CS-E4840
Information visualization D

Lecture 6: Colors
Mar 16, 2023

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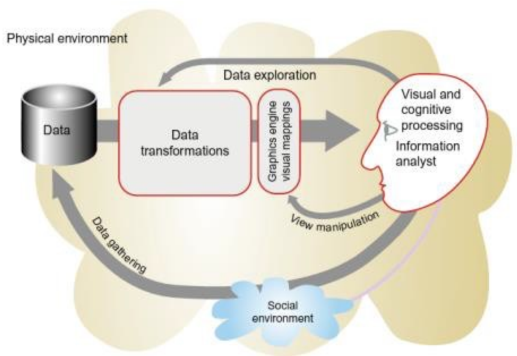
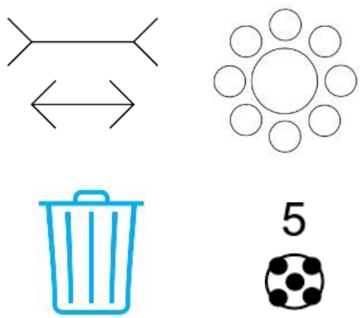
Recap of last lecture

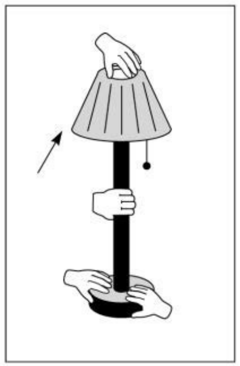
visualization process



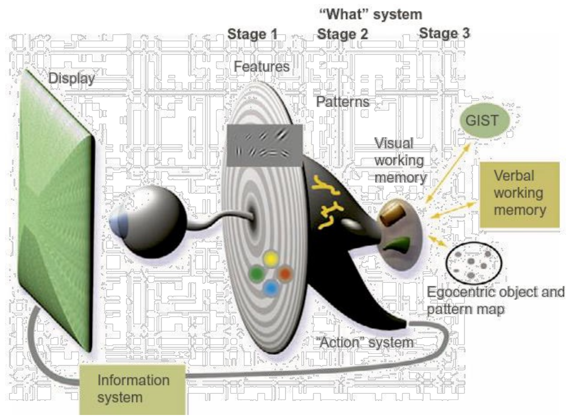
semiotics
sensory & arbitrary symbols

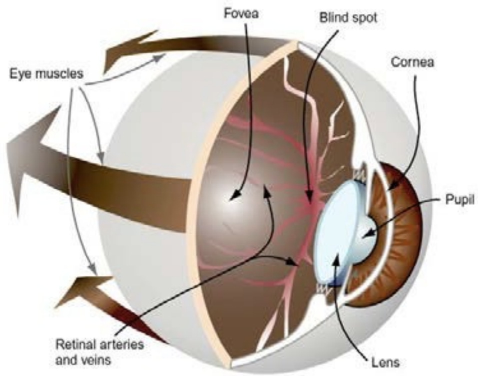


affordance theory

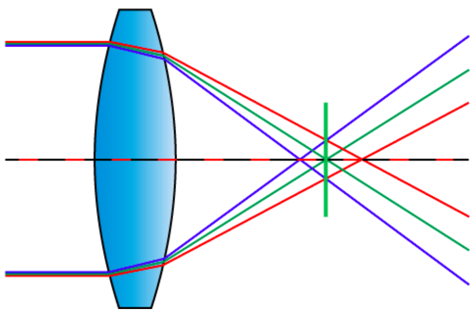


model of perceptual processing



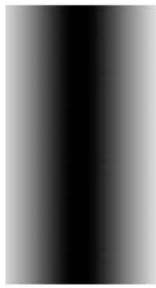


human eye

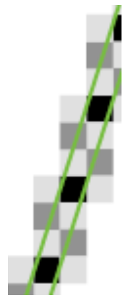


optics

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

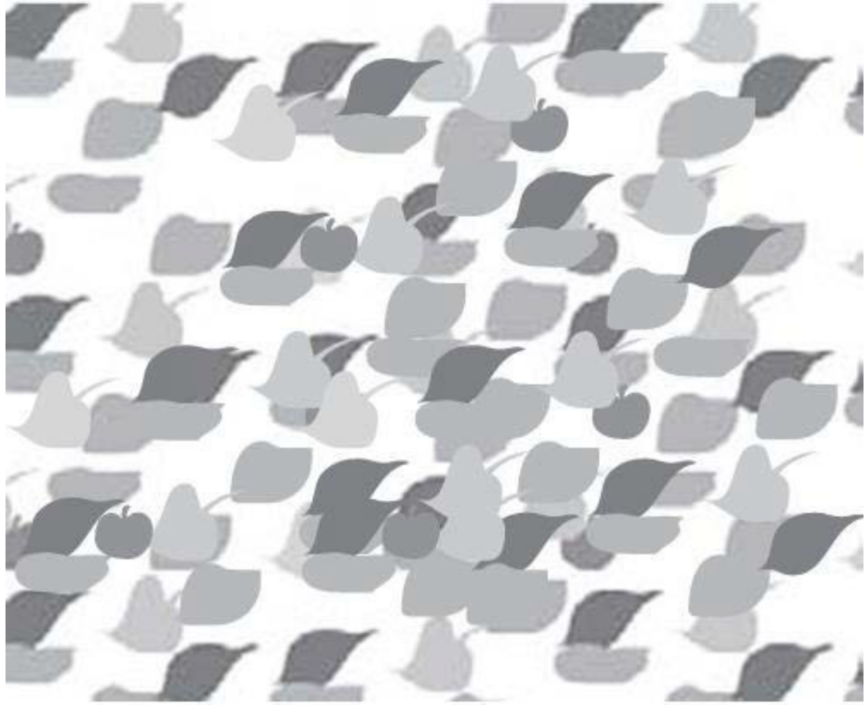
- Acuity and contrast sensitivity:
  - simple acuity (maximal at fovea, c. 1')
  - super-acuities (achieved by integrating the output of several retinal receptors, 10")
  - contrast sensitivity

Eye is *not* like a camera

- 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

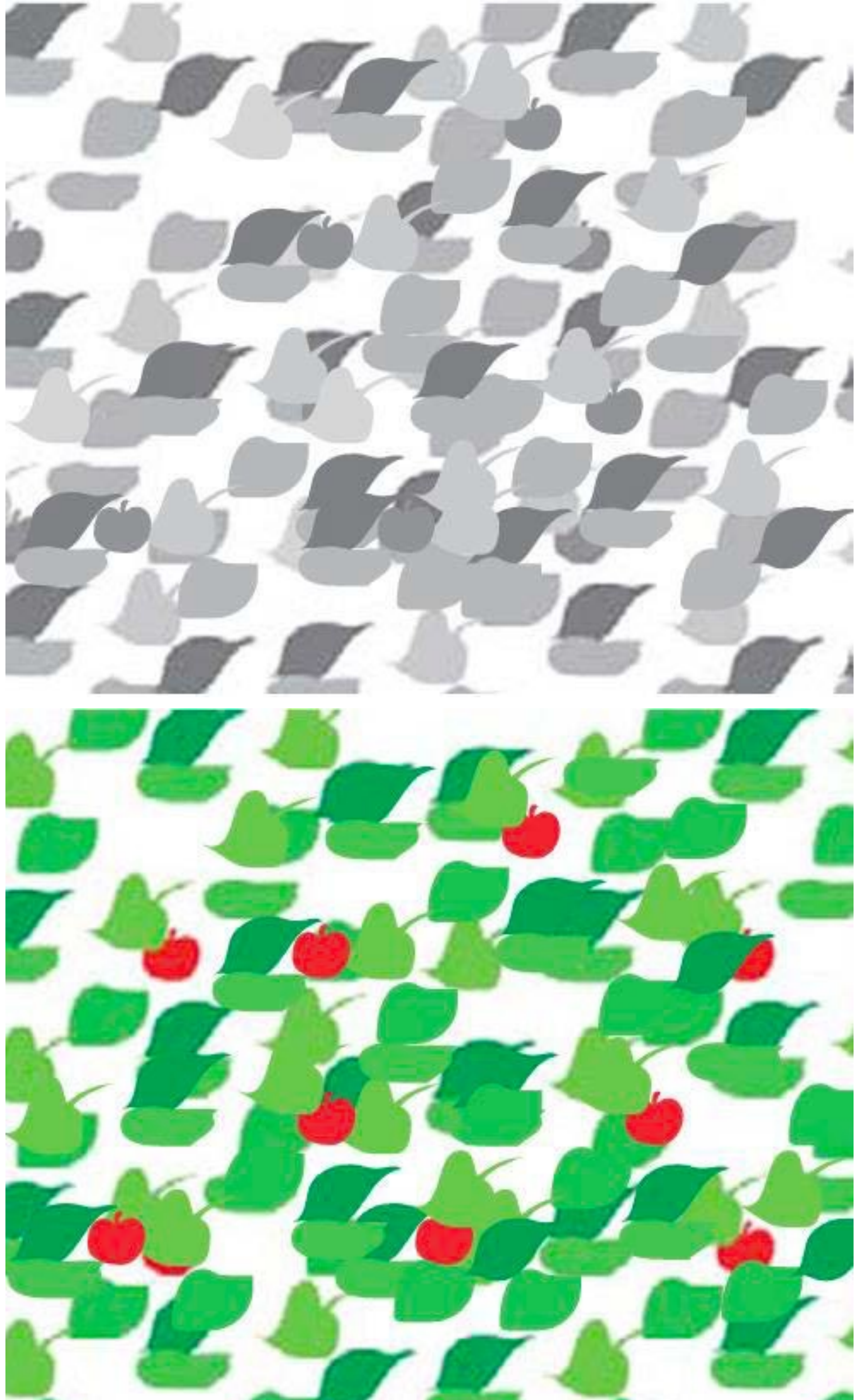
spot the cherries



Why colors?

- Color breaks camouflage
  - some things differ visually from their surroundings only by their color
  - e.g., with color we can easily see the cherries hidden in the leaves
- Color tells us about material properties of objects
  - e.g., which fruit are ripe? Which food has gone bad?
- Color 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

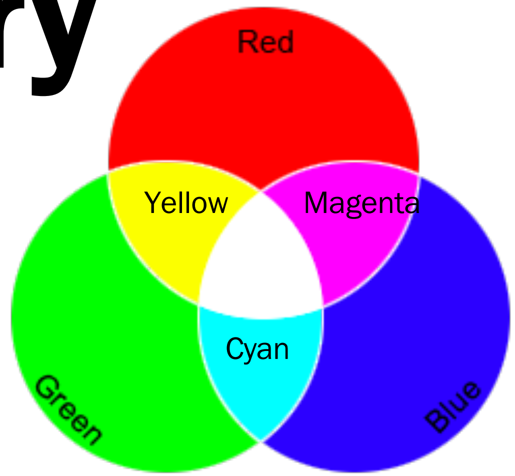


Color in visualisation

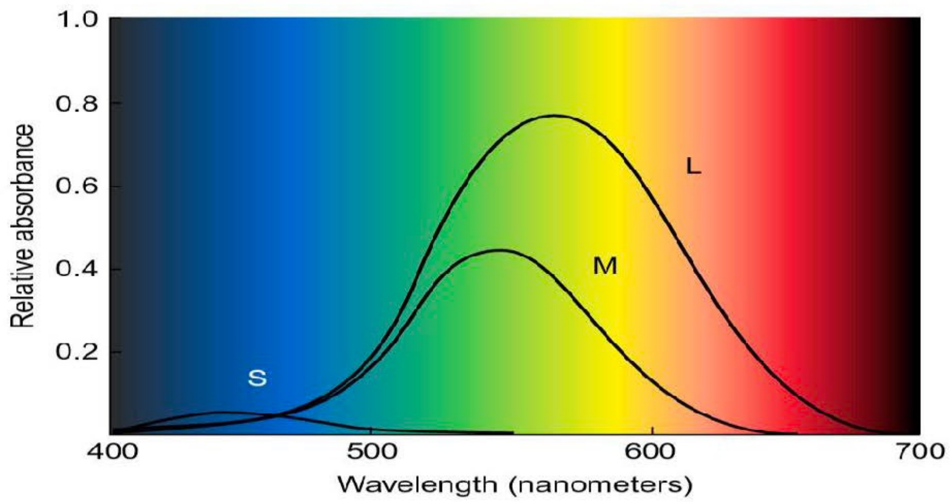
- One of the most (academically) studied topics

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

Trichromacy theory

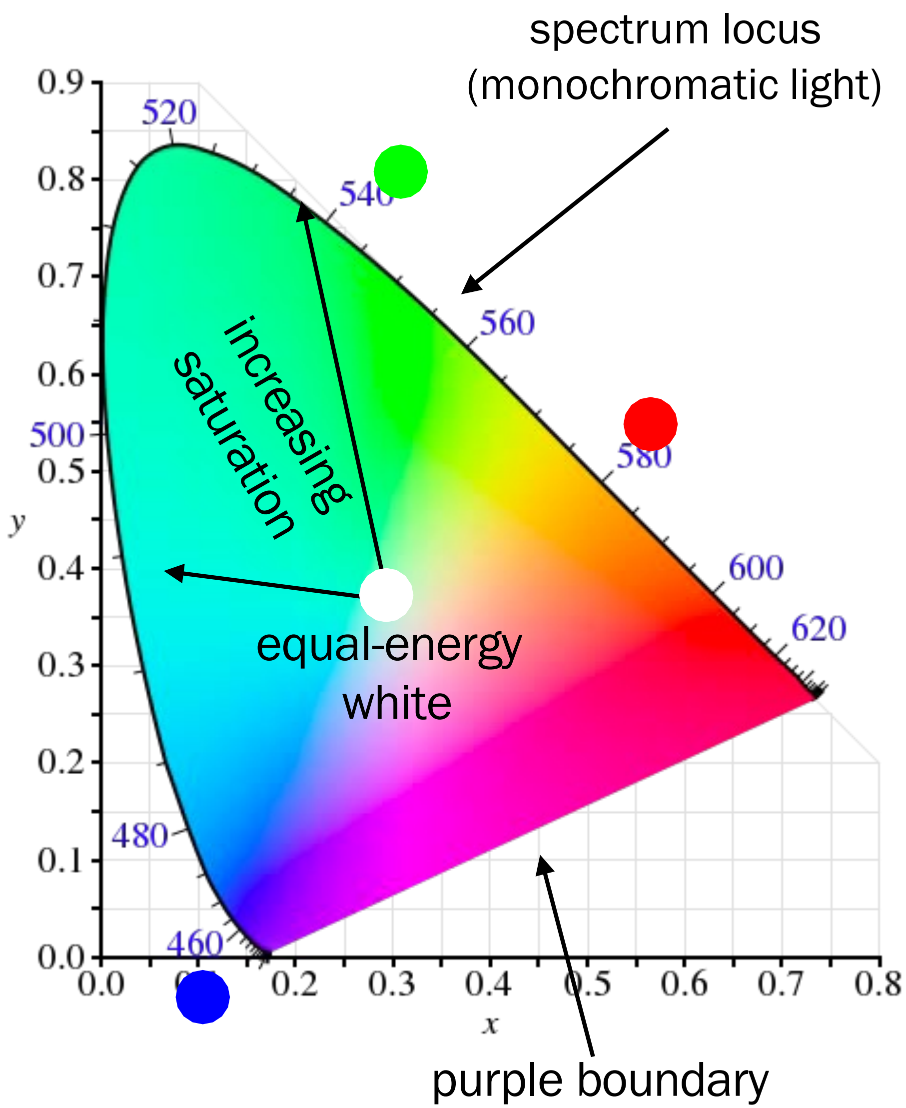


- The human eye has 3 distinct color receptors, called cones (chicken have 12!)
  - Red (sensitive to long-wavelength light) L
  - Green (sensitive to medium-wavelength light) M
  - Blue (sensitive to short-wavelength light) S
- Red, green, blue = primary colors of light (light primaries, additive primaries)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



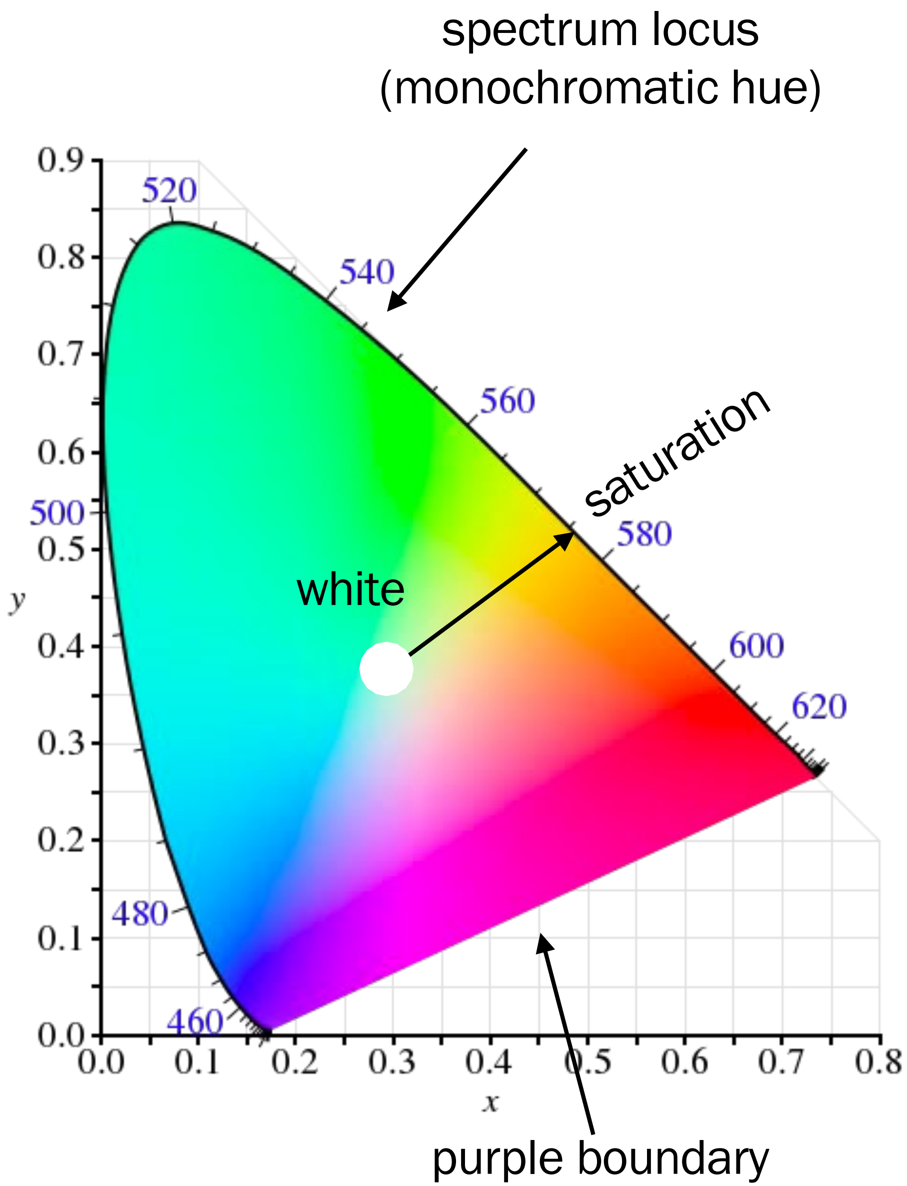
CIE xyY model: chromaticity diagram

- Color 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 color 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 colors could present all perceivable colors
- 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 colored 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

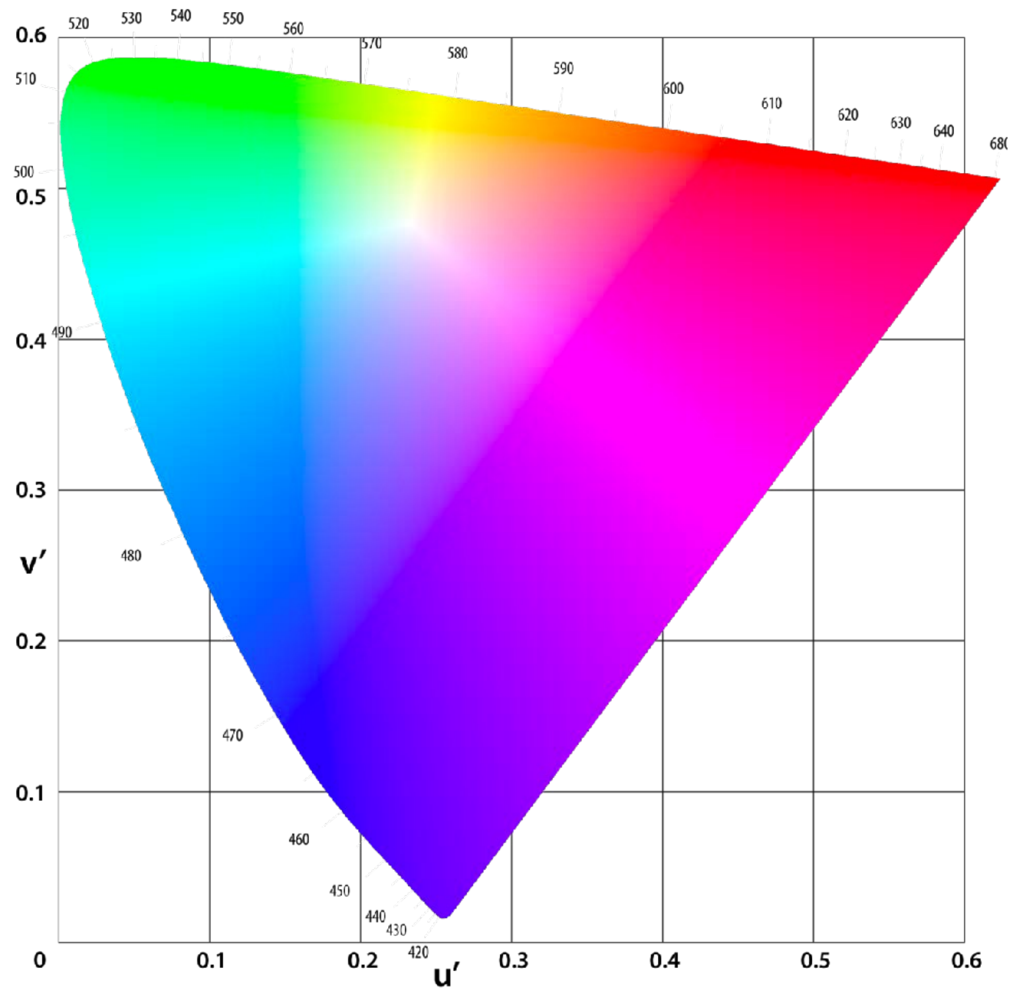


Perceptually more uniform CIELUV

- 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 colors is about

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

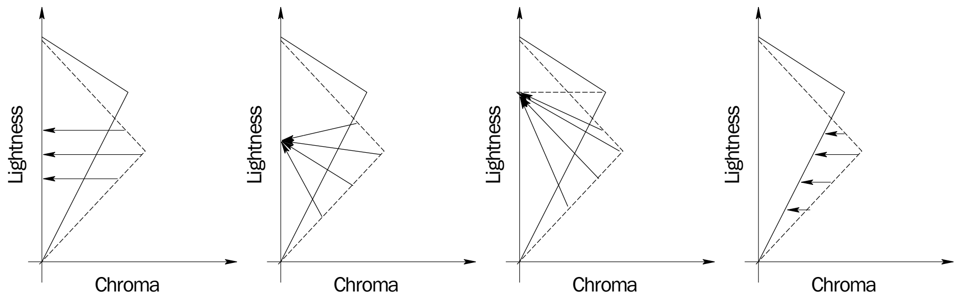
where 1 = approximately just noticeable difference



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

Gamut

- Any physical device with finite number of primary colors 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)

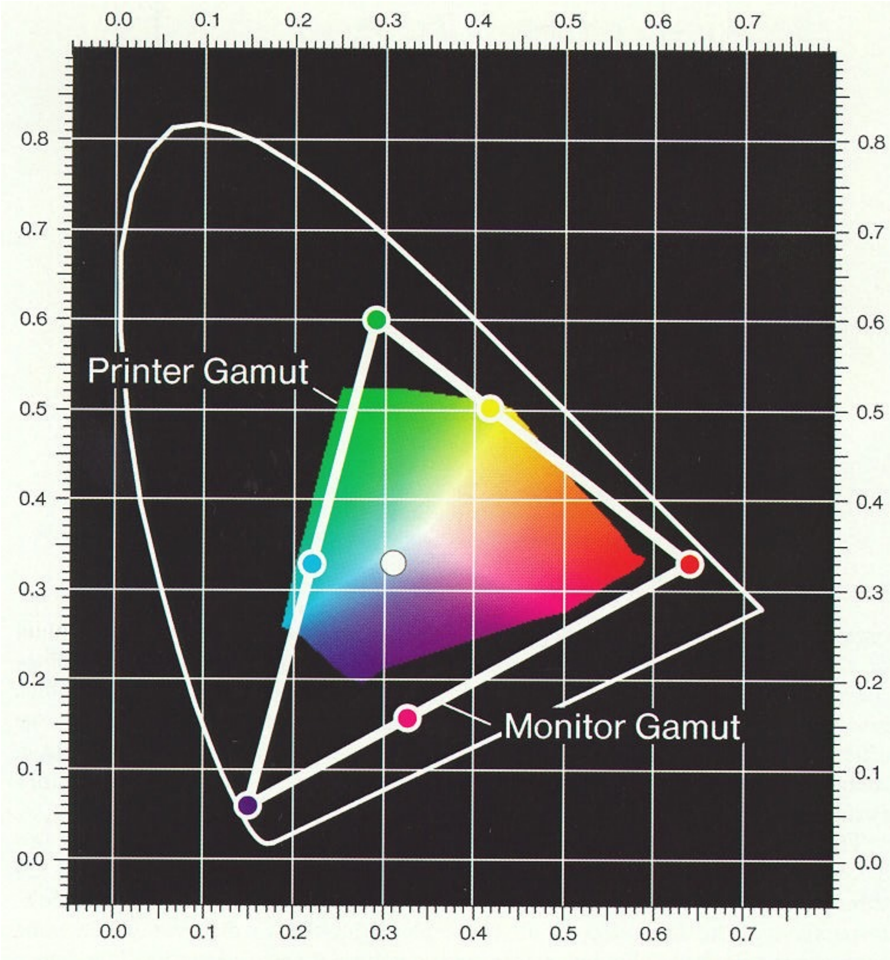
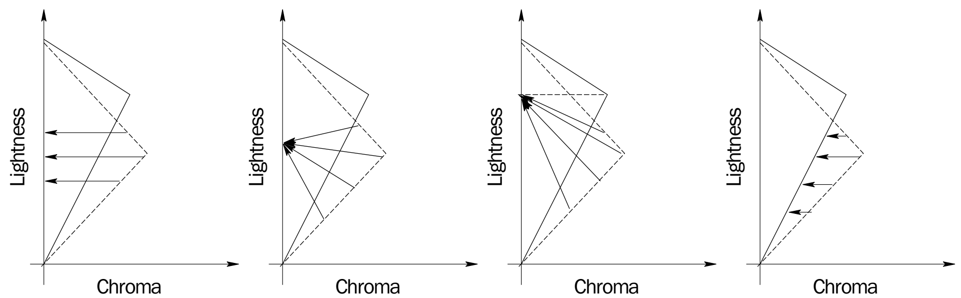


Fig. 8. Gamuts of the Cromalin proof and a typical color monitor overlaid on the CIE chromaticity diagram. The horseshoe shaped plot is the spectrum locus; that is, its interior contains all observable colors represented as chromaticity coordinated.

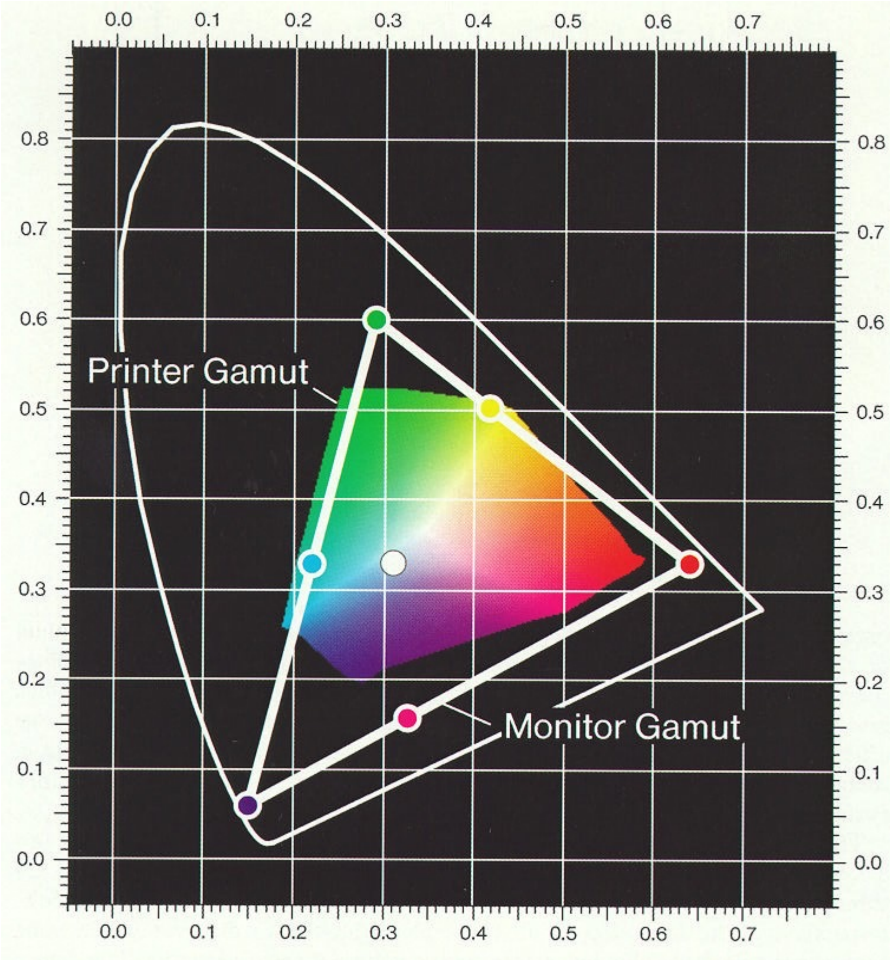
Stone et al. Color Gamut Mapping and the Printing of Digital Color Images. ACM Transactions on Graphics, 7(4): 249-292,1988.

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 colors on monitor cannot be reproduced on paper)
- Truncate colors to printing-ink gamut boundary



(Morovič, 1997)



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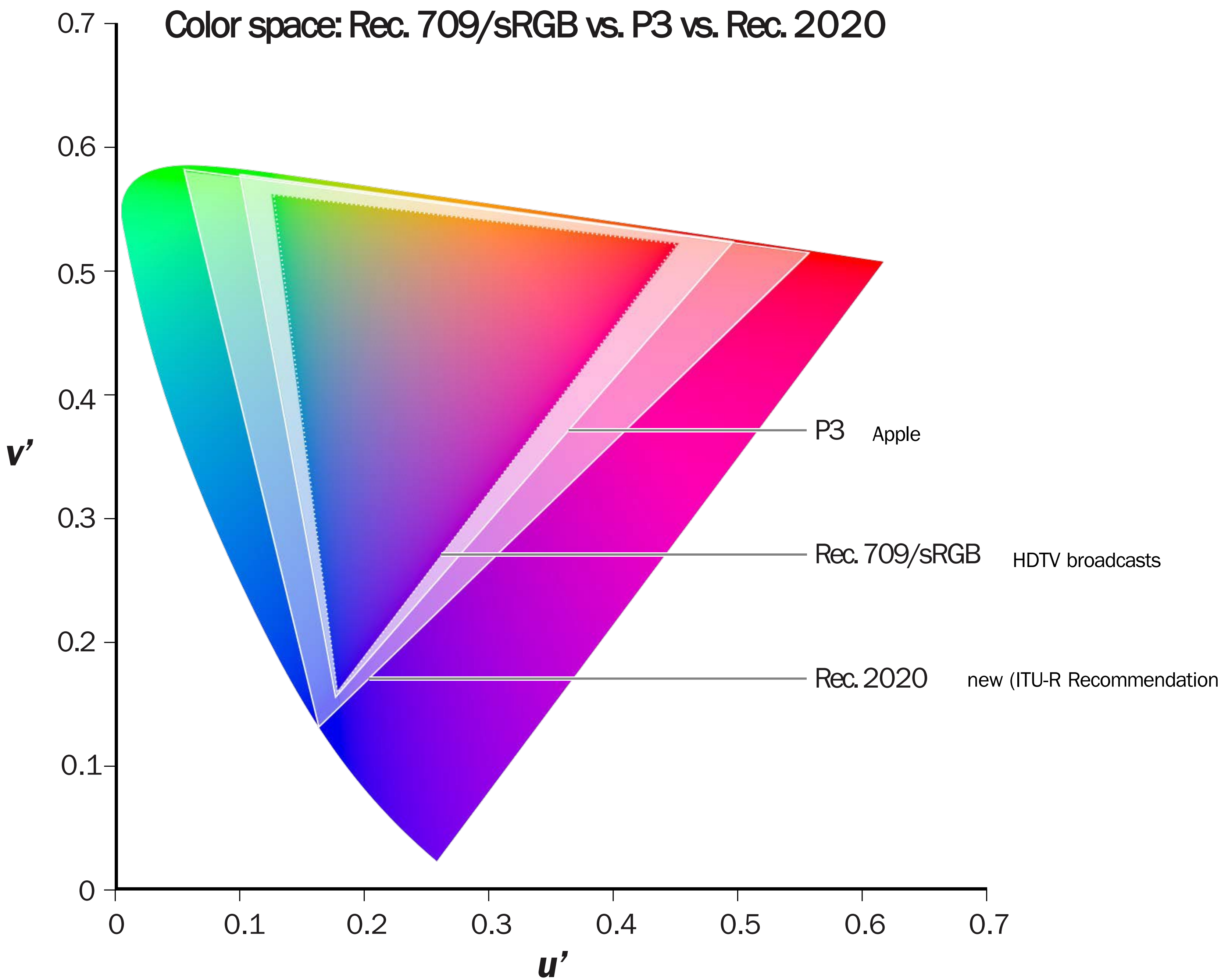
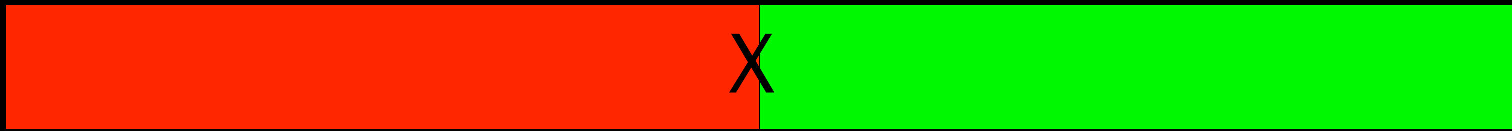
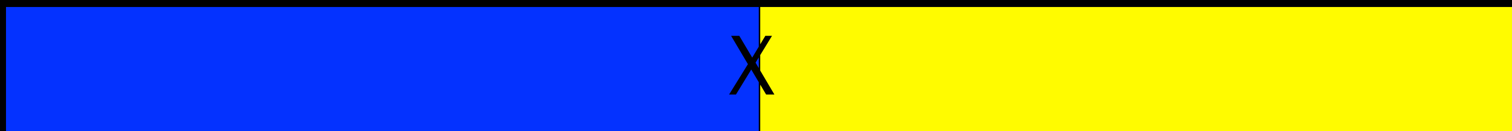


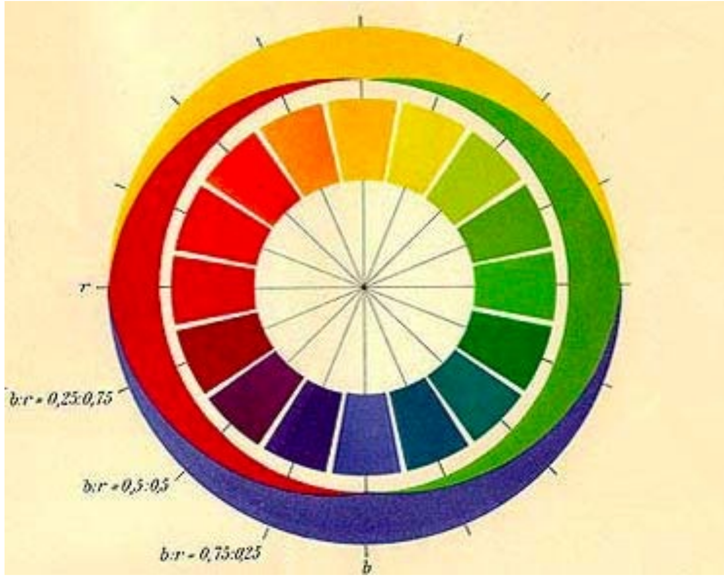
https://images.apple.com/final-cut-pro/docs/Wide_Color_Gamut.pdf

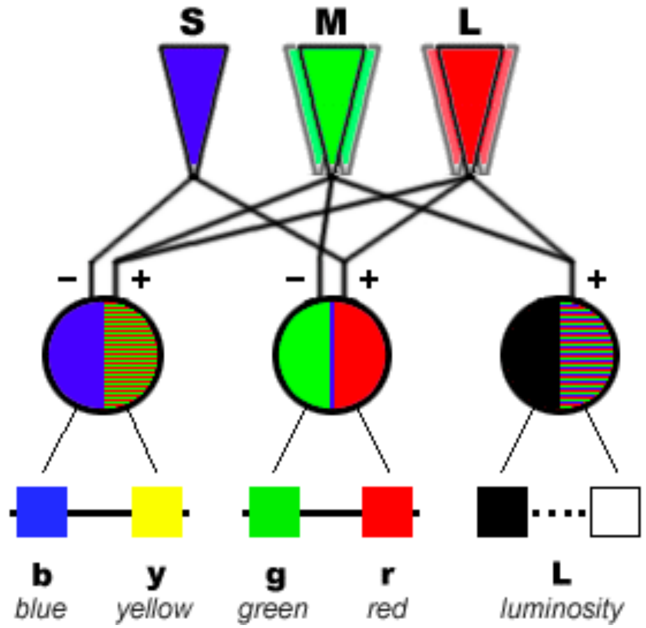


Look at the X for 30 seconds.Then look at white background and blink.



Opponent color theory



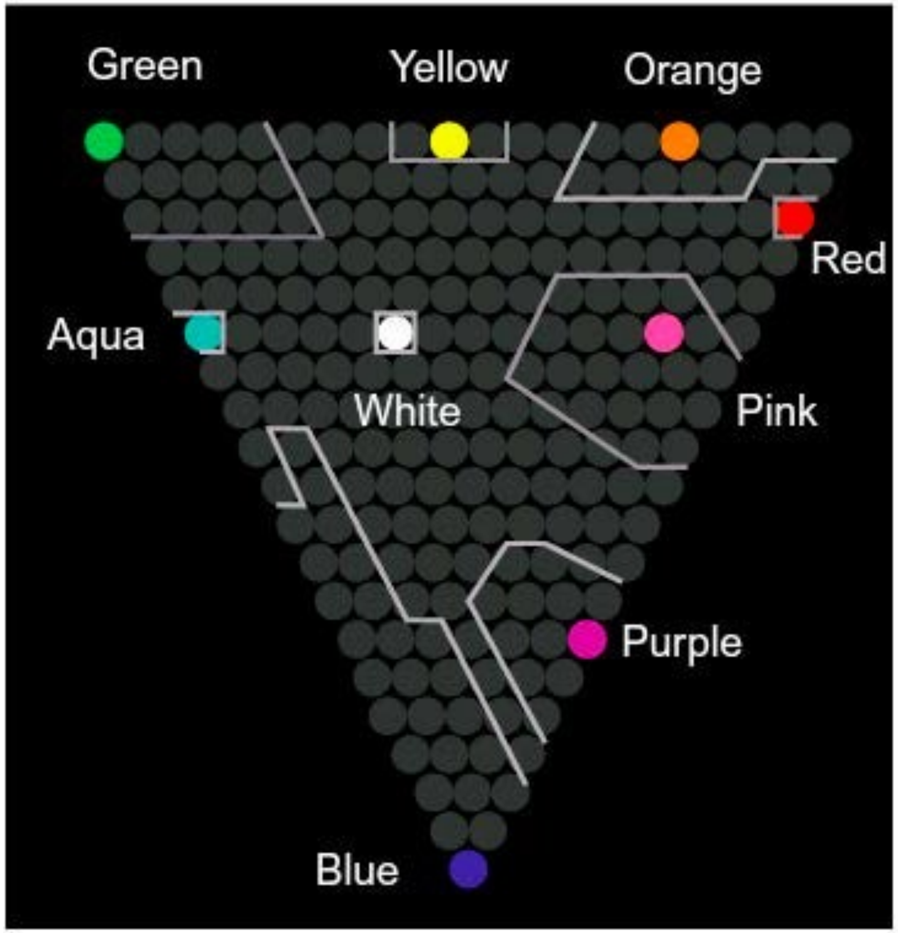


https://www.handprint.com/HP/WCL/color2.html

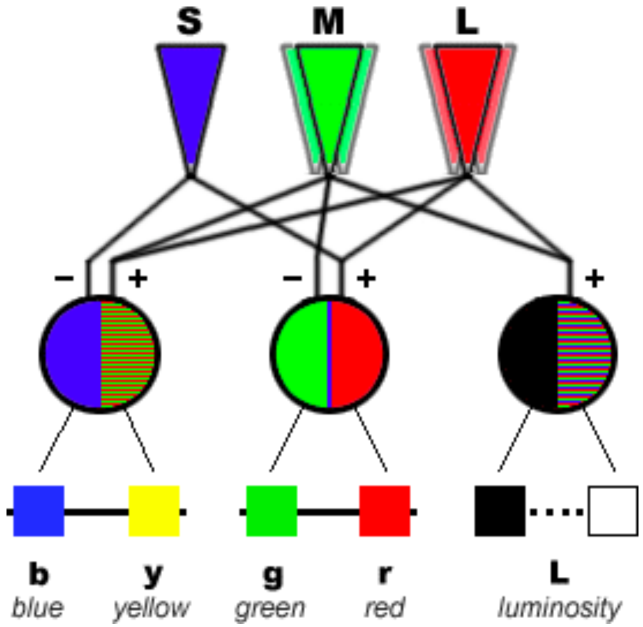
- There are 6 elementary colors. These colors are arranged perceptually as opponent pairs along 3 axes (Hering 1920):
  - black-white, red-green, and yellow-blue
  - Cone signals are transformed into 3 distinct channels:
    - black-white (luminance), red-green, and yellow-blue
- Theory predicts that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

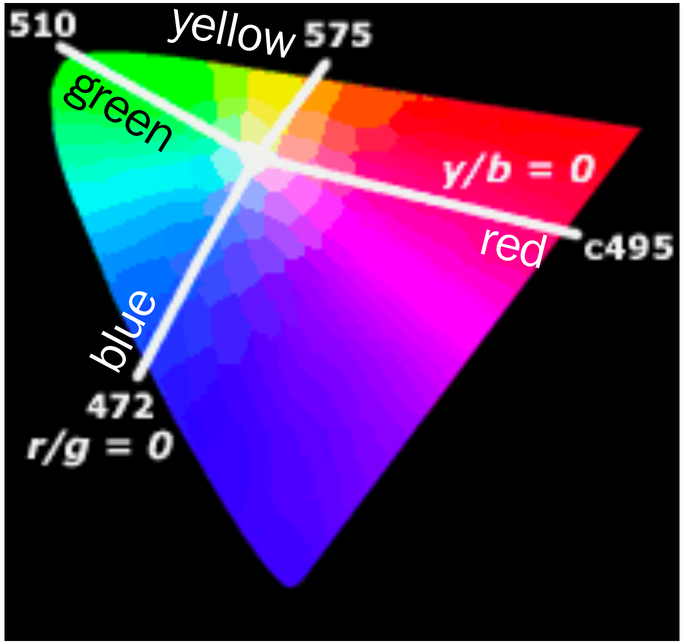
Opponent color theory

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



Color blindness





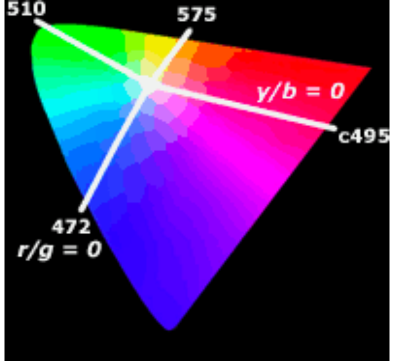
CIELUV

- 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 color 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

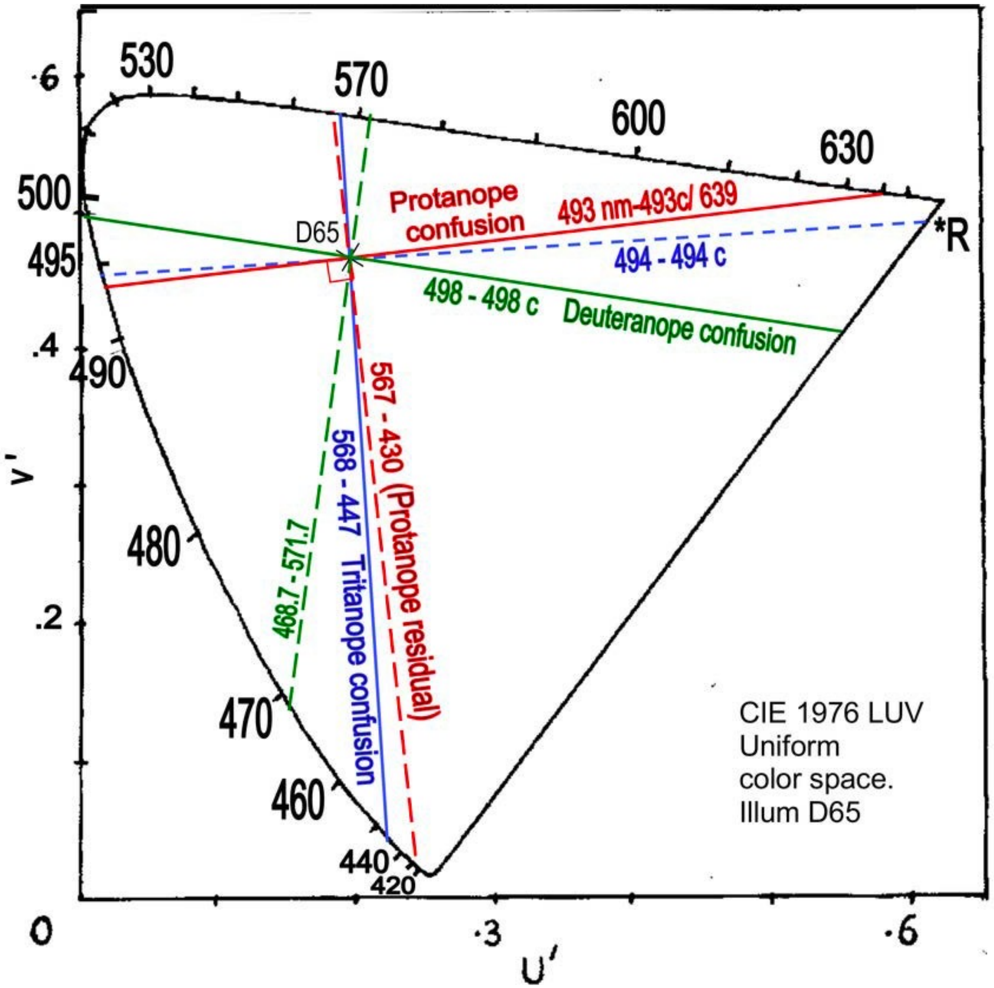


- Pure dichromacy is due to lack of one type of cones
  - L (long-wave, red) → protanopia
  - M (mid-wave, green) → deuteranopia, or
  - S (short-wave, blue) → tritanopia

red-green confusion

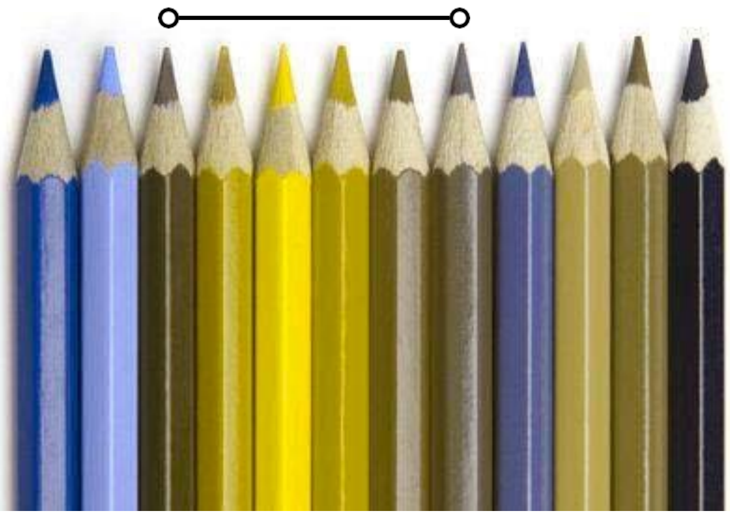
blue-yellow confusion

- 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 →

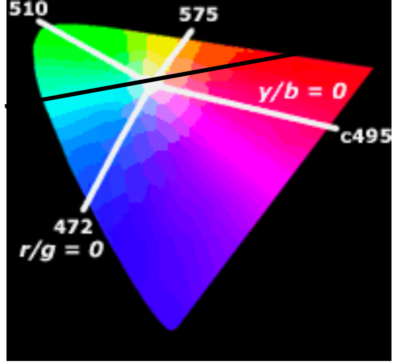


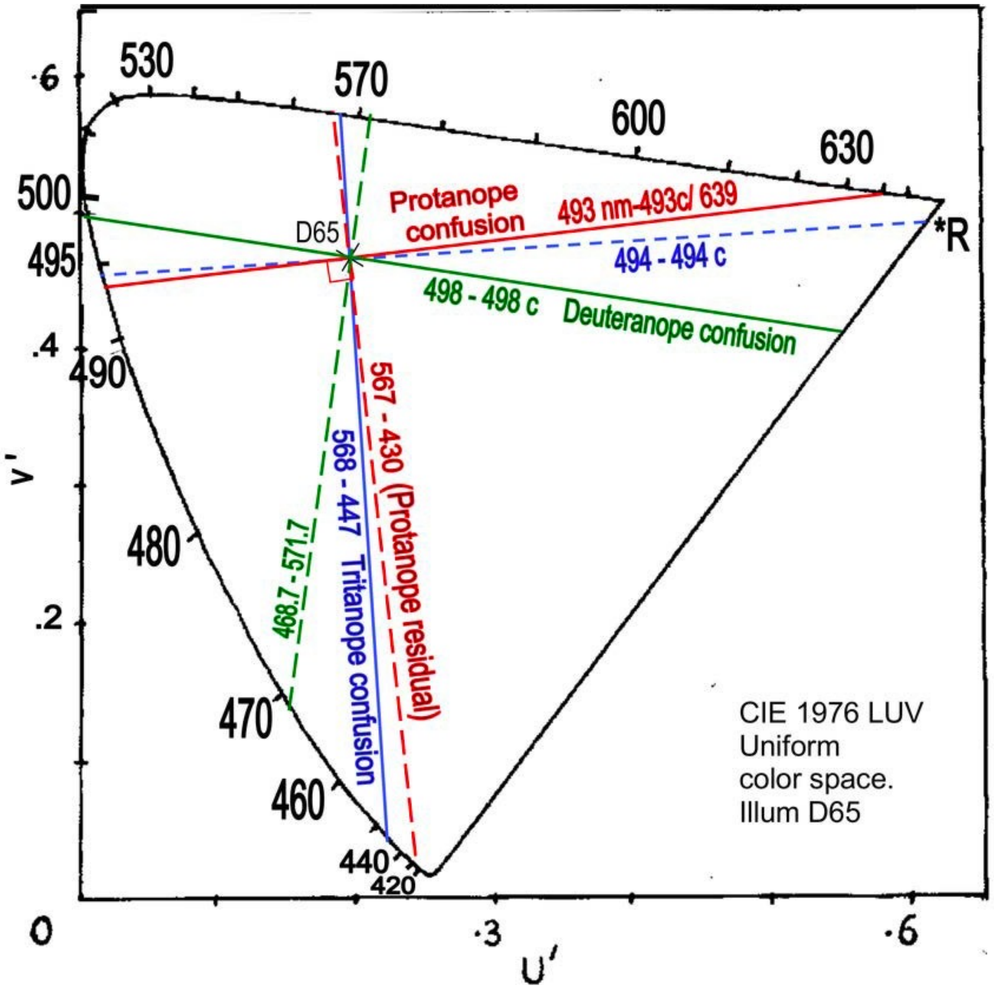
Pridmore 2014$_{3}$,$_{7}$ https://doi.org/10.1371/journal.pone.0107035

normal vision



protanopia

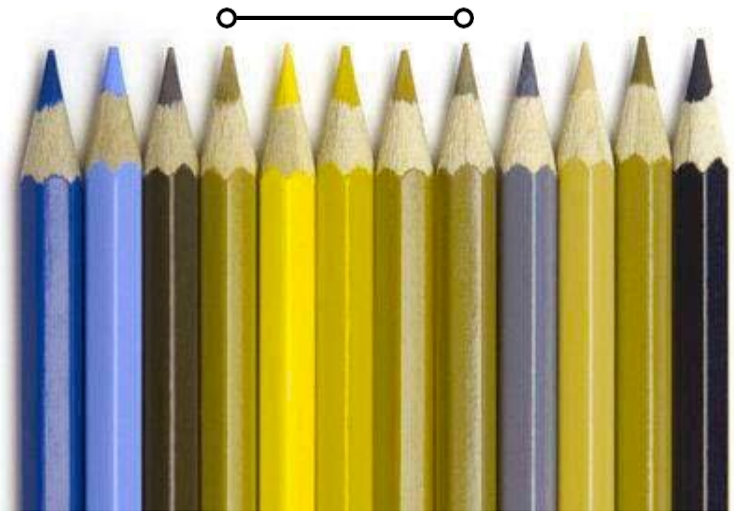




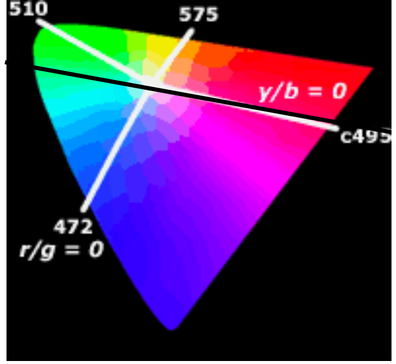
- Protanopia, lack of L cones
- ~ 1% males and ~ 0.01% females
- cannot distinguish red from green

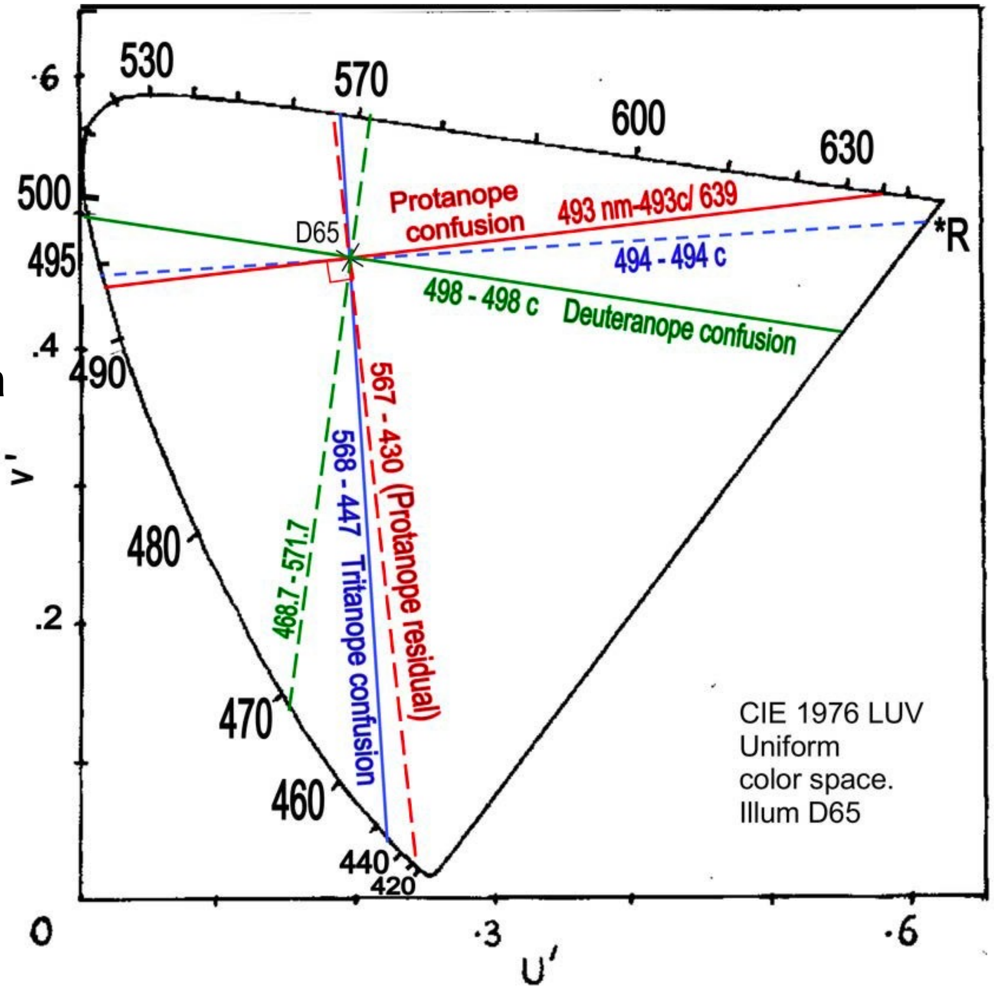
Pridmore 2014[3,8] https://doi.org/10.1371/journal.pone.0107035

normal vision



deuteranopia

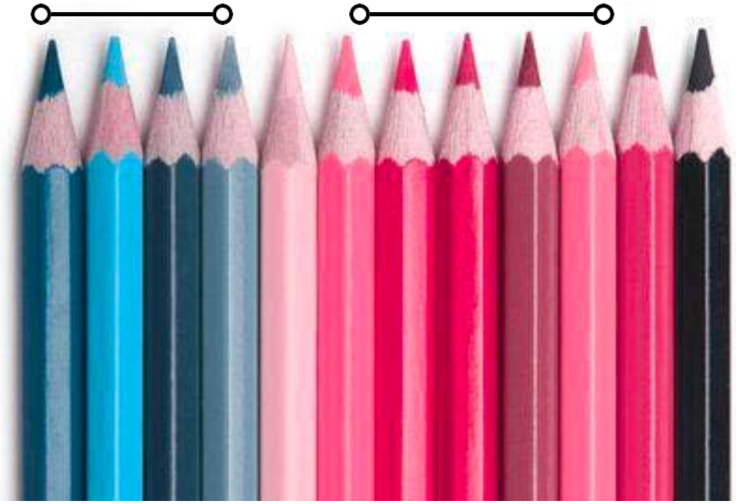




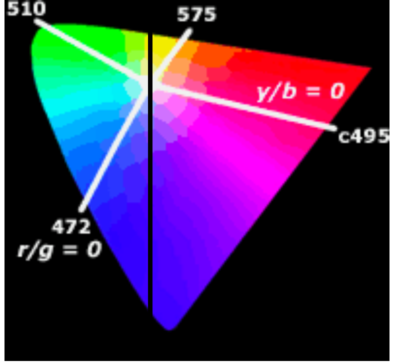
- Deuteranopia, lack of M cones
- ~ 1.5% males and c. 0.01% females
- cannot distinguish red from green

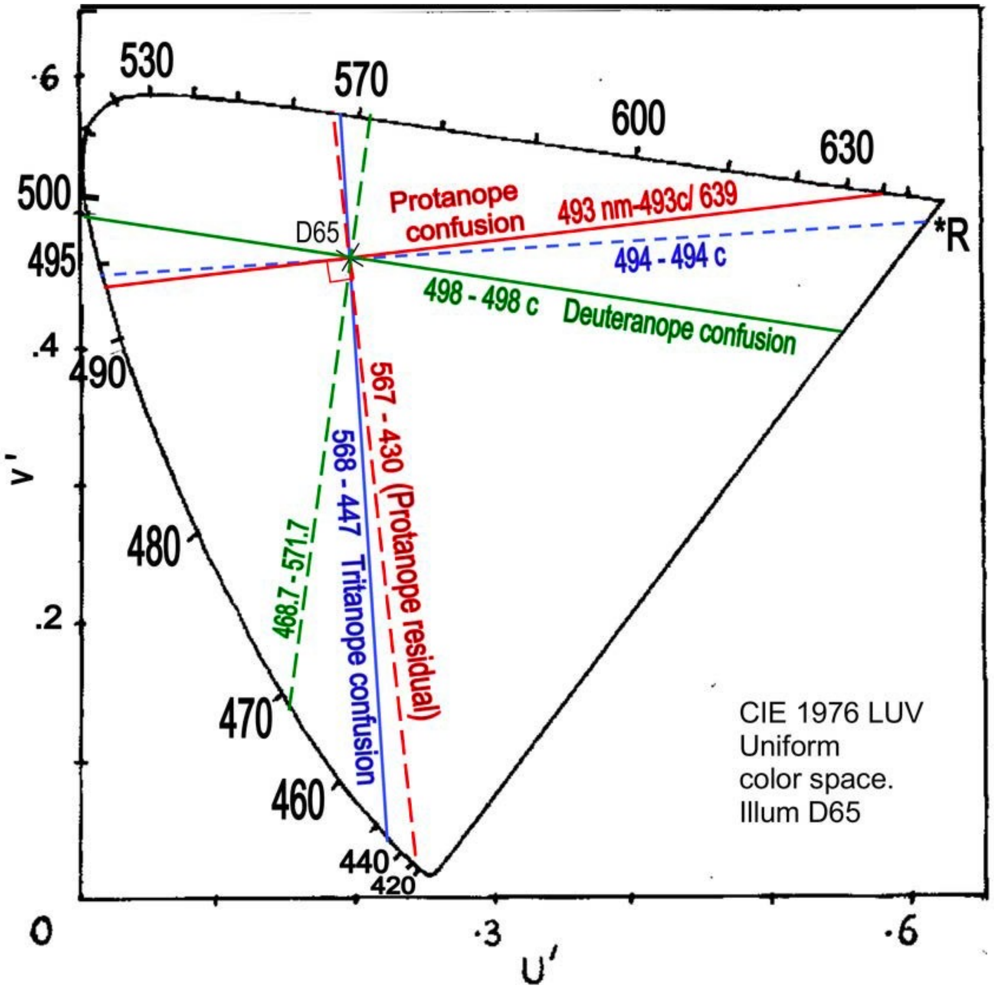
Pridmore 2014$_{3,9}$https://doi.org/10.1371/journal.pone.0107035

normal vision



tritanopia

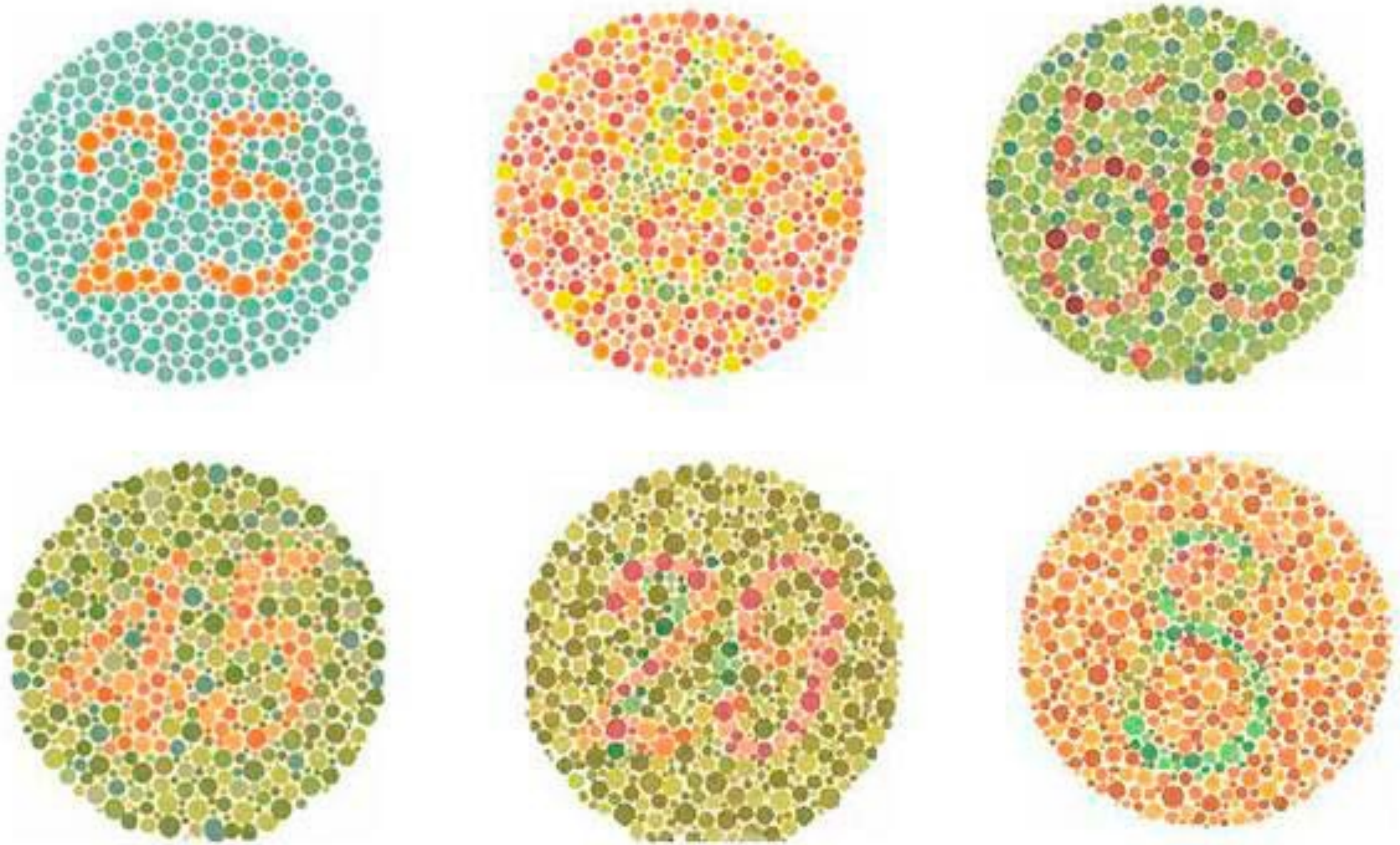




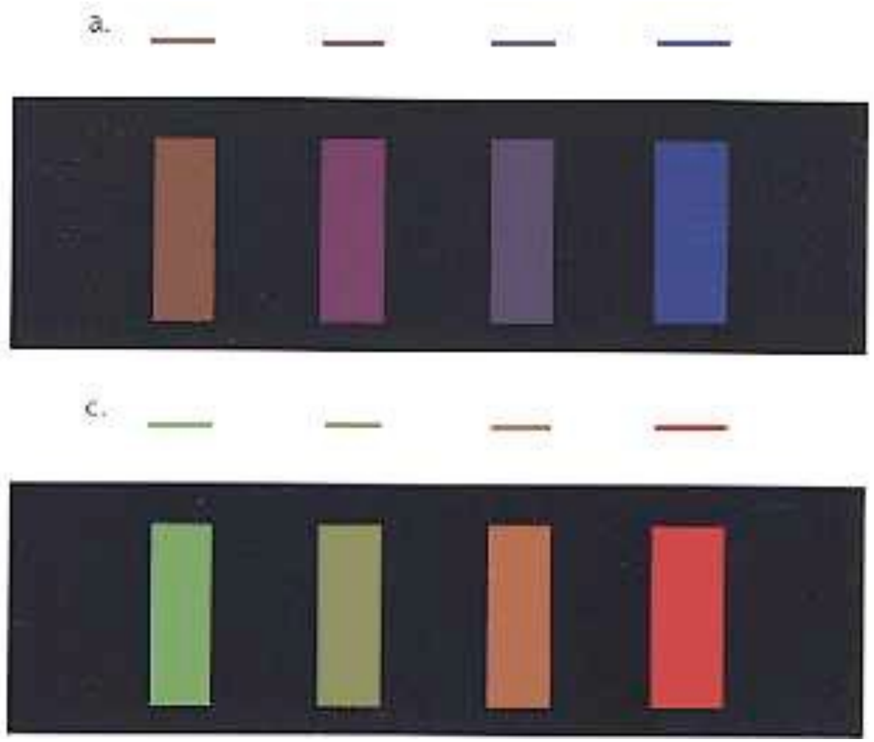
- Tritanopia, lack of S cones
- Less than 0.01%
- cannot distinguish blue from green, yellow from violet

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

Ishihara color test

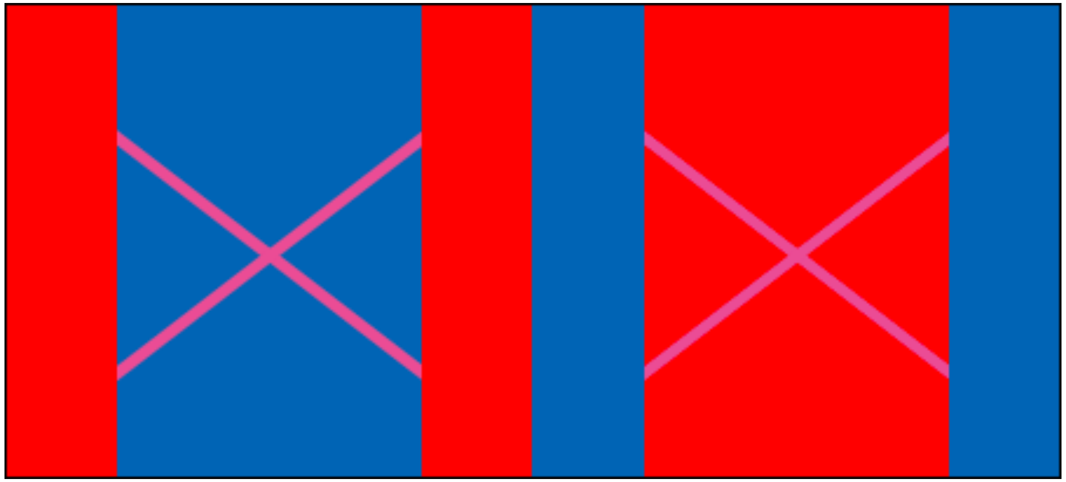


Small field color blindness



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

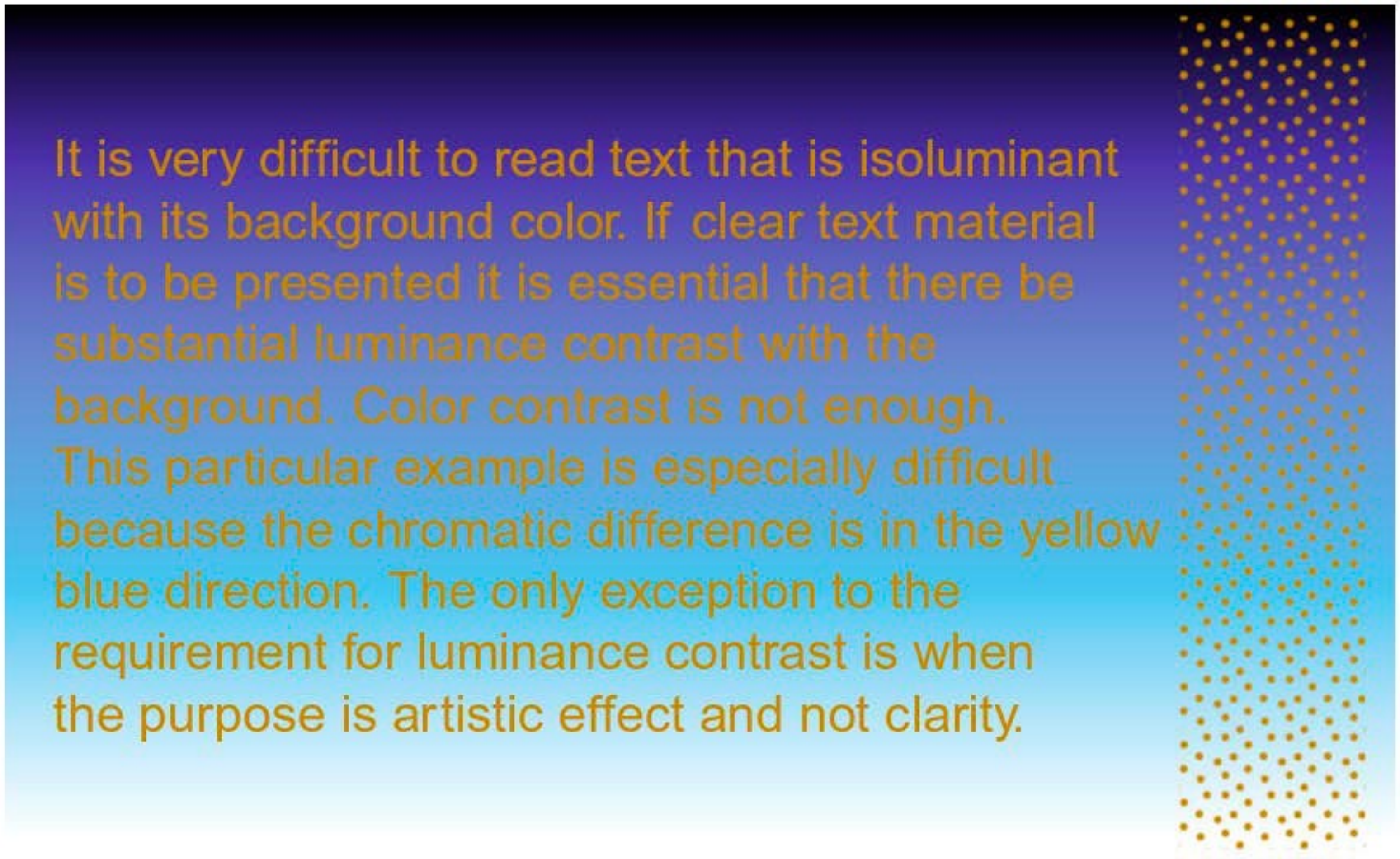
Color contrast

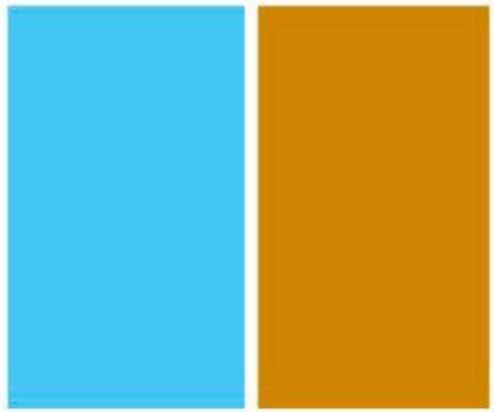


- The Xs are of the same color on both sides, but they are perceived differently depending on the background
- Chromatic contrast can distort reading from color-coded maps
- Message: relative color is often more important than absolute color (as with grayscale!)

Color vs. luminance

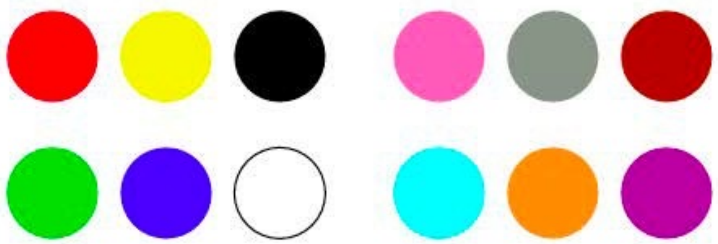
- Color channels have less spatial resolution than luminance channel
- Perception of shape or motion is due to mainly luminance channel
- Color channels are therefore better for labelling than data values

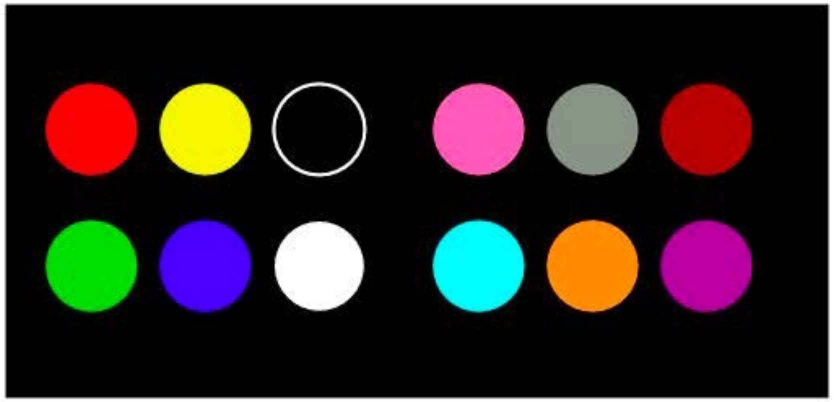




Color for labelling

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





Color for labelling

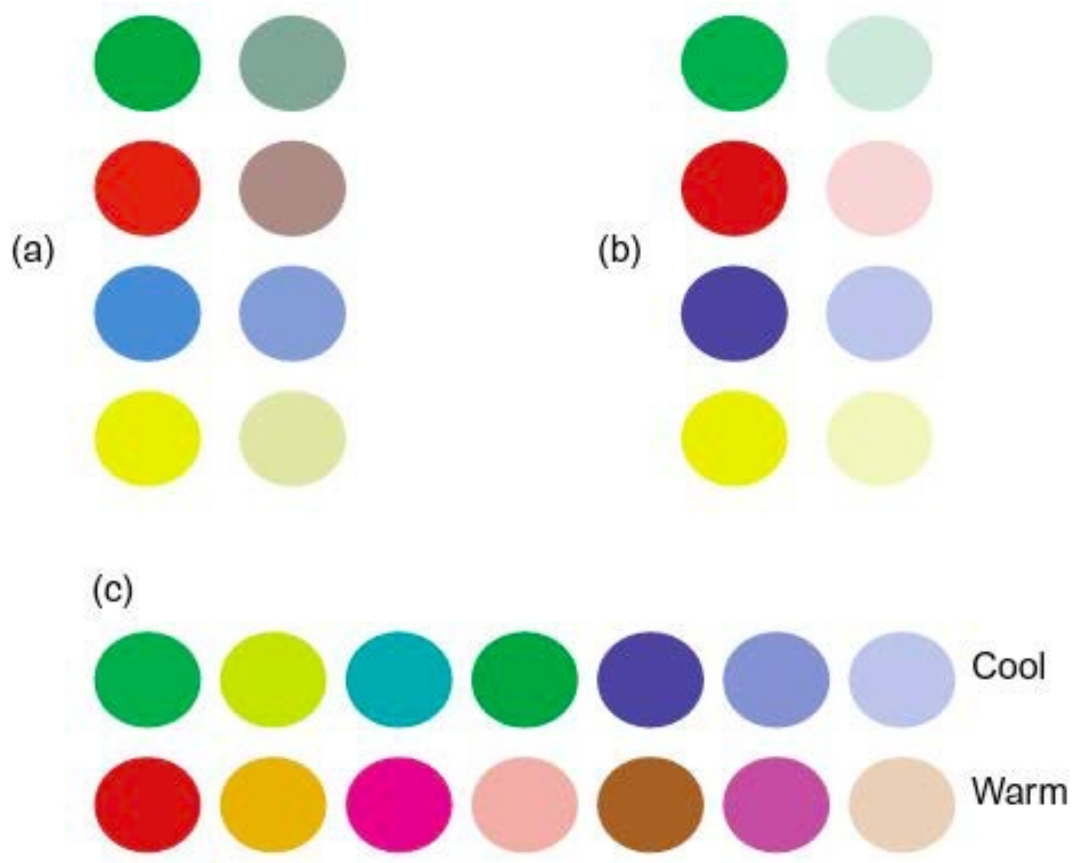


Figure 4.25 Families of colors. (a) Pairs related by hue; family members differ in saturation. (b) Pairs related by hue; family members differ in saturation and lightness. (c) A family of cool hues and a family of warm hues.

Color for labelling

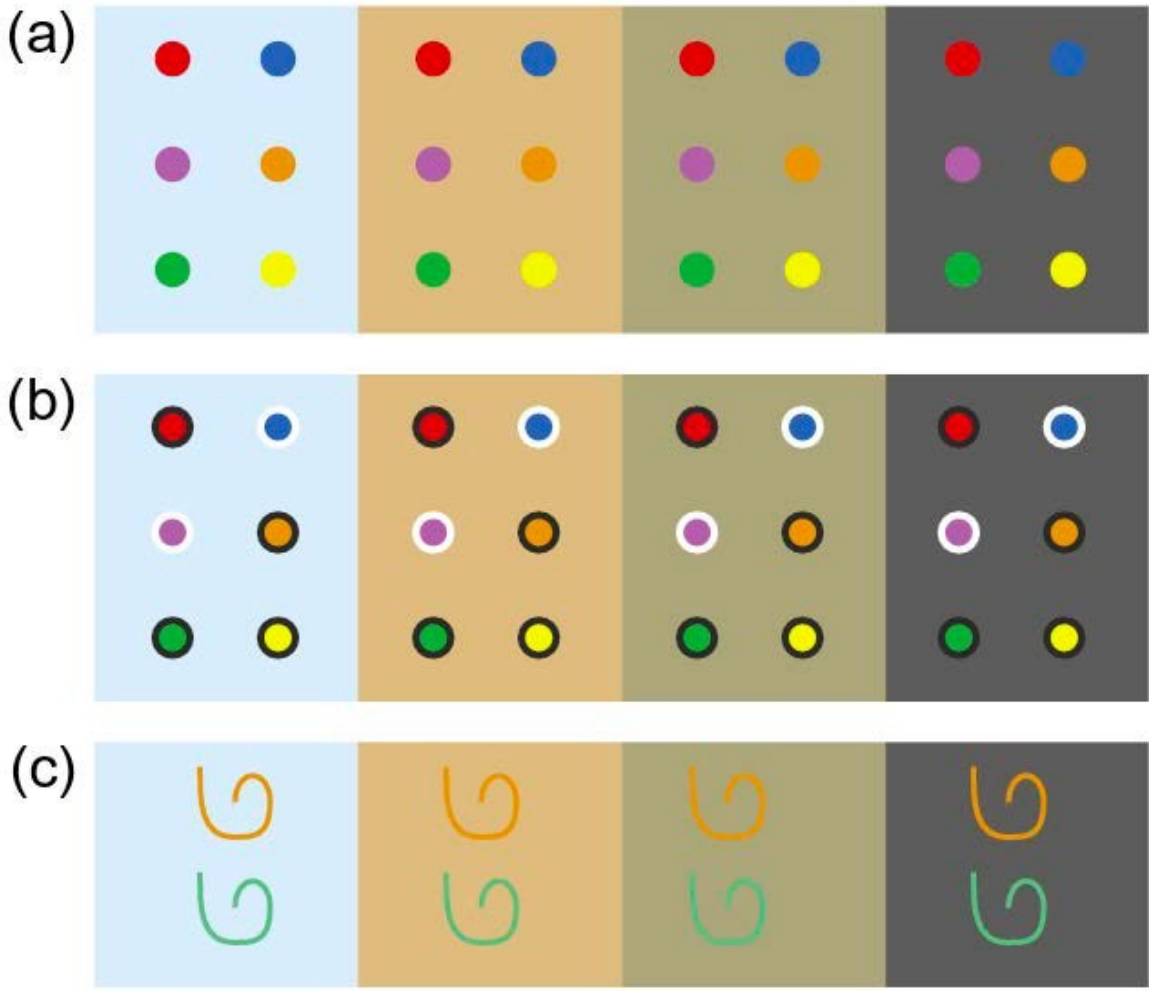


Figure 4.21 (a) Note that at least one member of the set of six symbols lacks distinctness against each background. (b) Adding a luminance contrast border ensures distinctness against all backgrounds. (c) Showing color-coded lines can be especially problematic.

Color scales

- Some differences are not perceived by color blind (avoid red-green channel!)
- Perceptually ordered channels are in general formed from the six color 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 color 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 colors
  - you can even follow a spiral in color space
- Misclassification of data: color category boundaries may cause misclassification of data

Color 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...

Color scales

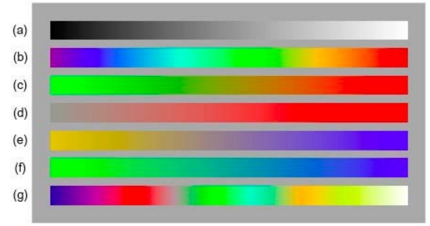
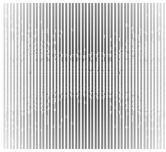
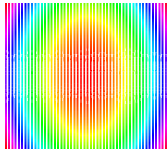


Figure 4.27 Seven different color sequences: (a) Grayscale. (b) Spectrum approximation. (c) Red–green. (d) Saturation. (e, f) Two sequences that will be perceived by people suffering from the most common forms of color blindness. (g) Sequence of colors in which each color is lighter than the previous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





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

Color scales

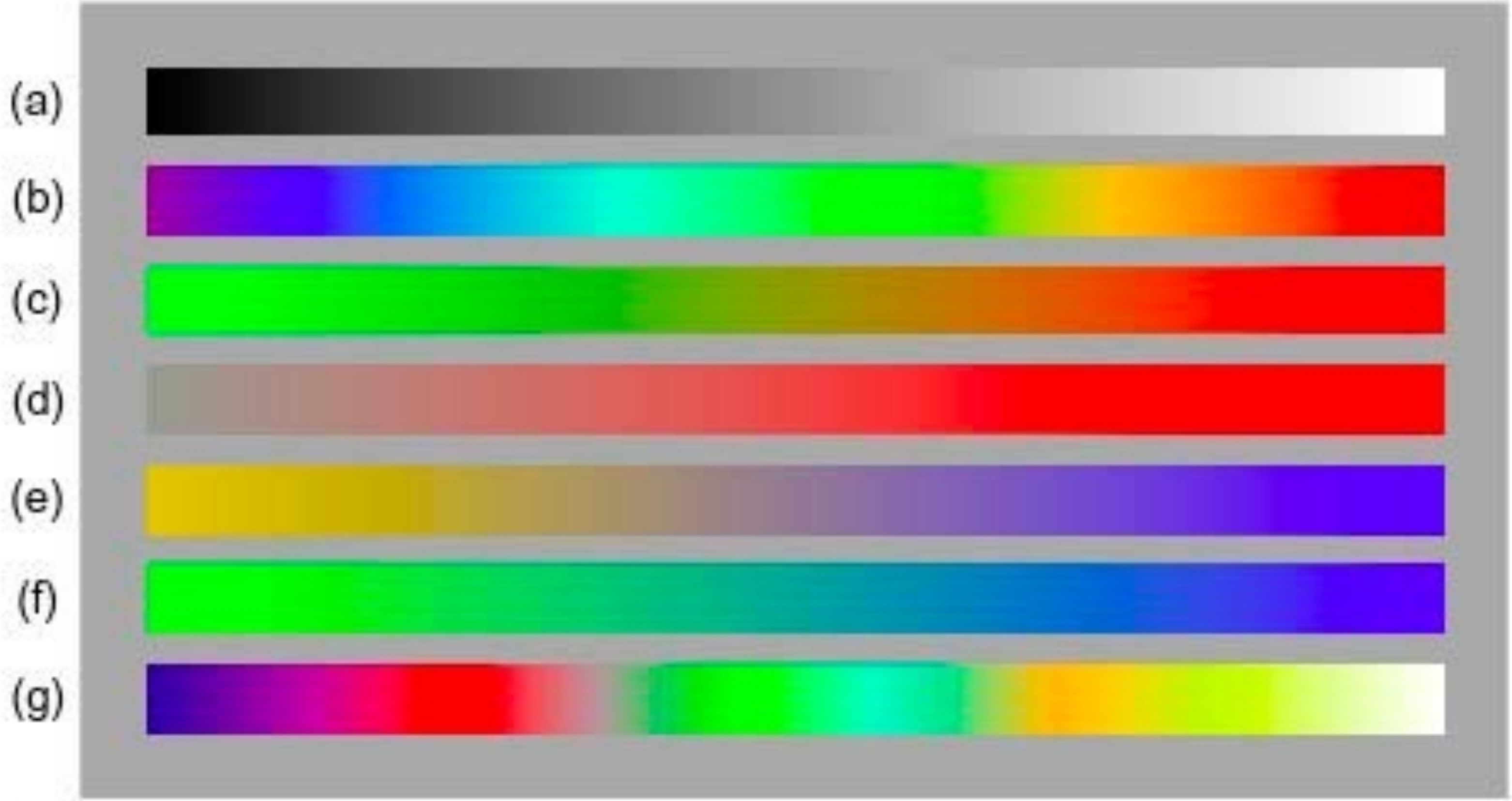
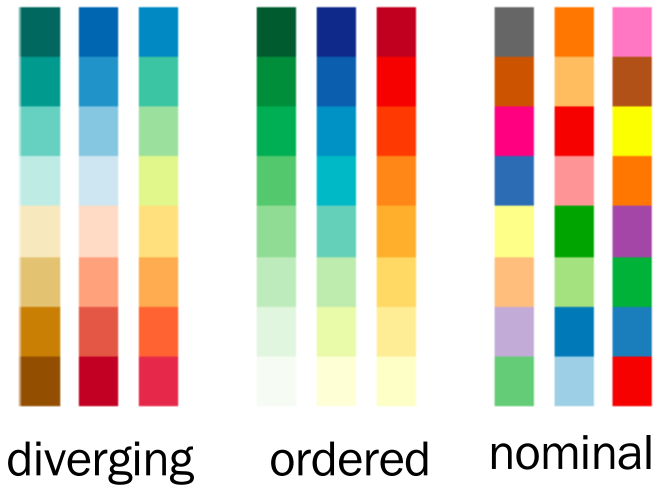


Figure 4.27 Seven different color sequences: (a) Grayscale. (b) Spectrum approximation. (c) Red–green. (d) Saturation. (e, f) Two sequences that will be perceived by people suffering from the most common forms of color blindness. (g) Sequence of colors in which each color is lighter than the previous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

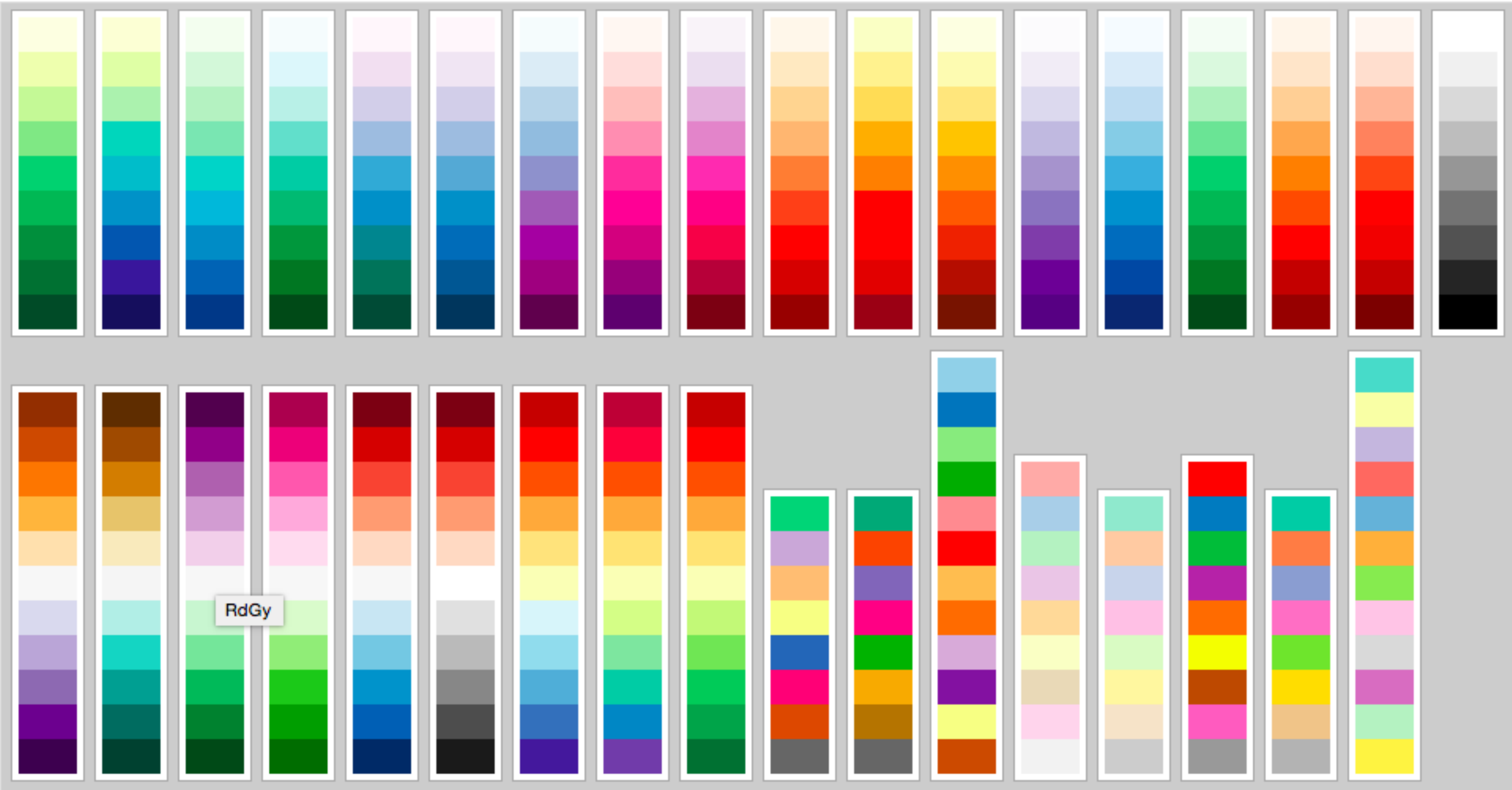
Color scales



- Some hints on selecting suitable color scale
- Nominal (values have no order):
  - Same as using color 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 color (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 color space, or clearly defined (discretised) color 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.

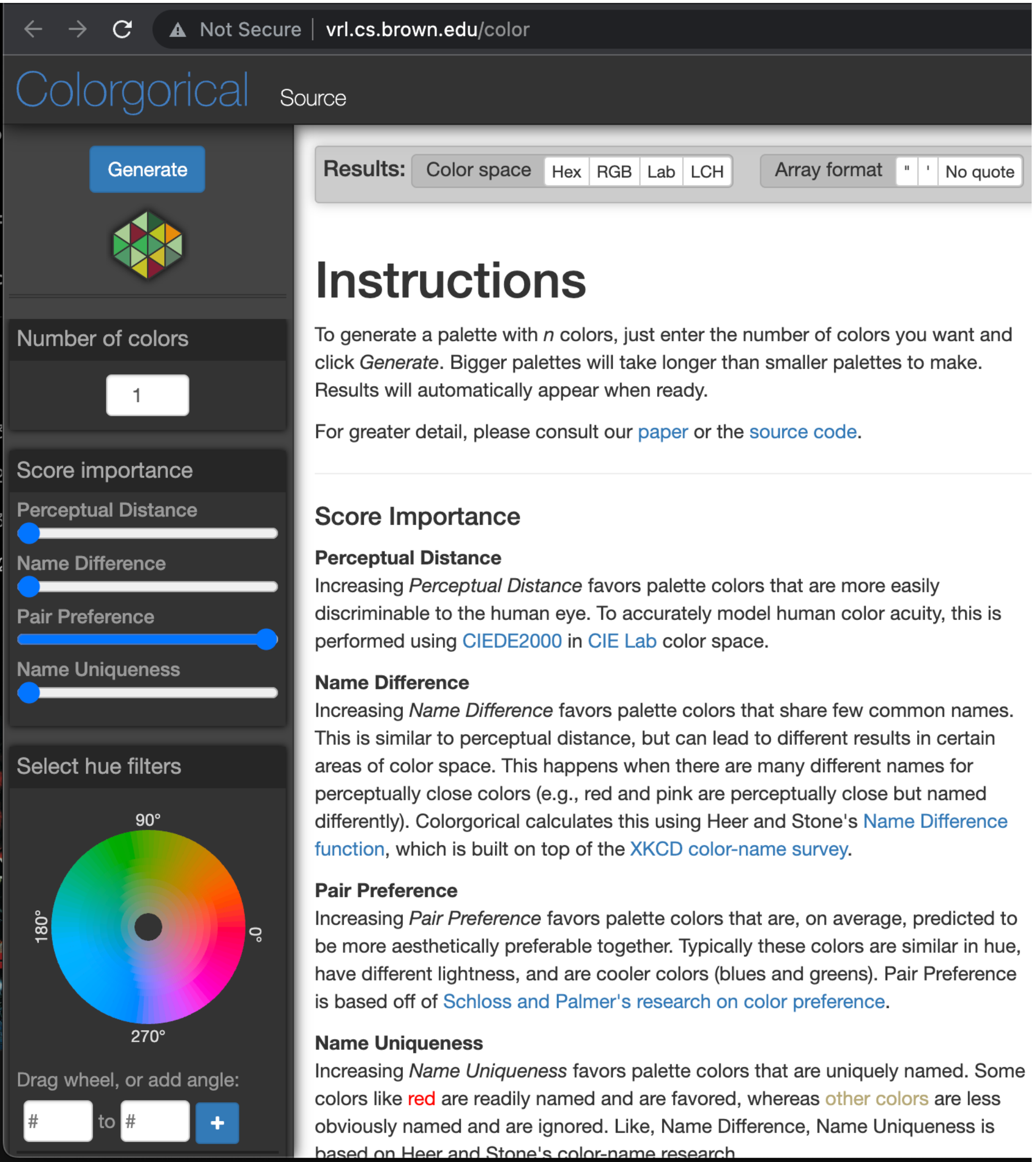
Color scales

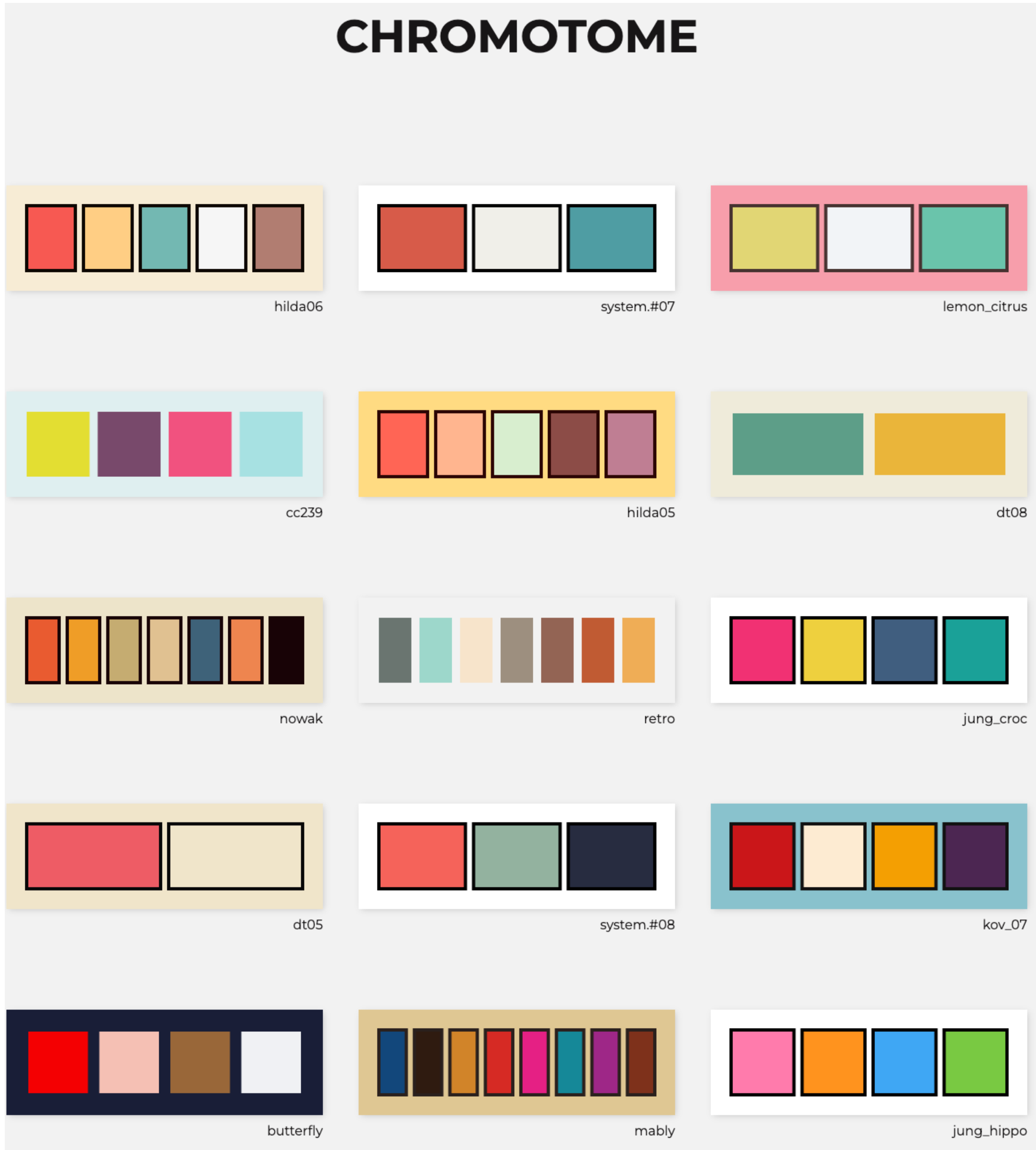
RColorBrewer color scales http://colorbrewer2.org/



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

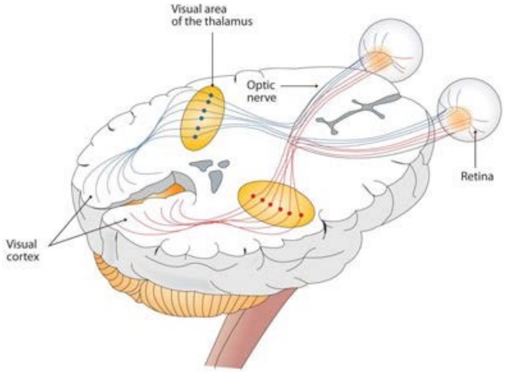
Color scales



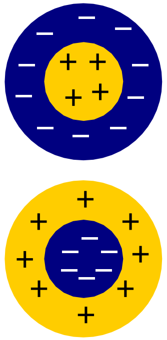


Summary

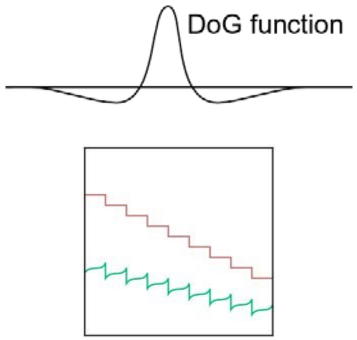
from retina to brain



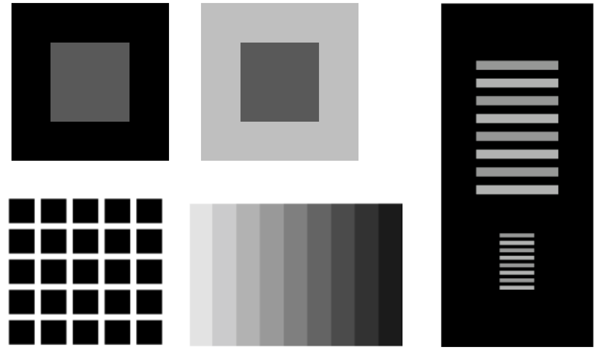
receptive field

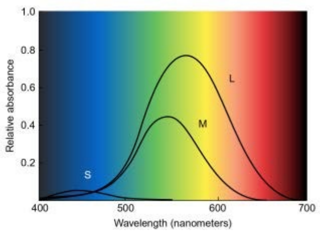


Difference of Gaussians



contrast illusions and crispening

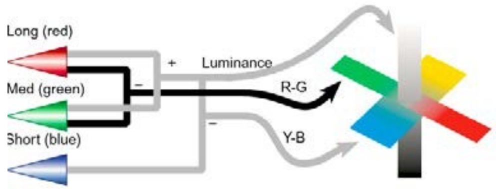




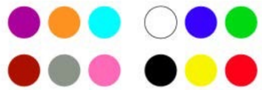
Trichromacy theory

color blindness

color spaces



opponent color theory



color 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)