Display and Color
Part 1

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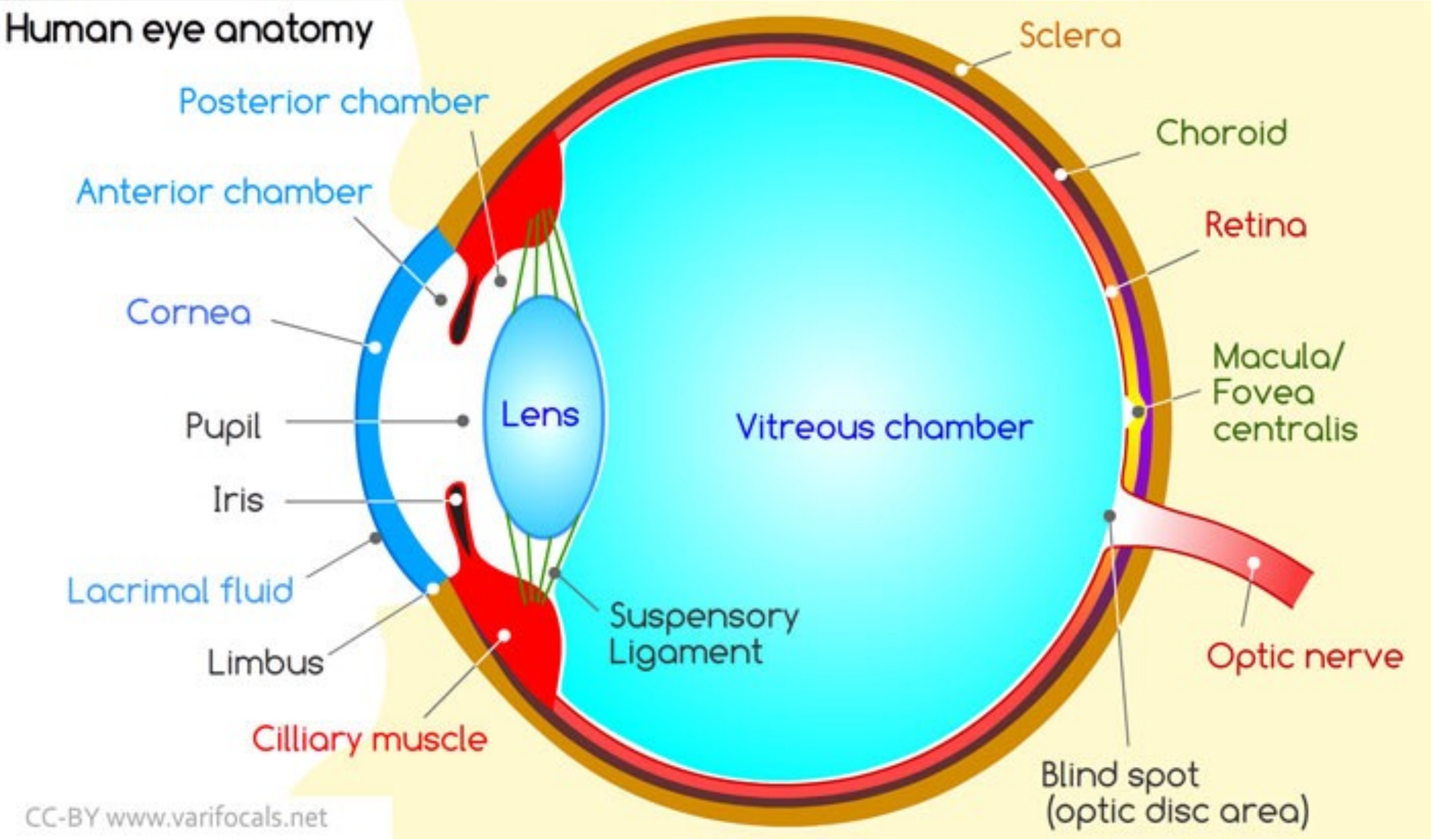
Goal For This Week and Next

- 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 physical structure of visual system
- Much of the material drawn from Ware chapters 2-6.

Struture of the Eye



https://www.varifocals.net/human-eye/

Structure of the Eye

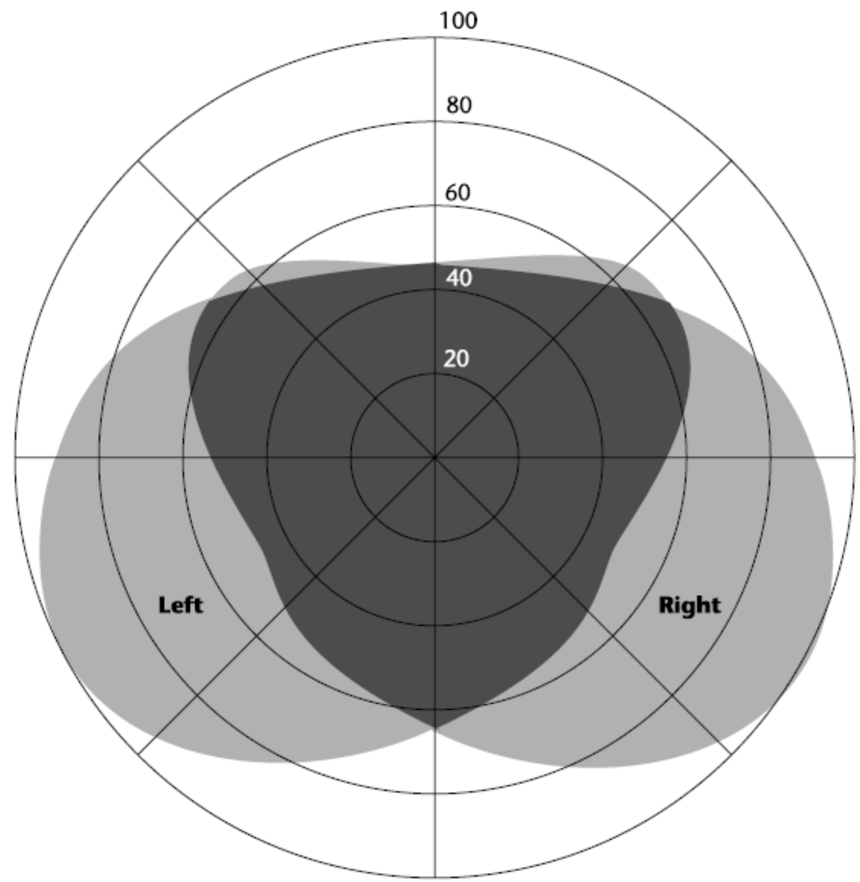
- Cornea
  - Main source of refraction (~40 diopters)
- Pupil (surrounded by Iris)
  - Aperture – controls amount of light let in to eye
  - Affects depth of field
- Lens
  - Forms remainder of compound lens system (with cornea)
  - Variable focus (when younger), muscles contracting lens
  - About 12 diopters range when young, lose ~2 per decade as lens stiffens with age
    - Hypothesis; there is an alternative that the lens grows with age, and the nature of
  - Older adults can't adjust their focus like younger people

Structure of the Eye (continued)

- Retina – basically the “sensor” (receptor cell) array of the eye
- Lens system projects image onto the retina
  - Stimulates receptor cells
  - Electrical impulses from each cell are carried from optic nerve to the brain
    - Location of nerve creates a blind spot in the eye
- Receptors are not uniformly spread across the retina

Field of View

- Human eye can see about:
  - 30 degrees up,
  - 70 degrees down,
  - 45 degrees toward nose,
  - 100 degrees away from nose
- Note: 1 degree is about size of thumbnail at arm's length

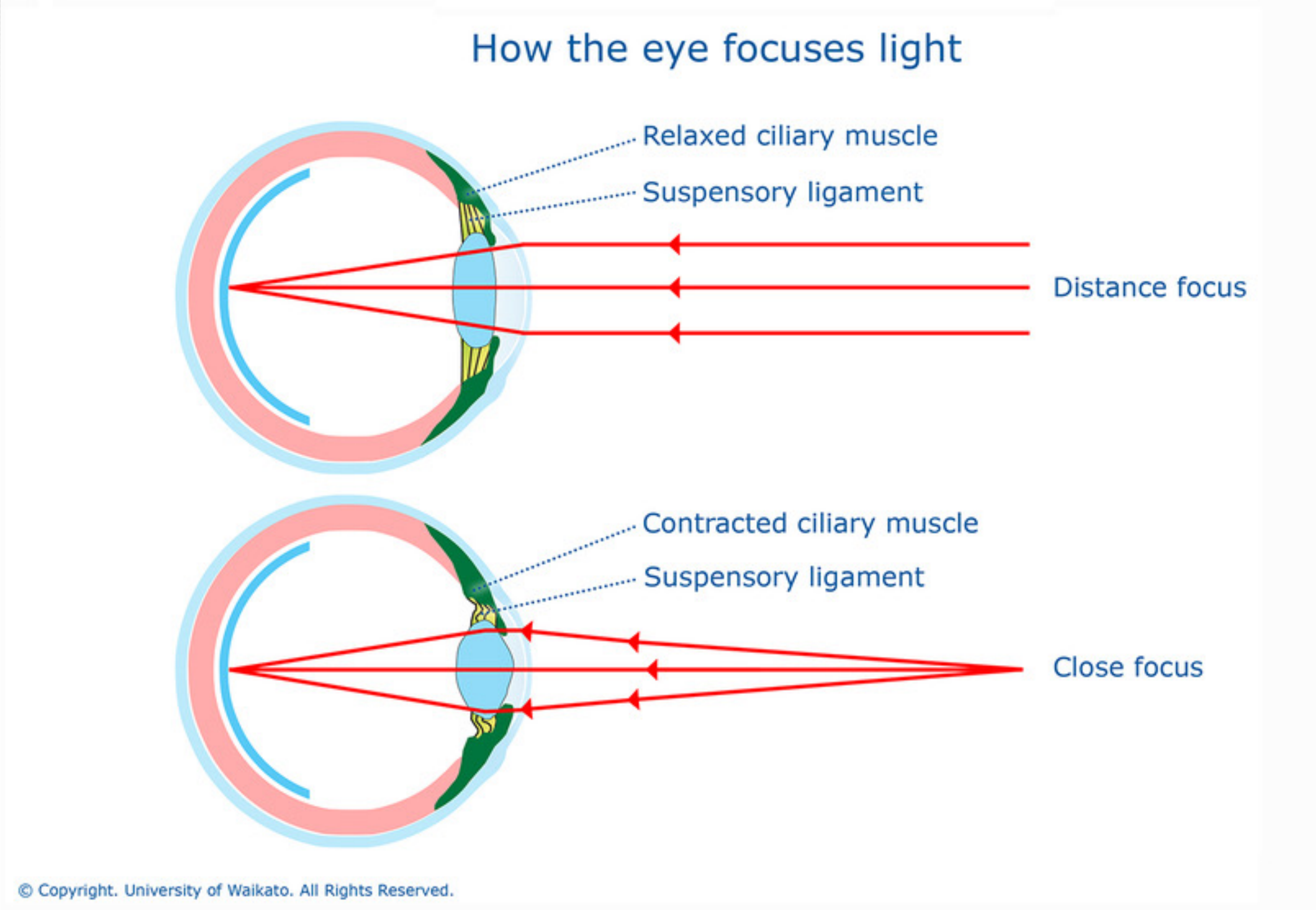


https://www.researchgate.net/figure/The-human-visual-field-of-view-when-gazing-straight-ahead-The-fields-are-constrained-by_fig7_46300830; Image is taken from Ware's book

Focal Length

- Focal length (f) measured in terms of diopters (1/f).
  - 1 m focal length = 1 diopter
- Eye system is about 59 diopters
  - Based on 17 mm distance from focal point of eye to retina
- Lens allows focus to different depths
- Note: focal length computations tend to be inverse
  - To find f_3 from two lenses f_1, f_2: $1/f_3 = 1/f_1+1/f_2$
  - i.e. add diopters

Focus on Nearby Objects



https://www.sciencelearn.org.nz/resources/50-how-the-eye-focuses-light

Depth of Focus

- Depth of focus: what is in focus for eye at a particular distance
  - Depends on diopters and on size of pupil
  - Generally things within ~ 1/3 a diopter are “in focus”
  - 3mm pupil, eye focus at infinity, things ~3m or farther are in focus
- This implies what you can show in focus for something a fixed distance away
  - Assume pupil at 3 mm
  - Viewing distance 50 cm (~screen distance), 43 to 60 cm is in focus
  - For 1m, 75 cm to 1.5 m is in focus
  - For 2m, 1.2 to 6 m is in focus
  - For 3m, 1.5 m to infinity is in focus
  - For infinity (i.e. can’t/don’t adjust lens), 3m+ is in focus

VR/AR Headsets

- The depth of field and focus have direct implications for AR/VR headsets and display of information inside
- VR headsets set virtual focal distance ~2m away, so 1.2m to 6m are in focus
  - Closer/farther should use depth-of-field effects in rendering, ideally.
- AR headsets
  - Focus of overlaid images need to be at same (or close) virtual depth as focus
  - tracking eye direction, depth of focus is critical
- Angle of view
  - Uncomfortable to hold eyes more than 10 degrees off center for long
  - Best to keep text/key information within an 18 degree cone
- Light field displays may offer some benefits, eventually

Chromatic Aberration

- The human eye does not correct for chromatic aberration(!)
  - Thus, red light focuses at a different point than blue
- Means we need to be careful about color patterns since red/blue may come into focus differently
- Pure blue (text/pattern) on black background is especially bad
  - Eye will automatically focus toward red/white on screen, and thus blue will be out of focus
  - Combine in some red/green to counter effect
- Red/blue on black background perceived as at different depths
  - But, red on blue can particularly stand out

The Retina

- Key cells are receptor cells of two types: rods and cones
- Main focal point at center of retina is the **fovea**
  - Largest concentration of receptor cells
  - Takes up about a 2 degree field of view, with key part being a ½ degree field of view

Rods and Cones

- Rods
  - About 100 million in eye
  - Mainly on periphery; none at fovea
  - Highly sensitive to intensity only (good for night vision; nearly useless in daylight)
- Cones
  - About 6 million in eye
  - 3 types (often called Red/Blue/Green, but not actually just those)
  - Make up fovea; densest region
    - 20-30 arc seconds apart from each other

Cells of Retina

- Signals from rods/cones are combined over a few layers of cells
- Thousands of rods tend to be combined
- Ganglion cells send signals to brain through optic nerve

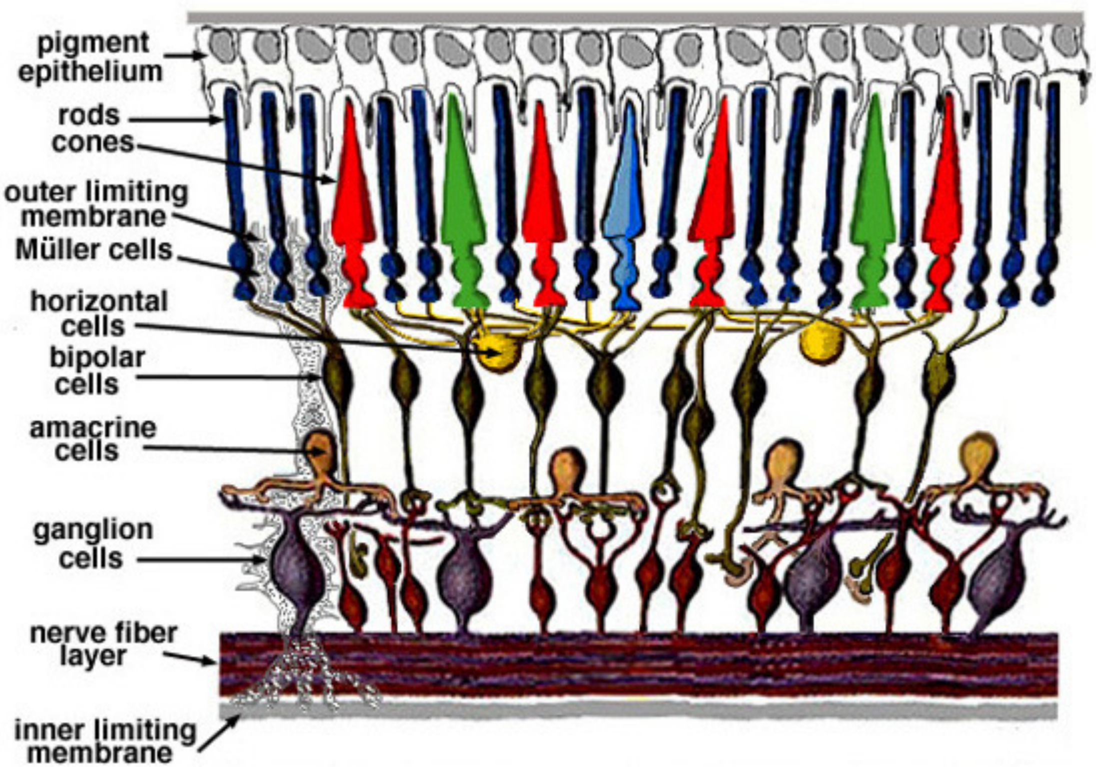
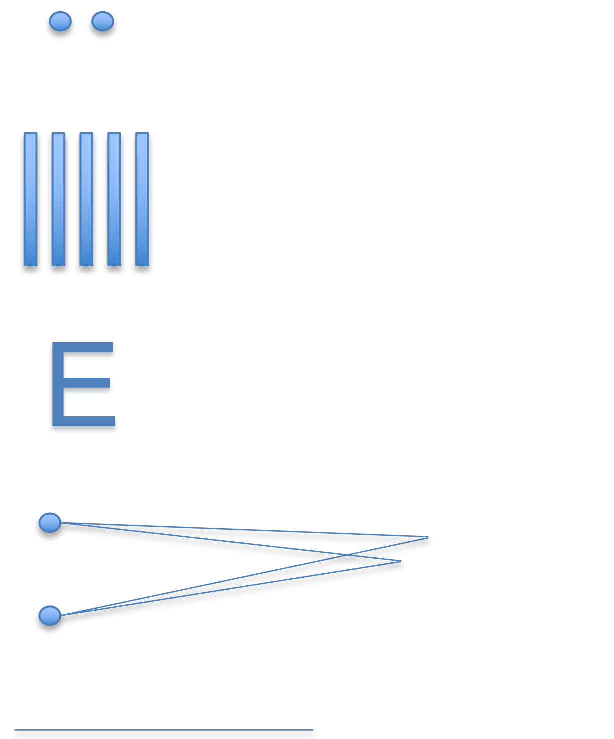


Fig. 2. Simple diagram of the organization of the retina.

https://webvision.med.utah.edu/book/part-i-foundations/simple-anatomy-of-the-retina/

Visual Acuity

- How “sharply” we can see is measured in different ways
- Point acuity:
  - Distinguish 2 points
  - 1 arc minute
- Grating acuity:
  - Distinguish parallel bars
  - 1-2 arc minutes
- Letter acuity:
  - Distinguish letters
  - 5 arc minutes
- Stereo acuity:
  - Distinguish depth
  - 10 arc seconds
- Vernier acuity
  - Distinguish lines aligning
  - 10 arc seconds



Neural Processing

- Receptor cells are (at closest) just 20-30 arc seconds apart
  - But, we have some “superacuities” (like Vernier), where we can perceive 10 arc seconds difference.
  - Indicates that the post-receptor neural processing is able to detect even finer detail
- Binocular view gives greater acuity and better contrast sensitivity
  - i.e. Brain is merging signals from both eyes at a very fundamental level

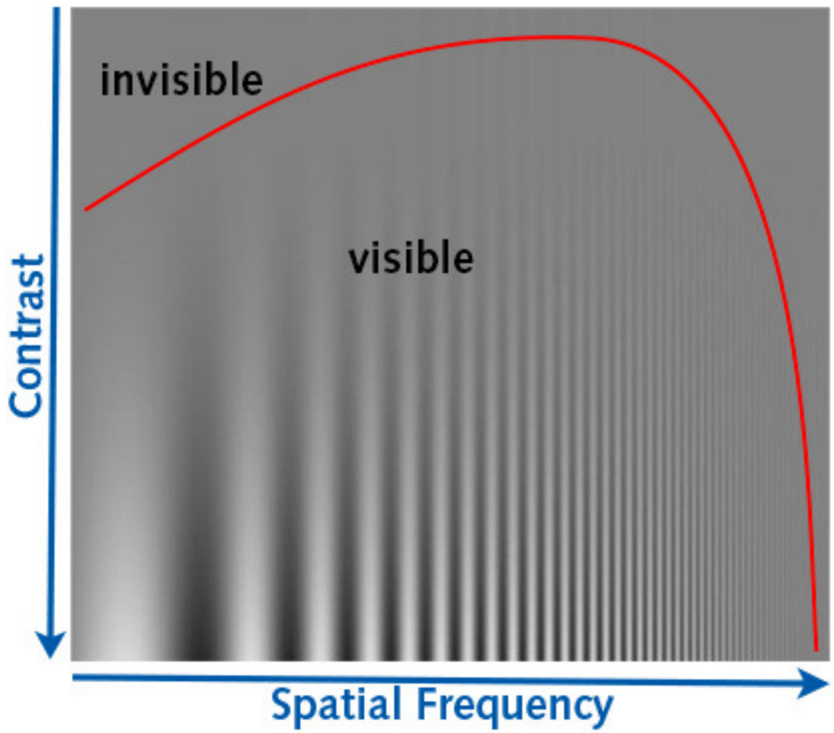
Visual Acuity and Fovea

- Visual acuity falls of quickly away from the fovea
- Nearly exponential decay
- Factor of 10 difference when 10 degrees out from fovea

http://anstislab.ucsd.edu/illusions/peripheral-acuity/

Contrast and Frequency

- Eyes are sensitive to different levels of contrast, frequency
- This changes with age
  - Older: less able to distinguish higher frequencies
- Low sensitivity at low frequency
  - People can't notice patterns as easily if a low frequency pattern is displayed on large screen



https://www.psychophysics.uk/spatial-contrast-sensitivity/

Other Visual Factors

- Temporal (flicker) sensitivity also varies
  - Humans generally can't notice >50 Hz
  - Optimal sensitivity seems to be 2-10 Hz
    - Can reduce the lack of low-frequency sensitivity
- Certain flicker patterns with some high frequency, high contrast patterns can induce physical problems
  - E.g. trigger epileptic seizure

Next Time

- We will focus more on lightness, contrast, and color