Display and Color
Part 2

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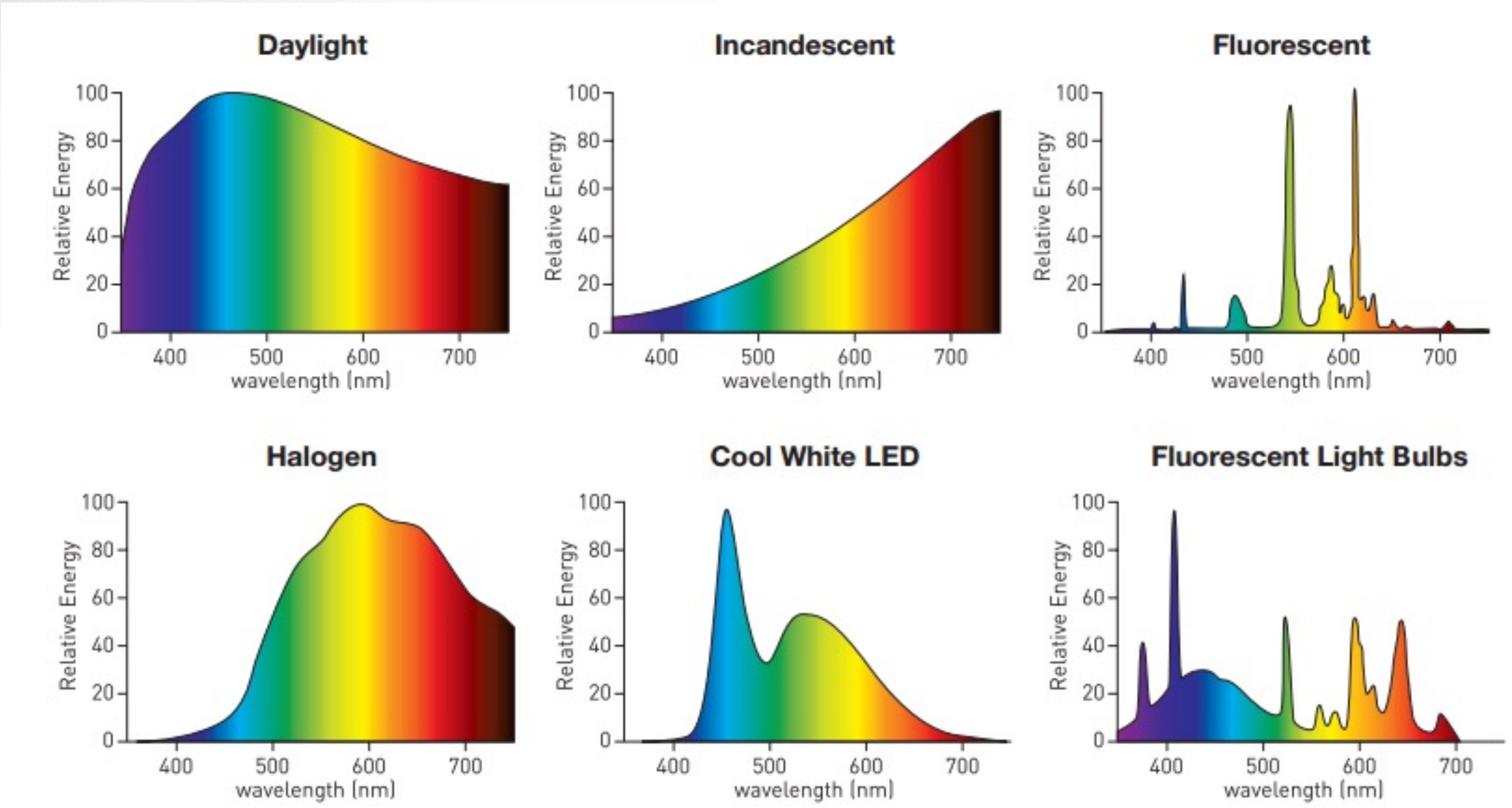
Goal For This Week and Next

- Understand display and perception
  - What the human visual system can perceive
    - In terms of color, patterns, etc.
    - Based on the structure of the eye and the processing within the brain
  - What is possible to display/see/understand
    - Can influence how we design visualizations
  - Today we will discuss lightness, contrast, and color
- Much of the material drawn from Ware chapters 2-6.

What is Color?

Light spectrum



Frequency * Wavelength = Constant

(so frequency and wavelength are interchangeable)

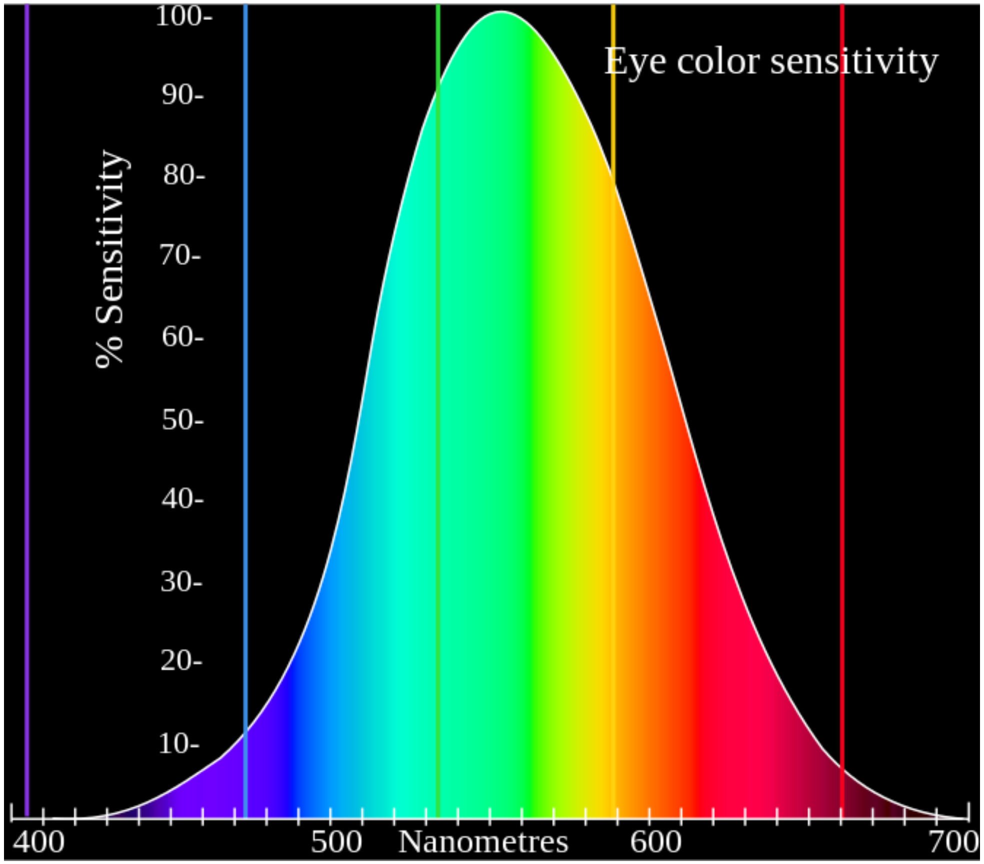
https://medium.com/@jasonlauritzen/blue-light-and-health-plus-how-to-make-your-own-blue-blocking-glasses-1a3d2694ad60

What is Color?

- Not just related to the wavelength of light.
  - Light is not just one wavelength, it's a combination of many
  - We see colors that don't correspond to a wavelength of light, e.g. Maroon
- Color is a perceptual effect
  - How we perceive a spectrum of wavelengths
  - Retina, ganglion cells, brain

Overall Response of Eye

- Eye responds to different wavelengths differently
  - Much stronger response in middle of visual spectrum around green/yellow

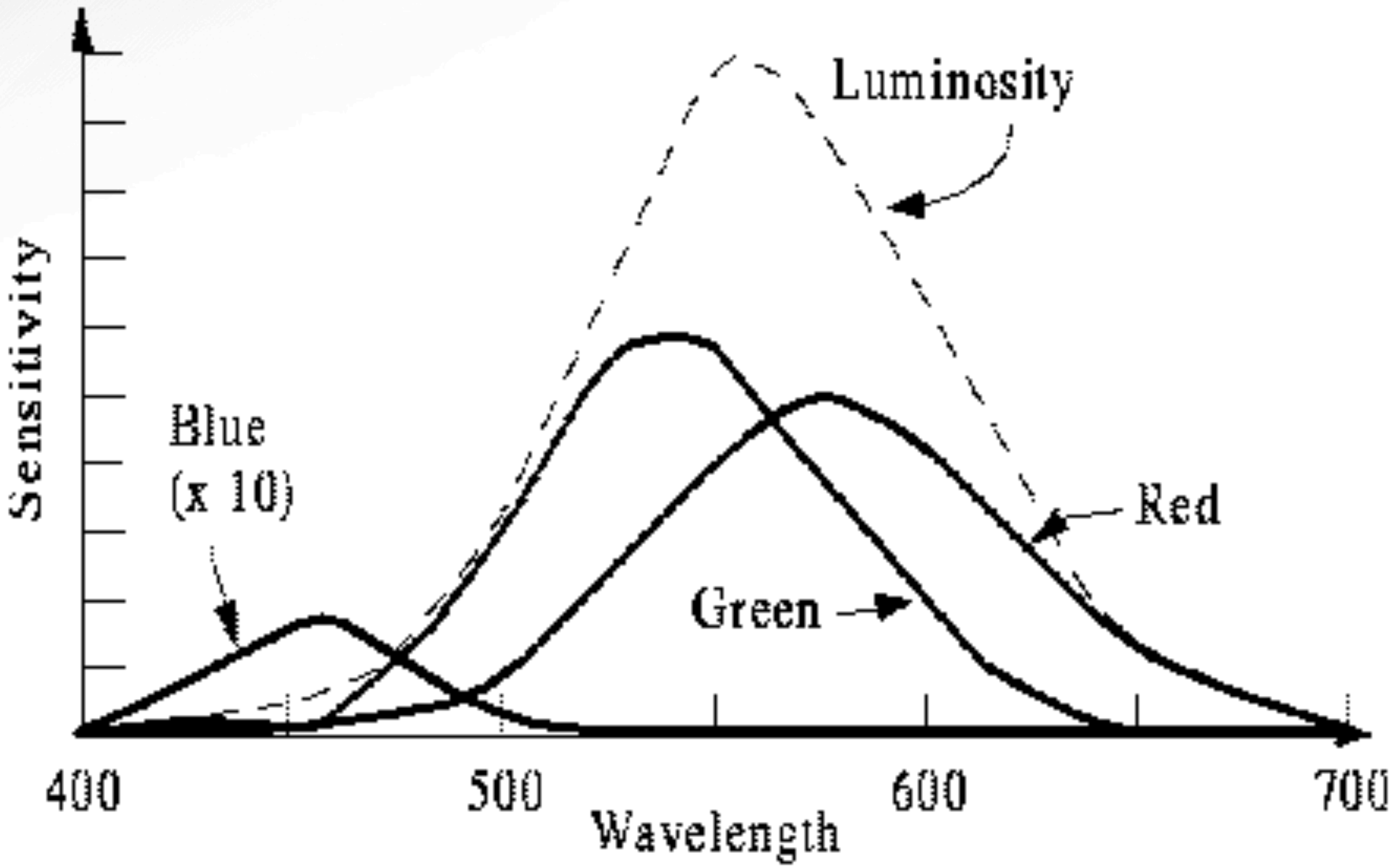


https://ux.stackexchange.com/questions/38334/what-is-a-good-color-combination-visibility-for-outside-use

Receptor Cells

- Rods are saturated (fully stimulated) in bright environments
  - Don’t contribute significantly to color
- Cones come in 3 types
  - S, M, L (short, medium, long wavelengths)
  - Also sometimes called Blue, Green, Red, even though both M, L are basically in green
  - Each type responds differently to different frequencies/wavelengths of light
  - Some women have 4th type but little evidence that brain makes use of this in significant ways

Response



http://www.cs.ru.nl/~ths/rt2/col/h2/2fundENG.html

Tristimulus Theory

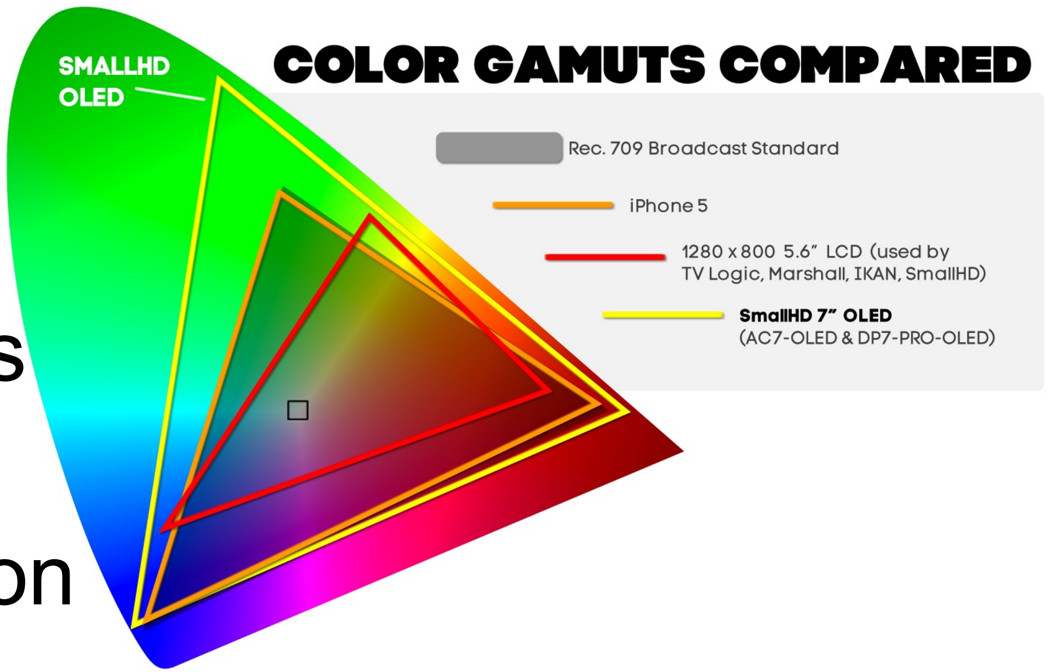
- **Anything (any light spectrum) that stimulates the cones the same way appears as the same color**
- This means that color (as humans perceive it) is three-dimensional
- We can thus generate a range of colors by combining three different primary colors
  - We don’t have to match the spectrum, just the response of the cones!

Implications

- Cones only respond to limited range of wavelengths
  - This defines the “visible” spectrum
- Missing a cone type leads to color blindness
  - 10% of men, 1% of women
  - Effectively reduces to 2 dimensions
  - Many people may not even know!
- Any particular primary color will be at one point in this 3D color space
- There is a standardized system for describing color precisely (CIE XYZ)
  - But, other systems are also possible, and sometimes better for particular applications

Gamut

- Depending on primaries, the gamut (range of displayable colors) will vary.
- So, an RGB value is not the same on different monitors
- sRGB is a standard based on RGB for monitors

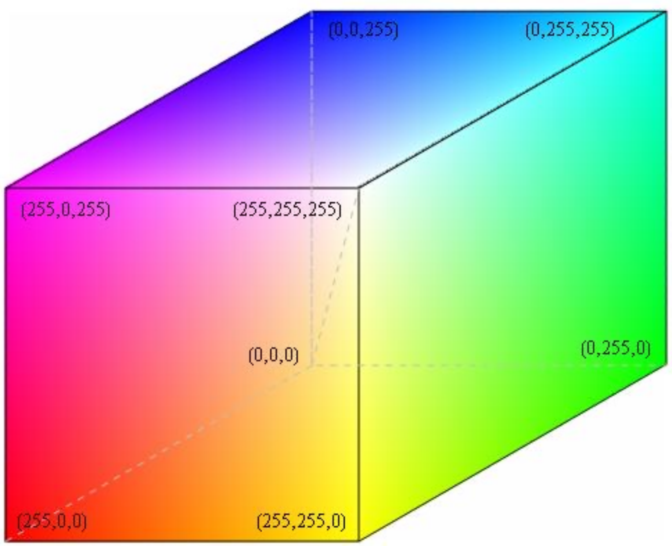


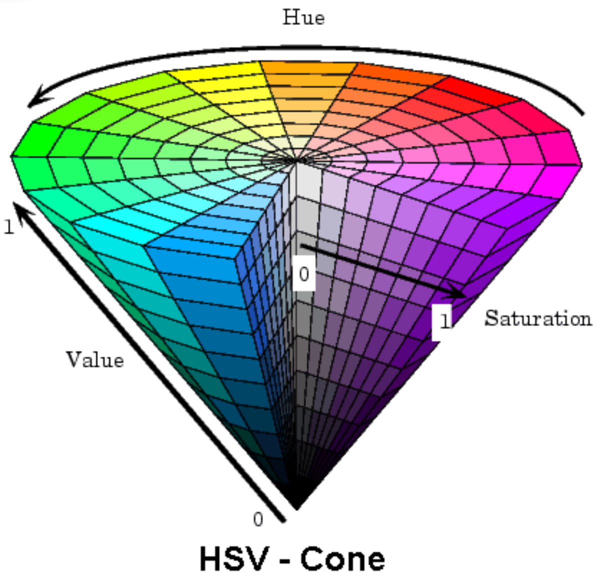
https://www.prweb.com/releases/christmas_comes_early_for_cinematographers_with_the_release_of_smallhd_s_first_reference_quality_monitor_with_true_hd/prweb11110164.htm

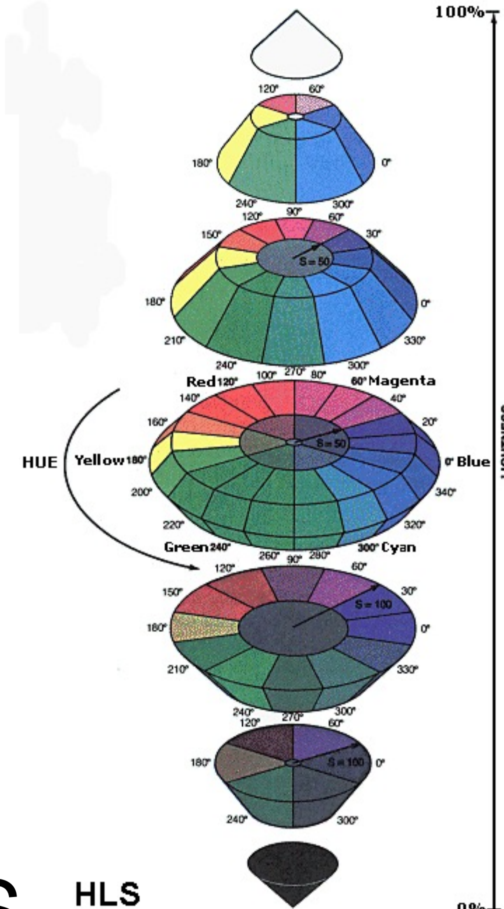
Color Spaces

- There are multiple 3D color spaces that have different characteristics and usefulness in different environments
  - XYZ: CIE standard
  - RGB: correspond to monitor primaries
  - HSV: Hue, Saturation, Value
  - HLS: Hue, Lightness, Saturation
  - LUV: CIE standard - perceptually more uniform
  - LAB: CIE standard - perceptually more uniform

Color Spaces



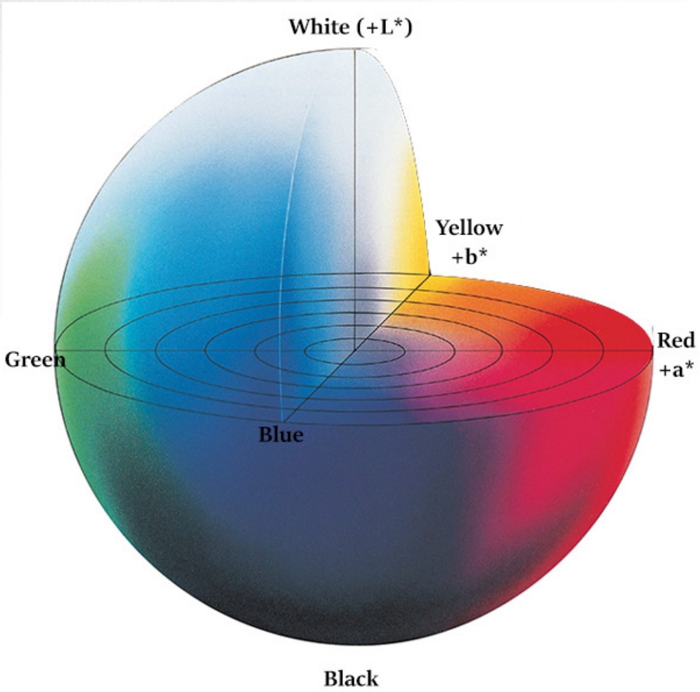


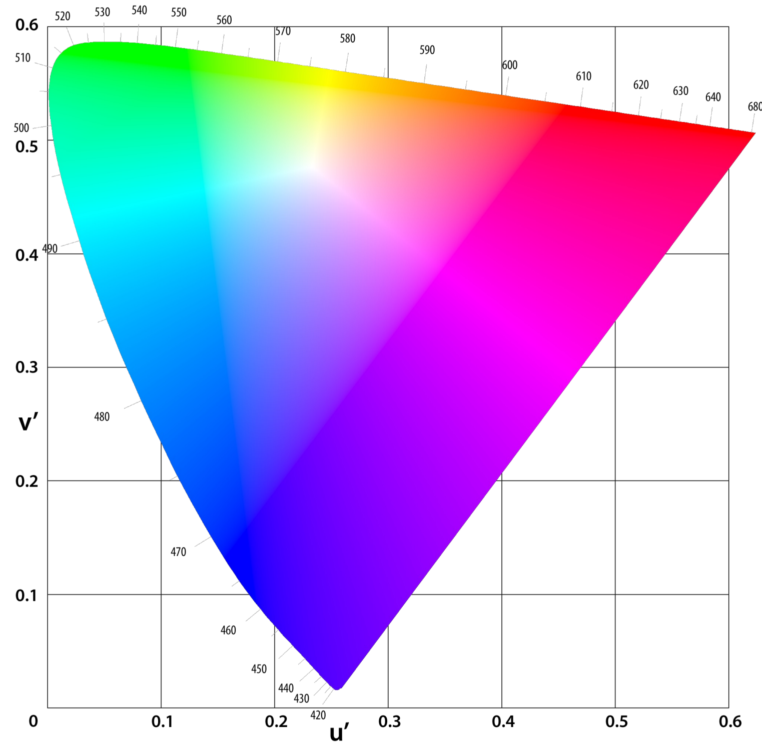


RGB HSV HLS

https://people.eecs.berkeley.edu/~sequin/CS184/TOPICS/ColorSpaces/Color_0.html

Color Spaces





CIELAB

CIELUV

https://sensing.konicaminolta.asia/what-is-cie-1976-lab-color-space/

Perceptually Uniform Spaces

- Idea: measuring numerical difference between two color values (in 3D space) corresponds to perceptual difference
- Perceptual spaces have some limitations since other perceptual factors play a larger role in how colors are seen.
  - Larger patches of color make differences seem larger
  - Yellow-blue direction tends to highlight differences

Opponent Process Theory

- Idea is that there are 6 primary colors, arranged in 3 opposing pairs:
  - Black/White
  - Red/Green
  - Blue/Yellow
- Cone responses easily support this. Neurophysiology as well
- Naming: People don’t use combinations of opposing pairs in describing colors
- Language: Across 100 languages, every one has black/white; next is red; next is yellow or green, then is the other; sixth is blue; next is brown
- People are better at identifying these primary colors consistently (especially yellow) vs. other colors, where there is more variation
- CIE LAB system closely resembles this model (3 axes are the 3 pairs)

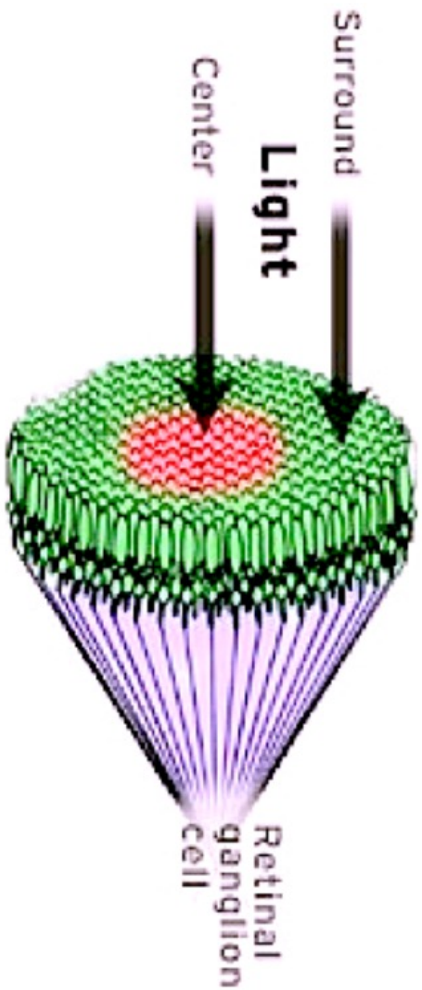
Color - Luminance

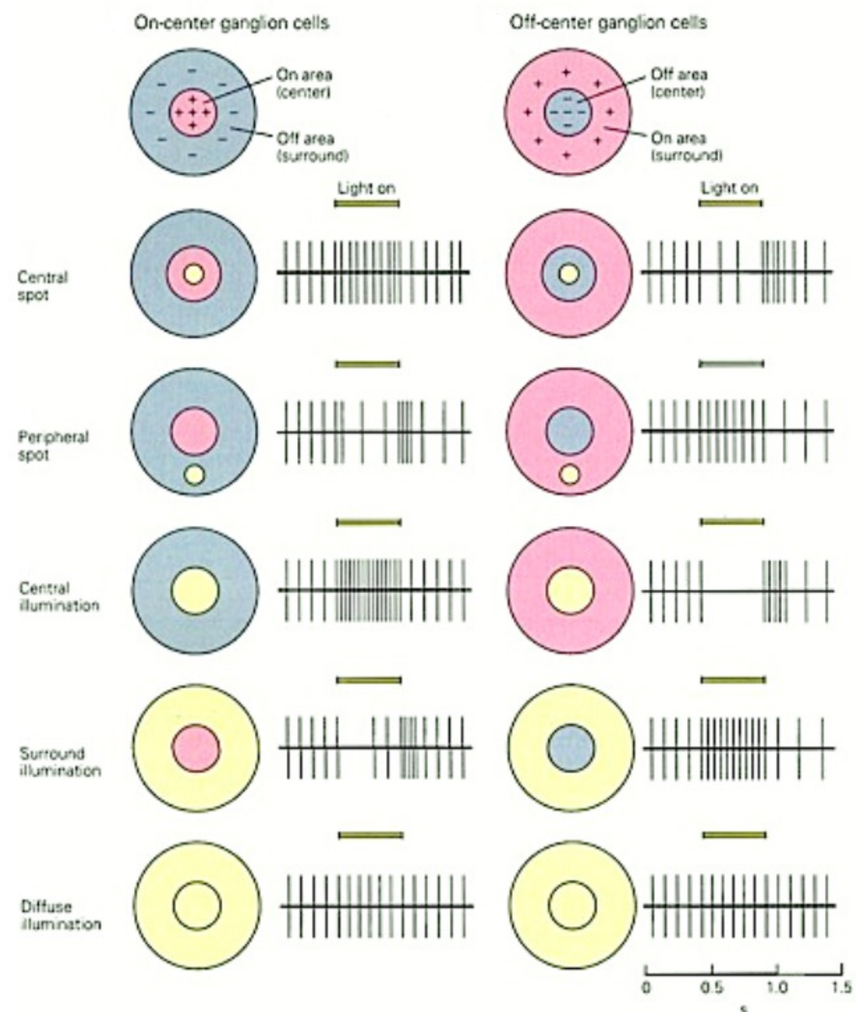
- Luminance (L in the CIE LUV/LAB systems) is common to use in one channel
  - Other two channels make up chromaticity
  - Perception is best along luminance channel
  - Need luminance difference to judge distance
  - Need for judging motion well
  - Key to perceiving shape and form
- **Always want luminance difference for text or small symbols on background** (not just chromaticity)

Low-Level Vision

- At lowest level, ganglion cells combine the signals from multiple receptors
- Travels on optic nerve through lateral geniculate nucleus, toward visual cortex area 1 (which then sends to subsequent areas of visual cortex)
- This early processing tends to identify receptive fields: stimulated within circle, inhibited just outside

Retinal Receptive Fields

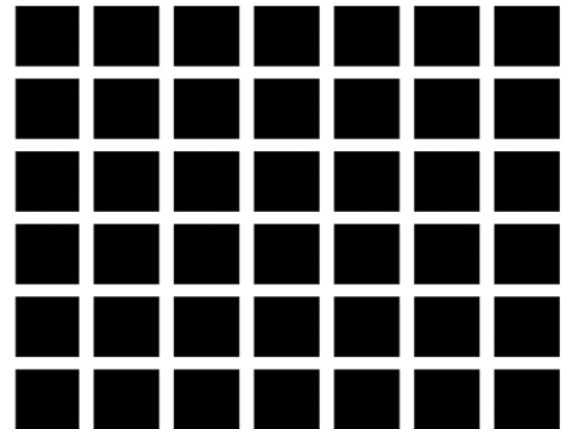


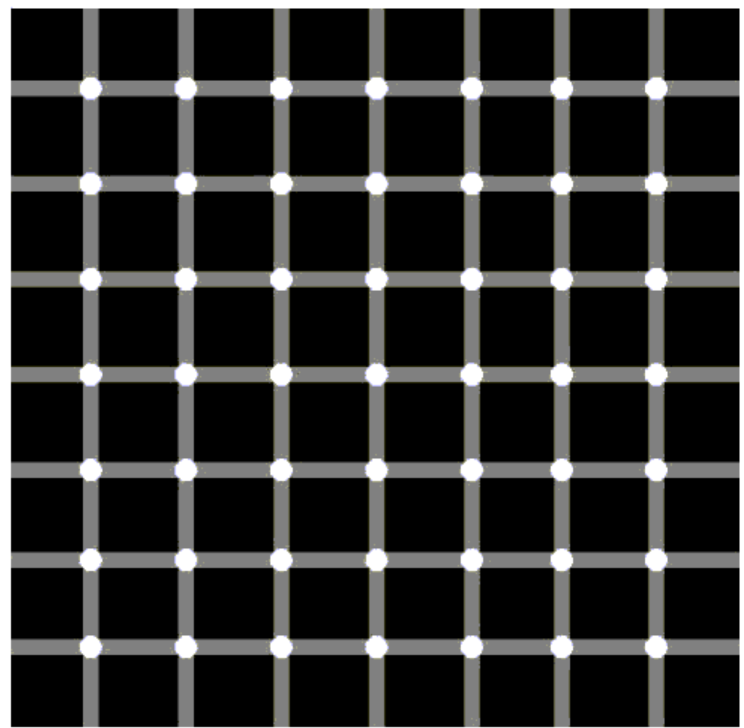


https://project.inria.fr/keops/what-are-retinal-receptive-fields//

Receptive Fields

- Receptive fields lead to perceptual effects
  - Low-level processing, not something you "think" about
  - Can cause certain features to appear stronger or to be perceived when not there
    - These effects can be modeled by seeing how a response of overlapping receptive fields would behave

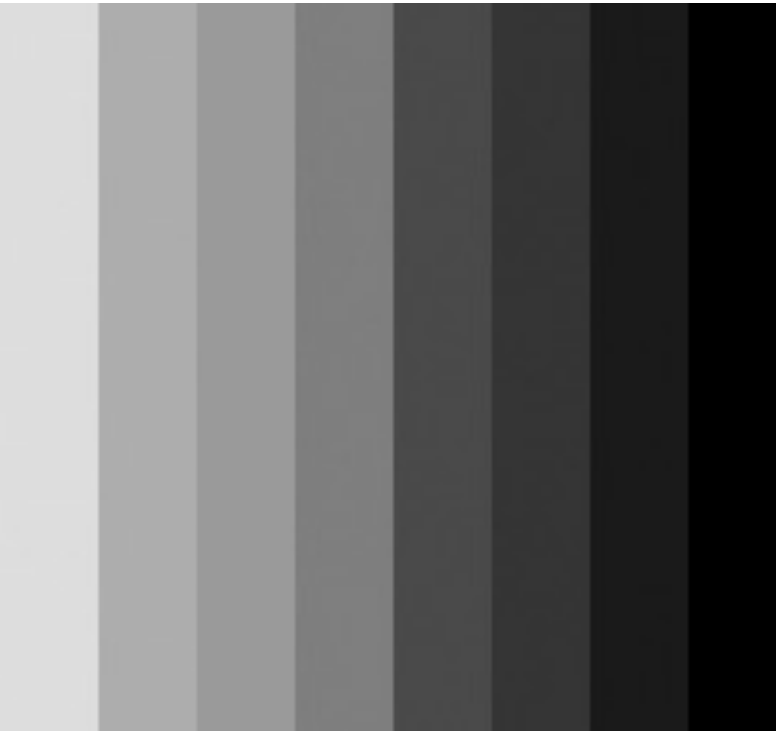




https://www.netmarkers.com/2019/08/13/top-10-best-examples-of-optical-illusions-that-will-leave-you-confused/

Mach Banding

- When there is a sharp change in luminance, the perceived edge effect is stronger
- Makes uniform regions appear to have gradient
- Makes edges sharper



http://www.wikiradiography.net/page/Mach_Bands

Simultaneous Brightness Contrast

- Contrast with background will make some intensities appear lighter/darker
- Makes gray scale very poor for encoding numerical data on a map

https://www.frontiersin.org/articles/10.3389/fnhum.2014.00566/full
http://www.color-theory-phenomena.nl/11.03.htm

Perceived vs. Actual Luminance

- Luminance: actual physical value
- Brightness: *perceived* amount of light

- Brightness = Luminance^n
  - n varies by size of patch of light
  - Point light: $n = 0.5$
  - Circular patch 5 deg. visual angle: $n = 0.333$

- Gamma in displays helps counter this
  - For intensity of input S, actually draw luminance of S^γ. γ can be chosen (2.0 counteracts $n=0.5$)

https://ux.stackexchange.com/questions/38334/what-is-a-good-color-combination-visibility-for-outside-use

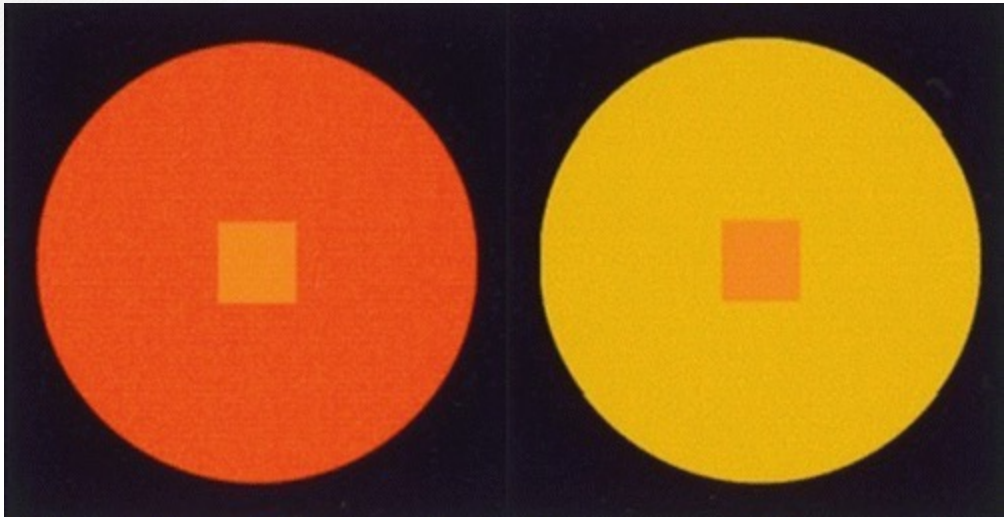
Perceived Grayscale Differences

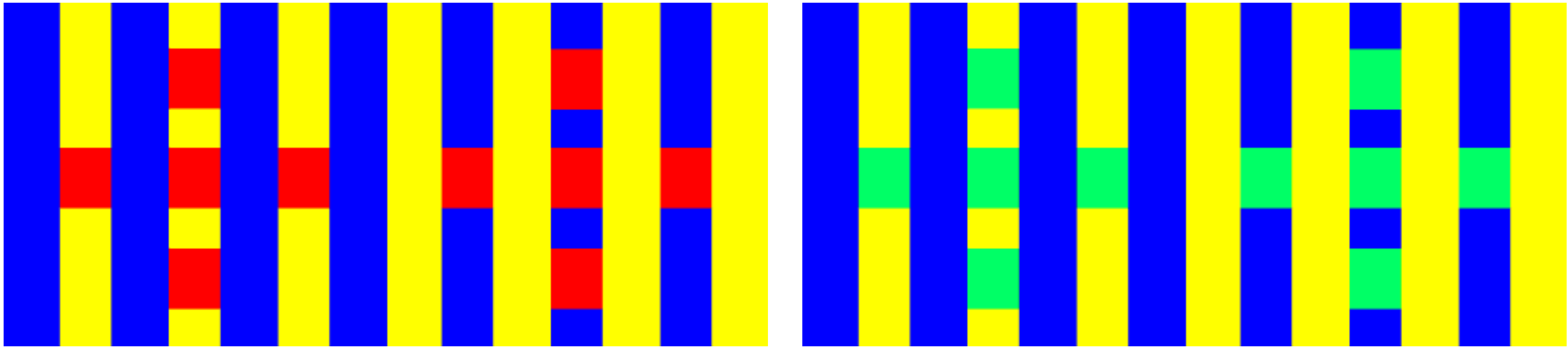
- Weber's Law: Given a luminance L and a superimposed patch L+δ, the value of δ that makes this just visible is determined by δ/L
  - That is, the relative intensity, not absolute, matters.
  - Humans perceive with $\delta = 0.005$ (about). i.e. can perceive a 0.5% change in grayscale
- Can use this to determine the number of intensity levels needed to have "smooth" grayscale

Color Perception

- The effects of luminance variation extend to color
  - Since luminance is one dimension of color
  - Many effects are similar, though not as strong, for chromaticity
- Surrounding colors affect the appearance of a color
  - Highlighting of edge effects
  - Highlighting of contrast in chromaticity, not just luminance
- Cone types adapt/saturate differently from each other
  - Can change what is needed for something to seem “white”
- **Relative color is more noticeable than absolute color**
- Perception of saturation does not align well with actual saturation
  - Red/blue/green appears more saturated than cyan/magenta/yellow
  - Saturation is poor for encoding numerical data, and shouldn’t be used for more than about 4 levels of ordinal data is advisable
- Brown is seen as distinct from dark yellow.

Chromatic Effect of Simultaneous Contrast





https://link.springer.com/referenceworkentry/10.1007/978-3-642-27851-8_268-1
https://www.colorcube.com/illusions/scstripe.htm

Continuing From Here

- Many other effects can be seen related to human perception
- We will next turn to how color choices should be made in visualizations
- Subsequently, we will discuss perception of finer details: texture and glyphs