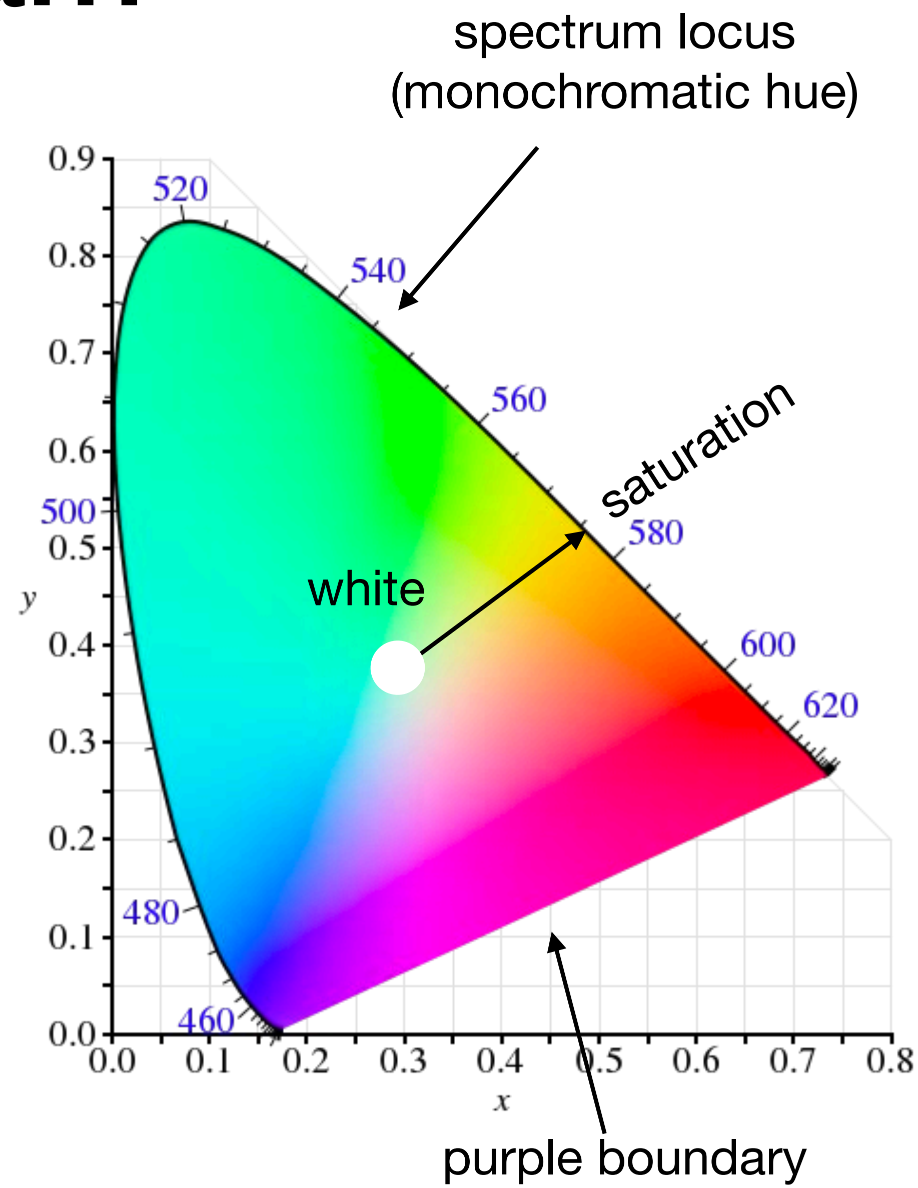
CIE xyY model: chromaticity diagram

- Colour is 3-dimensional: luminance (Y,1d) + **chromaticity (xy, 2d)**
- It can be used to present all visible colors as a combination of 3 primary colors at (x,y) coordinates (0,0), (0,1), (1,0).
- *Standard observer* is a hypothetical person whose colour sensitivity is held to be that of a typical person (measurements are from prior 1931)
- **Problem 1:** primary colors (xyY) are non-physical & no combination of 3 physical colours could present all perceivable colours
- **Problem 2:** colors are perceptually non-uniform



CIE xyY chromaticity diagram

- All colors on a line between two colored lights can be created by mixing these two colors
- Any set of three coloured lights specifies a triangle. All points within the triangle can be represented as a mixture of the given lights.
- All realisable colors fall within the spectrum locus (the set of chromaticity coordinates representing single wavelength colors)
- The purple boundary is the line connecting the chromaticity coordinates of the longest and shortest visible wavelengths
- The chromaticity coordinates of equal-energy white are 0.333, 0.333
- Excitation purity (saturation) is a measure of the distance along the line between a pure spectral wavelength and the white point



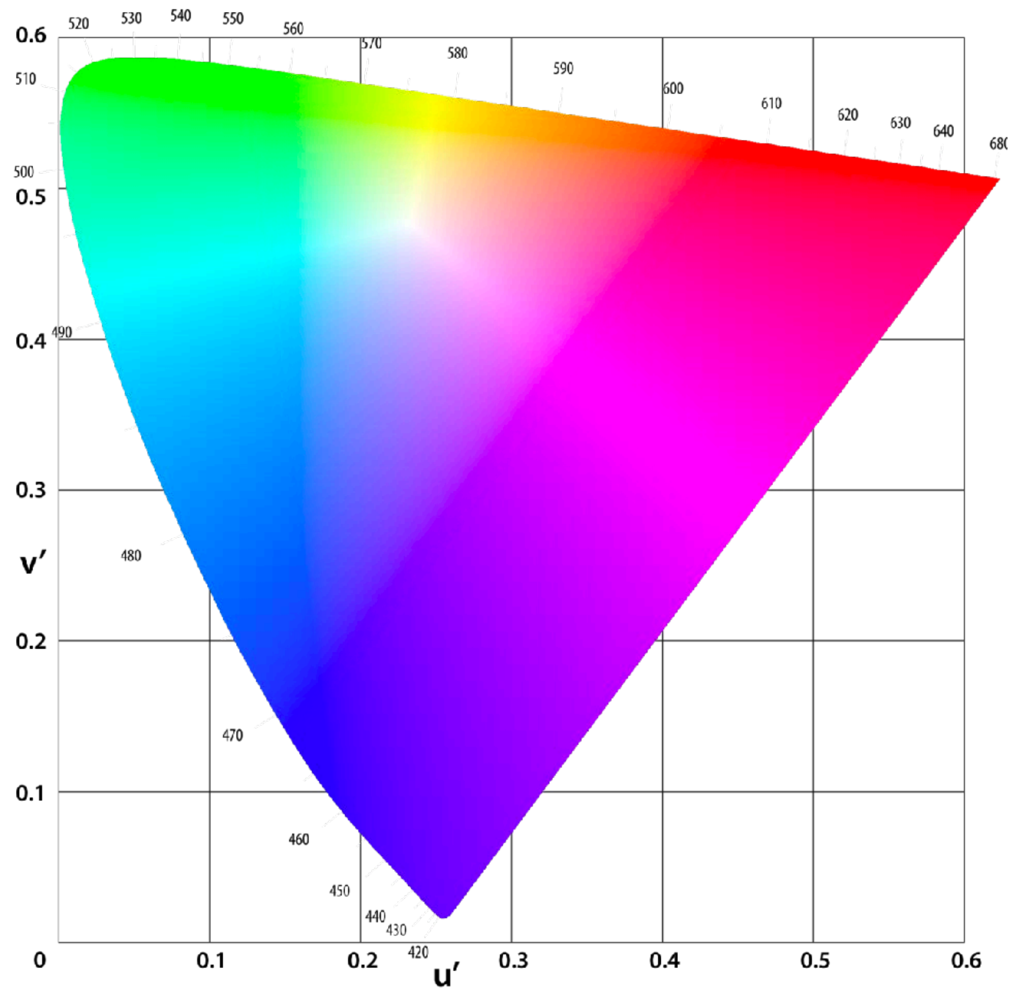
Perceptually more uniform CIELUV

- Derived from the CIE XYZ tristimulus model
  - **CIE XYZ** reference white at (X_n,Y_n,Z_n)
  - **CIE xyY** equations are
    - $x = X/(X+Y+Z)$
    - $y = Y/(X+Y+Z)$
  - **CIELUV** equations are
    - $L^* = 116(Y/Y_n)^{1/3}-16$
    - $u^* = 13L^*(u'-u_n')$
    - $v^* = 13L^*(v'-v_n')$
    - where $u'=4X/(X+15Y+3Z)$ and $v'=9Y/(X+15Y+3Z)$

- **CIELUV** is perceptually more uniform, i.e., the perceptual difference of colours is about

$$\Delta E_{uv}^2 = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2}$$

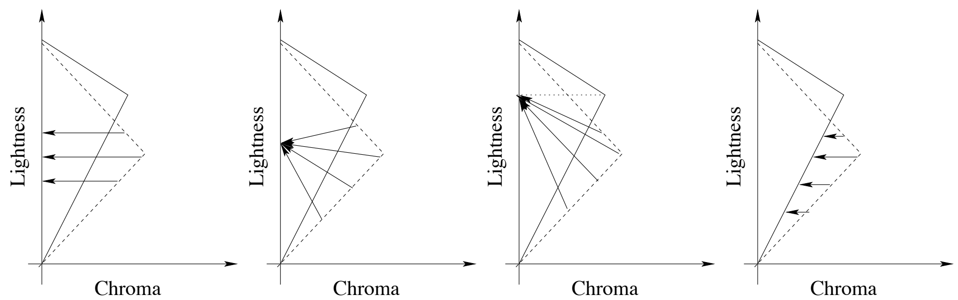
where 1 = approximately just noticeable difference



https://en.wikipedia.org/wiki/CIELUV#/media/File:CIE_1976_UCS.png

Gamut

- Any physical device with finite number of primary colours can present only a subset of perceivable colors
- **Gamut** = set of colors that a device can reproduce
- Gamut mapping is needed for devices with different gamuts



(Morovič, 1997)

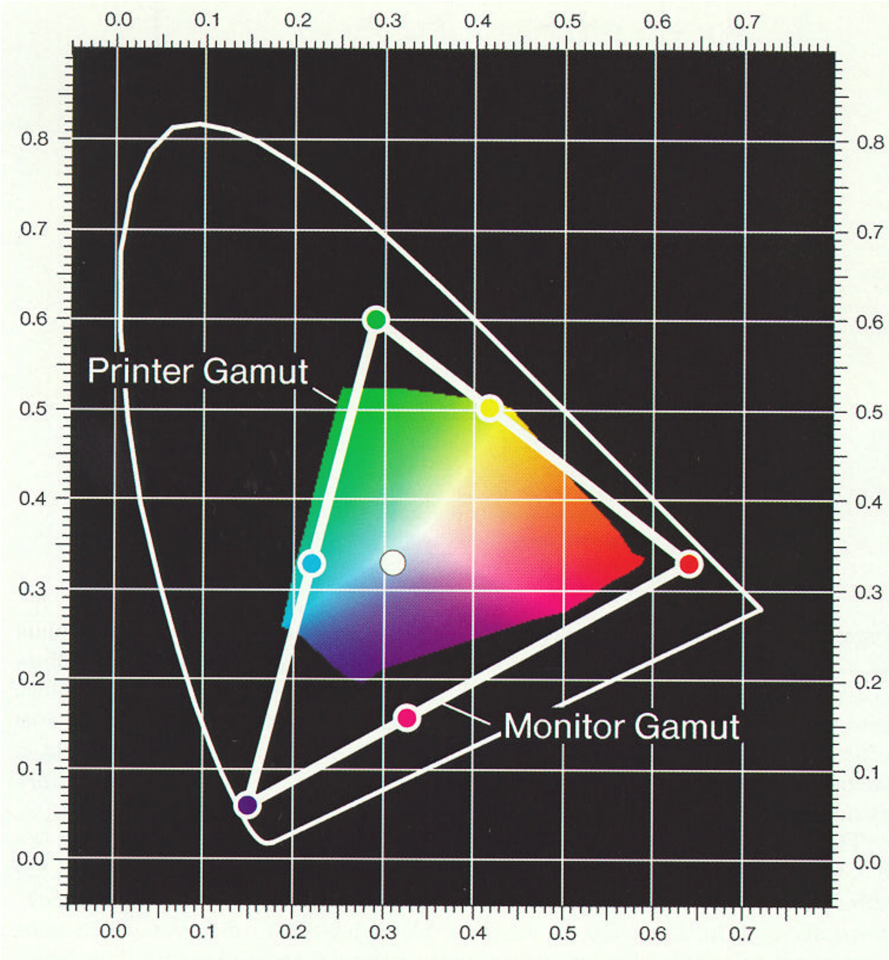
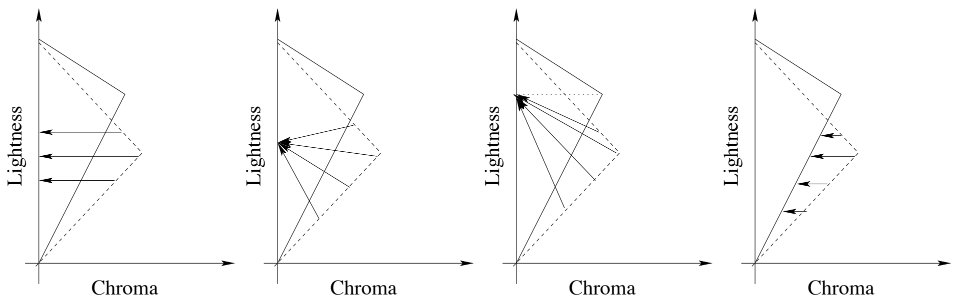


Fig. 8. Gamuts of the Cromalin proof and a typical color monitor overlaid on the CIE chromaticity diagram. The horseshoe shaped plot is the spectrum locus; that is, its interior contains all observable colors represented as chromaticity coordinated.

Stone et al. Color Gamut Mapping and the Printing of Digital Color Images. ACM Transactions on Graphics, 7(4): 249-292,1988.

Gamut mapping example

- **Calibrate** monitor and printing device in a common reference system
- **Scale** monitor gamut about black point to equate the luminance range of the source and destination images
- **Rotate** the monitor gamut to equate the monitor white to the paper white
- **Scale** monitor gamut radially with respect to black-white axis to get monitor gamut within printing gamut range (some colours on monitor cannot be reproduced on paper)
- **Truncate** colours to printing-ink gamut boundary



(Morovič, 1997)

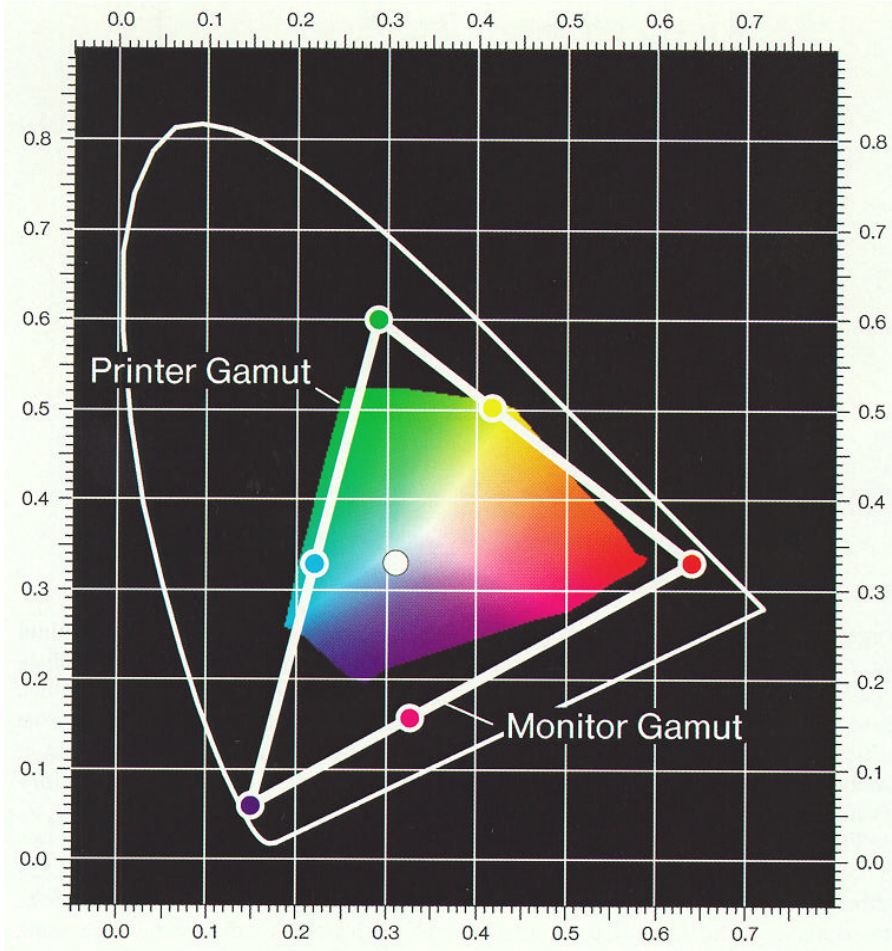
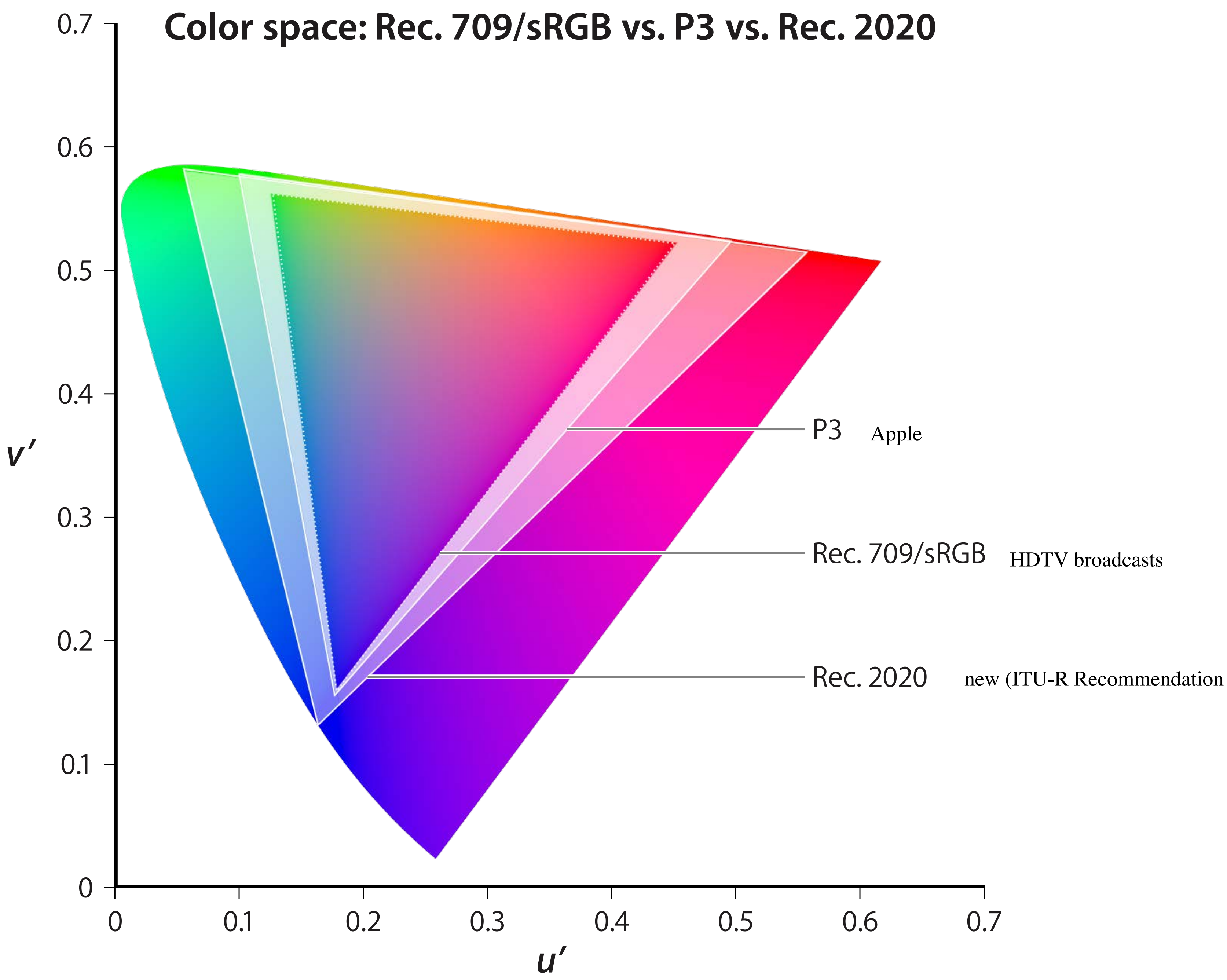
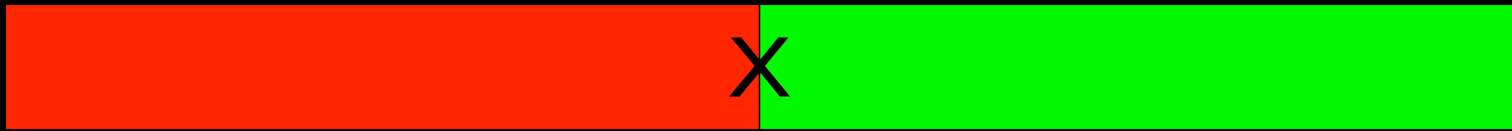


Fig. 8. Gamuts of the Cromalin proof and a typical color monitor overlaid on the CIE chromaticity diagram. The horseshoe shaped plot is the spectrum locus; that is, its interior contains all observable colors represented as chromaticity coordinated.

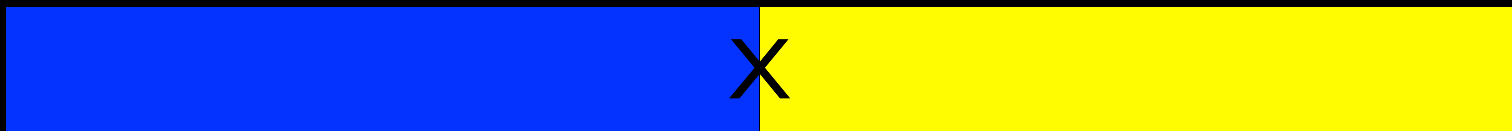
Stone et al. Color Gamut Mapping and the Printing of Digital Color Images. ACM Transactions on Graphics, 7(4): 249-292,1988.



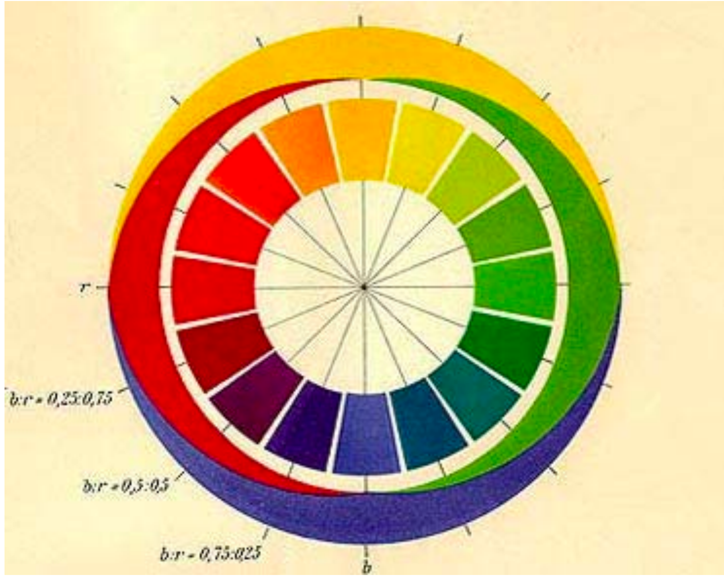
https://images.apple.com/final-cut-pro/docs/Wide_Color_Gamut.pdf

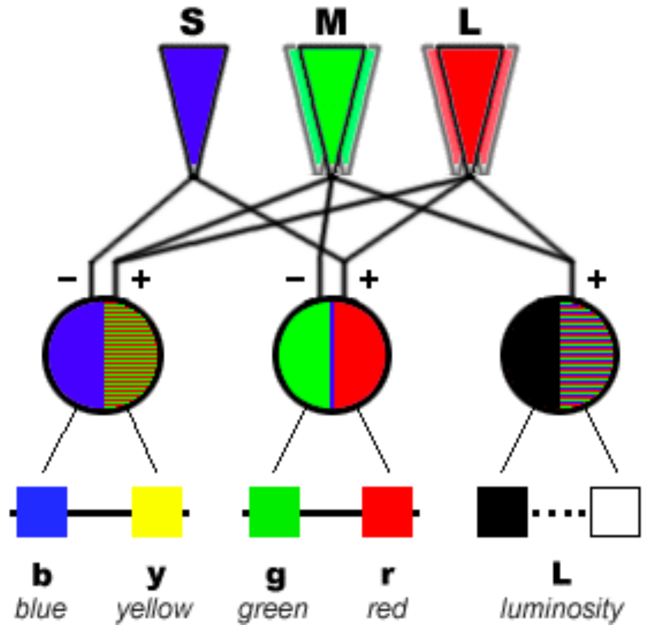


Look at the X for 30 seconds. Then look at white background and blink.



Opponent colour theory



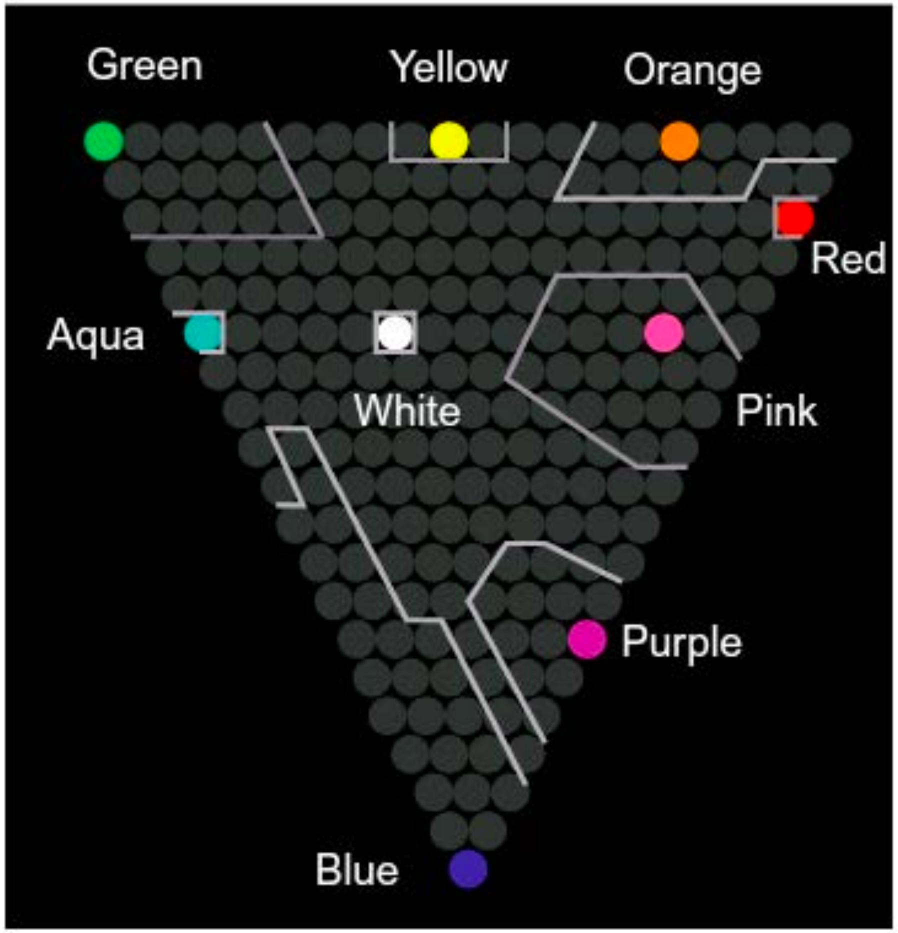


https://www.handprint.com/HP/WCL/color2.html

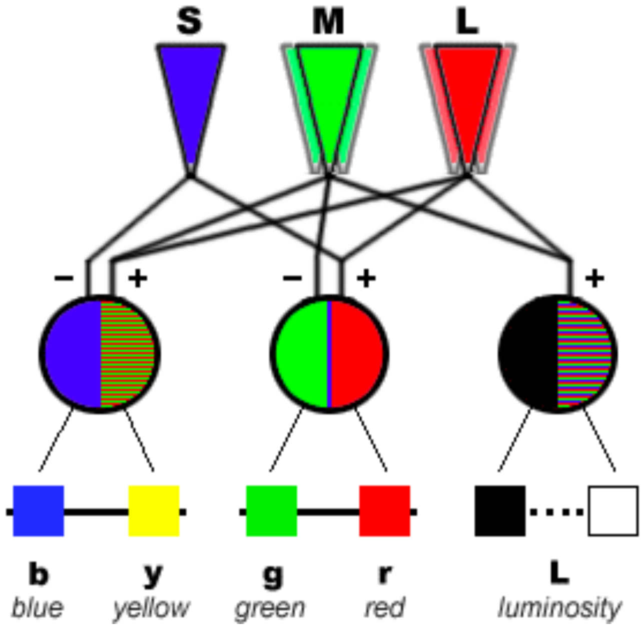
- There are 6 elementary colours. These colours are arranged perceptually as opponent pairs along 3 axes (Hering 1920):
  - black-white, red-green, and yellow-blue
- Cone signals are transformed into 3 distinct channels:
  - black-white (luminance), red-green, and yellow-blue
- Theory predicts that people will never use “reddish green” or “yellowish blue”
- People tend to divide colours to a few basic categories
- The closer the colour is to the “pure colour”, the easier it is to remember

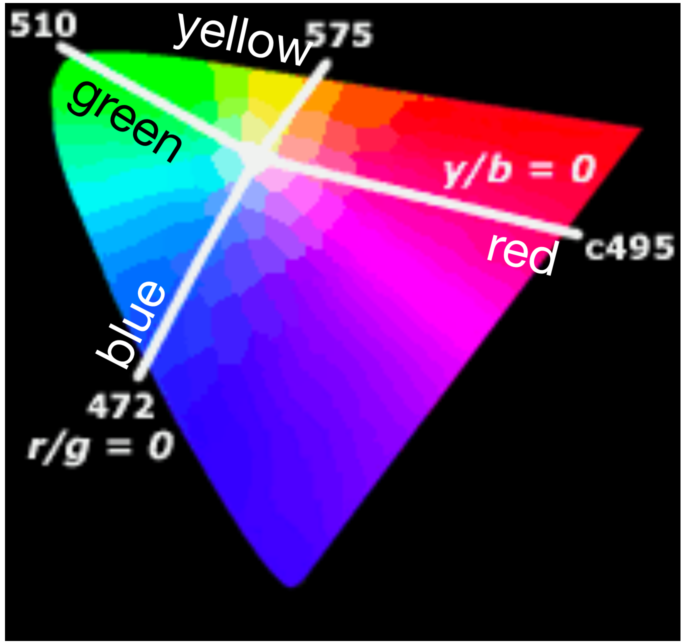
Opponent colour theory

- People tend to divide colours to a few basic categories
- The closer the colour is to the “pure colour”, the easier it is to remember
- The results of an experiment in which subjects were asked to name 210 colours produced on a computer monitor.
- Outlined regions show the colours that were given the same name with over 75% reliability



Colour blindness





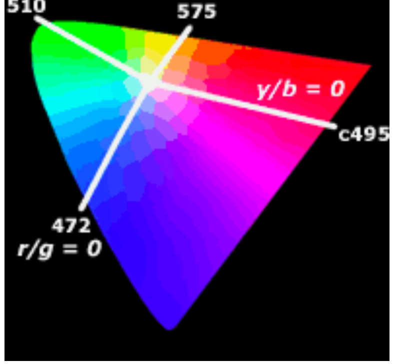
CIELUV

- c. 8% of males and c. 0.5% of females suffer from pure dichromacy or anomalous trichromacy
- The most common form is to have the light response of M (green) and/or L (red) cones to shift toward the other, which reduces range of trichromatic perception and can have variable effects on colour vision (*anomalous trichromacy*)

- [Errata: minor adjustements to prevalence percentages in slides 37-41 pursuant to https://www.ncbi.nlm.nih.gov/books/NBK11538/]

https://www.handprint.com/HP/WCL/color2.html

Pure dichromacy

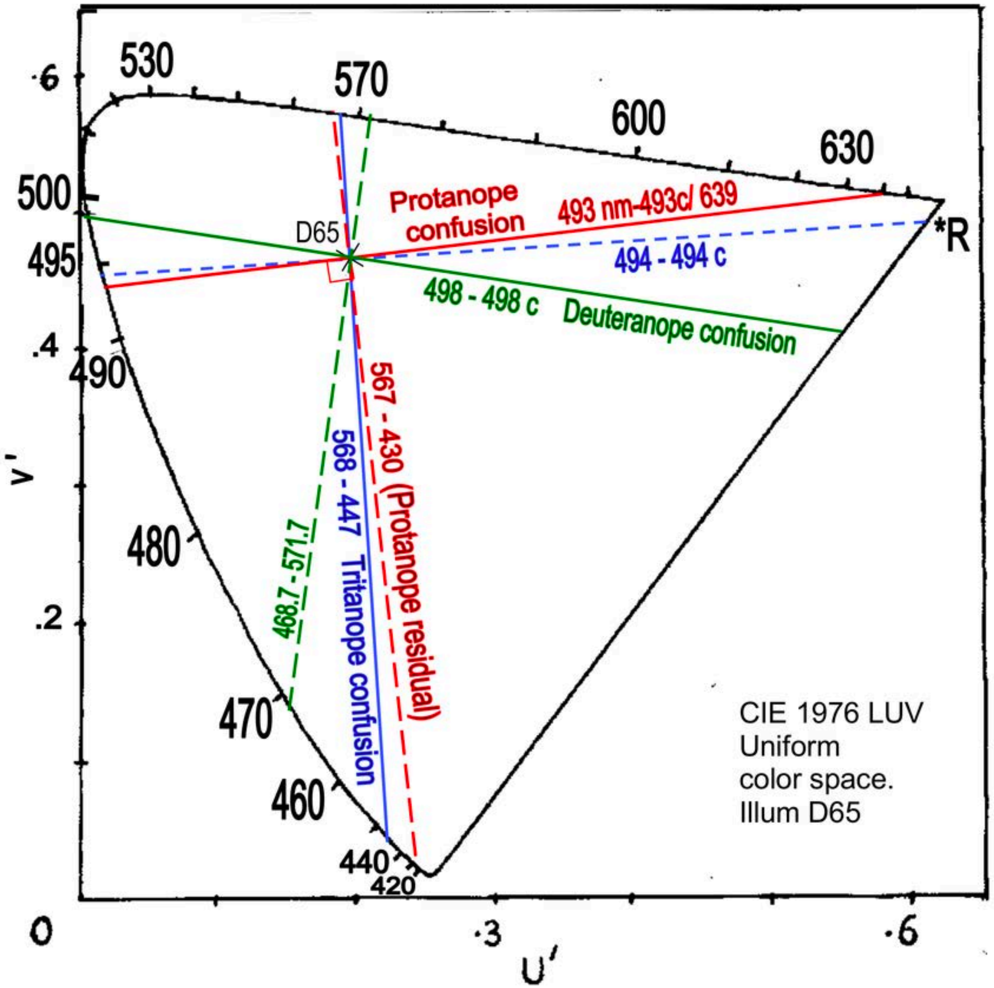


- Pure dichromacy is due to lack of one type of cones
  - L (long-wave, red) → *protanopia*
  - M (mid-wave, green) → *deuteranopia*, or
  - S (short-wave, blue) → *tritanopia*

red-green confusion

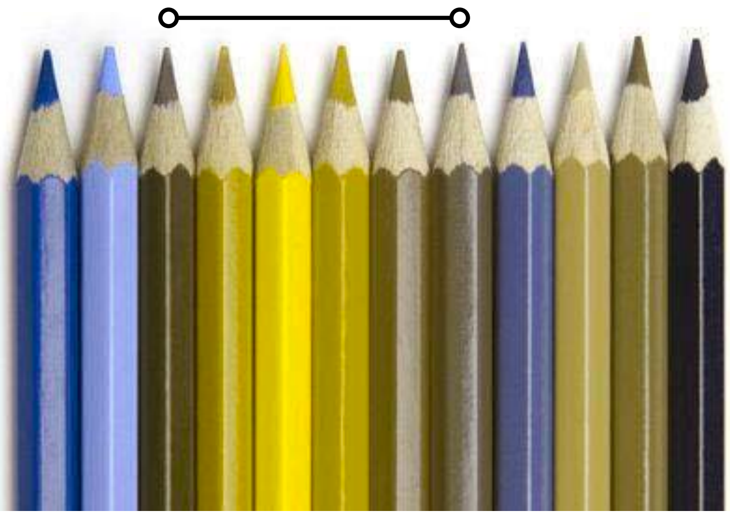
blue-yellow confusion

- Pure dichromacy can be seen as collapse of the 2d chromatic space into 1d
  - the remaining 1D axis shown ➜ as dashed line in the figure

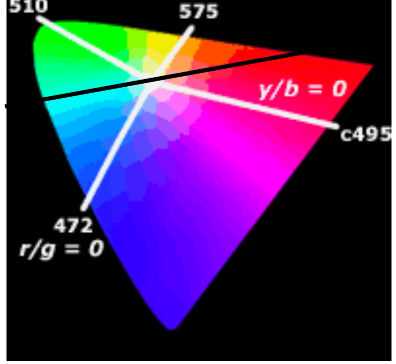


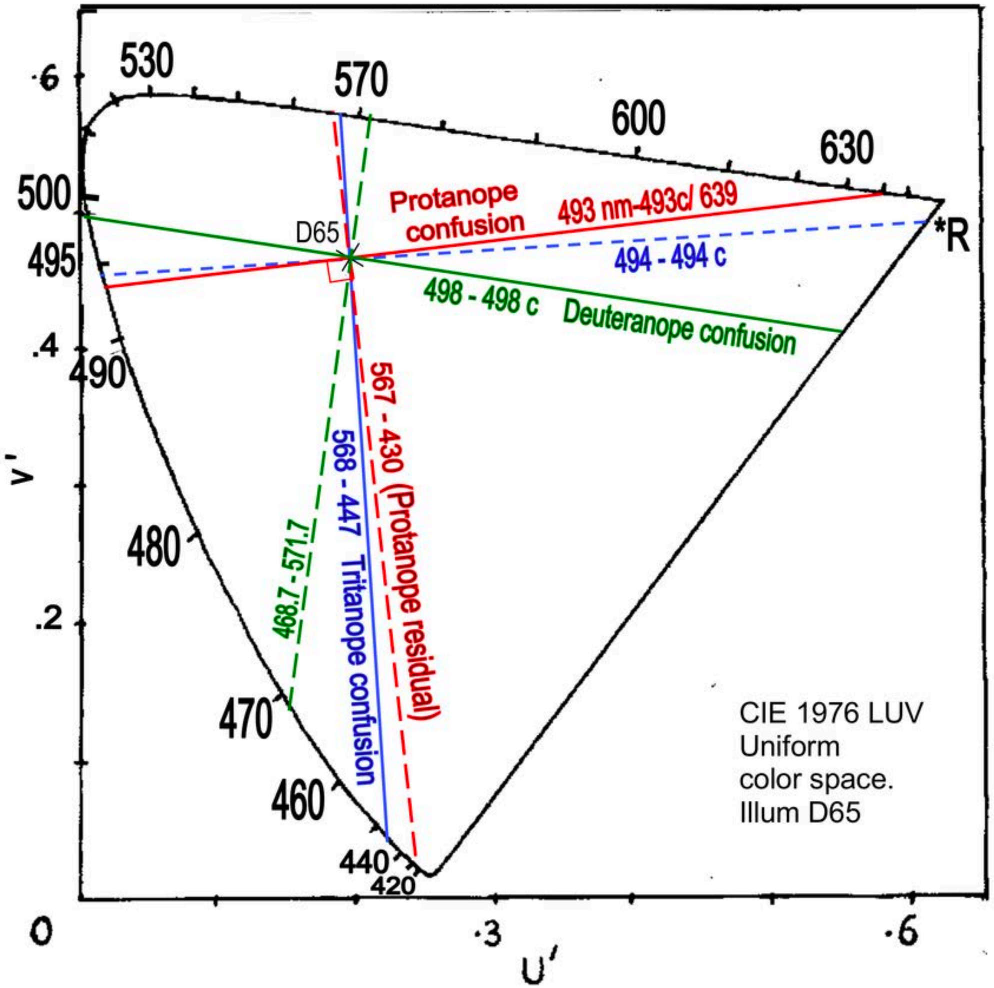
Pridmore 2014, https://doi.org/10.1371/journal.pone.0107035

normal vision



protanopia

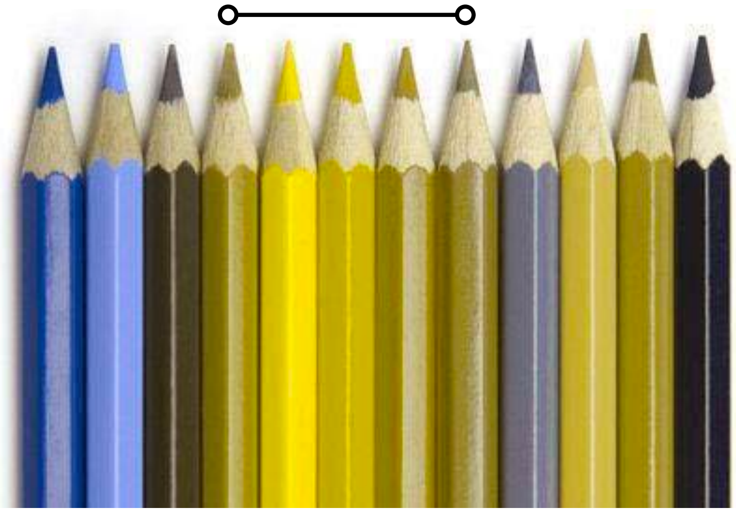




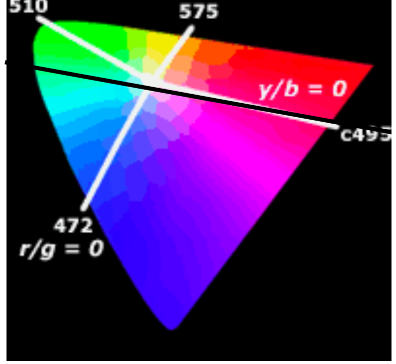
- **Protanopia**, lack of L cones
- c. 1% males and c. 0.01% females
- cannot distinguish red from green

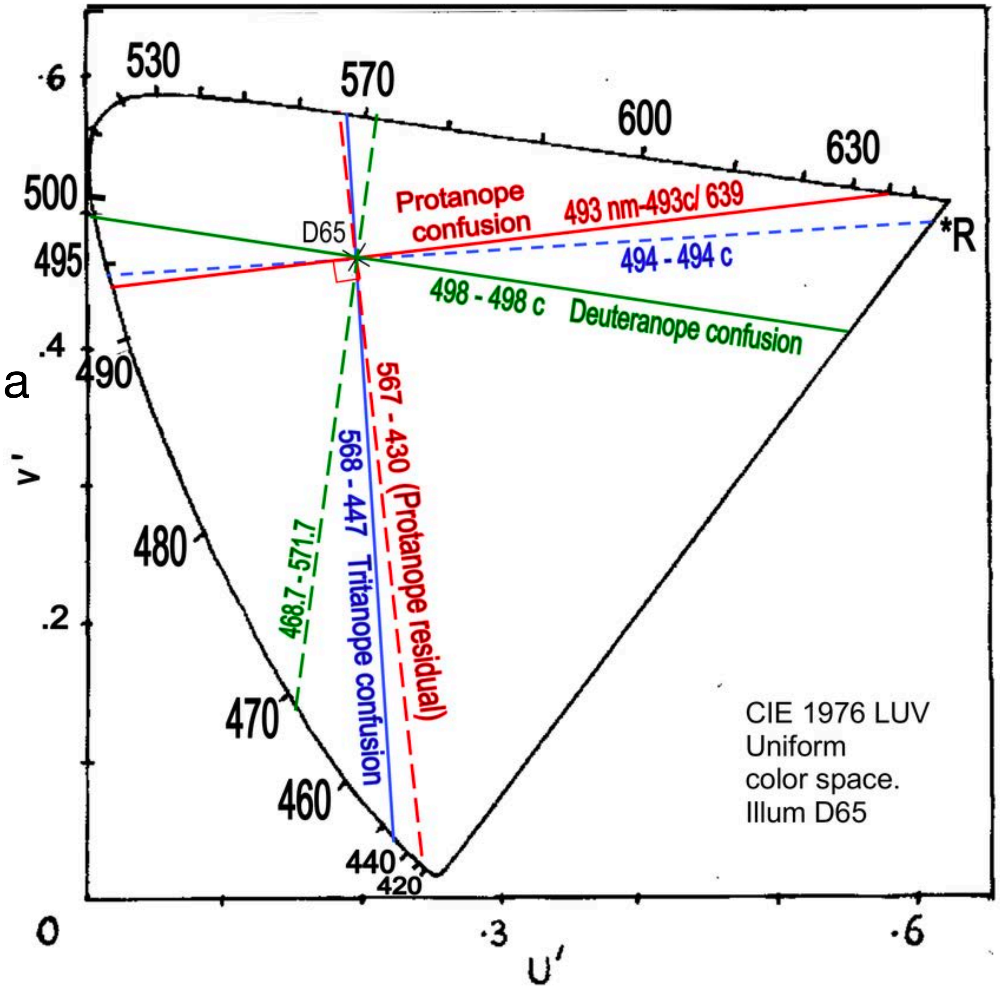
Pridmore 2014, https://doi.org/10.1371/journal.pone.0107035

normal vision



deuteranopia

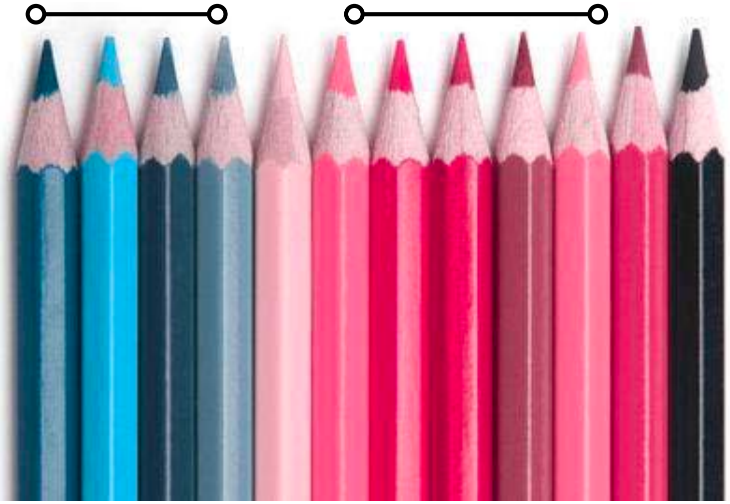




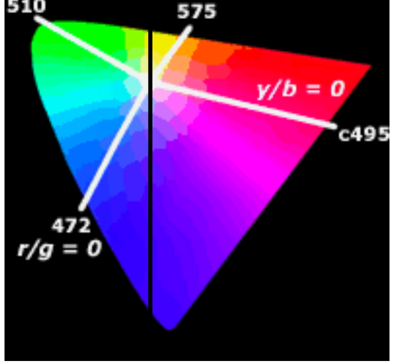
- **Deuteranopia**, lack of M cones
- c. 1.5% males and c. 0.01% females
- cannot distinguish red from green

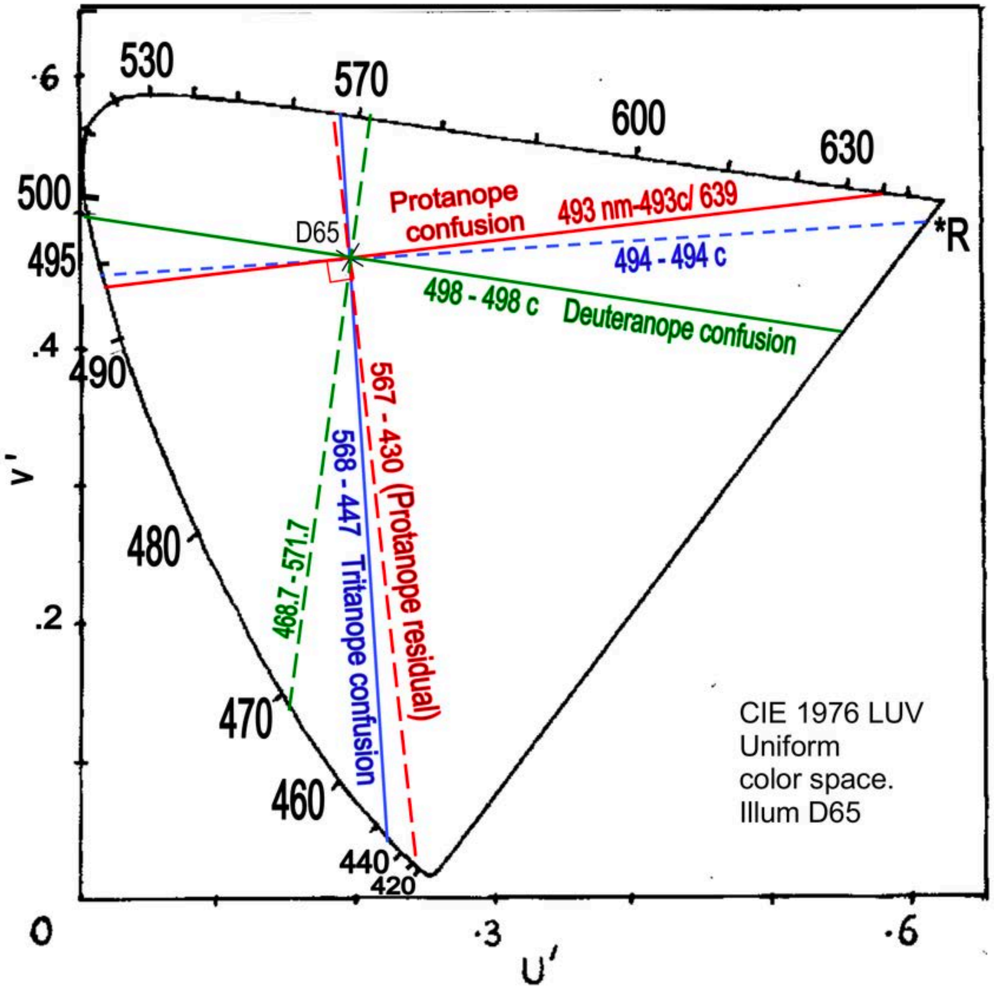
Pridmore 2014, https://doi.org/10.1371/journal.pone.0107035

normal vision



tritanopia

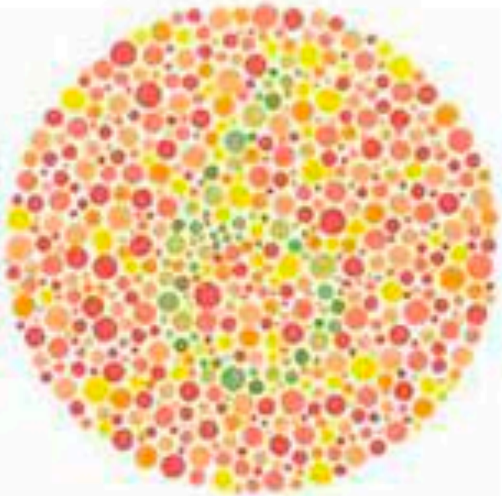
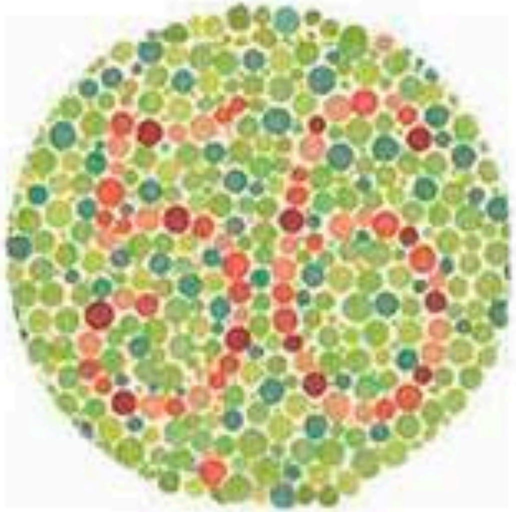
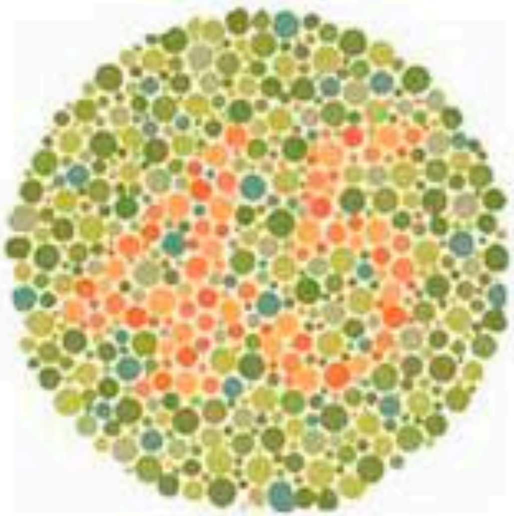
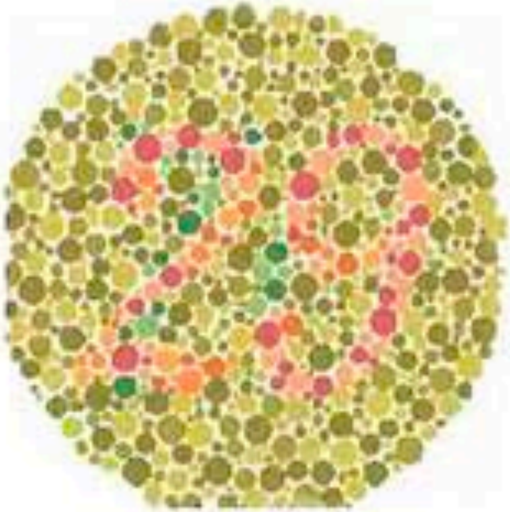
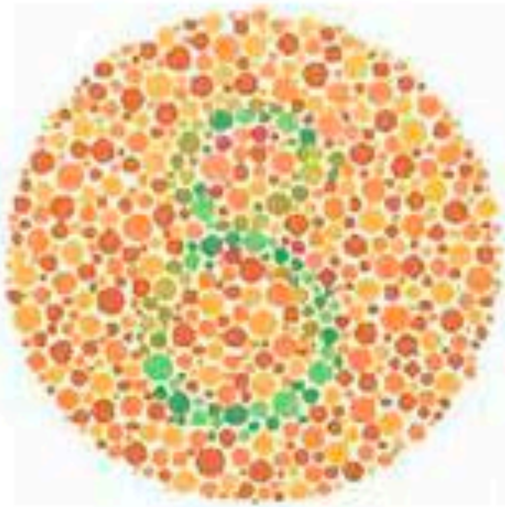




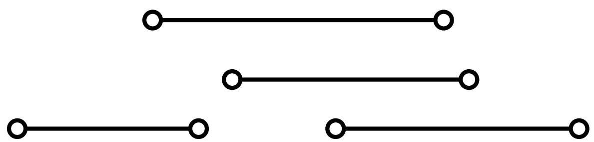
- **Tritanopia**, lack of S cones
- Less than 0.01%
- cannot distinguish blue from green, yellow from violet

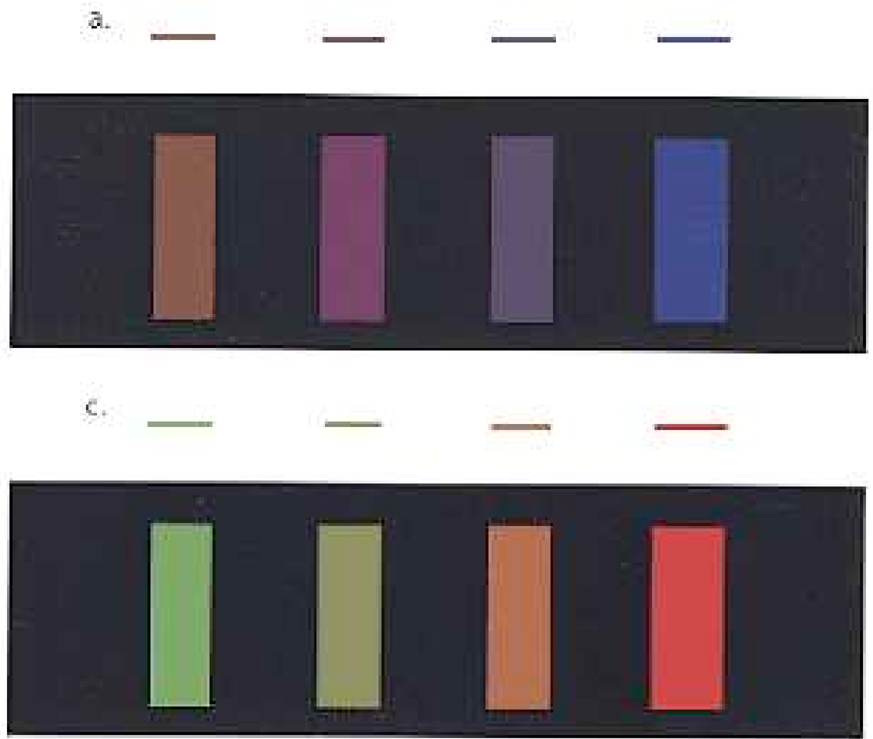
Pridmore 2014, https://doi.org/10.1371/journal.pone.0107035

Ishihara colour test

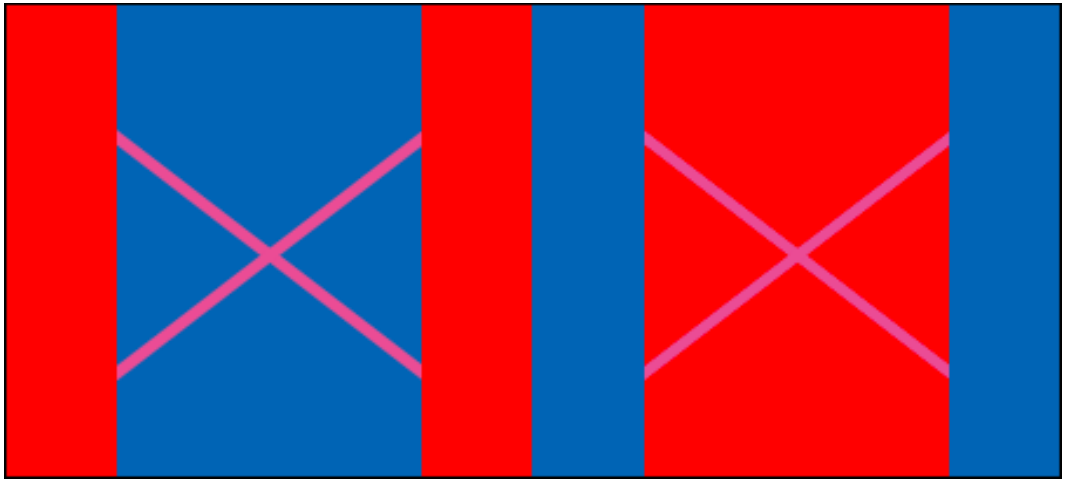
Small field colour blindness





- Size of colour patches affects the perception of colour differences
- For very small patches inability to distinguish colour differences occurs (small field colour blindness)

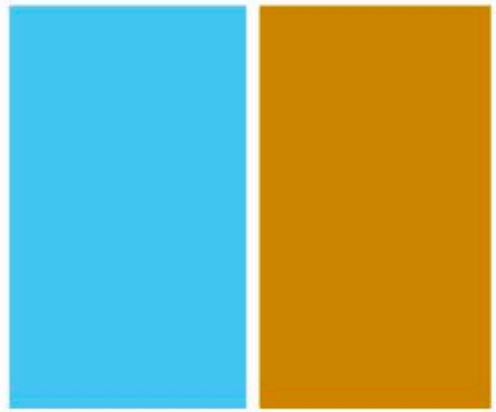
Colour contrast



- The X's are of the same colour on both sides but they are perceived differently depending on the background
- Chromatic contrast can distort reading from colour-coded maps
- Message: relative colour is often more important than absolute colour (as with grayscale!)

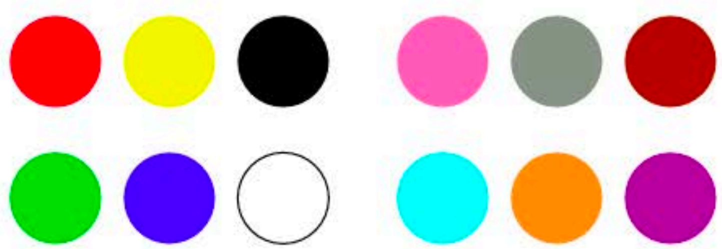
Colour vs. luminance

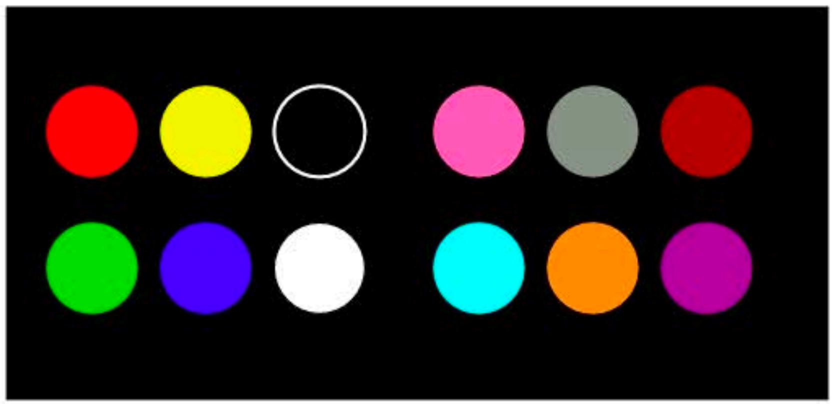
- Colour channels have less spatial resolution than luminance channel
- Perception of shape or motion is due to mainly luminance channel
- Colour channels are therefore better for labelling than data values



Colour for labelling

- For **nominal data** (e.g., coloured symbols represent companies from different sectors) ensure the following when choosing colours for labels:
    - distinctness
    - unique hues
    - contrast with background
    - colour blindness (avoid red-green distinctions)
    - number (5-10 colours can be rapidly distinguished)
    - field size
    - convention (in west: red = danger, hot; green = good, go, etc)





Colour for labelling

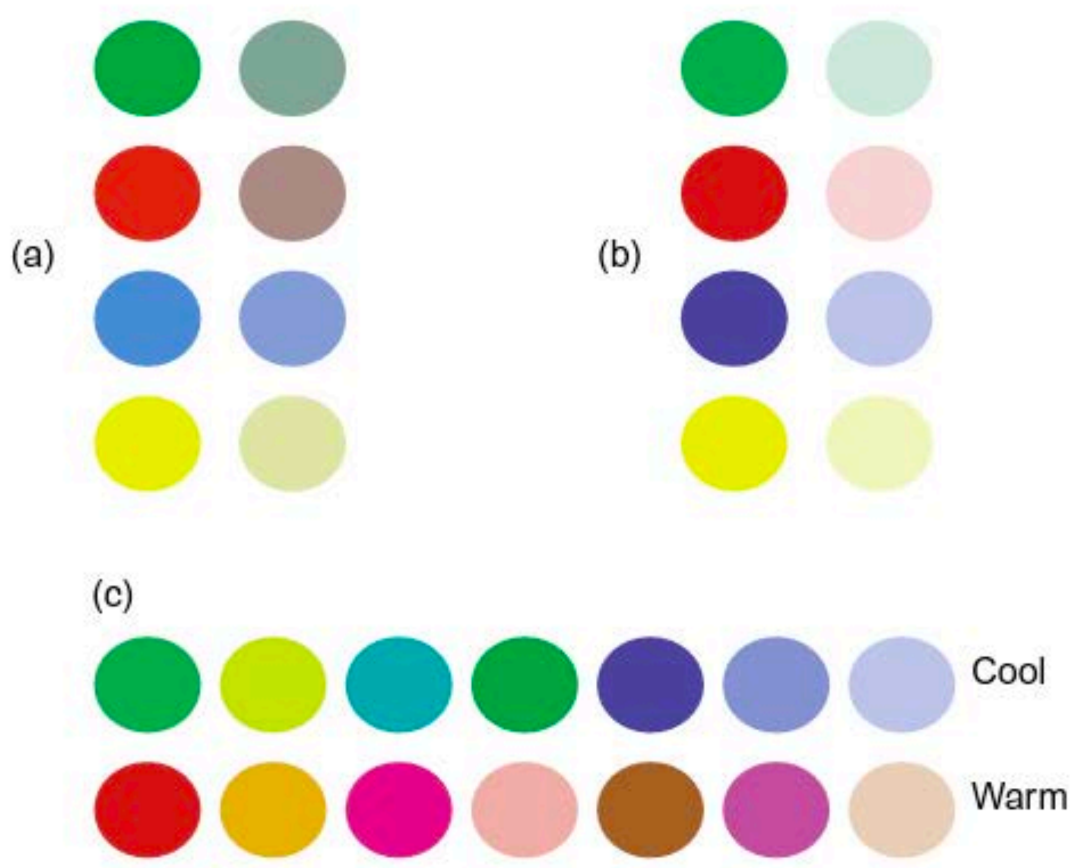


Figure 4.25 Families of colors. (a) Pairs related by hue; family members differ in saturation. (b) Pairs related by hue; family members differ in saturation and lightness. (c) A family of cool hues and a family of warm hues.

Colour for labelling

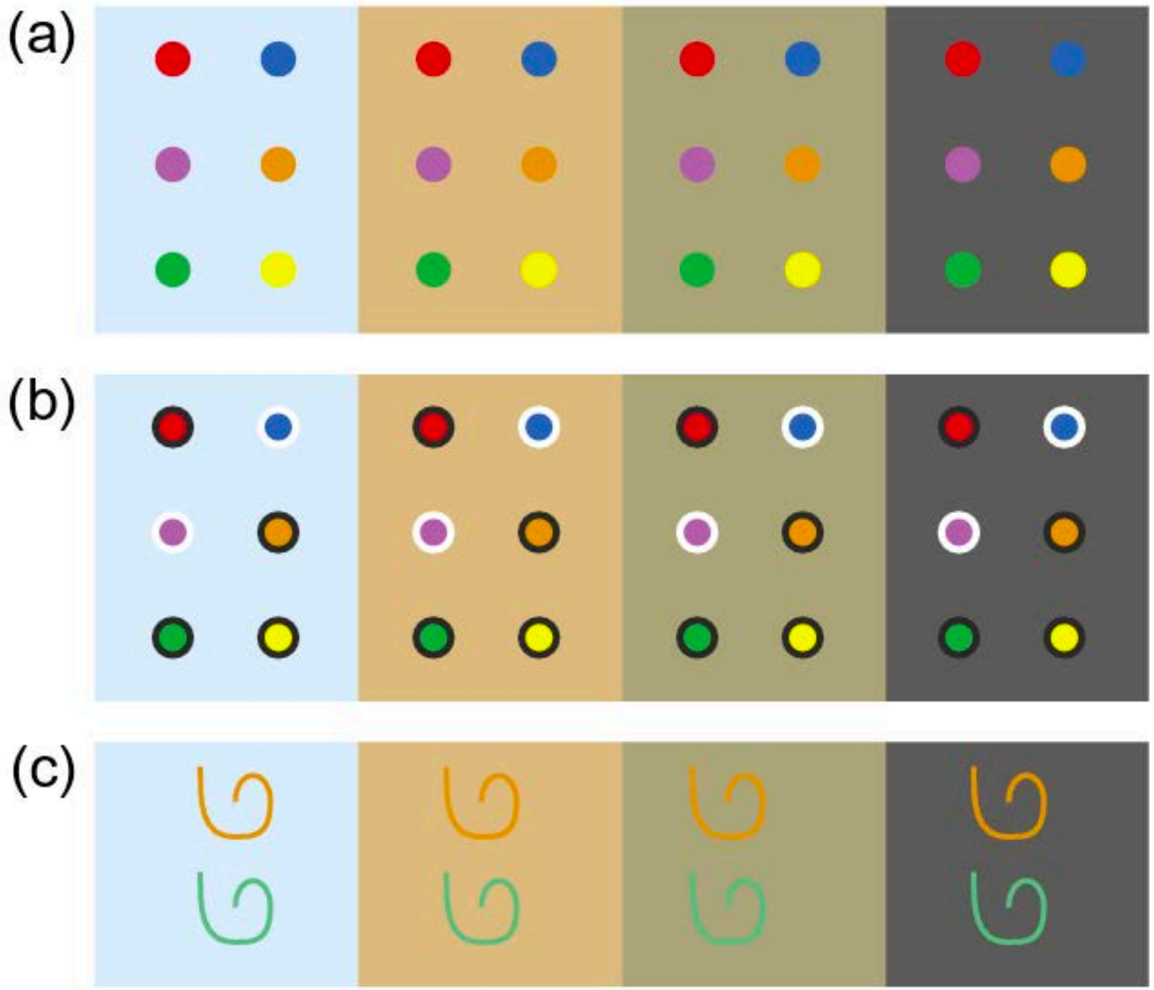


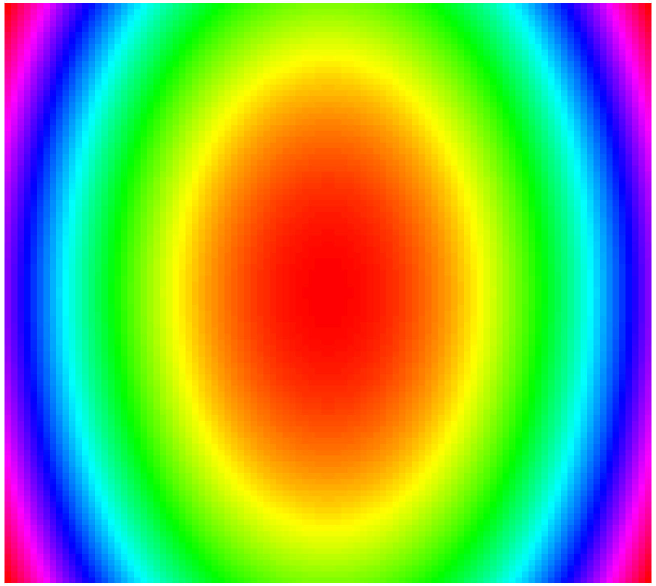
Figure 4.21 (a) Note that at least one member of the set of six symbols lacks distinctness against each background. (b) Adding a luminance contrast border ensures distinctness against all backgrounds. (c) Showing color-coded lines can be especially problematic.

Colour scales

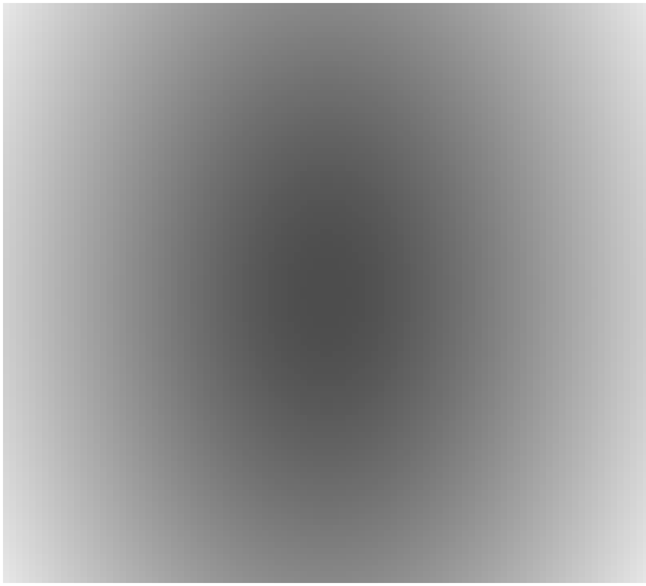
- Some differences are not perceived by colour blind (avoid red-green channel!)
- Perceptually ordered channels are in general formed from the six colour opponent channels. Other ordering include cold-hot, dark-light.
- **Level of detail:** luminance (e.g., grayscale) shows highest level of detail.
- **Perceptually constant steps:** Uniform colour spaces (e.g., CIELUV) can be used to construct scales with perceptually constant steps
- **Reading values from the scale:** minimise contrast effects by cycling through many colours
  - you can even follow a spiral in colour space
- **Misclassification of data:** colour category boundaries may cause misclassification of data

Colour scale examples

- **Spectrum (rainbow) scale**
  - perceptually very non-uniform and not ordered
  - can create “false contours”
  - good for reading values back from the a scale
  - should not be used if the shape of the data is important



- **Grayscale**
  - not good for reading back values
  - shows detail and shape of the data well



...but usually you should use something else...

Colour scales

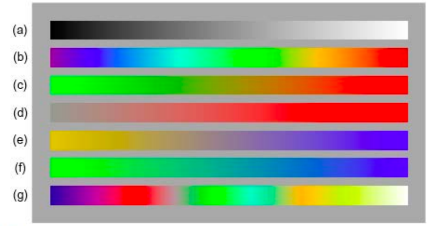
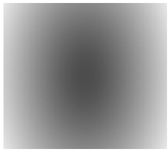
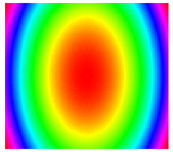


Figure 4.27 Seven different color sequences: (a) Grayscale. (b) Spectrum approximation. (c) Red–green. (d) Saturation. (e, f) Two sequences that will be perceived by people suffering from the most common forms of color blindness. (g) Sequence of colors in which each color is lighter than the previous one.

	 grayscale	 spectrum	
Shows detail	**+++**	**---**	?
Perceptually constant steps	**++**	**---**	?
Reading values from a scale	**---**	**+**	?
Show true shape	**+++**	**---**	?
Ordering is shown well	**++**	**--**	?
Good for labeling	**---**	**++**	?
Colour-blind safe	**+++**	**-**	?
Shows zero point	**---**	**--**	?
...	?	?	?

Colour scales

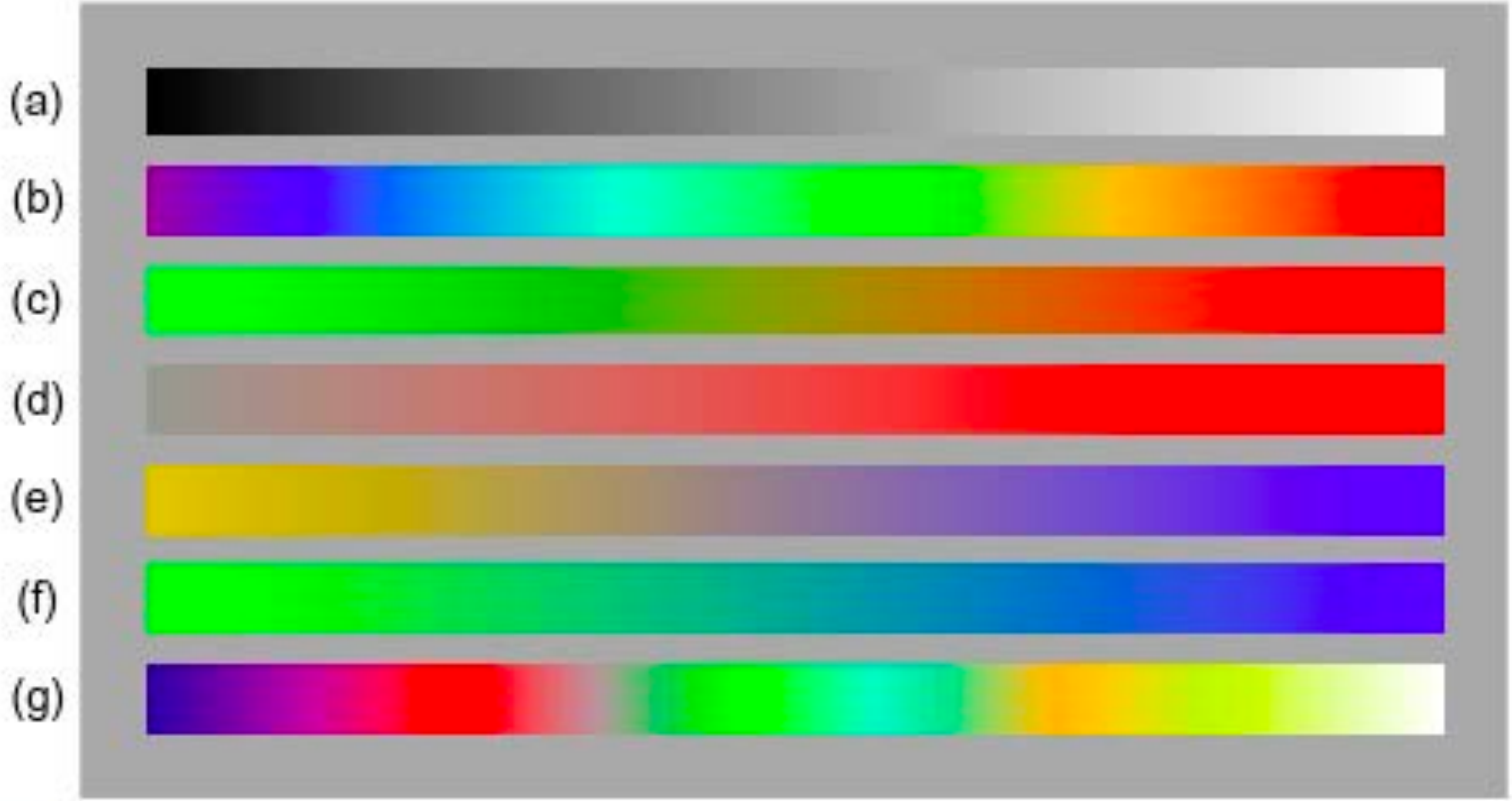
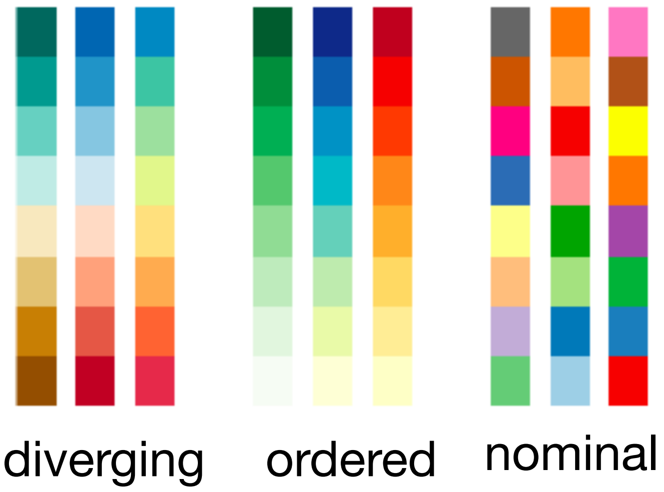


Figure 4.27 Seven different color sequences: (a) Grayscale. (b) Spectrum approximation. (c) Red–green. (d) Saturation. (e, f) Two sequences that will be perceived by people suffering from the most common forms of color blindness. (g) Sequence of colors in which each color is lighter than the previous one.

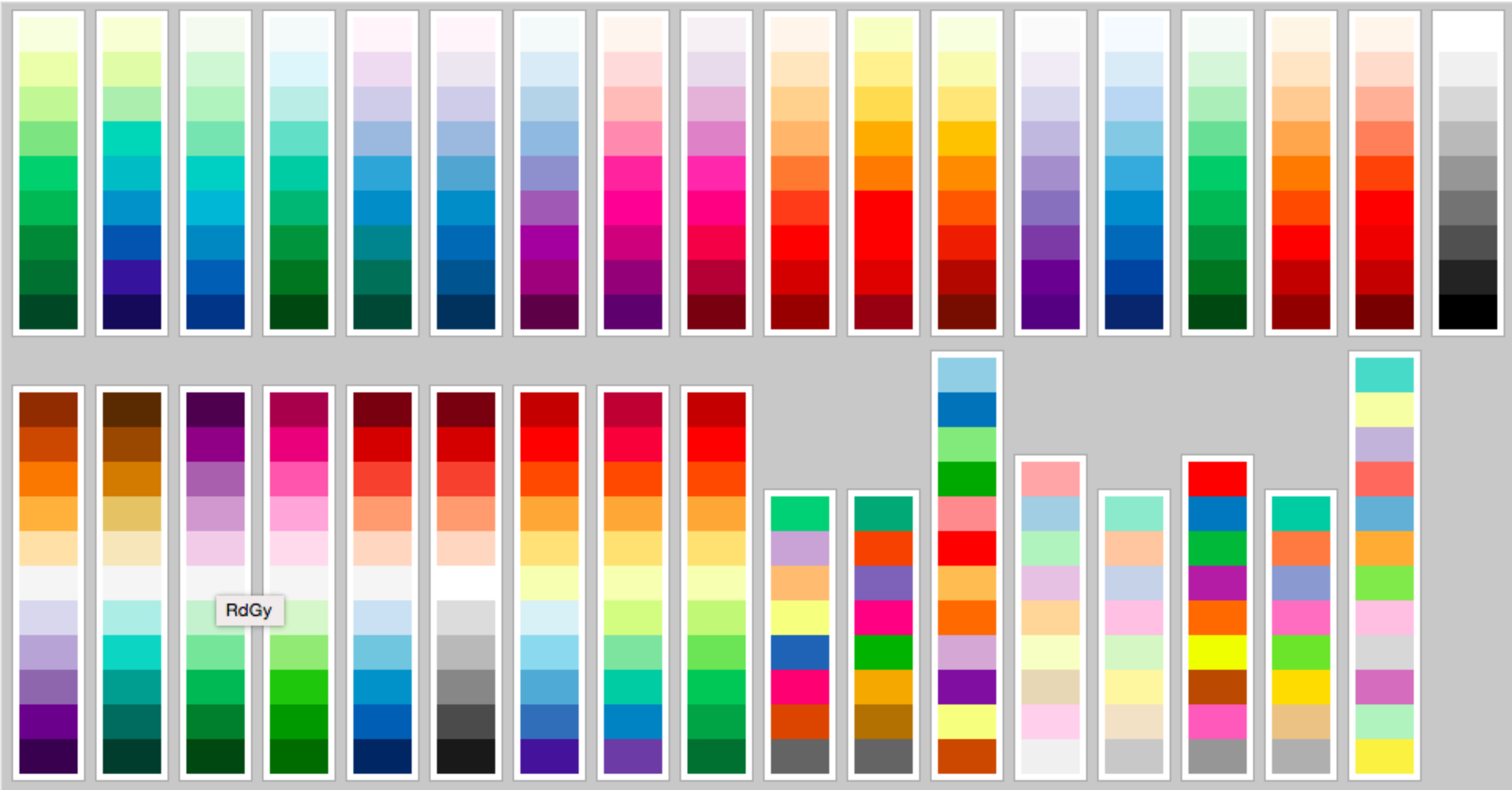
Colour scales



- Some hints on selecting suitable colour scale
- **Nominal** (values have no order):
  - Same as using colour for labelling. Colors should be as distinctive as possible.
- **Ordinal sequence** (values have order):
  - Colors should have perceptually the same ordering as the scale. Use luminance channel (if possible) as well as colors.
- **Ratio sequence** (values have order, there is a true zero and values can be negative)
  - Use diverging sequences: zero has neutral colour (gray or white). Opposite ends use opponent colors.
- **Interval sequence** (difference between two values is what matters)
  - Colors changes should perceptually reflect the differences in the data.The scale should be based on a uniform colour space, or clearly defined (discretised) colour steps should be used. Adding a contour map is a good option here.
- **Reading the actual value from data is important**:
  - Difficult task due to contrast issues. Consider cycling through many colors. Use luminance channel to indicate order.

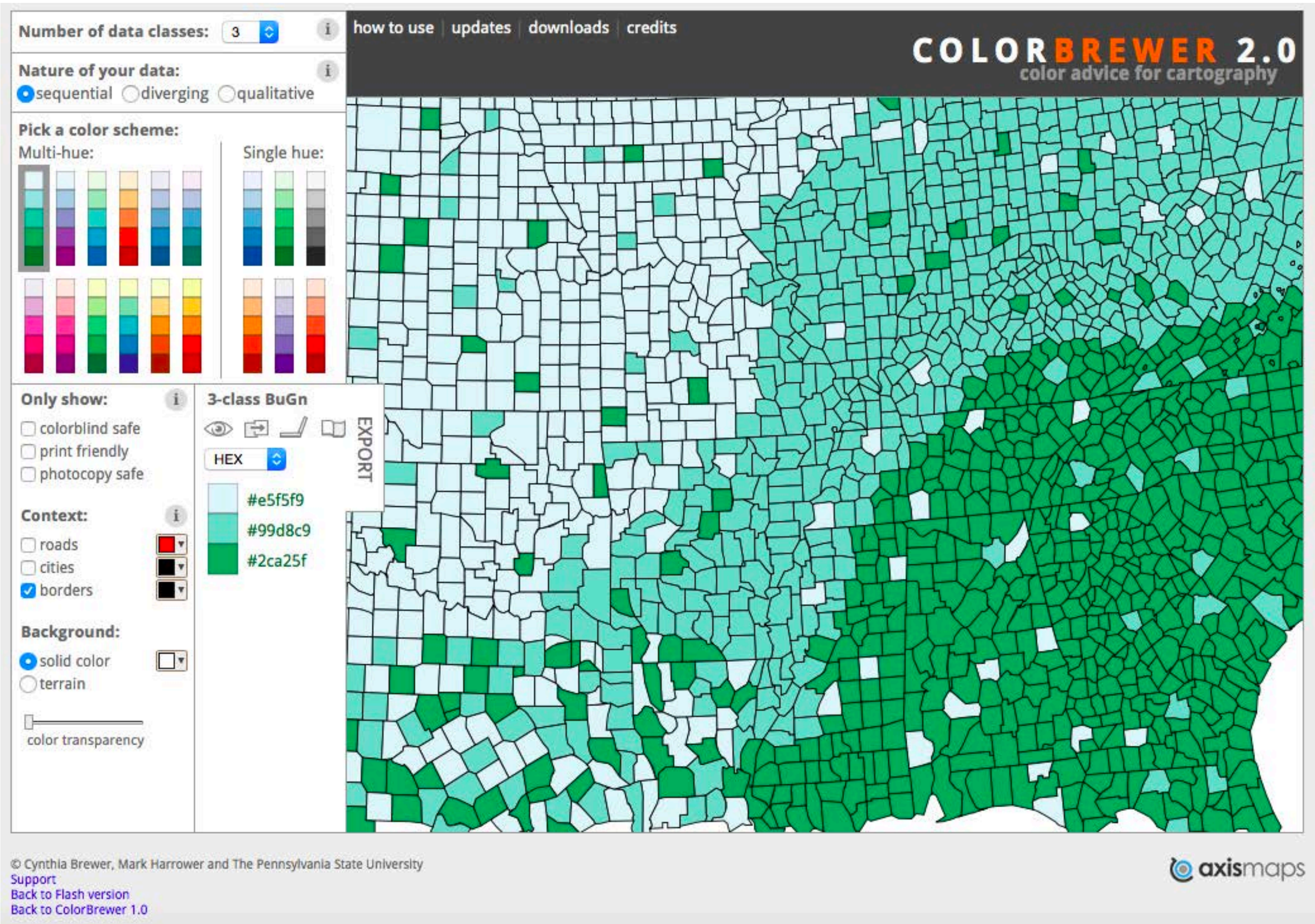
Colour scales

RColorBrewer colour scales   http://colorbrewer2.org/



https://bl.ocks.org/mbostock/5577023

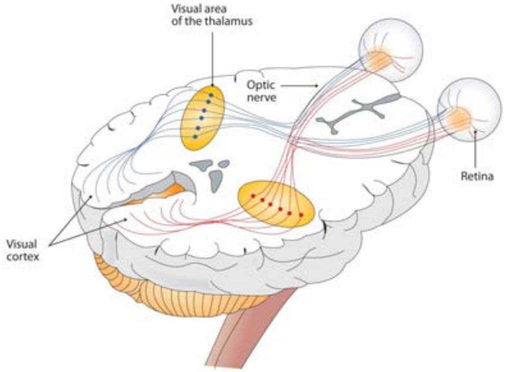
Colour scales



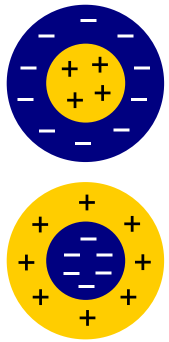
Harrower, Brewer. ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps, The Cartographic Journal, 40:1, 27-37, 2003. https://doi.org/10.1179/000870403235002042

Summary

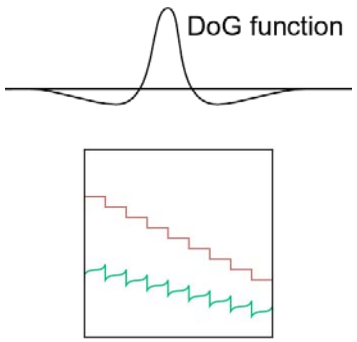
from retina to brain



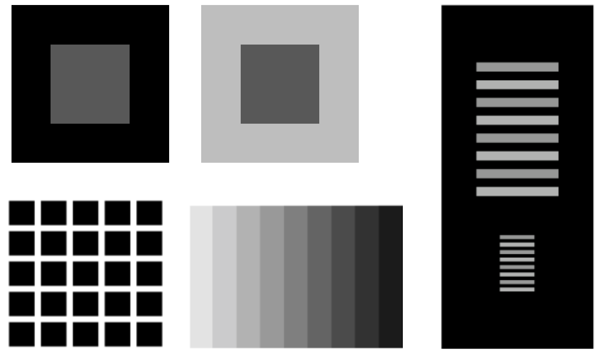
receptive field

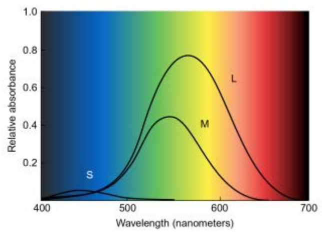


Difference of Gaussians

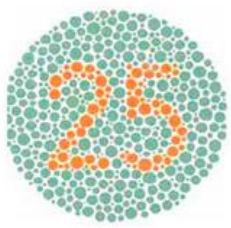


contrast illusions and crispening



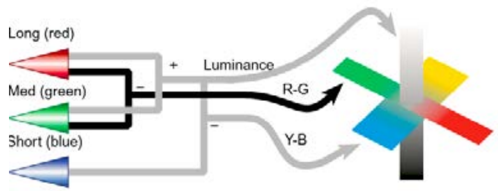


Trichromacy theory

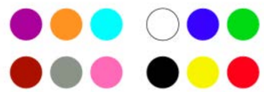


colour blindness

colour spaces



opponent colour theory



colour for labels, scales, multidimensional data, reproduction

Next lectures

- Visual salience and finding information (Ware Ch 5)
  - guiding your attention
- Static and moving patterns (Ware Ch 6)

You can guide your attention to a degree

Read every other word, starting from the 1st or 2nd word:

Visual Human search perception is plays a an type important of role perceptual in task the requiring area attention of that visualization. typically An involves understanding an of active perception scan can of significantly the improve visual both environment ...

From https://en.wikipedia.org/wiki/Visual_search & https://www.csc2.ncsu.edu/faculty/healey/PP/

Read every other word, starting from the 1st or 2nd word:

Visual Human search perception is plays a an type important of role perceptual in task the requiring area attention of that visualization. typically An involves understanding an of active perception scan can of significantly the improve visual both environment ...

Now direct yourself to read *only the black text* or *only the red text*:

Visual Human search perception is plays a an type important of role perceptual in task the requiring area attention of that visualization. typically An involves understanding an of active perception scan can of significantly the improve visual both environment ...

From https://en.wikipedia.org/wiki/Visual_search & https://www.csc2.ncsu.edu/faculty/healey/PP/

How many 3s?

455865876864565749286555584765298742309847249473247
324879427149572389742982479280742938742564875647654
902842968476745464274784674573847648562484789847985

45586587686456574928655558476529874 2**3**09847249 47**3**247

324879427149572**3**8974298247928074 29**3**8742564875647654

9028429684767454642747846745 7**3**847648562484789847985

Sometimes it is difficult for you to guide your attention

Reading this text might be difficult because of the famous Finnish politician stealing your attention. Motion and especially *appearance* of a new object attracts attention. Human faces seem to be especially effective. This seems right and makes ecological sense. When early man was outside a cave, awareness of emerging objects in the periphery would have had clear survival value. Such movement may have signalled immediate and deadly danger.

A model for perceptual processing

1. Parallel processing to extract low-level properties of the visual scene
   - rapid parallel processing
   - extraction of features, orientation, colour, texture and movement patterns
   - iconic store
   - bottom-up, data driven processing
2. Pattern perception
   - slow serial processing
   - involves both working memory and long-term memory
   - arbitrary symbols relevant
   - different pathways for object recognition and visually guided motion
3. Visual working memory