CS-E4840
Information Visualization
Lecture 5: Human perception

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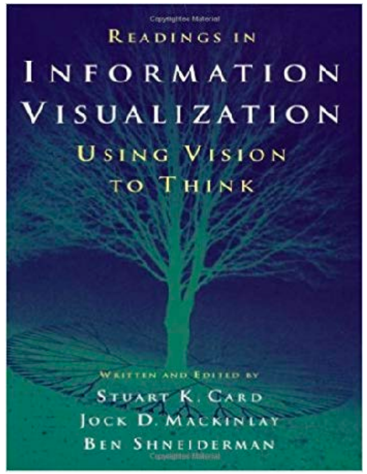
Recap

- **Techniques:**
  - Bars, boxes, lines, dots
  - multiple plots
  - reference lines and regions
  - rescaling /normalising / re-expressing
  - colours
- **Problems:**
  - axis ranges
  - use of 3D
  - overplotting
- **Scenarios:**
  - distribution analysis
  - ranking and part-of-whole analysis
  - time-series
  - high-dimensional data
- **Related reading:** *Few. Now you see it. Analytic Press, 2009.*
- **Older but relevant:** *Card et al. Readings in Information Visualization: Using Vision to Think. Morgan Kaufmann, 1999.*

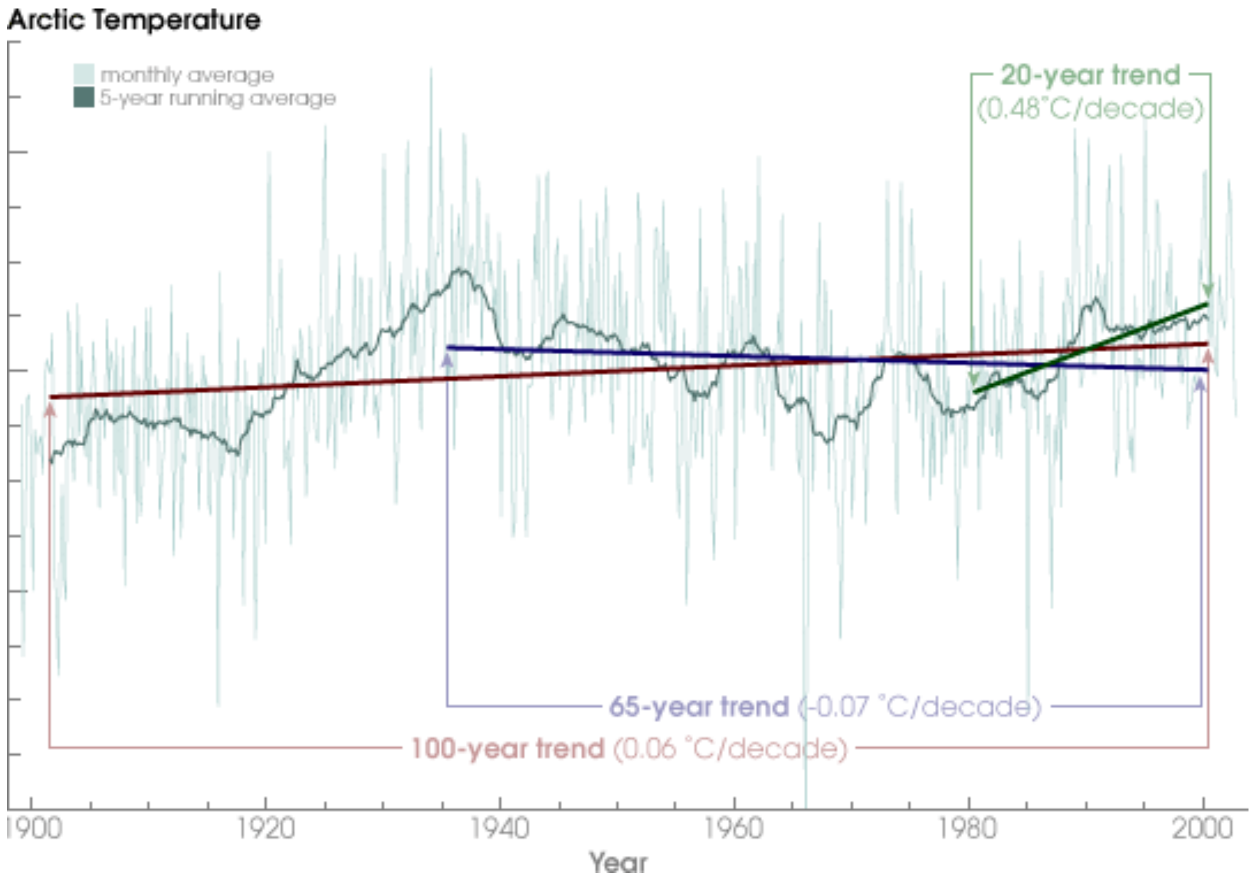


Time-series displays

- 7 types of graphics are useful for examining time-series
  - Line graphs
  - Bar graphs
  - Dot plots
  - Radar graphs
  - Heat-maps
  - Box plots (and similar) for analyzing distribution over time
  - (Animated) scatter plots

Time-series displays

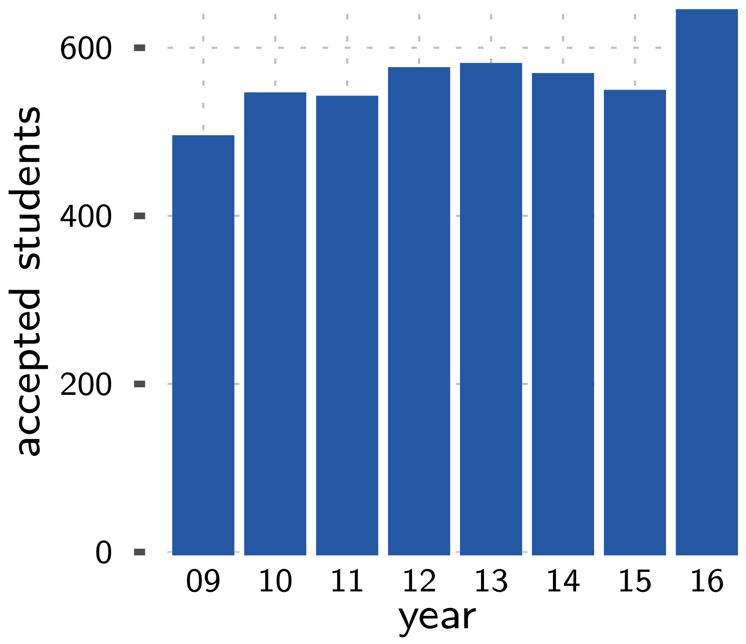
- Line graph is typically the best choice
- use it show patterns over time:
  - increasing / decreasing trend
  - variation / volatility over time
- exceptions / outlier behaviour

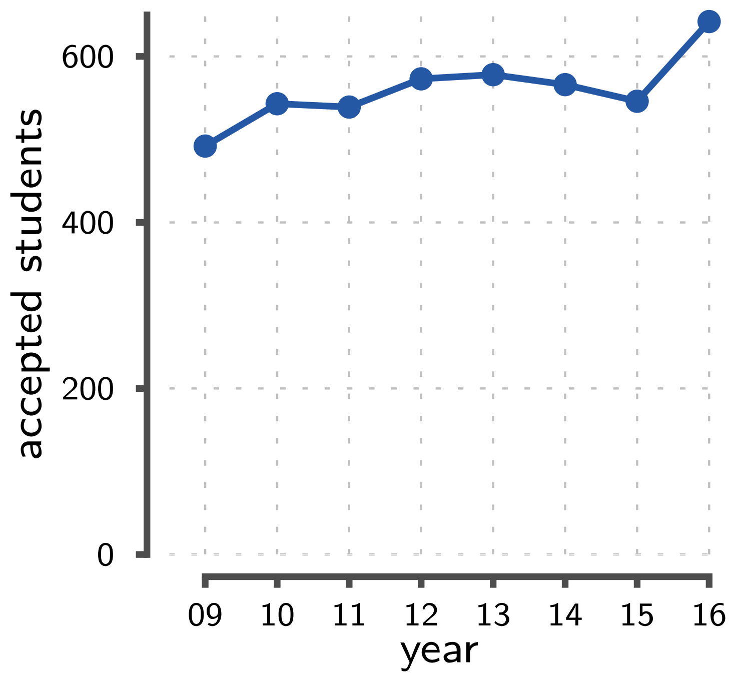


https://earthobservatory.nasa.gov/Features/ArcticIce/arctic_ice3.php

Time-series displays

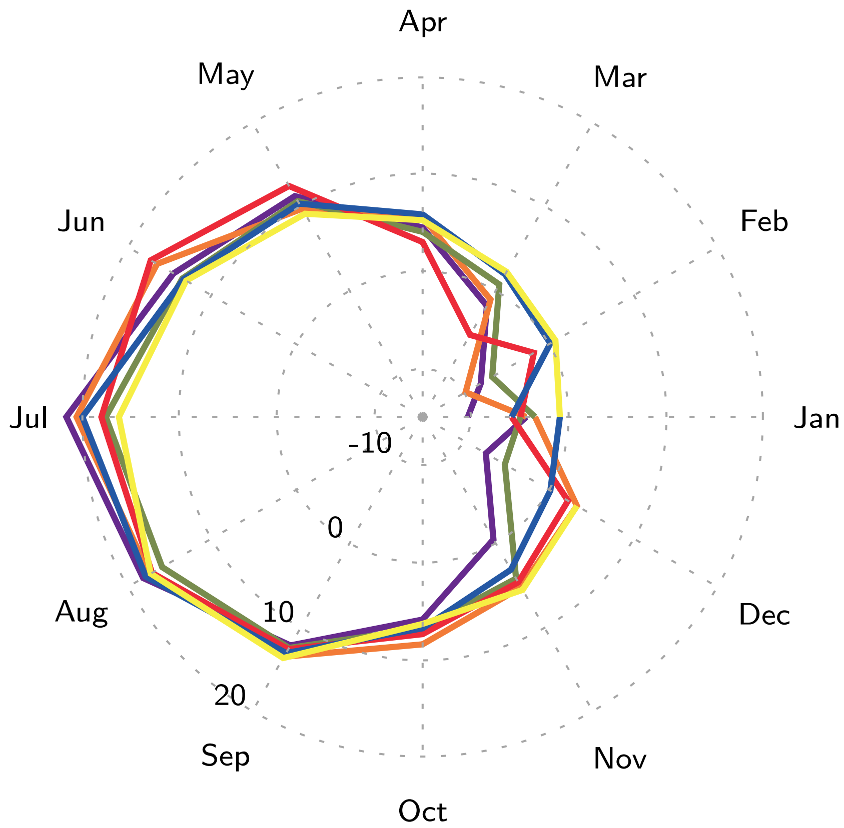
- Bar graph works better
  - if you want to compare individual values
- You should use dot plot if you cannot use line chart
  - measurements at irregular time intervals
  - you cannot guarantee that the intermediate values are close to linear interpolation

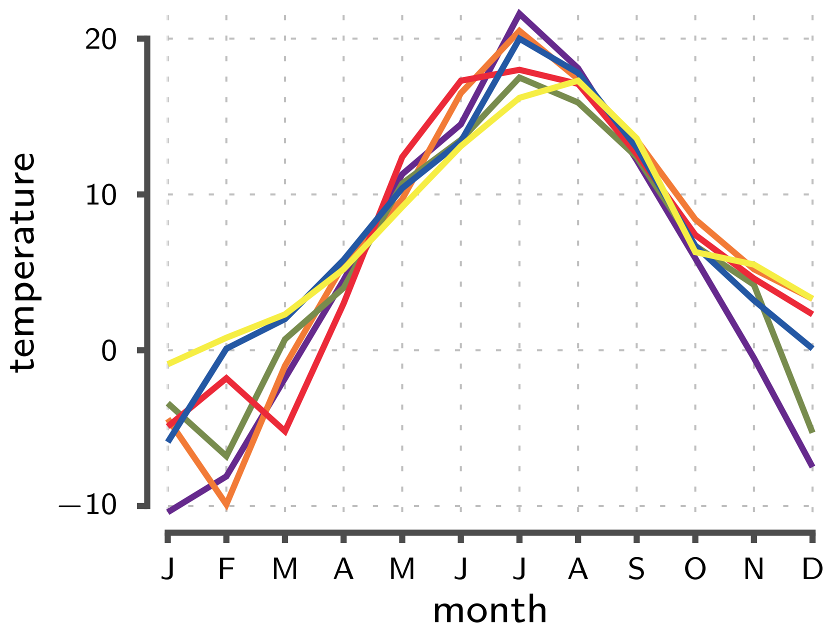




Time-series displays

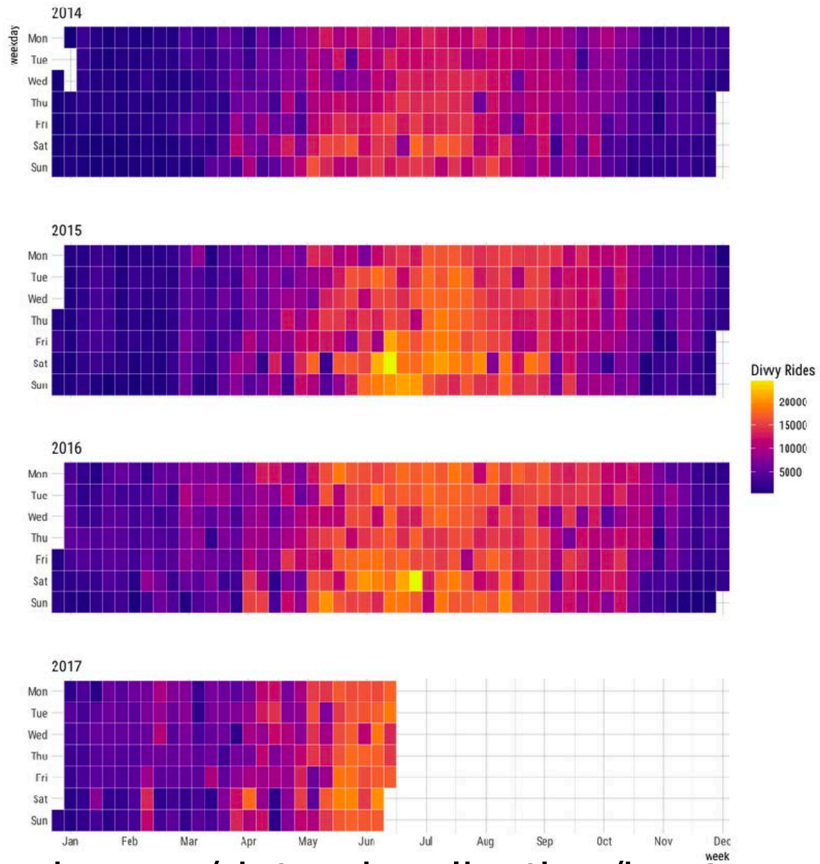
- Radar plots
  - can be used to show cycles over time
  - a line chart with superimposed lines is probably better





Time-series displays

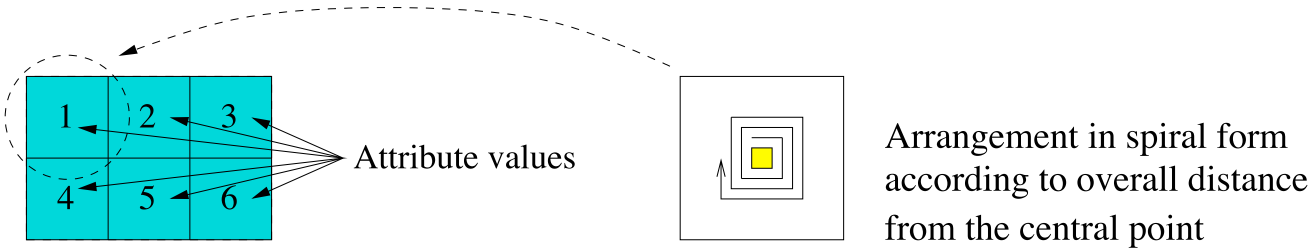
- A **heatmap** shows many time-series, if superimposition creates too cluttered picture
- y-axis is individual time series, x-axis is time, colour shows the value
- similar arrangement (but different encoding) than with small multiples

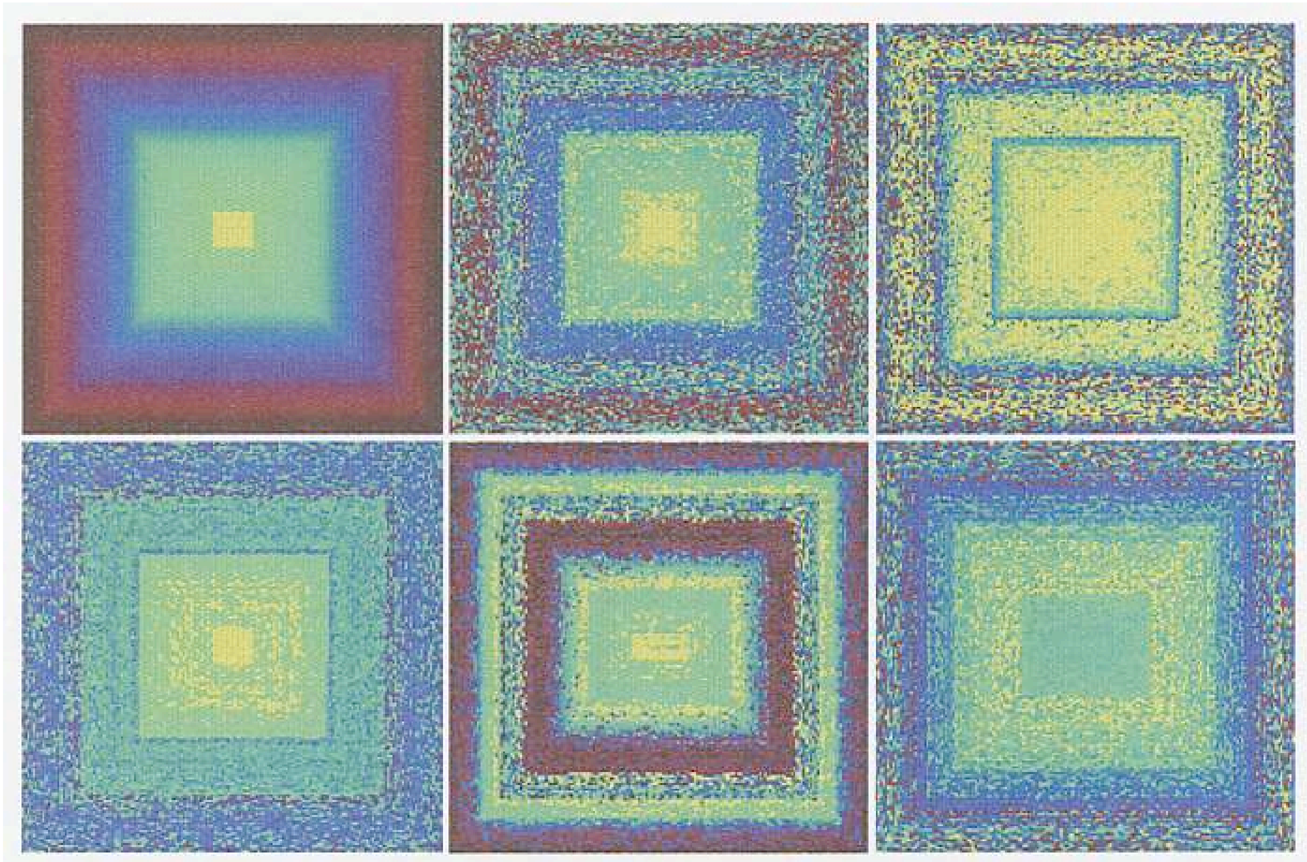


http://austinwehrwein.com/data-visualization/heatmaps-with-divvy-data/

Time-series displays

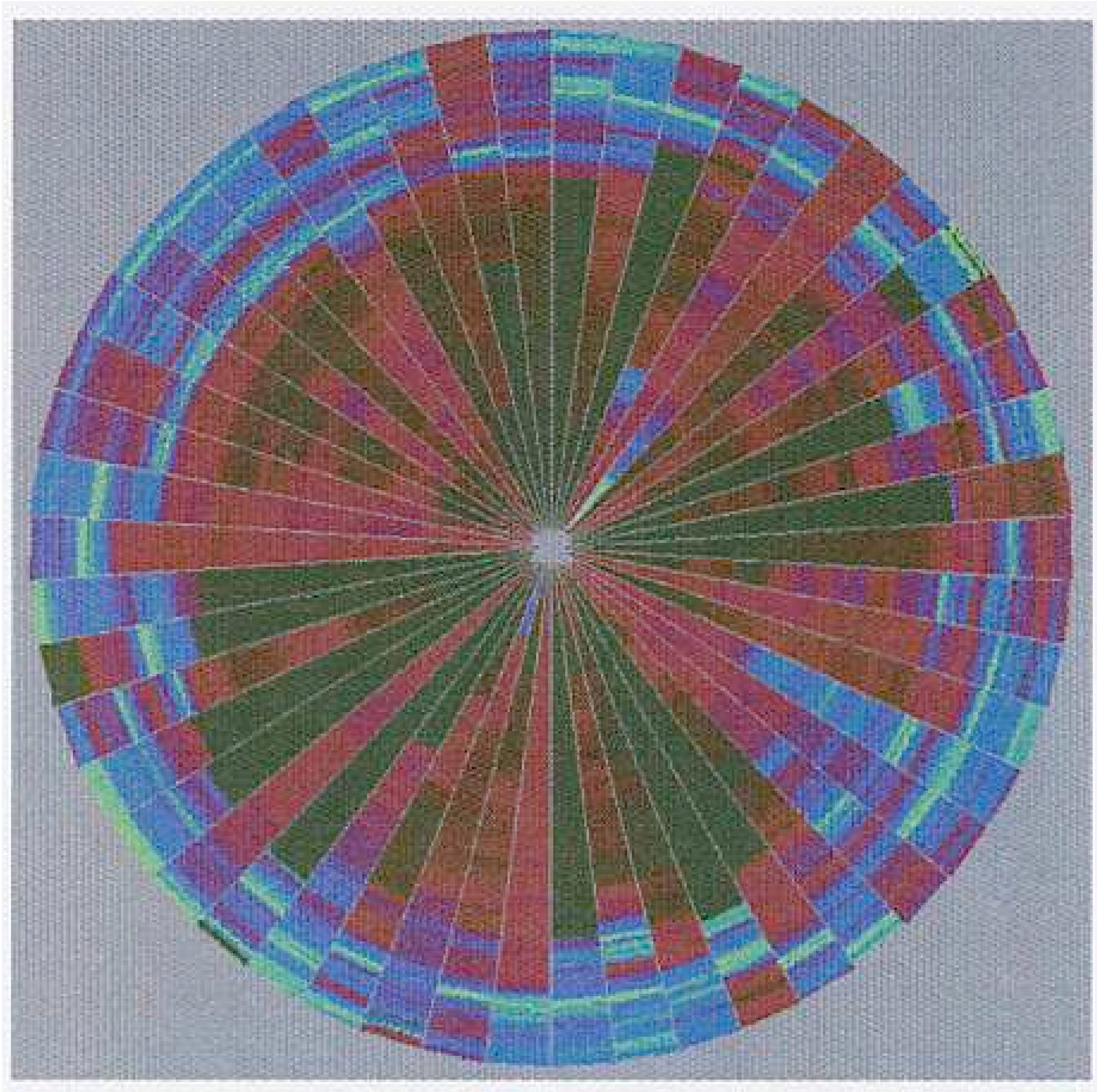
- **Pixel-oriented techniques**
  - Each attribute value is represented by one pixel (the value ranges are mapped to a fixed colour-map)
  - The attribute values for each attribute are represented in separate sub-windows





Time-series displays

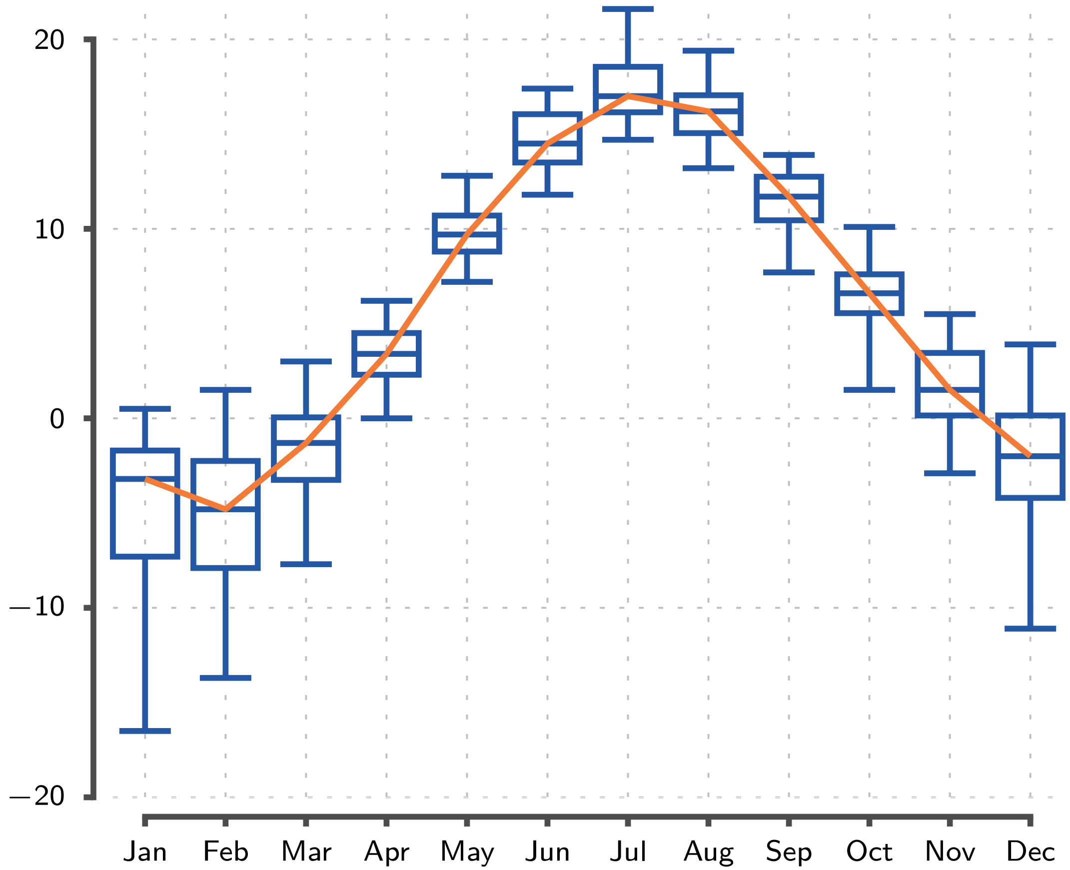
- **Pixel-oriented techniques**
  - Circle segments



Time series of 50 stocks of the Frankfurt Stock Index [K 50].

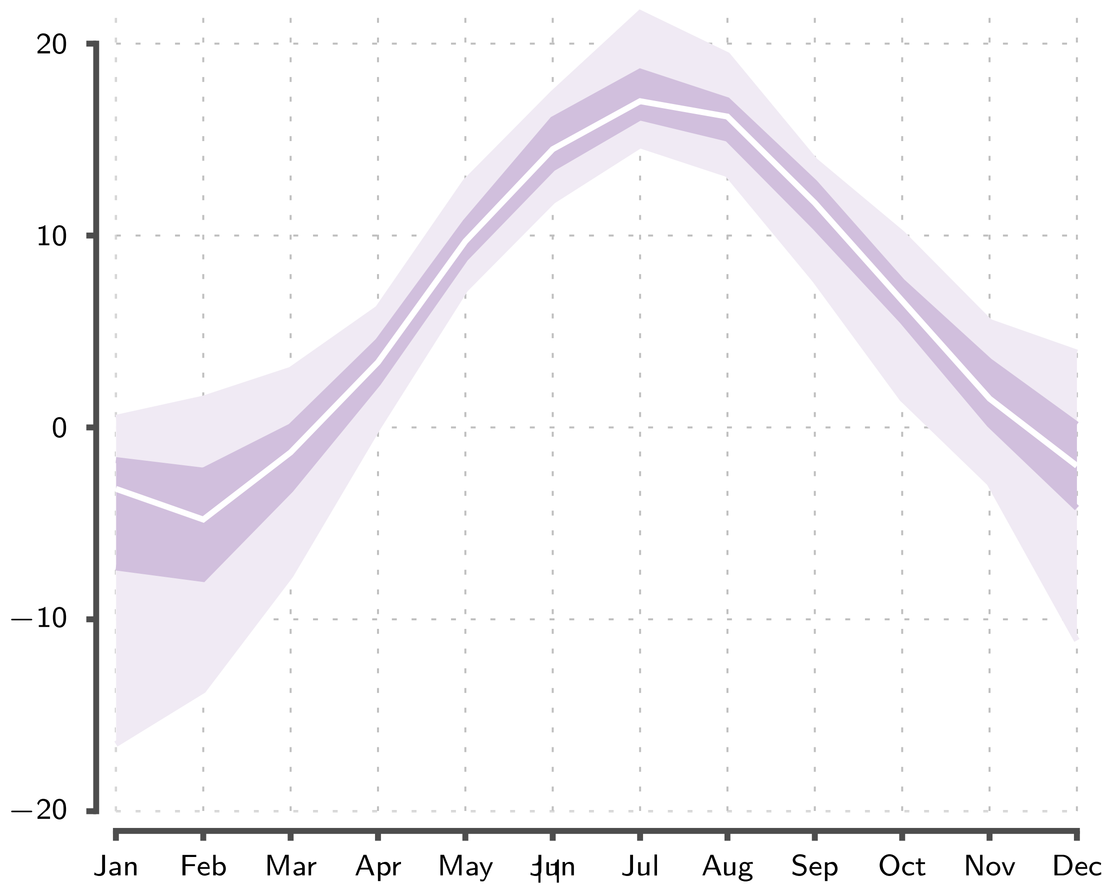
Time-series displays

- Box plots are useful
  - if you have significant number of time-series
  - you are only interested in how the distribution changes over time



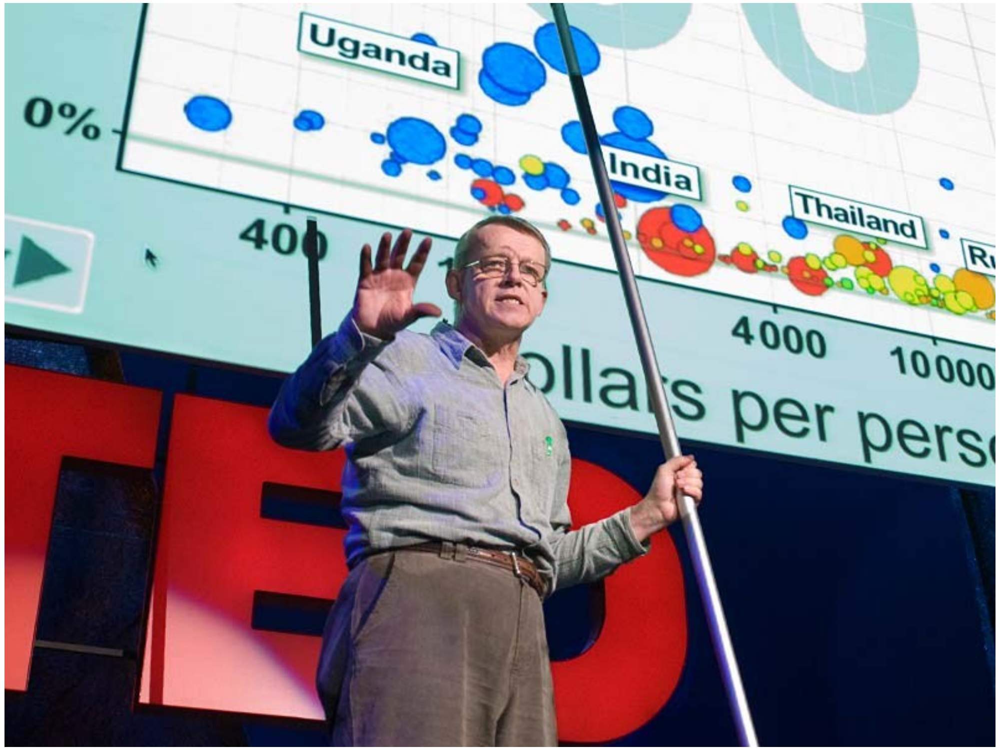
Time-series displays

- You can also plot the statistics as lines or areas
  - if you have significant number of time-series
  - you are only interested in how the distribution changes over time



Time-series displays

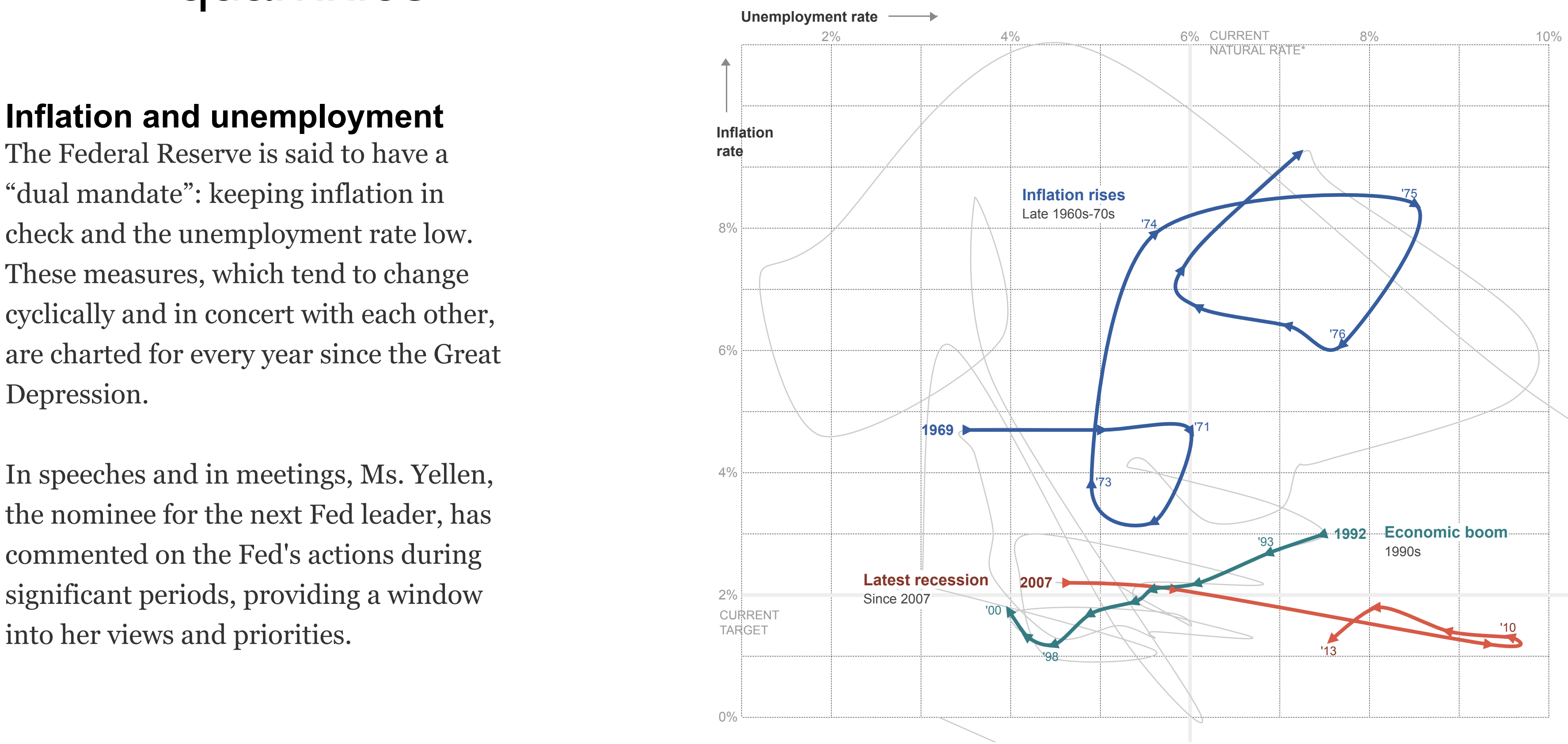
- Animation and scatter plots can be used
  - if you wish to show how two quantities change over time
  - more complex plots are possible (for example bubble maps)



https://ted.com/talks/hans_rosling_shows_the_best_stats_you_ve_ever_seen

Time-series displays

- These animations can be simulated on paper by showing trails
  - similar to space-time narratives but with abstract quantities



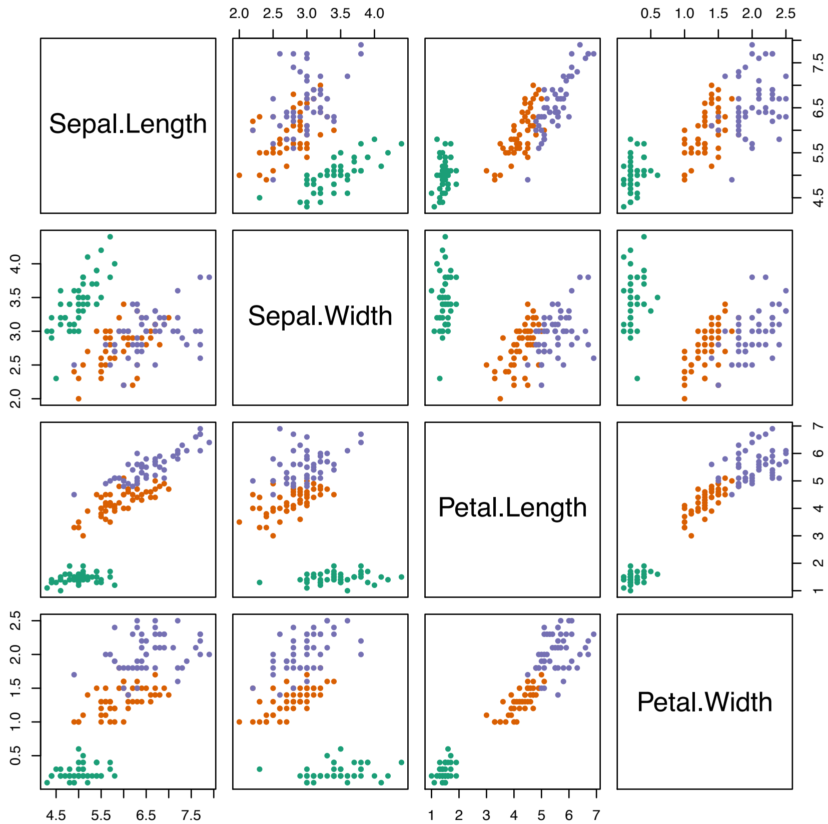
http://www.nytimes.com/interactive/2013/10/09/us/yellen-fed-chart.html

High-dimensional data

- Options for visualising high-dimensional multivariate data
  - small multiples with simple plots
  - heat-maps
  - parallel coordinates
  - glyphs
  - dimension reduction techniques
- All these techniques have problems
  - ask yourself what is the story that you are trying to tell and
  - visualise accordingly or
  - apply data mining tools to extract new knowledge from the data

High-dimensional data

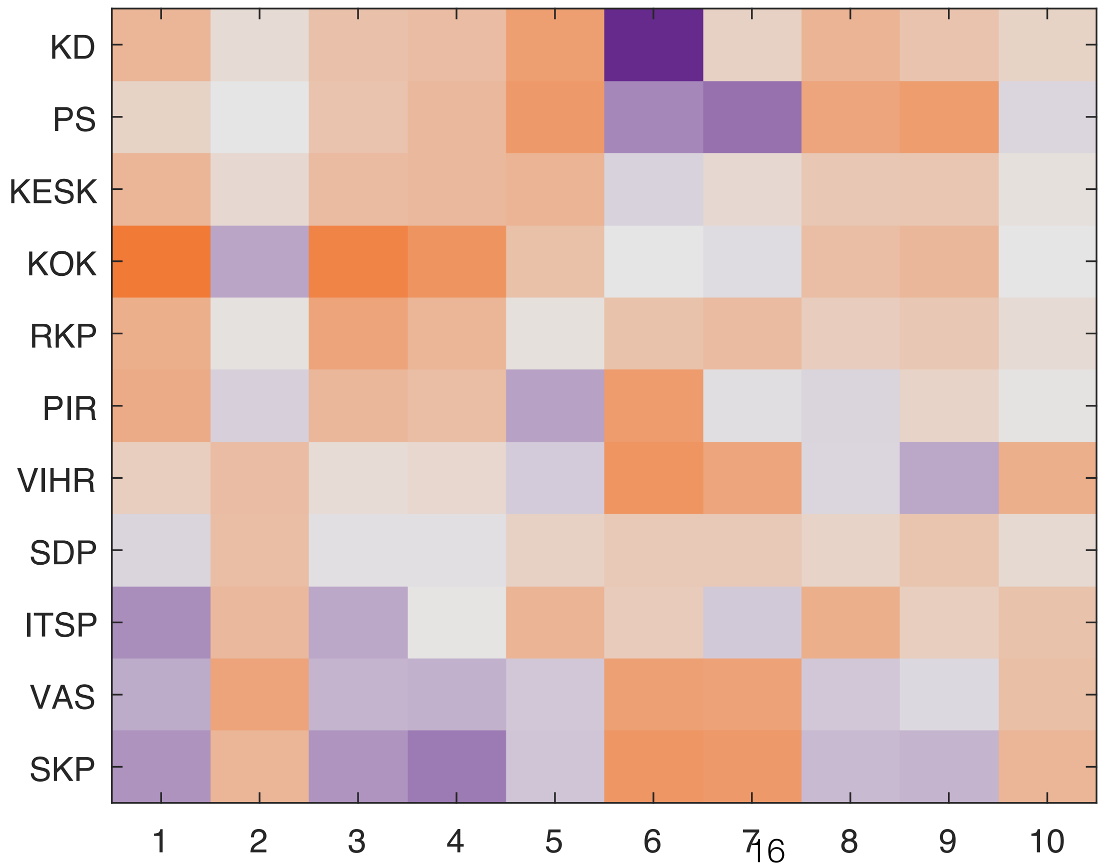
- Small multiples
    - array of a matrix of small plots
    - may result in an overwhelming plot




```
pairs(iris[,1:4],col=brewer.pal(3,"Dark2")[iris[,5]],pch=20)
```

High-dimensional data

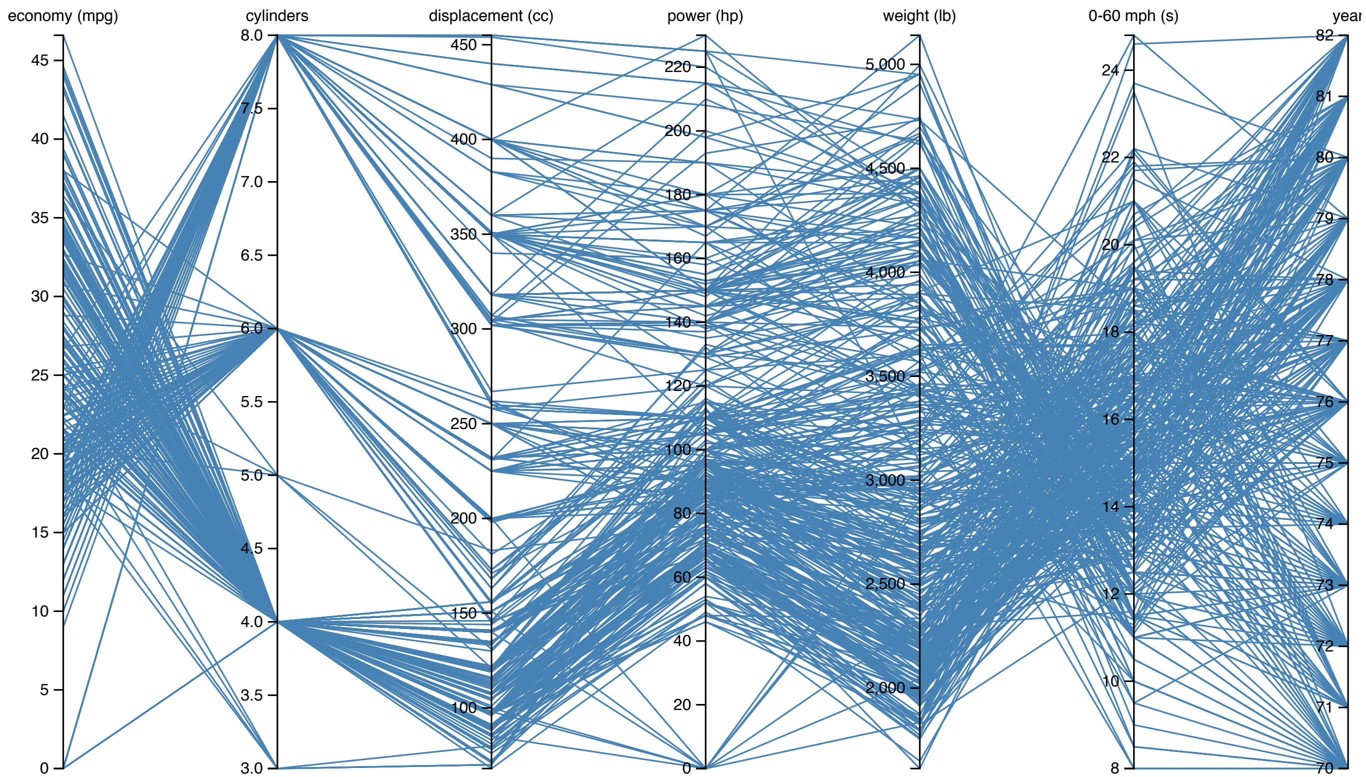
- Heat-map
  - dimensions are on x-axis
  - data points are on y-axis
  - colour represent the value
  - may be difficult to extract any information
  - ordering dimensions and data points is crucial



Questionaire by HS vaalikone

High-dimensional data

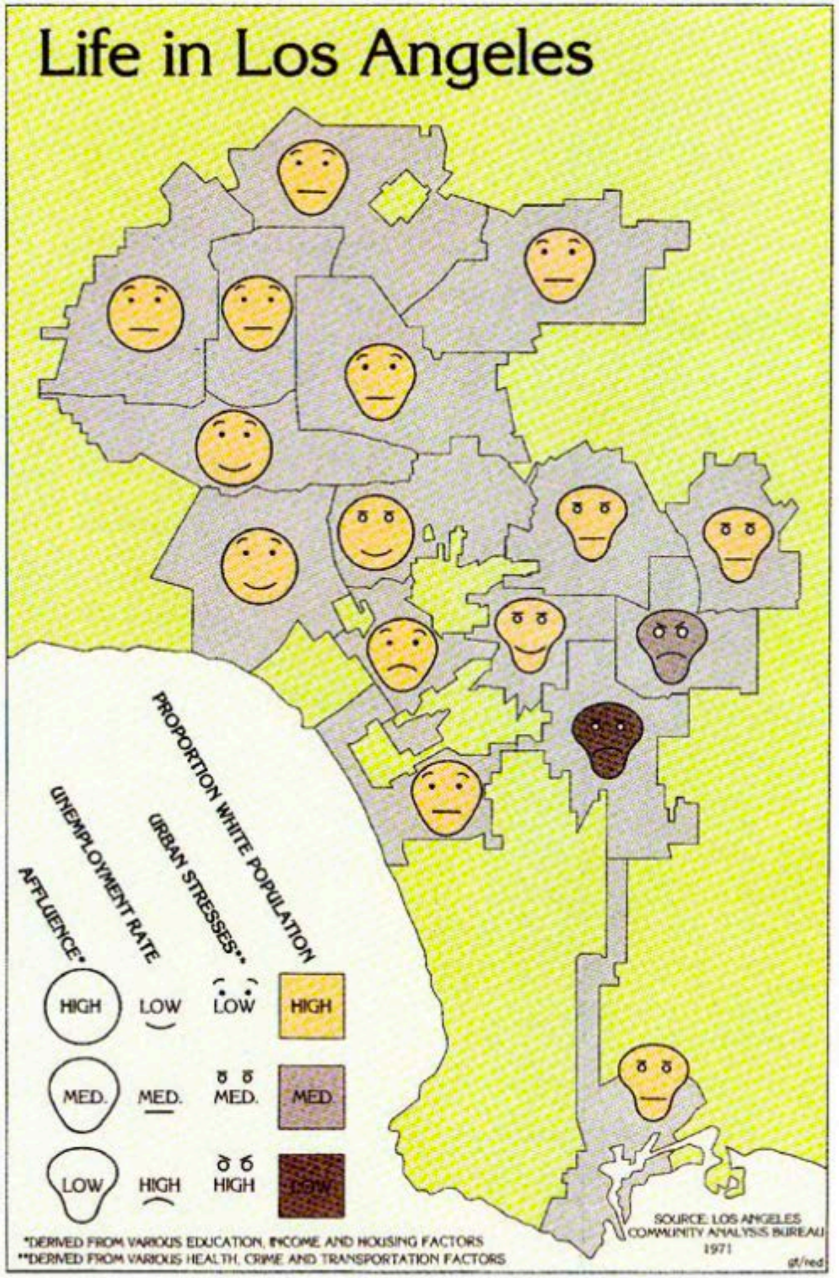
- Parallel coordinates
  - line graphs: x-axis are individual dimensions
  - each data point is a line
  - somewhat counter-intuitive and may result in cluttered picture
  - order of dimensions matter but may reveal information that is not visible in other designs
  - highlights clusters
  - may work better as an interactive tool



https://bl.ocks.org/jasondavies/1341281

High-dimensional data

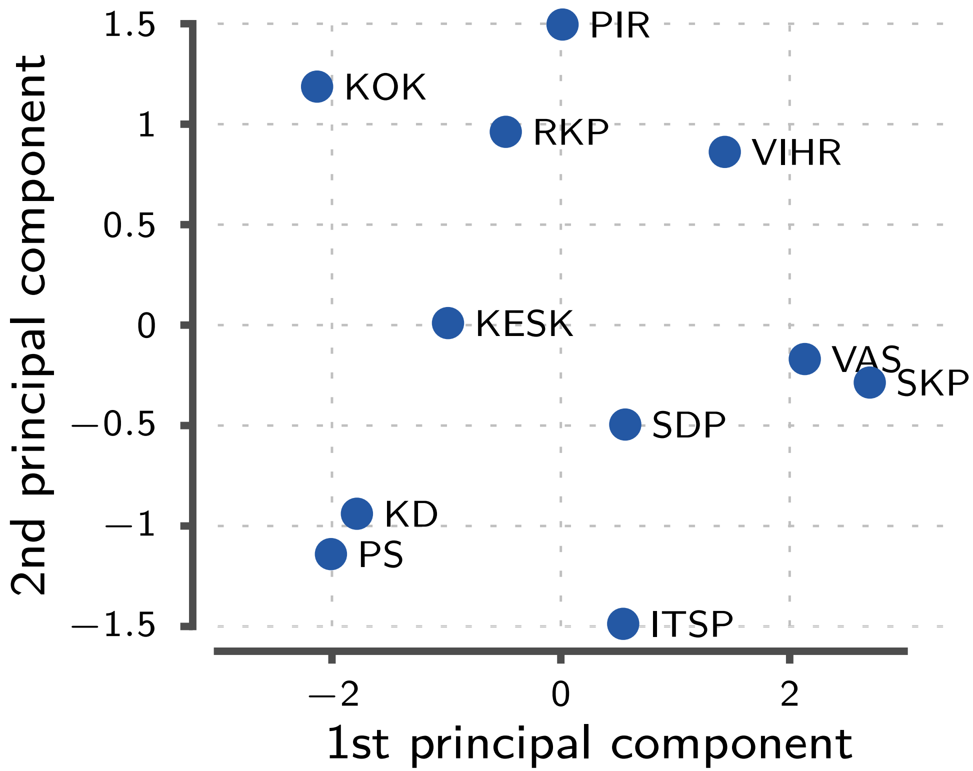
- Glyphs
    - shortened for hieroglyphs
    - small 'subplots' that can be placed in a scatter plot
    - at simplest glyphs are coloured dots
    - more complicated glyphs are possible to indicate more dimensions (for example Chernoff faces)
    - more on glyphs in Part II
    - can only carry limited information before the plot gets too cluttered



http://mapdesign.icaci.org/2014/12/mapcarte-353365-life-in-los-angeles-by-eugene-turner-1977/

High-dimensional data

- Reducing dimension
  - different techniques that try to plot high-dimensional data as a scatter plot
  - points that are ’close’/’far’ in the data are also close/far in the plot
  - powerful to reveal new knowledge hidden within the data
  - but almost always introduce distortion
  - [more during Part III]

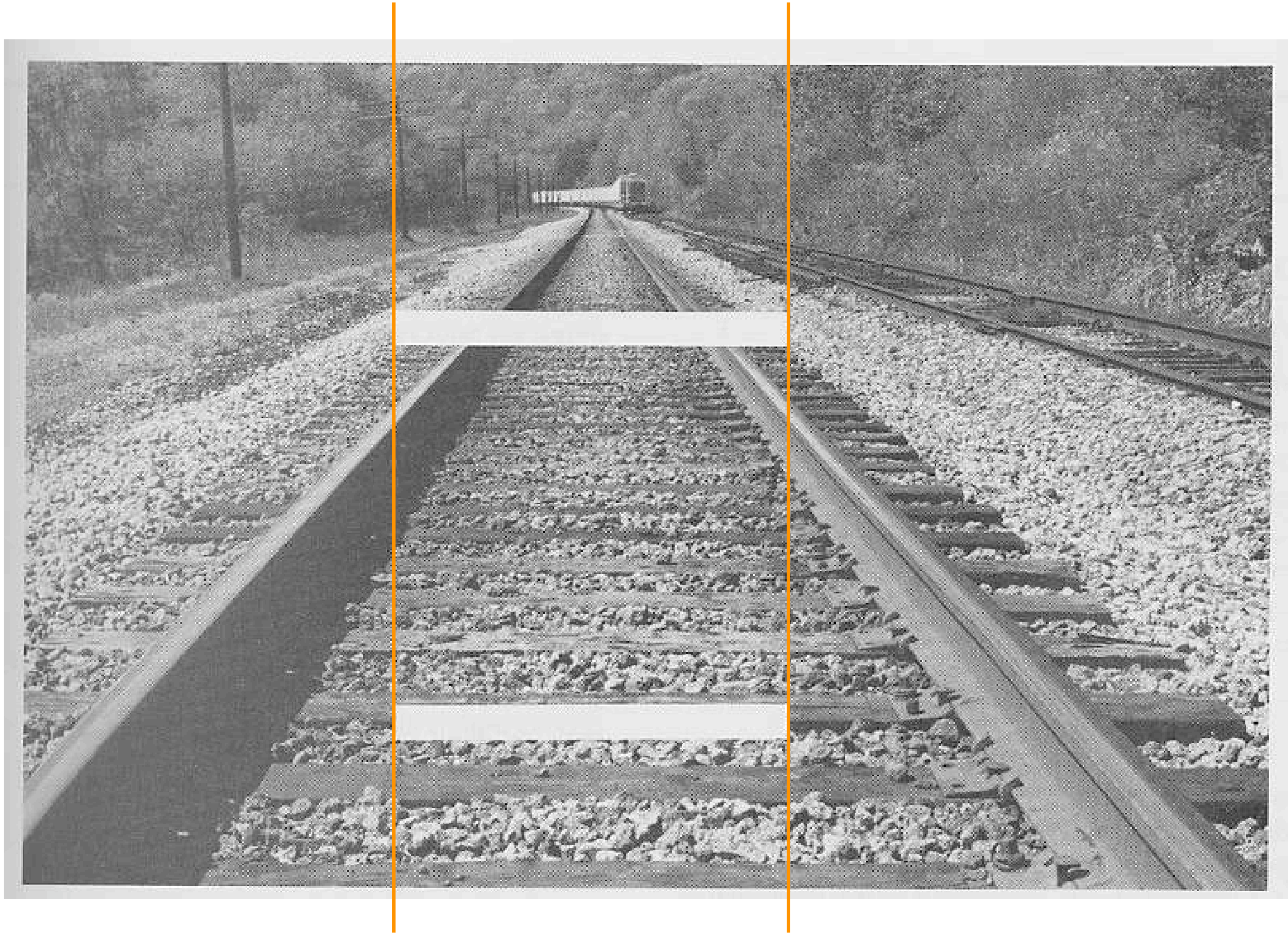


Graphing techniques: Summary

- four basic graphic elements:
  - points, lines, bars, and boxes
- use lines to show trends, variability
- use bars to compare individual numbers
- use reference lines/regions for comparison
- use multiple plots if story/data requires it:
  - small multiples, overview/detail, multiform
- rescale/re-express if the relative comparison is important
- muted colors for surfaces, bright colors for objects
- use opponent colors [more in Part II]

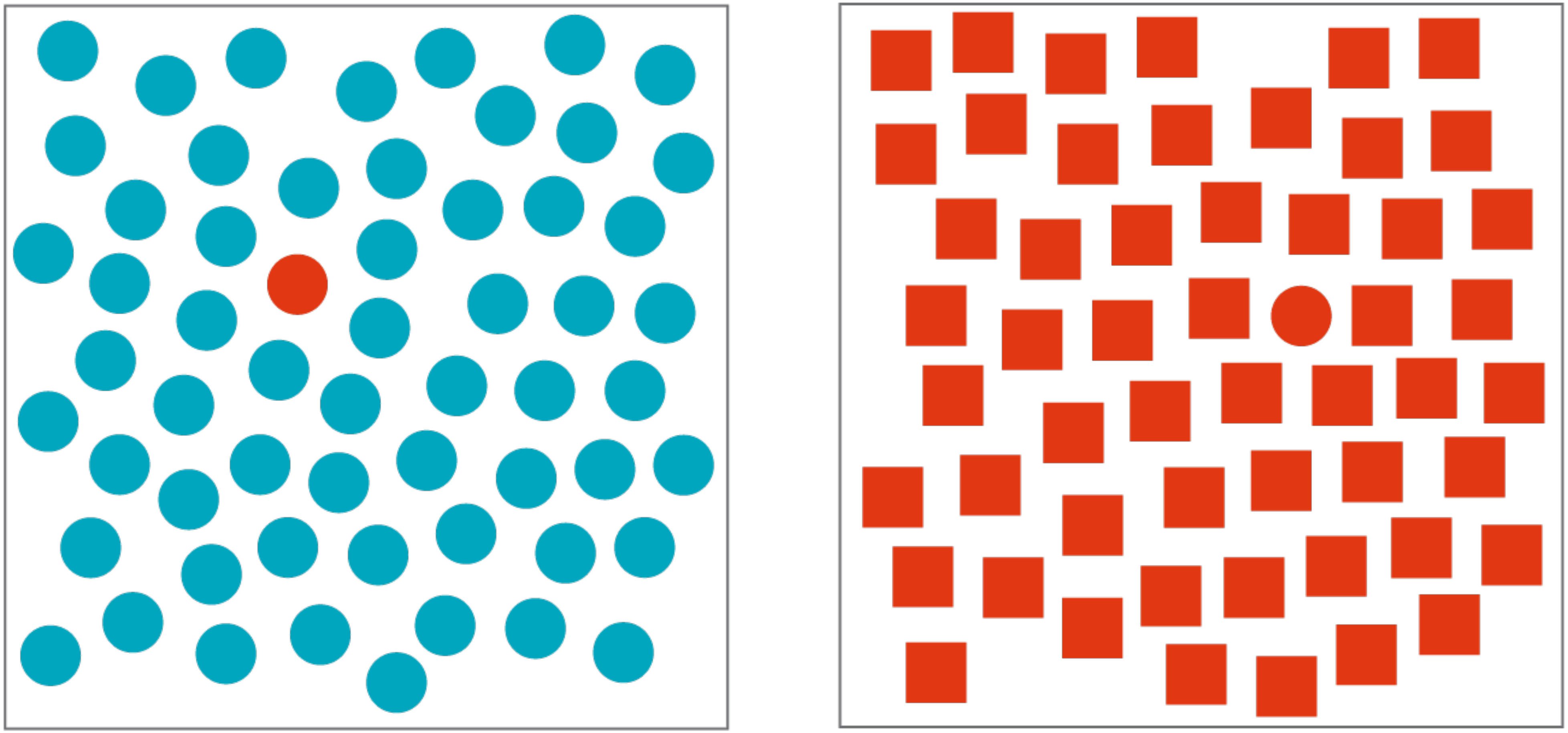
PART II
Visual Perception

Optical illusion



Ponzo or railroad track illusion [G 7.39].

Is there a red circle?



“We use context to help us perceive”

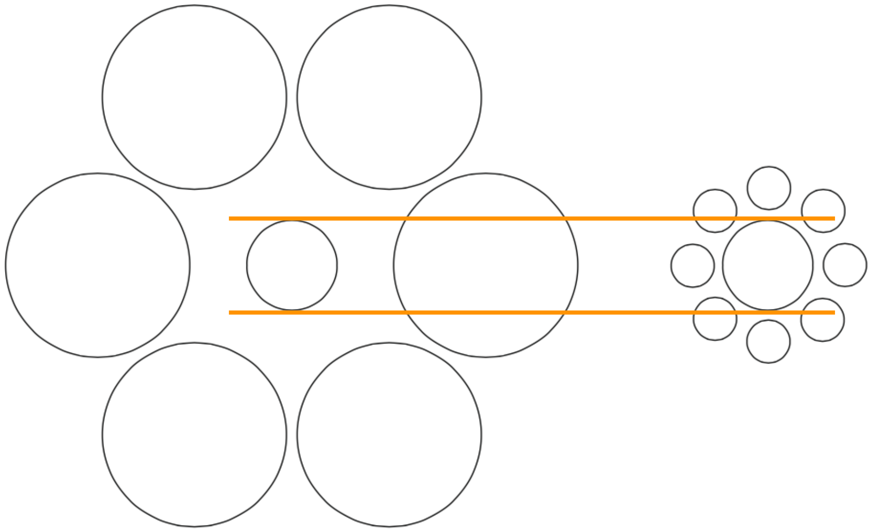
Aoccdrnig to rscheearch at Cmabrigde uinervtisy, it deosn’t mttaer waht oredr the ltteers in a wrod are, the olny iprmoetnt tihng is taht the frist and lsat ltteres are at the rghit pclae. The rset can be a tatol mses and you can sitll raed it wouthit a porbelm. Tihs is bcuseae we do not raed ervey lteter by it slef but the wrod as a wlohe.

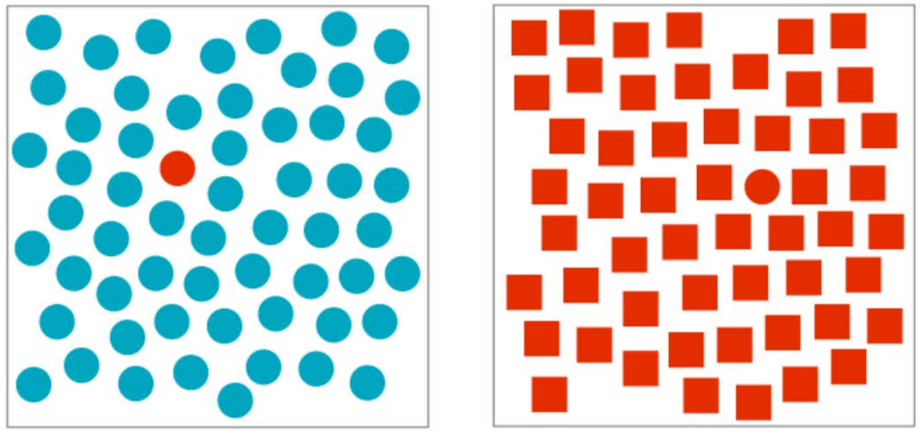
https://www.snopes.com/language/apocryph/cambridge.asp


GOOD


EVIL

What we perceive depends on what we focus our attention





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We have to

understand **human perception**

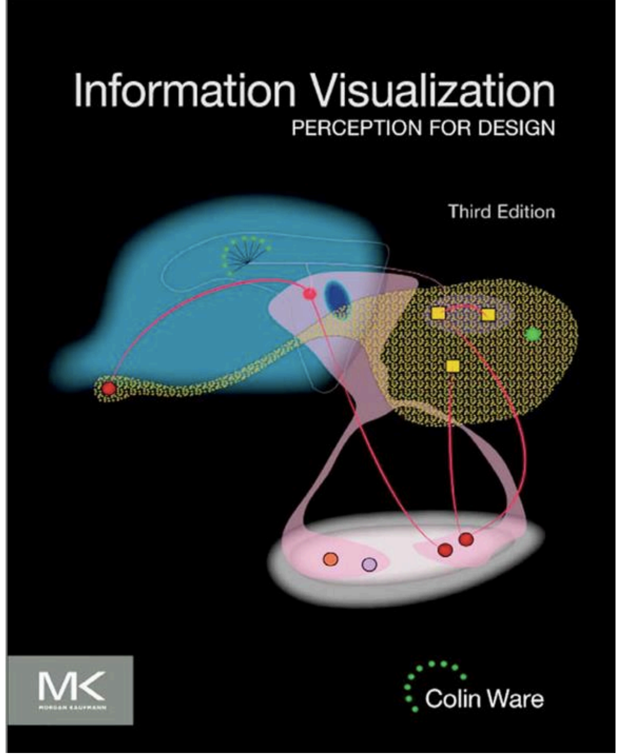
to

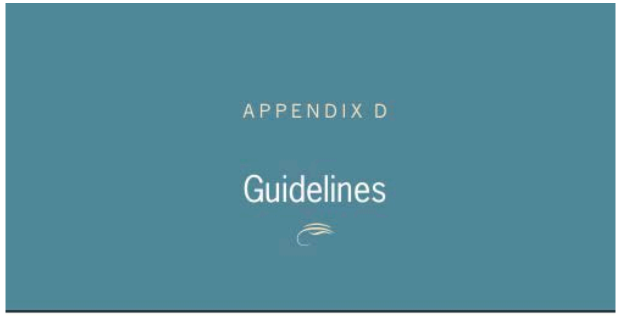
design **effective visualizations**

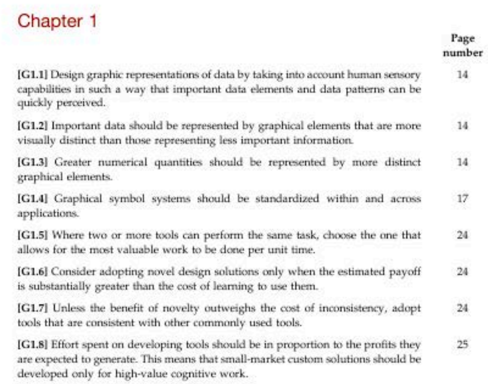
that **exploit the capabilities** and **manage the limitations** of human psychology

Textbook

- Ware. Information visualization: perception for design, 3rd edition. Morgan Kaufmann, 2012.
- Use the 3rd edition which has design guidelines!
- The book is available at the Aalto library as an ebook.
- Today: Chapters 1 and 2. Next days: the following chapters from Ware.



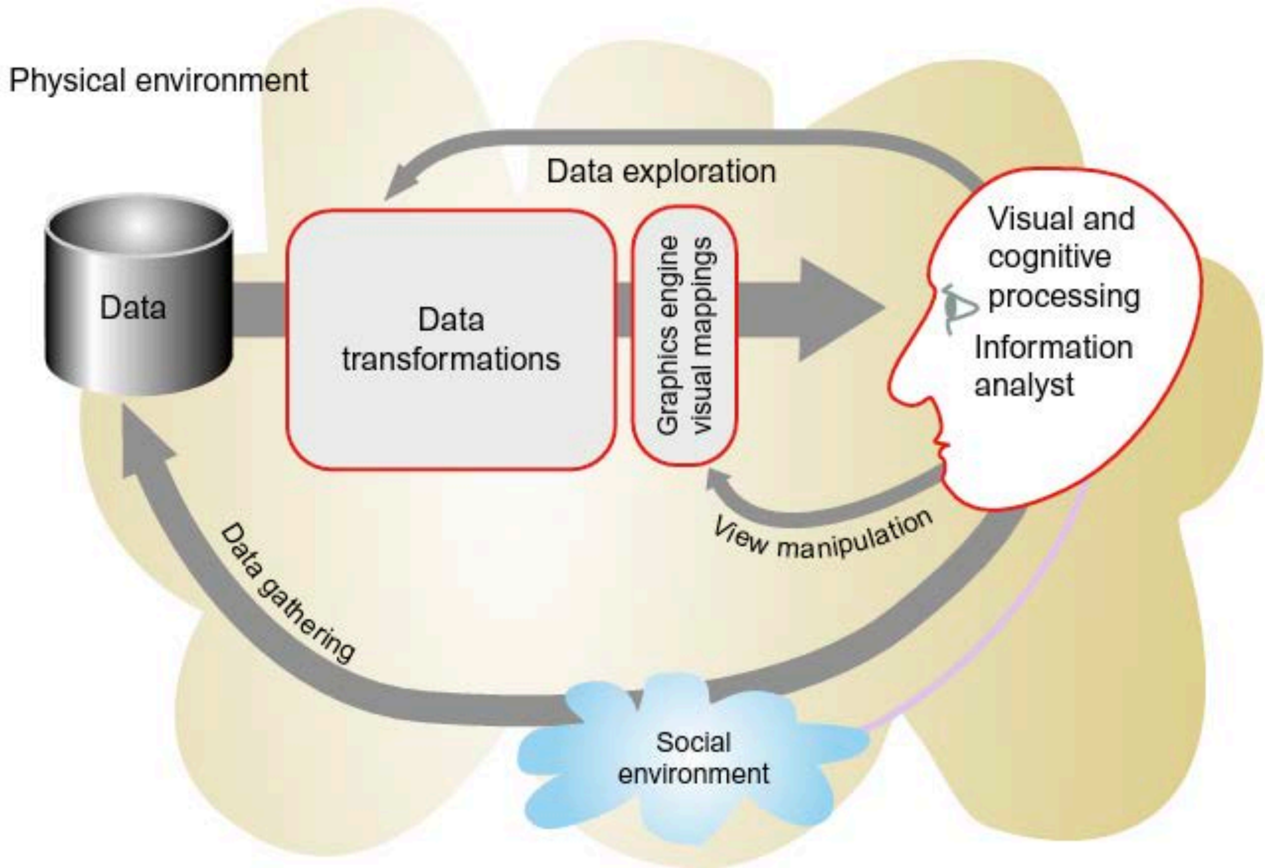




Chapter 1

	Page number
[G1.1] Design graphic representations of data by taking into account human sensory capabilities in such a way that important data elements and data patterns can be quickly perceived.	14
[G1.2] Important data should be represented by graphical elements that are more visually distinct than those representing less important information.	14
[G1.3] Greater numerical quantities should be represented by more distinct graphical elements.	14
[G1.4] Graphical symbol systems should be standardized within and across applications.	17
[G1.5] Where two or more tools can perform the same task, choose the one that allows for the most valuable work to be done per unit time.	24
[G1.6] Consider adopting novel design solutions only when the estimated payoff is substantially greater than the cost of learning to use them.	24
[G1.7] Unless the benefit of novelty outweighs the cost of inconsistency, adopt tools that are consistent with other commonly used tools.	24
[G1.8] Effort spent on developing tools should be in proportion to the profits they are expected to generate. This means that small-market custom solutions should be developed only for high-value cognitive work.	25

The visualization process



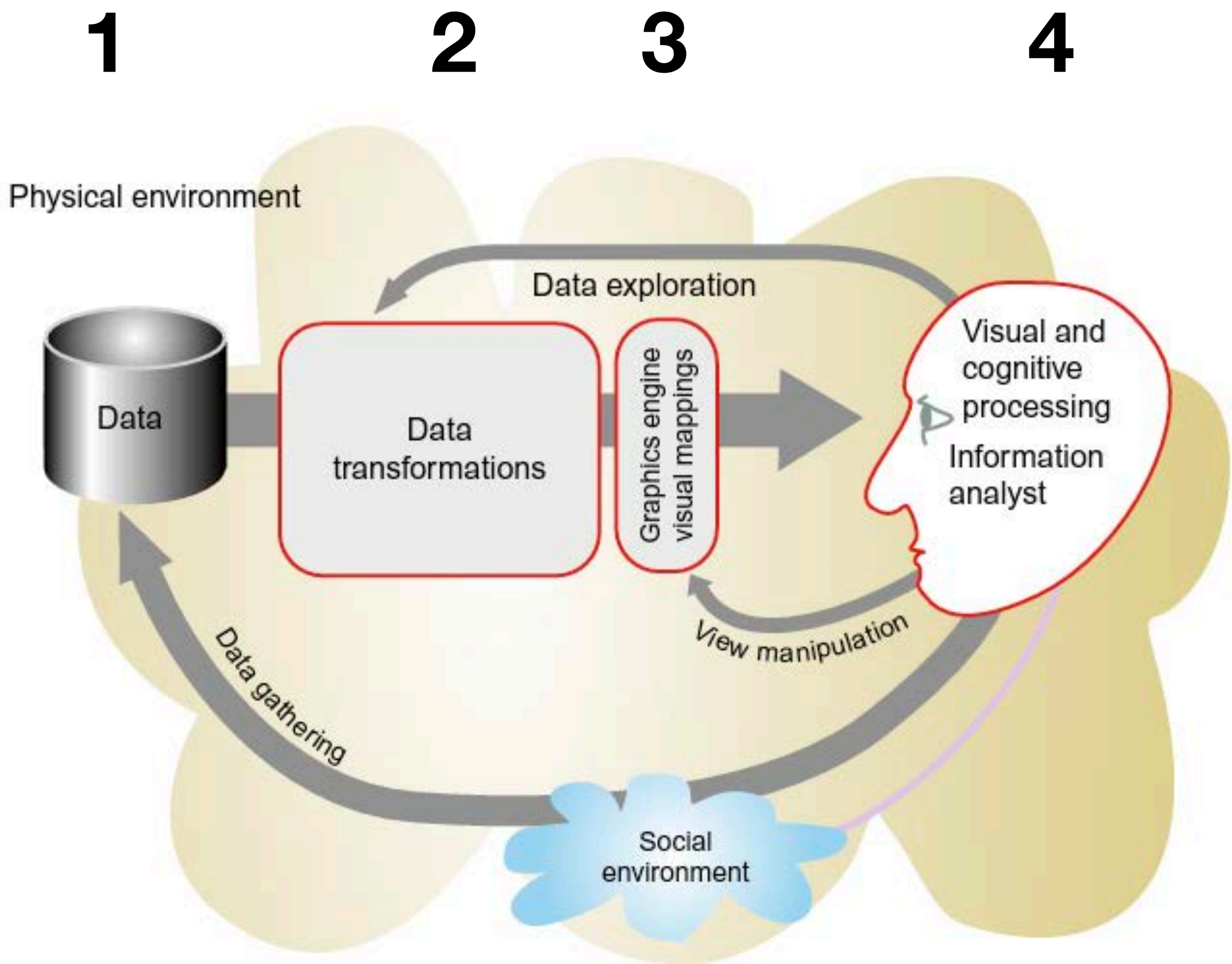
The visualization process

1. Data collection and storage

2. Data pre-processing (e.g., data reduction to reveal certain aspects)

3. Selected data mapped into visual representation

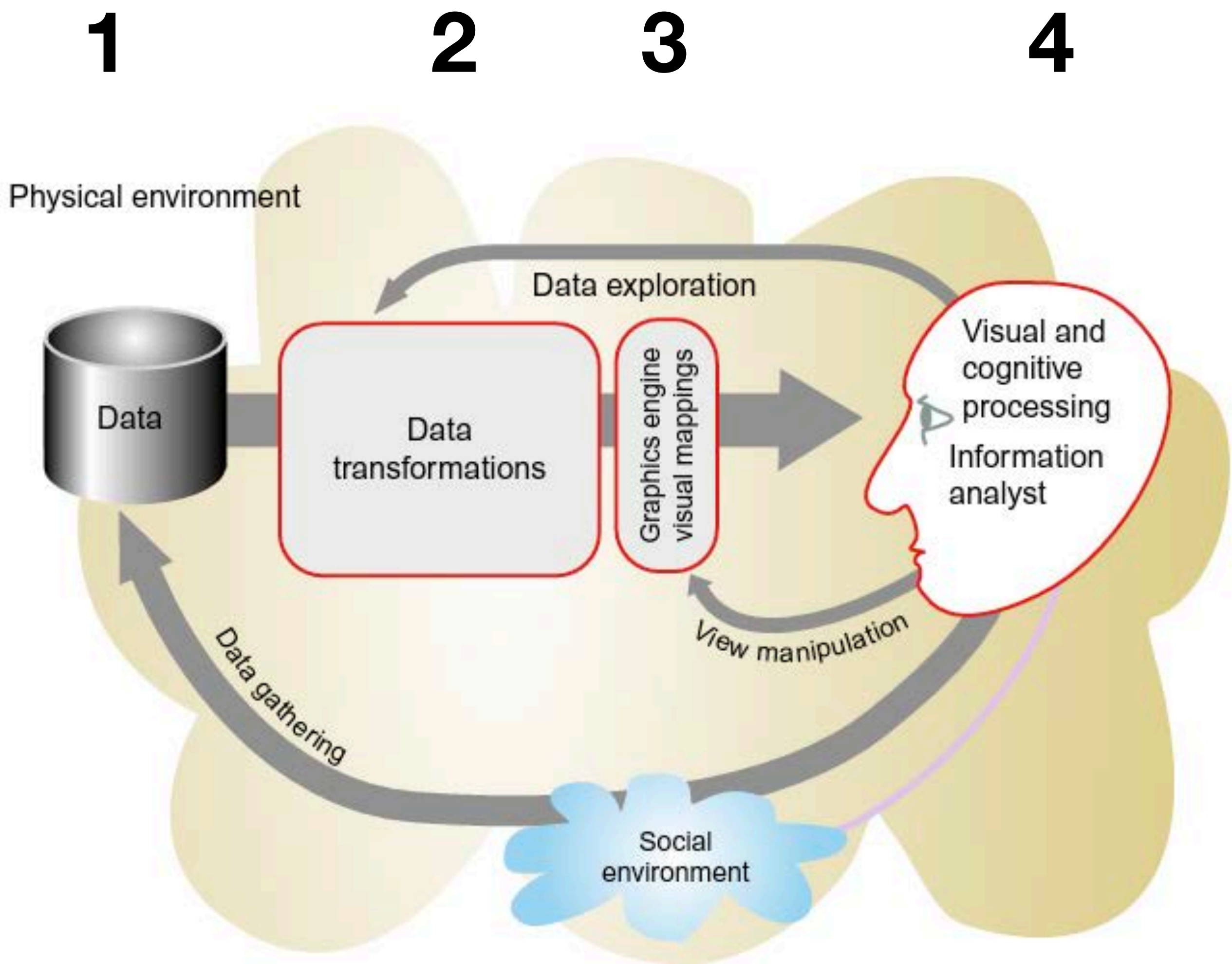
4. Human perceptual and cognitive system



The visualization process

Thus, in visualization it is important to

> encode the **data** into a **visual representation** that the human user can **easily and correctly understand** for timely and optimal *decision-making*



But, how can we do this best?

Semiotics of graphics

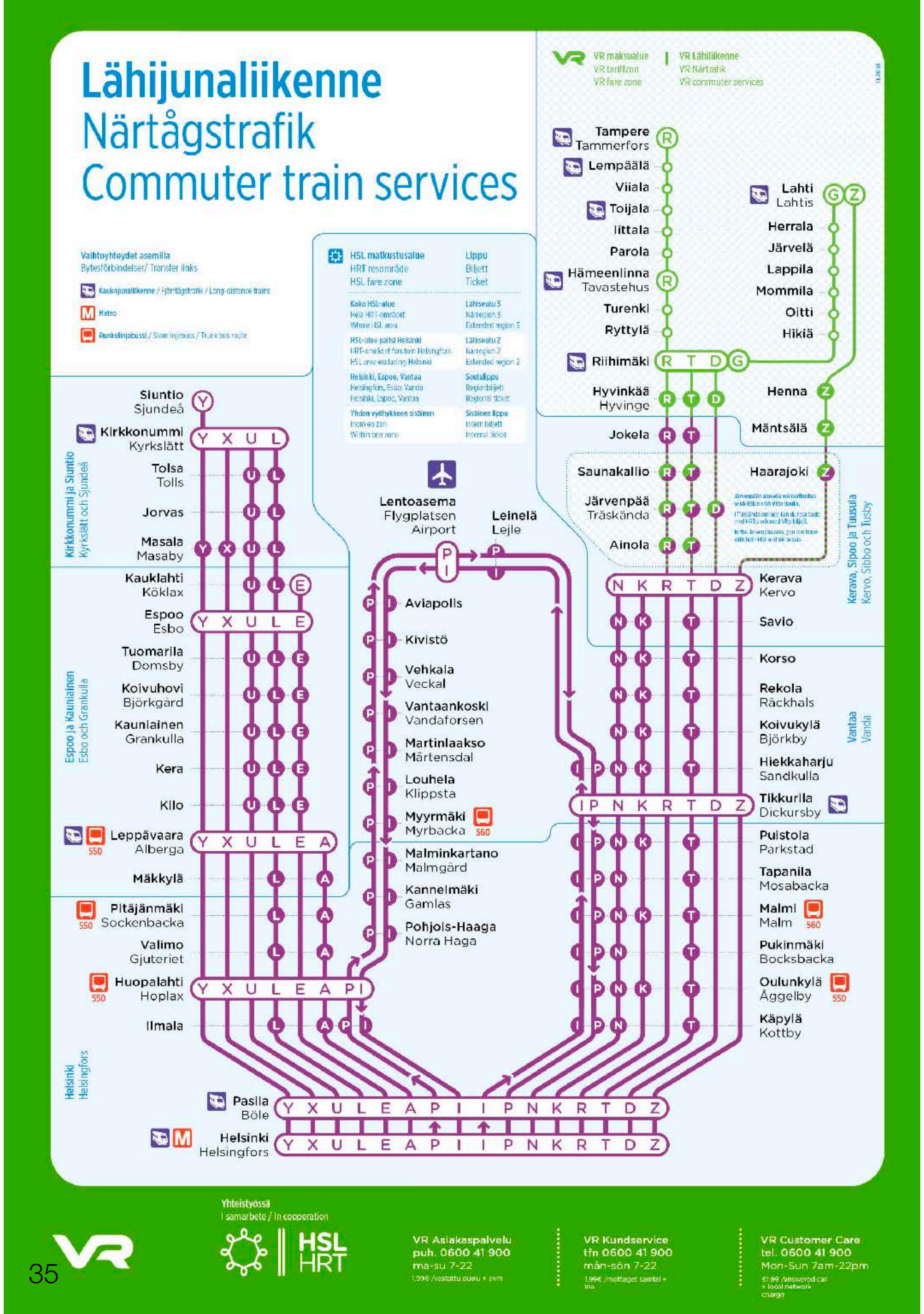
- Semiotics is the study of **symbols** and how they convey **meaning**
- A visualisation is made of "symbols", each conveying some information
- Picture is intended to represent something, not to be mistaken for it:

  You understood the above if you pass *the mirror test:* do you recognise yourself in the mirror? (Chimpanzees, orangutans, and humans pass the test, most animals don't.)
- F. **de Saussure** (1857-1913) argues...
  - a symbol can be assigned any arbitrary meaning
  - thus:
    - a symbol could have different meaning in different cultures and contexts
    - the meaning in one culture maybe non-sense in another

Train station

Route

(color indicates geographic location)



- Trash can as a symbol of deletion
- Meaningful to those who know how trash can is used and how it looks like (learned, culture-dependent!)

- Different visual representations could be used to show the same data
- But: those that consider the human perception are likely to be easy to read

Two ways to show relationships between entities. The connecting lines on the left are more effective than the symbols on the right, as elements that are visually connected are perceived as more related than elements with no connection.

Sensory vs. arbitrary symbols

- **sensory symbols**
  - understandable without learning
  - processing is hard-wired and fast
  - resistant to instructional bias
  - cross-cultural
- **arbitrary symbols**
  - hard to learn and easy to forget (except when overlearned)
  - formally powerful
  - capable of rapid change
  - culture-specific

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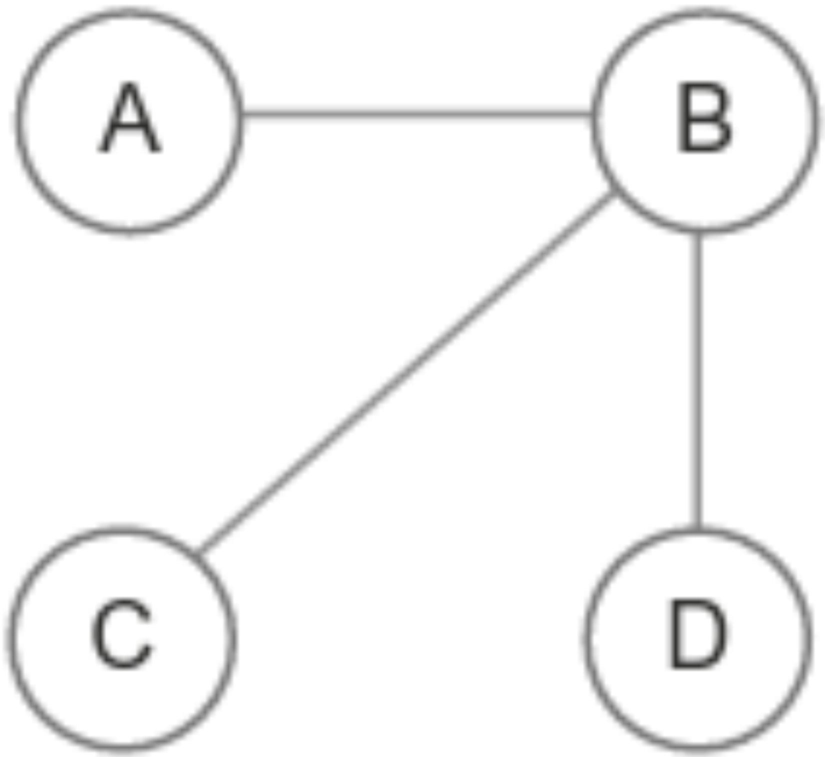

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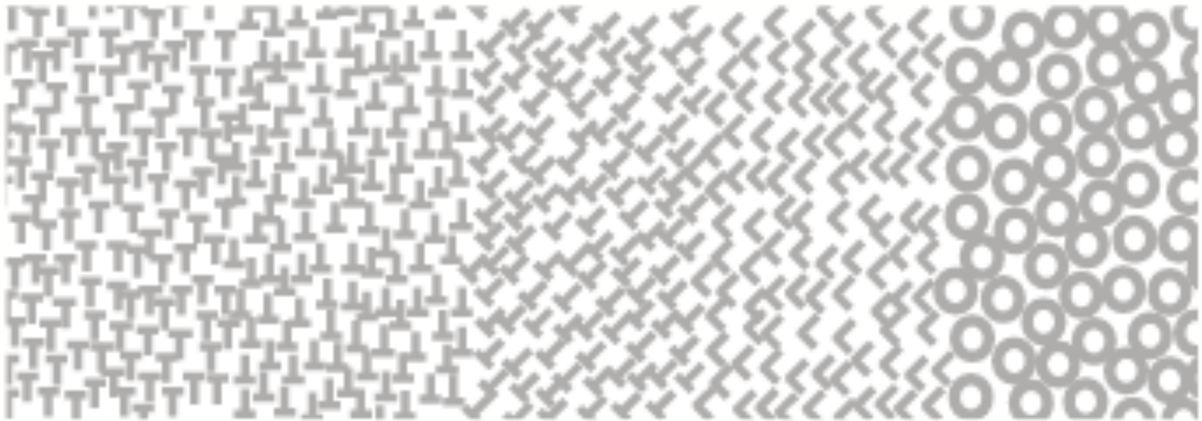

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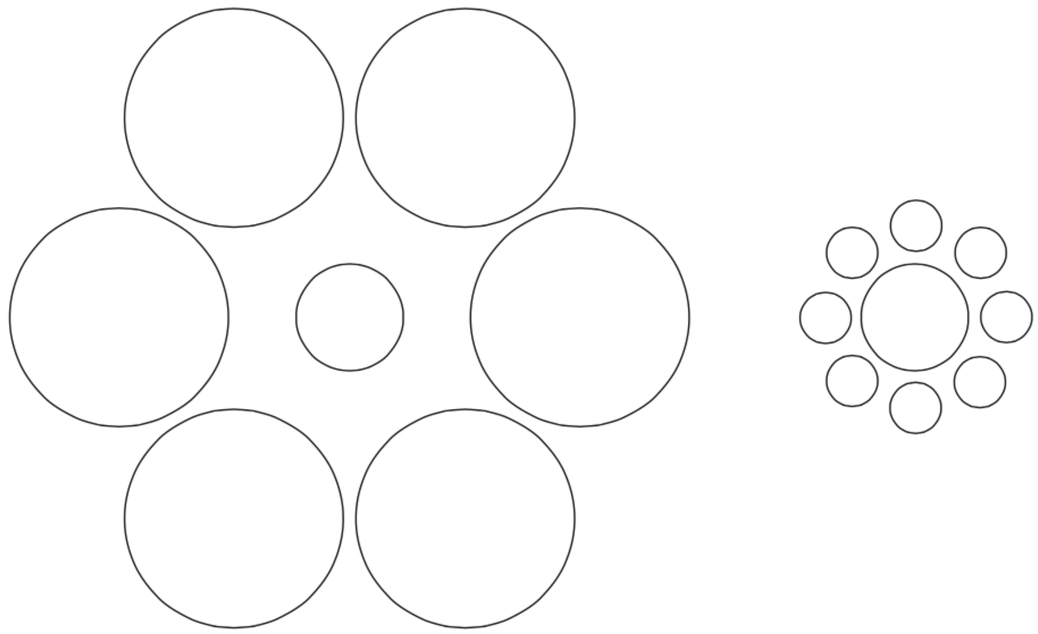

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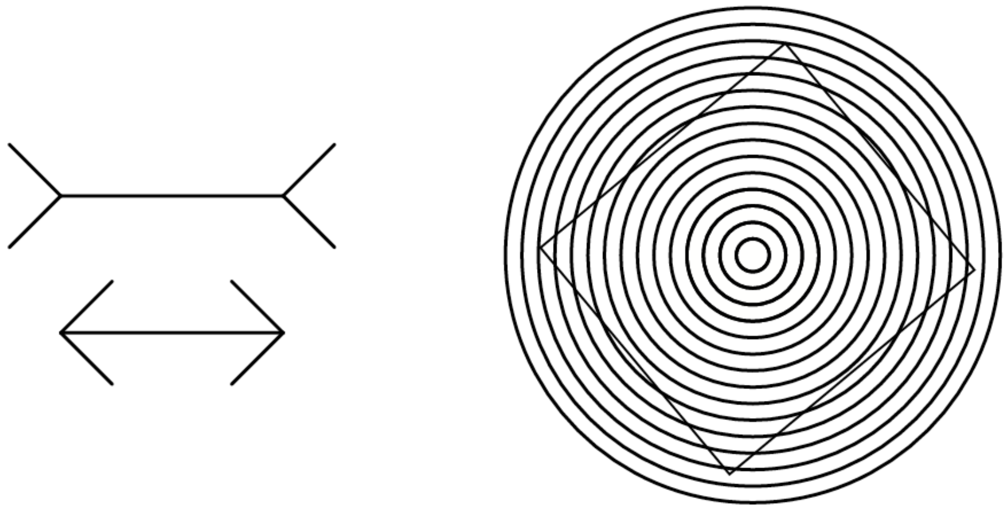

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learn to read and write
1234567890

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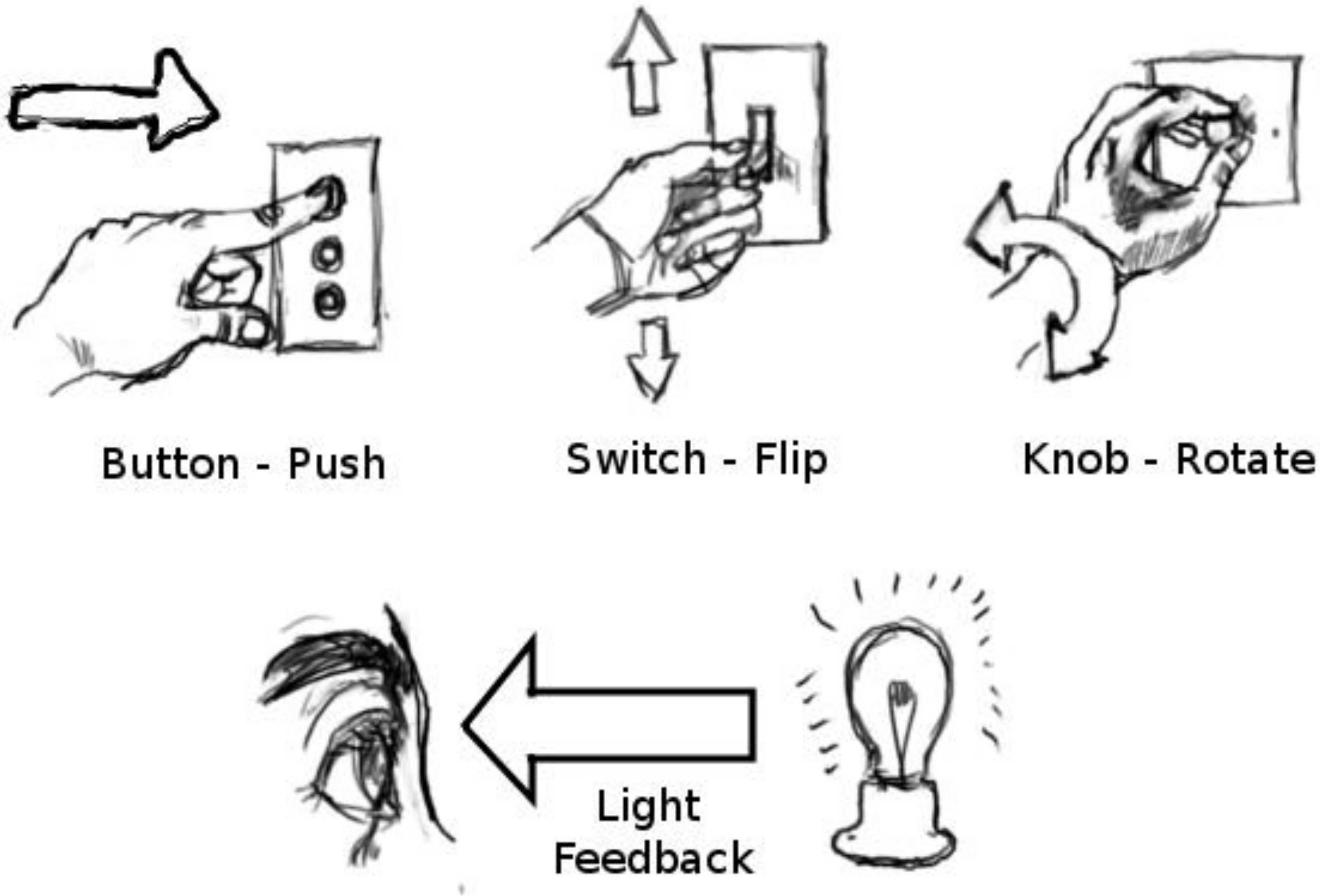
Finland: 1 234 567,89

UK: 1,234,567.89

Gibson's affordance theory

- We **perceive to operate** in the environment
- We do not perceive points of light but
  - we perceive **possibilities for action** in the environment, known as affordances
  - e.g., an open terrain affords walking; a stone on the ground affords tripping while walking
- We perceive affordances **directly** by the visual system as a whole and
  - not indirectly by the different components and operations in the visual system, as the visual system resonates to respond to properties of the environment
- Influential theory, but it is not to be taken too literally, unless we ignore years of vision research (e.g., what we know about colours)

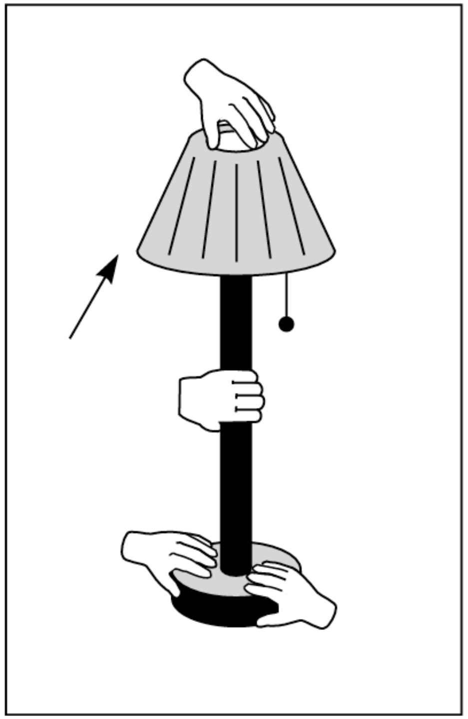
Gibson's affordance theory

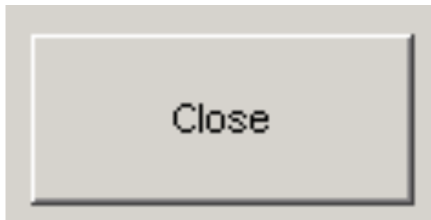


Gibson's affordance theory

Affordances in visualisation

- Gibson’s theory suggests to build interfaces that ‘beg’ to be operated
  - so affordances are perceptually evident to the user, making the user’s task easier
- But
  - GUIs have no clear physical affordances
    - e.g., does a screen virtual button “afford” pressing, as an open terrain affords walking?
    - Is it obvious in the real-world and to all cultures that a button “affords” pressing?
- Indirect link between perception and action when using a computer
  - e.g., we must learn that a picture of a button can be pressed with a mouse.
- Visualisation of data through computer graphics is indirect
  - due to various layers of processing between the data and the visual representation





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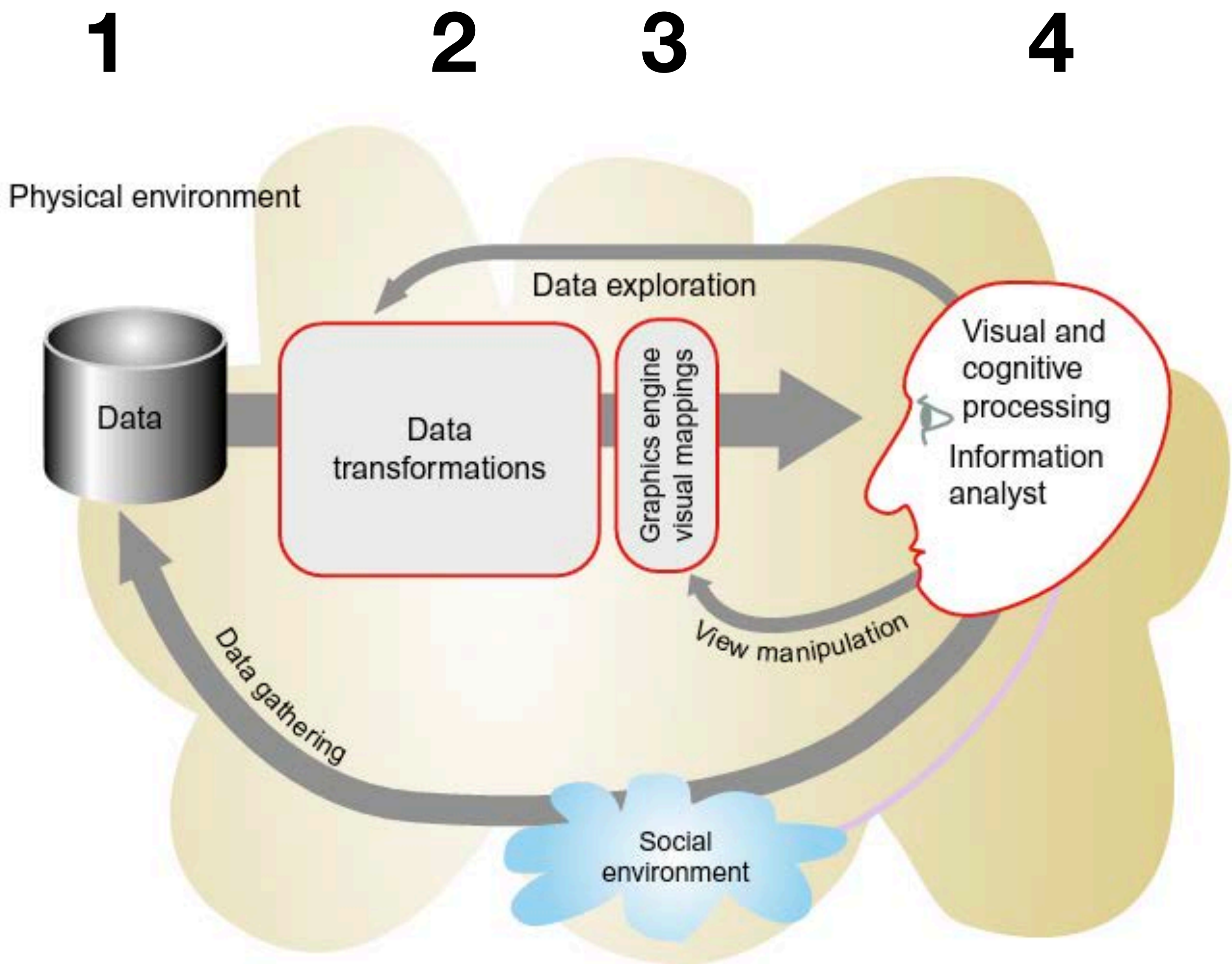
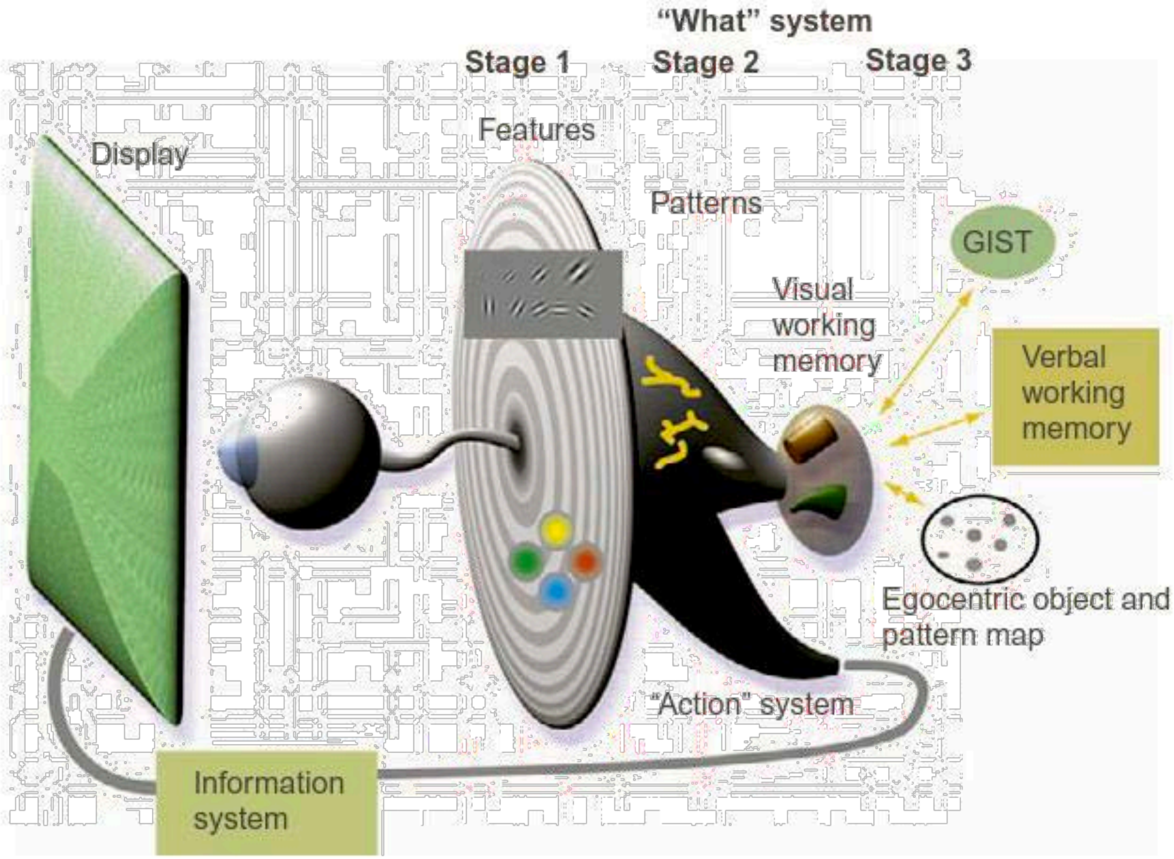
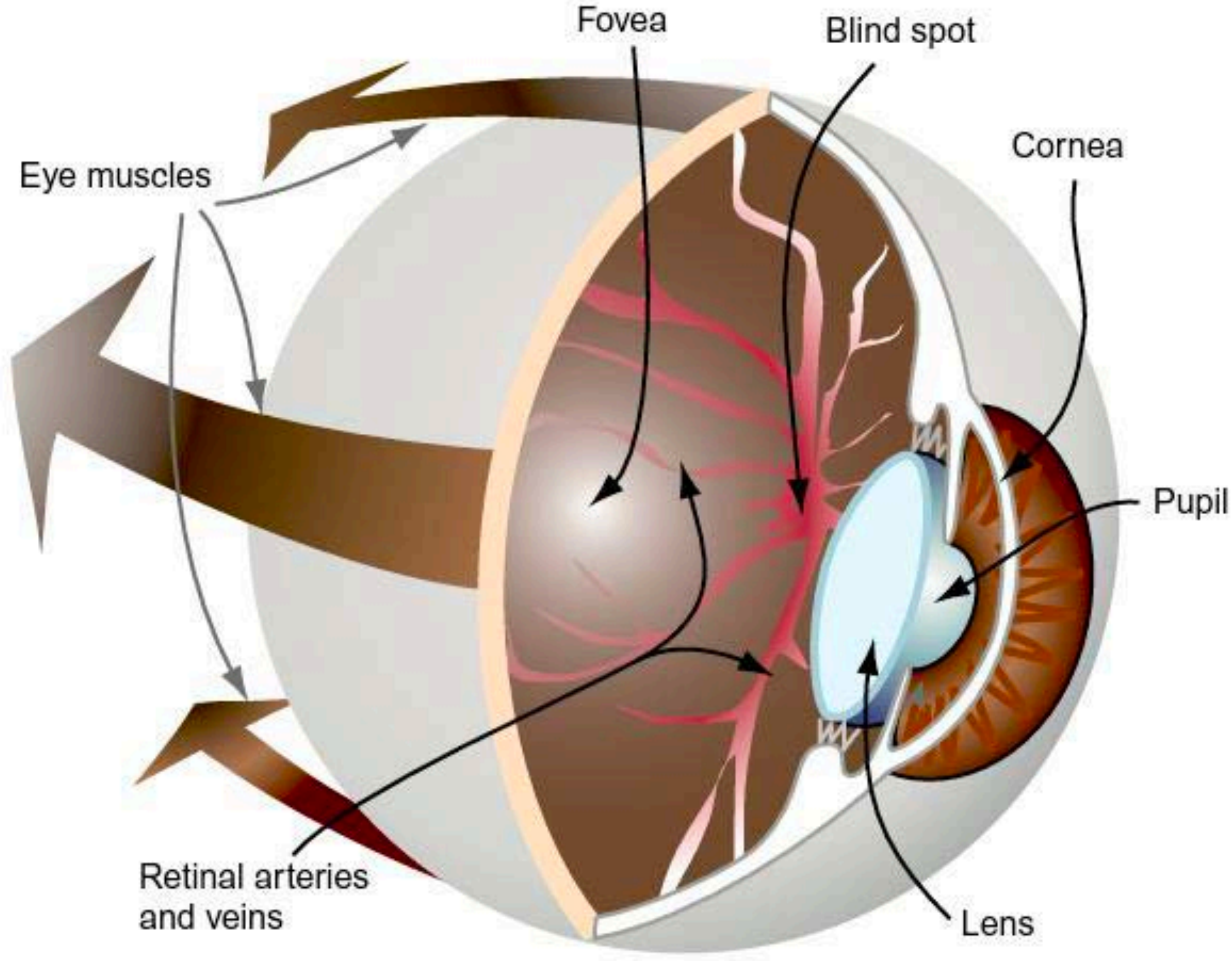


A model for perceptual processing

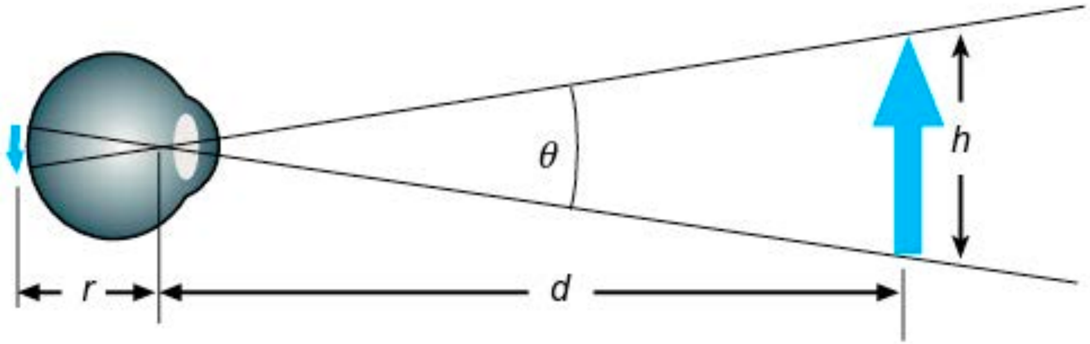
1. Parallel processing to extract low-level properties of the visual scene
    - rapid parallel processing
    - extraction of features, orientation, colour, texture and movement patterns
    - iconic store
    - bottom-up, data driven processing
2. Pattern perception
    - slow serial processing
  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



The human eye



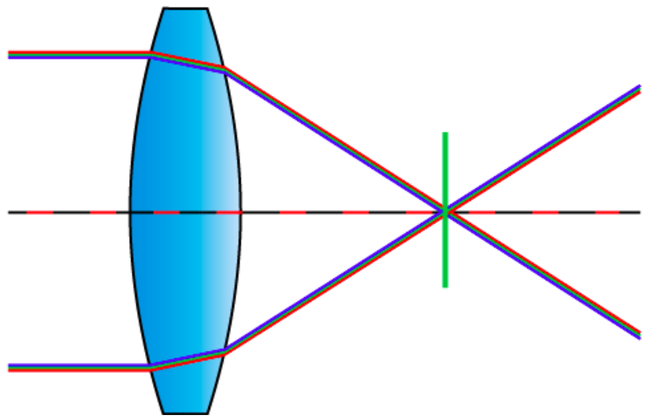
Optics

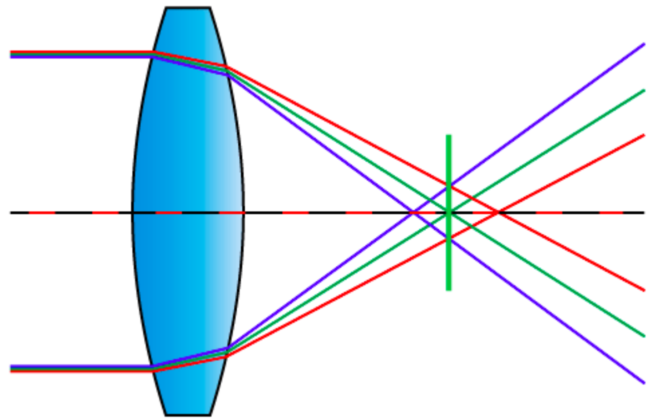


$$\frac{1}{f} = \frac{1}{d} + \frac{1}{r}$$

- **visual angle** = angle subtended by object at the eye, measured from the eye's optical centre
- **power of lens** (when f is measured in metres) = 1/f in units of diopters
- **human lens system**: r = 0.017 m, so power of lens = 59 diopters (when d = ∞)
- **depth of focus** = range over which objects are in focus when the eye is adjusted for a distance; varies by pupil size
  - e.g., 3 mm pupil, eye adjusted to ∞, objects between 3 m and ∞ are in focus
- Young children have a flexible lens that can adjust over a range of 12 diopters or more (can focus on objects as close as 8 cm)
- Flexibility drops by age at a rate of about 1 diopter per 5 years
  - at the age of 40-50 reading glasses are needed, by 60 years the lens is almost completely rigid

Optics





- An optical problem occurring when a lens focuses different colour wavelengths to different positions
- Human eye is not corrected against **chromatic aberration**
  - a lens of 1.5 diopters is needed to correct the difference of focus between blue and red
- Short-wavelength blue light is refracted more than long-wavelength red light

Optics

Do not use pure blue text on a black background as the text would be almost unreadable...

...especially if there is white or red nearby to attract the focusing mechanism.

- Do not use pure blue text on a black background, as the text would be almost unreadable
  - especially if there is white or red text nearby to attract the focusing mechanism
- Add red and green to pure blue to alleviate the problem
  - red and green add luminance and so help to perceptually define the colour boundary

Optics

(a) 60% see red closer than blue

(b) 30% see blue closer than red

(c) 10% see the colors in the same plane

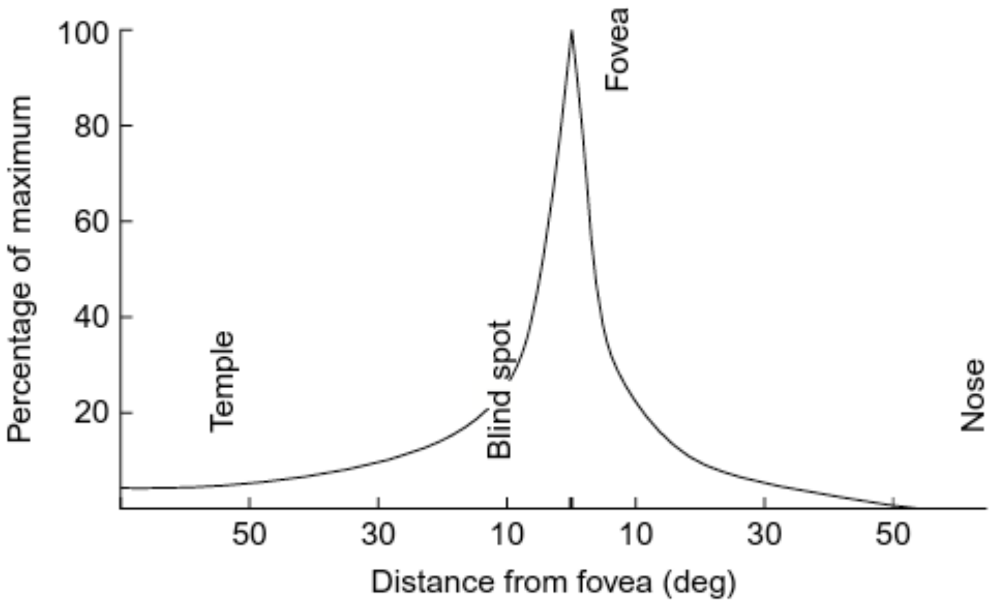
Deep blue background makes white and

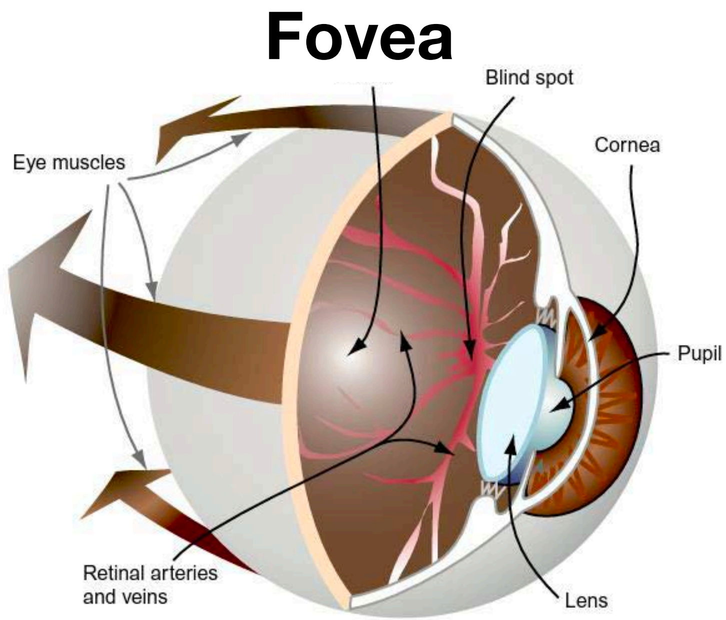
red letters appear to stand out for most people

Visual acuities

- The unit of acuity is minutes or seconds of arc
- full circle = 360 degrees = 360°
- 1° = 60 minutes of arc = 60'
- 1' = 60 seconds of arc = 60"
- For a viewing distance of 57 cm:
  - 1° = 60' = 3600" = 1 cm
  - 1' = 60" = 0.17 mm
  - 1" = 0.00028 mm

Visual acuities





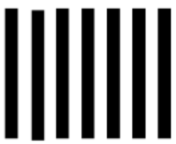
- Visual acuities are measurements of our ability to see detail
  - indicating limits on the information densities we can perceive
- Acuity is at maximum at the centre of the fovea
- Acuity outside of the fovea drops rapidly
  - we can only resolve about 1/10 of the details at 10° from the fovea

Visual acuities

Simple acuities are restricted by (and correspond to) the spacing of the receptor cells at the centre of the fovea (angular size of cone cell ≈ ca. 20")

point acuity (1')

the ability to resolve two distinct point targets



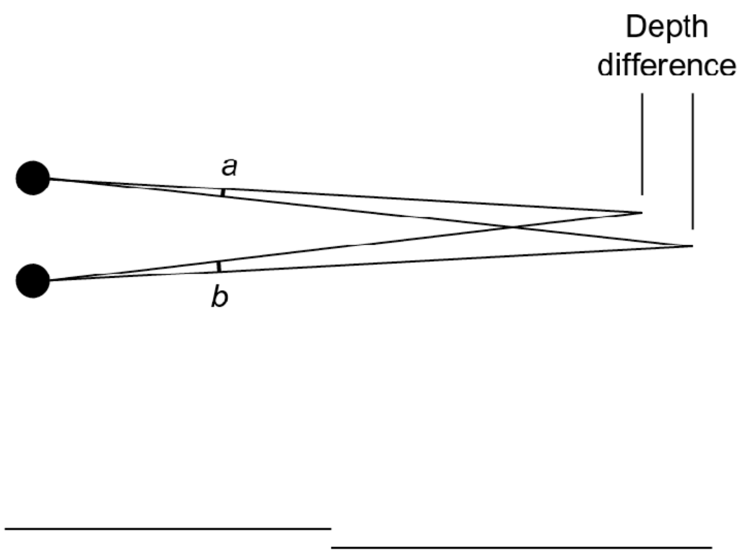
grating acuity(1-2')

the ability to distinguish a pattern of bright and dark bars from a uniform gray patch

letter acuity (5')

the ability to resolve letters

Visual acuities



- **Superacuity** is the ability to achieve better resolution by integrating information over space (or time)

  stereo acuity (10")

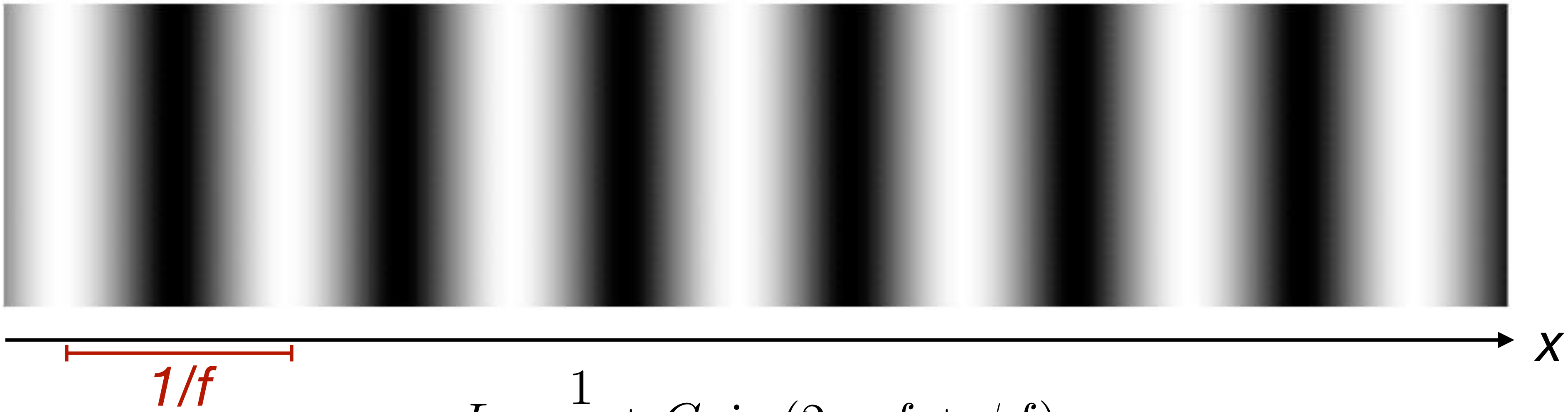
  the ability to resolve depth

  Vernier acuity (10")

  the ability to see if 2 line segments are collinear

  We can perform vernier acuity tasks with great accuracy at 10", that is to about 1/10 of a pixel

Contrast sensitivity

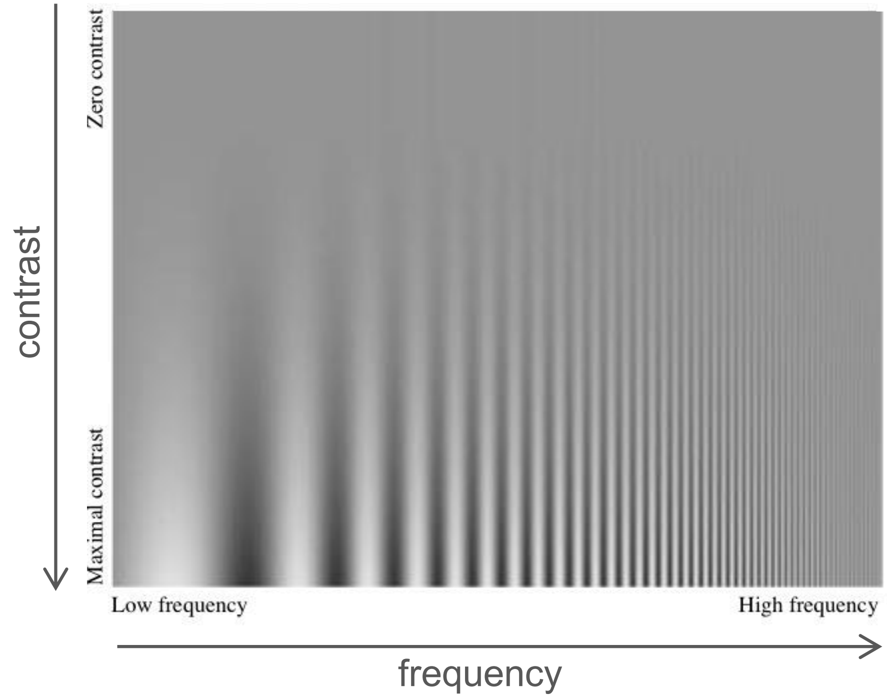


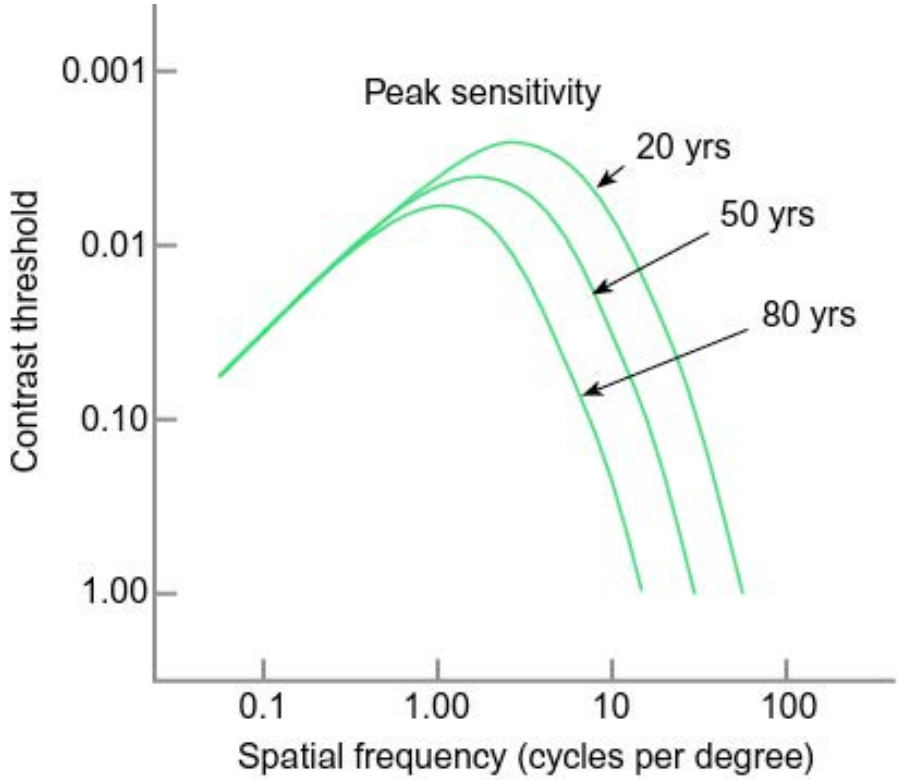
$$L = \frac{1}{2} + C \sin\left(2\pi x f + \phi f\right)$$

- *L* = luminance on the screen on a scale from 0 to 1, *C* = contrast on a scale from 0 to 1, *x* = position on the screen, *f* = frequency
- The luminance in this pattern (called sine wave grating) varies sinusoidally in one direction
- The amplitude of the sine wave varies the contrast, while the frequency changes the number of bars of the grating per degree of visual angle
- So this sine wave grating can be used to measure human sensitivity to contrast and see how sensitivity changes with frequency

Contrast sensitivity

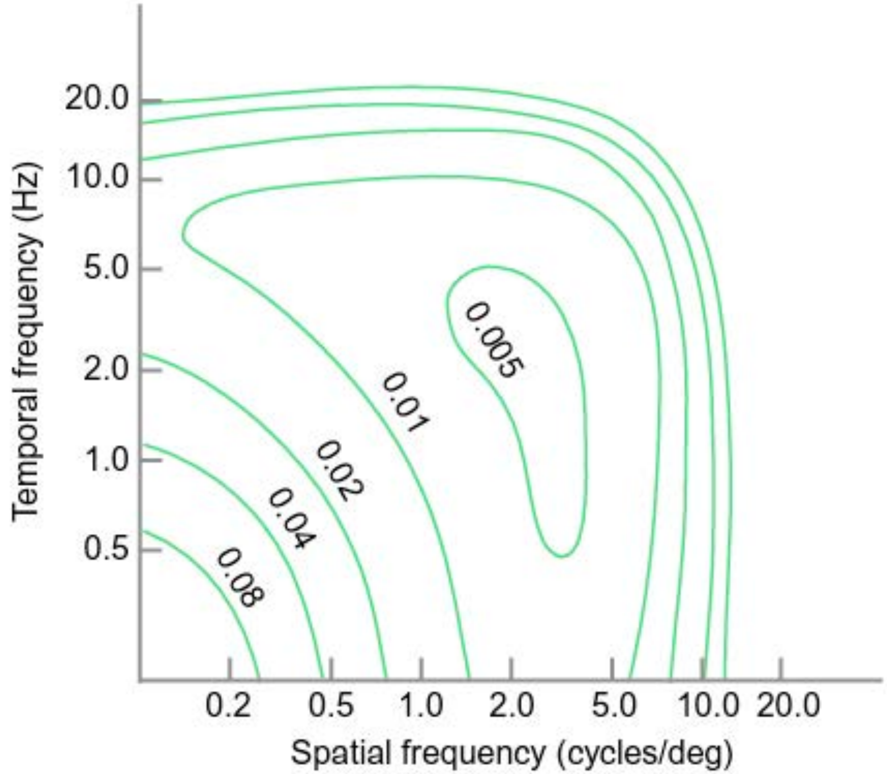
- Contrast sensitivity is lowest at high frequencies (zero sensitivity at 1' for young people)
- Lower contrasts can be seen at frequencies of around 1°
- Highest contrast sensitivity at about 20-30'
- Contrast sensitivity falls by age (become less sensitive to patterns below 1°)





Contrast sensitivity

- Patterns can vary in space (spatial frequency) and time (temporal frequency, below)
- Measure temporal sensitivity by causing a sine wave grating to oscillate in contrast from high to low and back over time, allowing both spatial and temporal sensitivity to be mapped
- Optimal contrast sensitivity achieved at 2-10 Hz flicker rates
- Patterns are best observed with 7-8 Hz flicker rates
- Humans are sensitive to flicker rates of up to 50 Hz

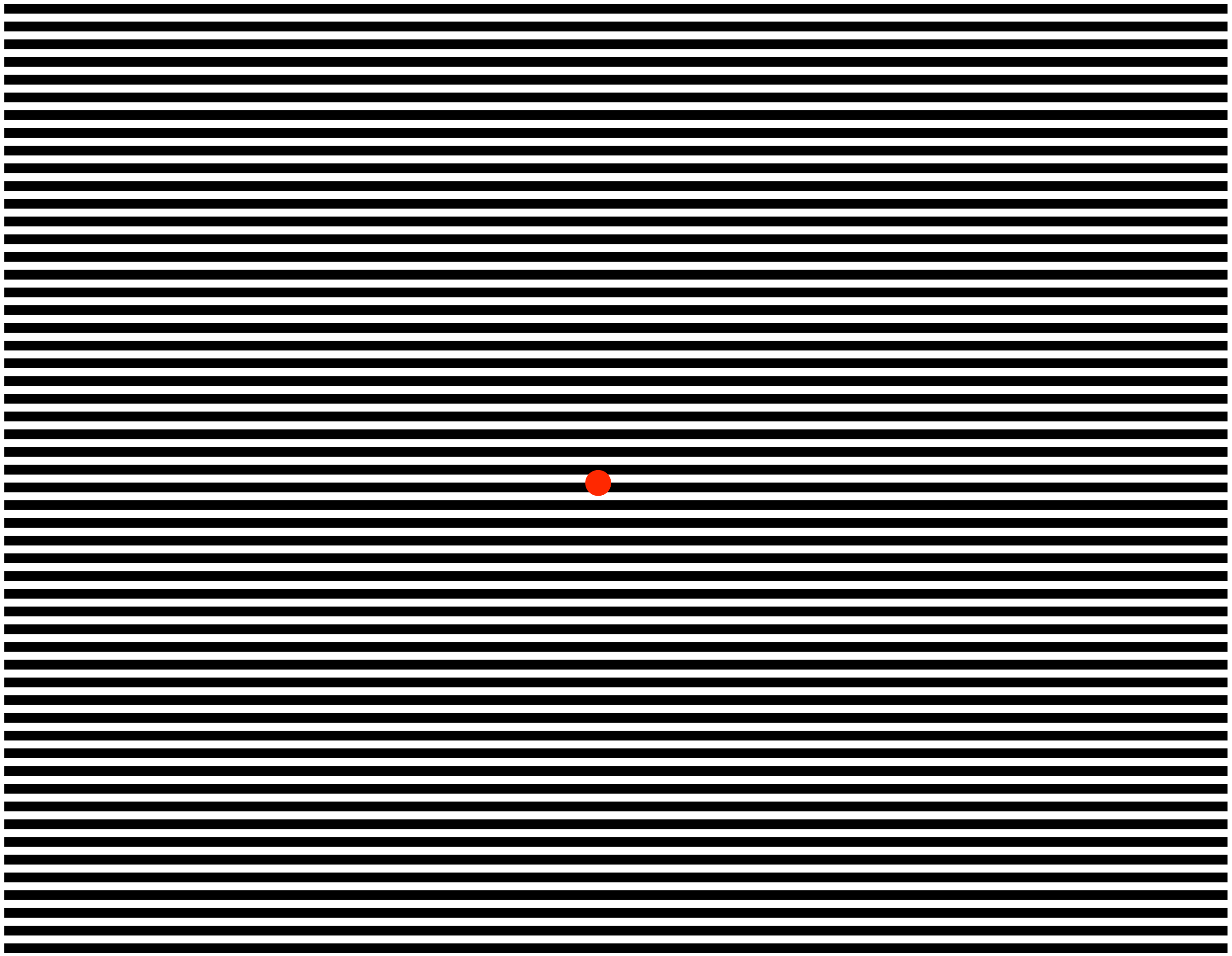


Visual stress

- Striped patterns and flicker cause visual stress
  - most people find them extremely stressful to look at
- Striped patterns and flicker can induce epileptic seizures in susceptible individuals (*pattern-induced epilepsy)*
- Most potent combination of spatial and temporal frequencies are striped patterns having:
  - spatial frequency of 20'
  - temporal frequency of 20 Hz
  - large overall pattern
- Example on next slide: stop looking at it if you feel ill!

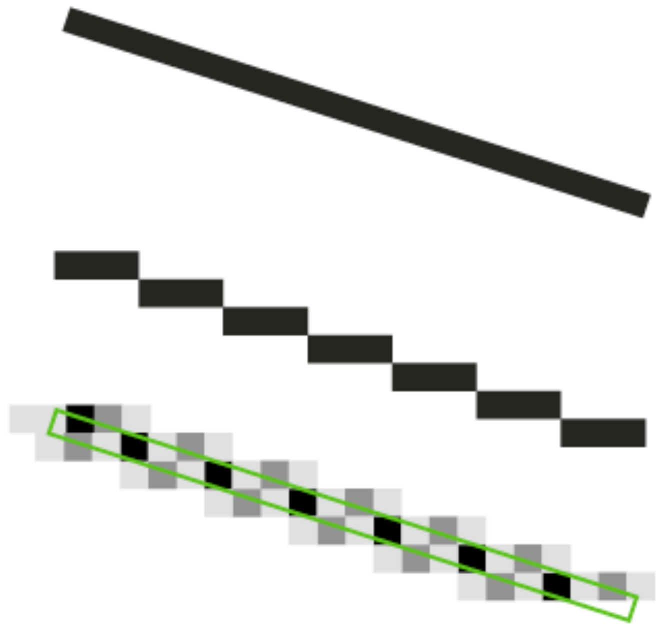
Visual stress

If this patterns causes you feel ill avoid looking at it.



Computer displays

- A 16,000 million pixel (≥ 4K) resolution monitor should be adequate for any perceivable visual task, excluding super-acuities
- But no standard computer display has such a resolution
- Super-acuities can be achieved with antialiasing
  - a few of the pixels causing the stairway pattern are coloured with intermediate shades of the required colour for a smoother transition into the background

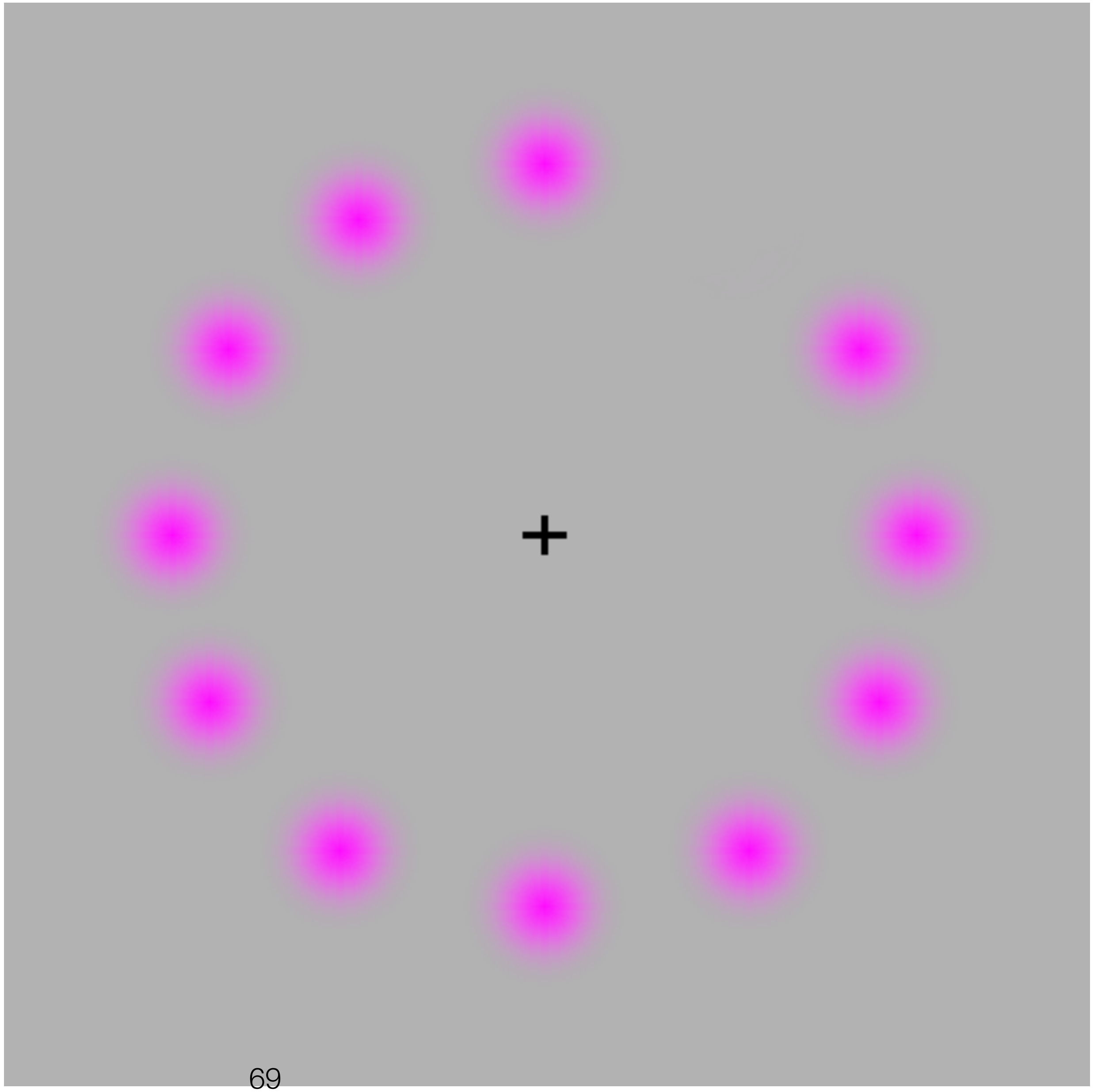


Eye is **a lot** like a camera

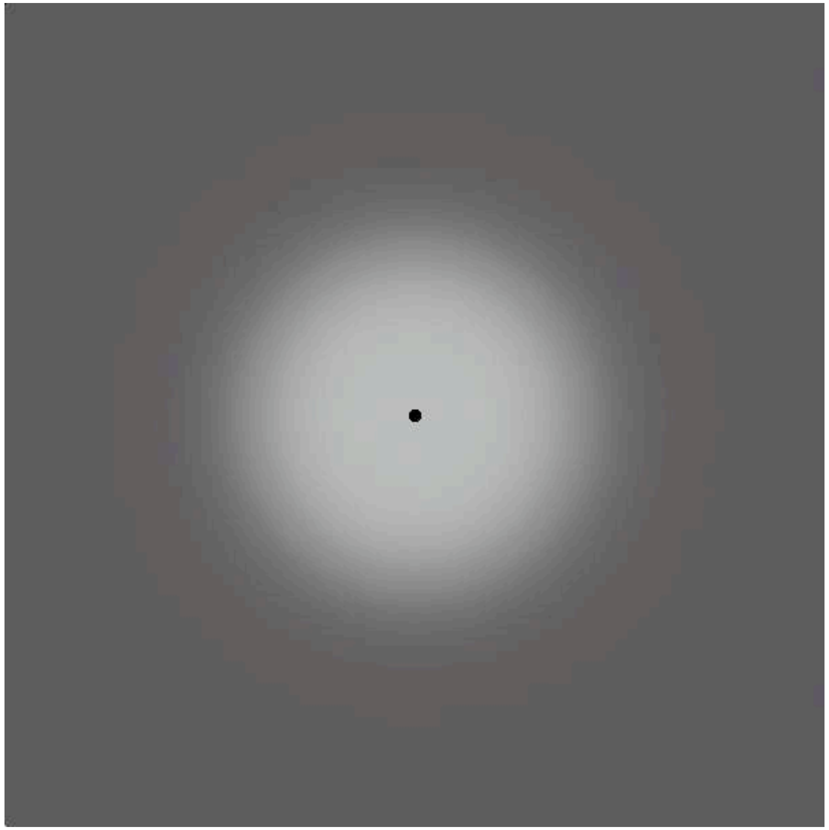
- Eye has a lens (obeys laws of physics, no flexibility left at age of c. 60) and retina is like a film
- Acuity and contrast sensitivity:
    - simple acuity (maximal at fovea, c. 1')
    - super-acuities (achieved by integrating the output of several retinal receptors, 10")
    - contrast sensitivity

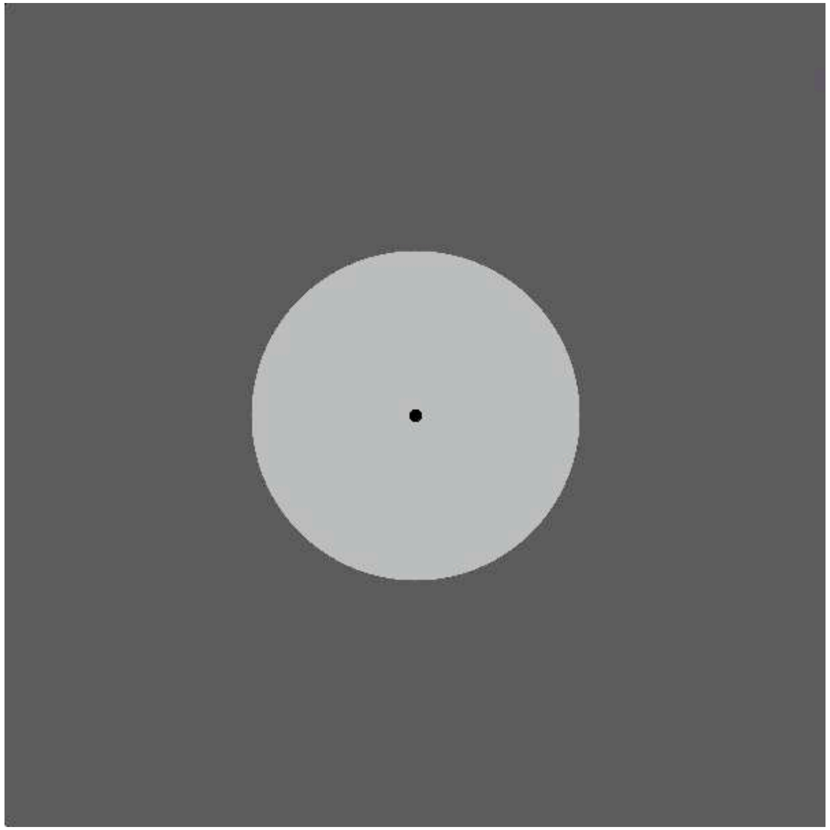
Eye is not like a camera

- 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

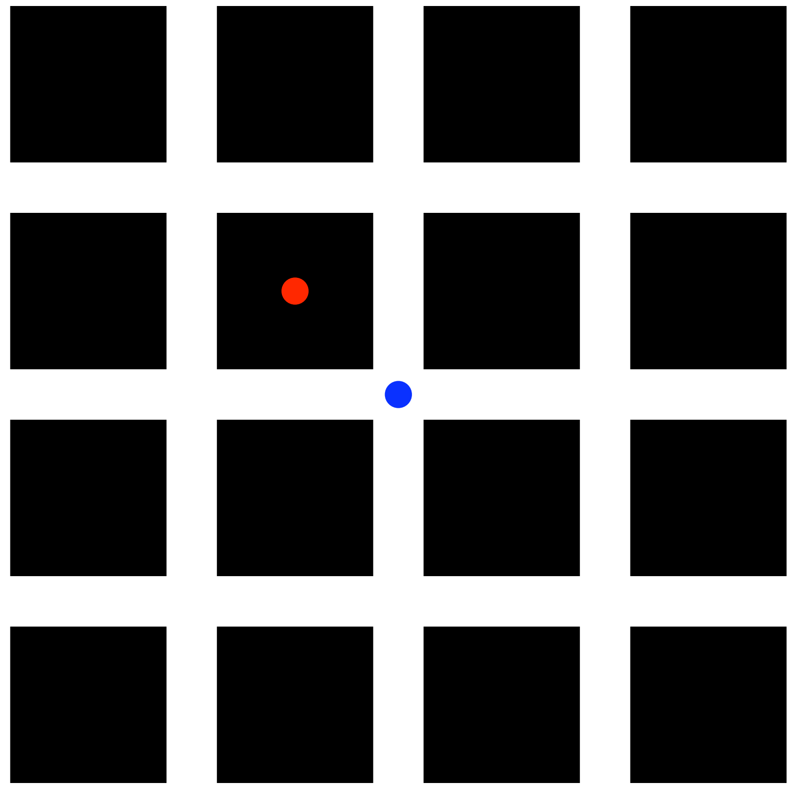




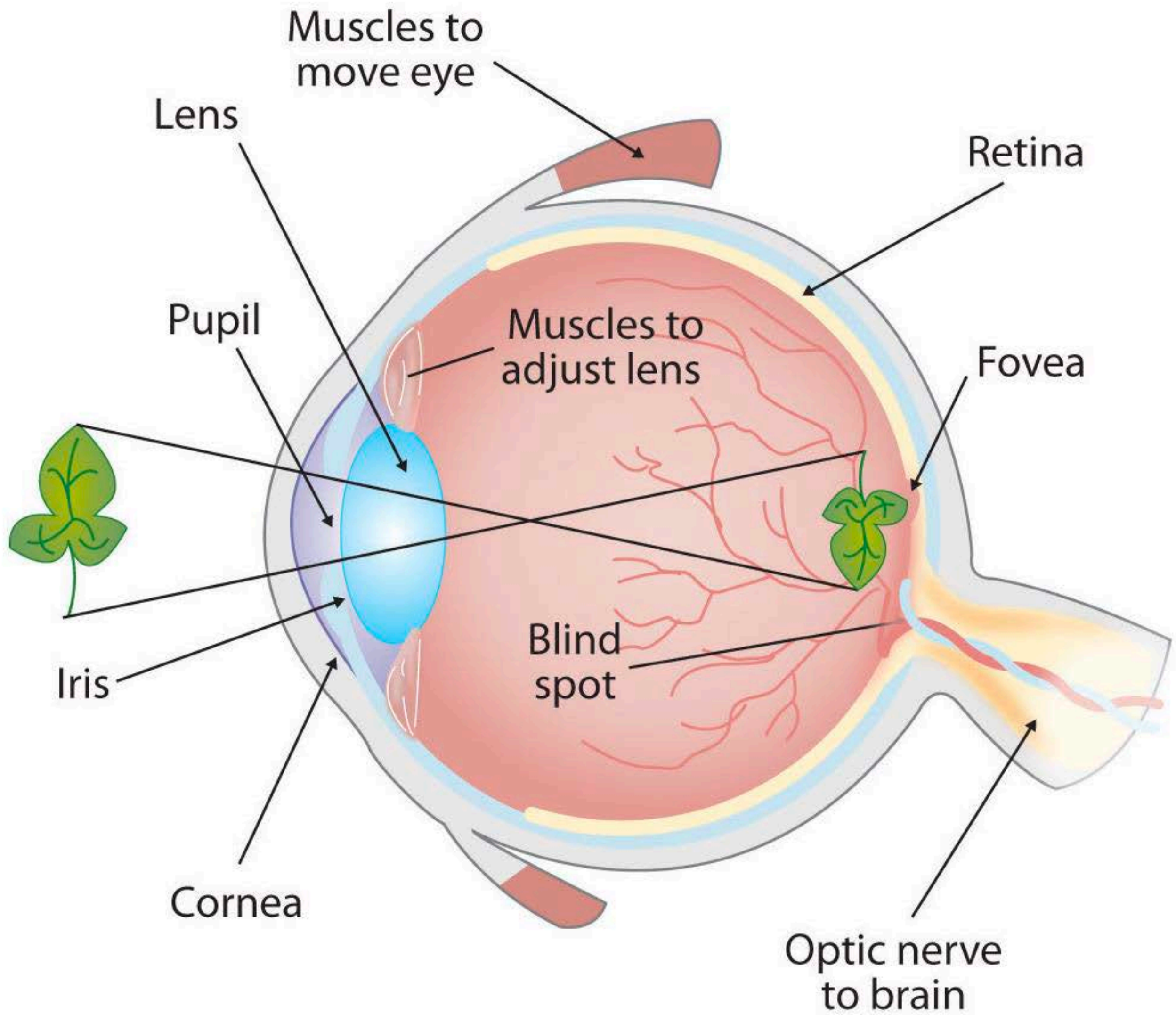
Close one eye. Look at the black dot at the center of the fuzzy disc for at least 30 seconds. Then look at the center of the sharp disc. Is there any difference?

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.



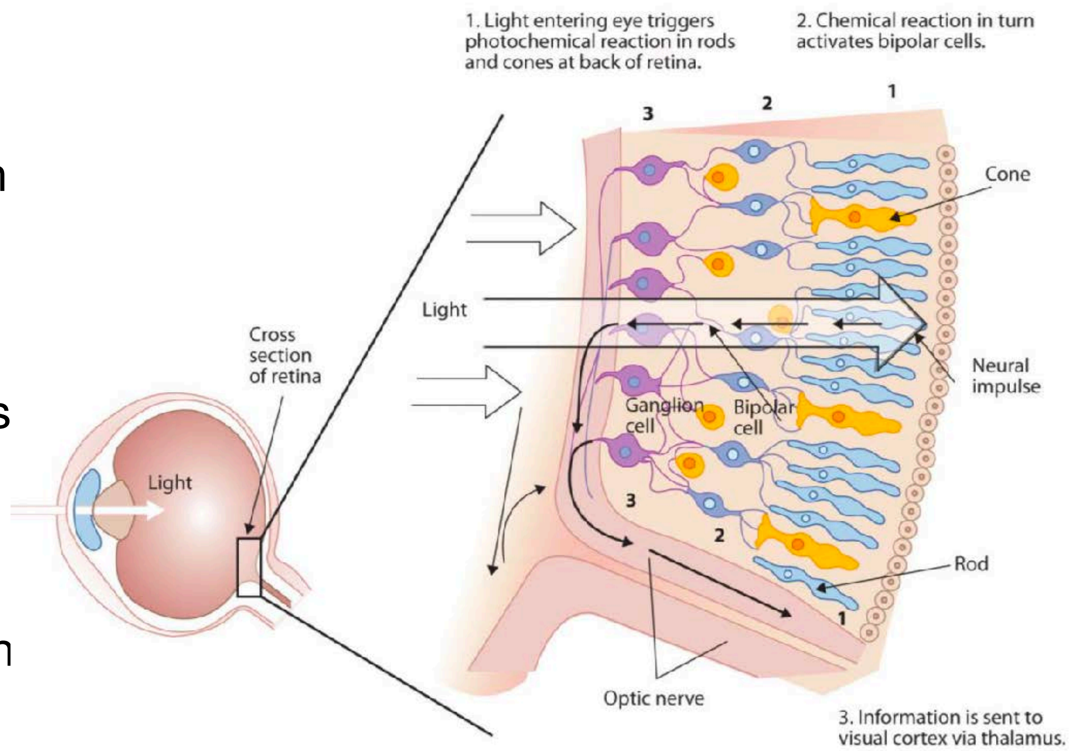
The human eye



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

The human eye

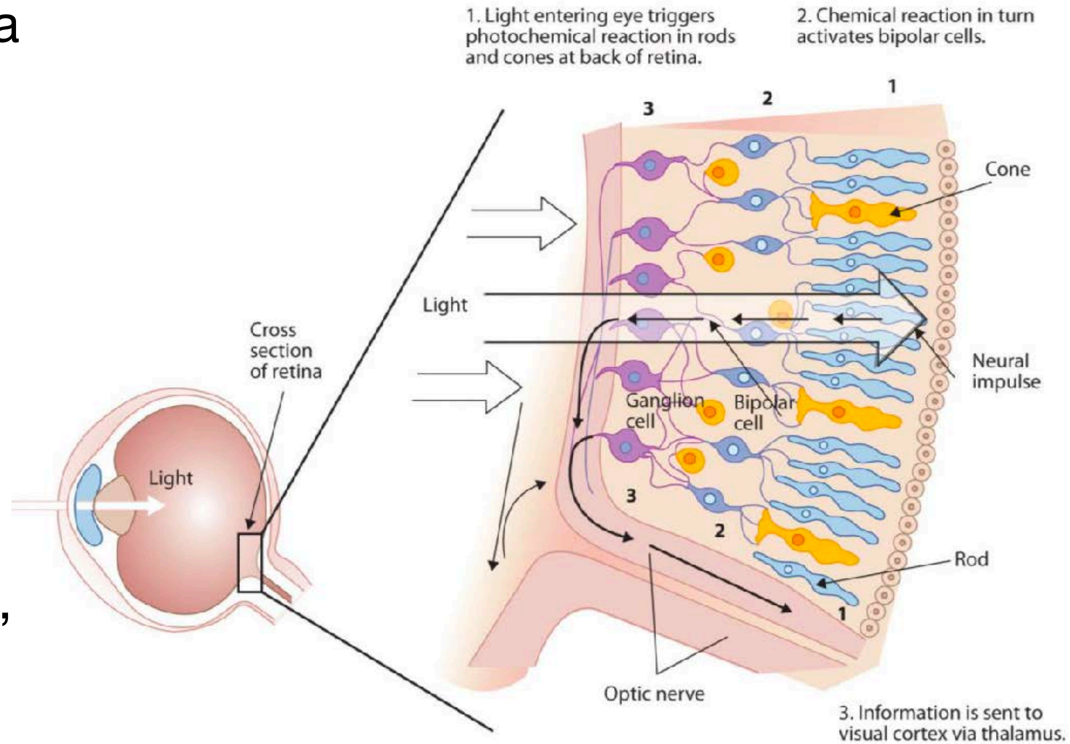
- The retina is made up of layers of neurons that respond to light
- Light falling on retina activates (1) receptor cells (i.e., rods and cones) which in turn activate (2) bipolar cells and then (3) ganglion cells through cascading photochemical reactions that transform the light into neural impulses, 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 (neuron) in a ganglion



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

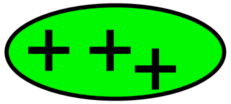
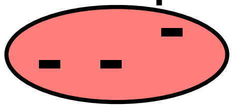
The human eye

- **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
- 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!)

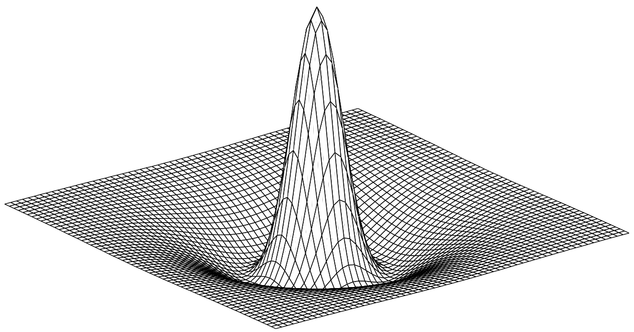


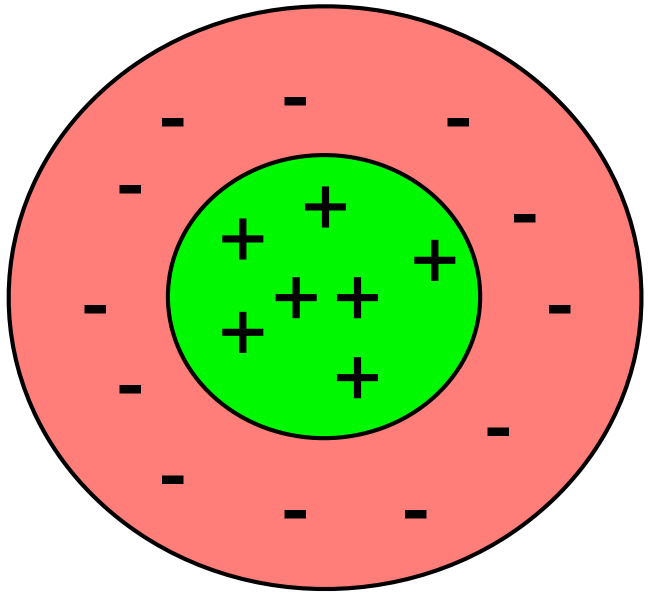
http://2012books.lardbucket.org/books/beginning-psychology/s08-02-seeing.html

Difference of Gaussians

- 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

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



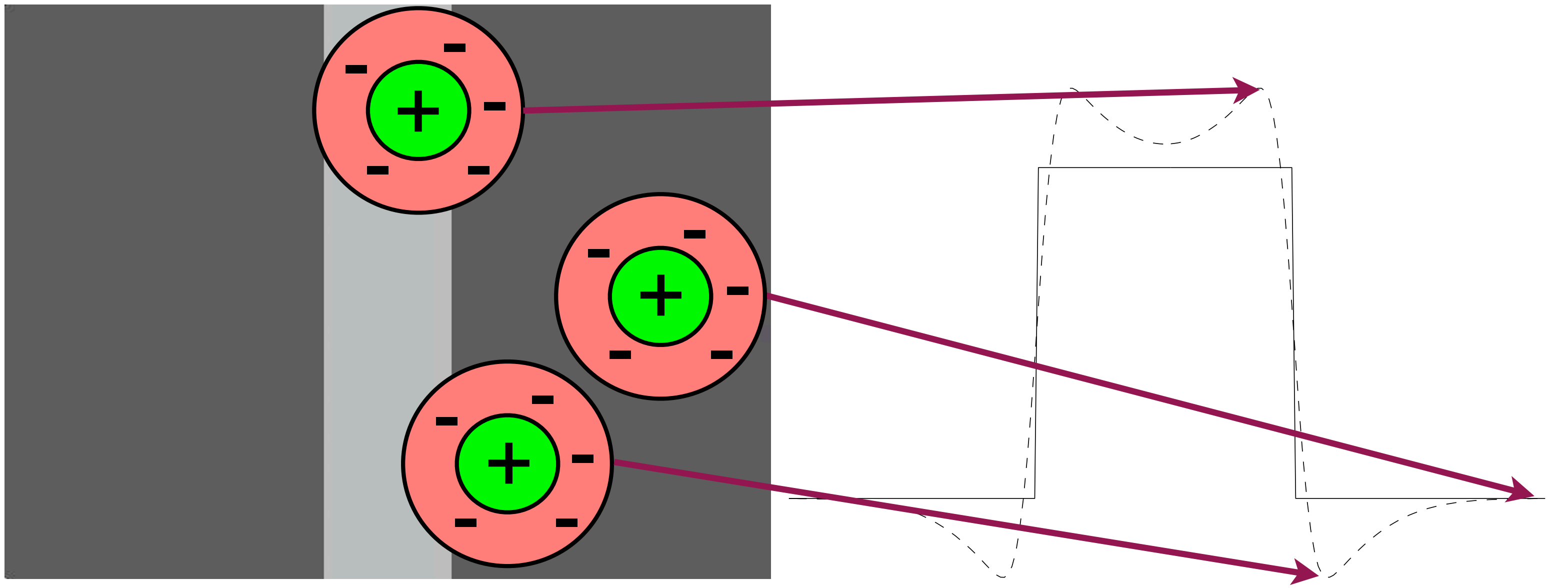


Difference of Gaussians

- 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

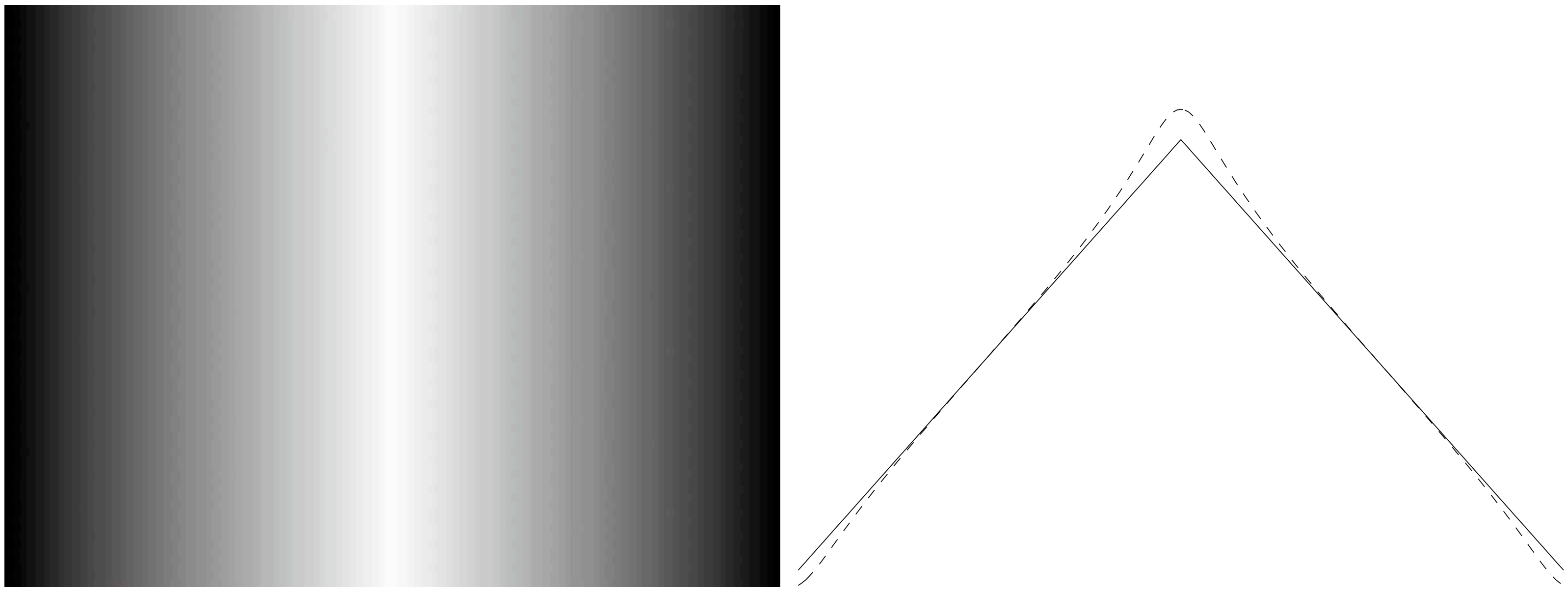
Discontinuous lightness profiles generate dark and light bands near the discontinuities (*Chevreul illusion*)



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

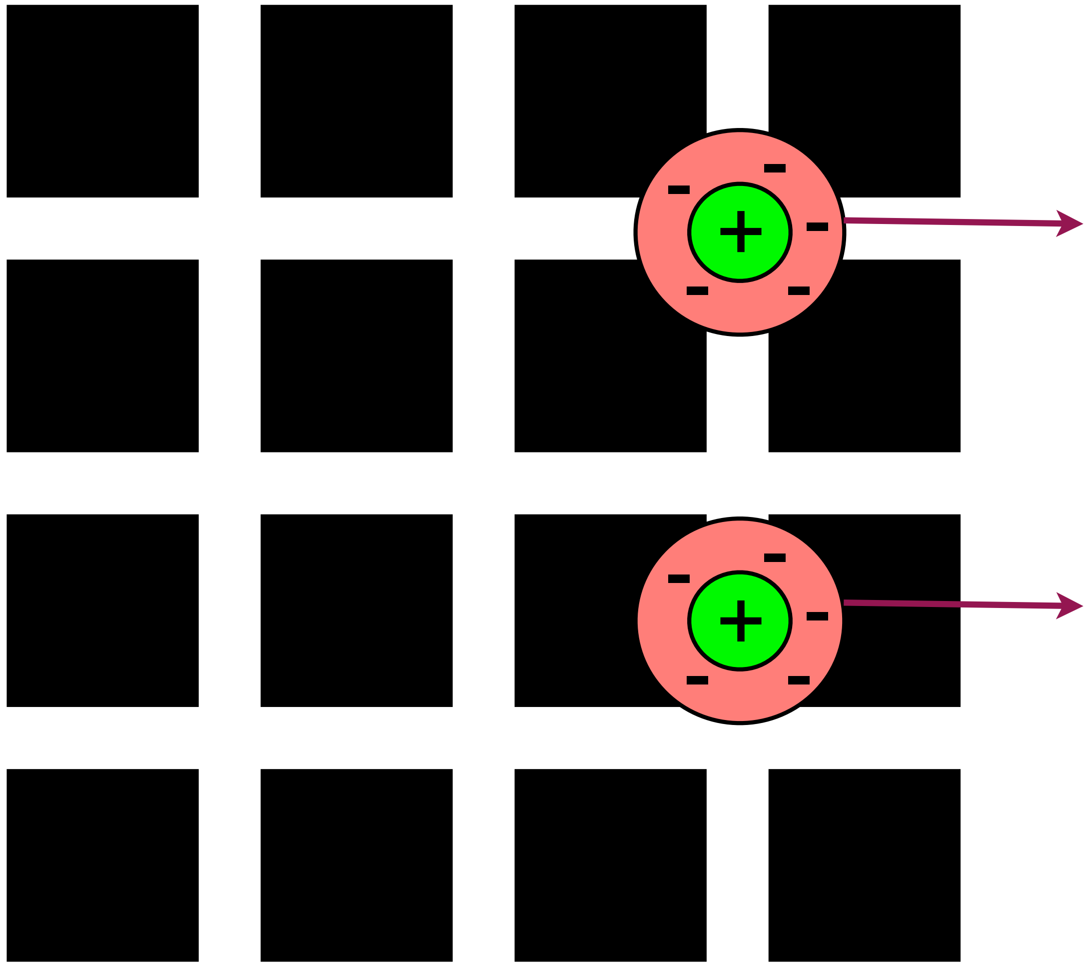
Mach bands

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



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

Hermann grid illusion

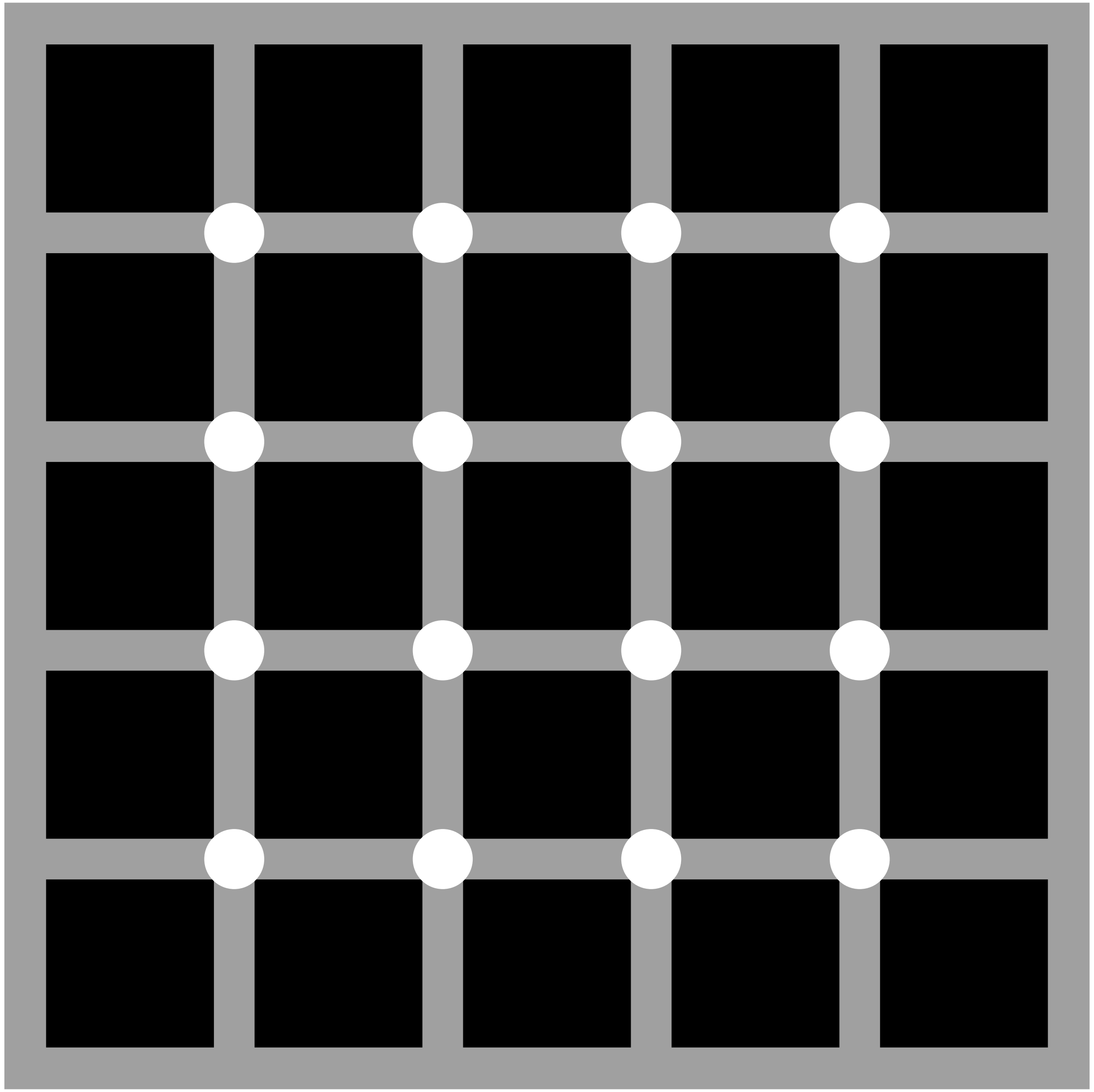


More inhibited rate
➜ darker spot

Less inhibited rate
➜ lighter spot

Hermann Grid illusion

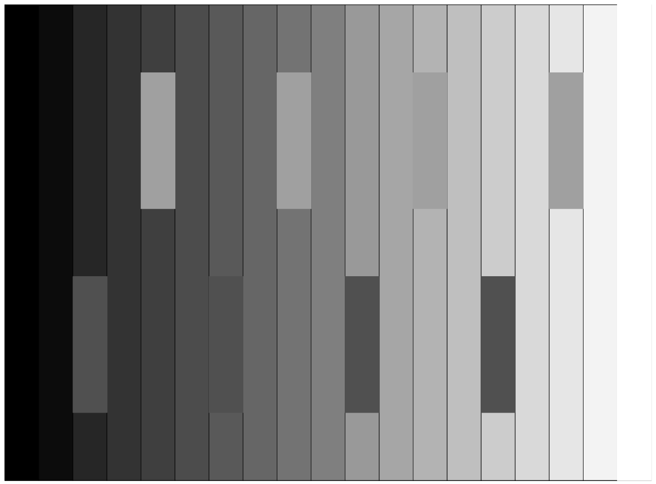
Hermann grid illusion

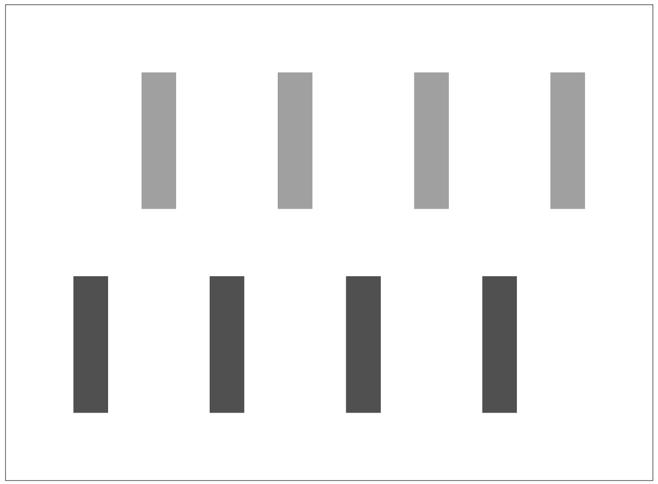


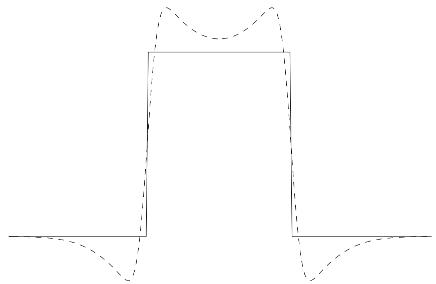
Modified Hermann grid illusion

Simultaneous brightness contrast

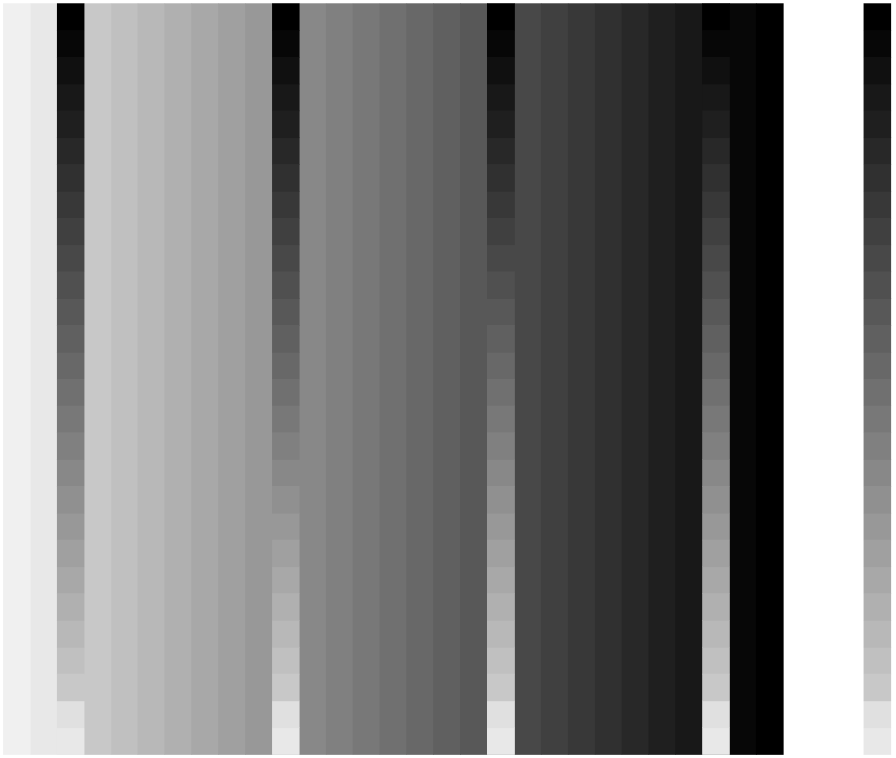
A gray patch placed on a dark background looks brighter than the same patch on a light background.







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

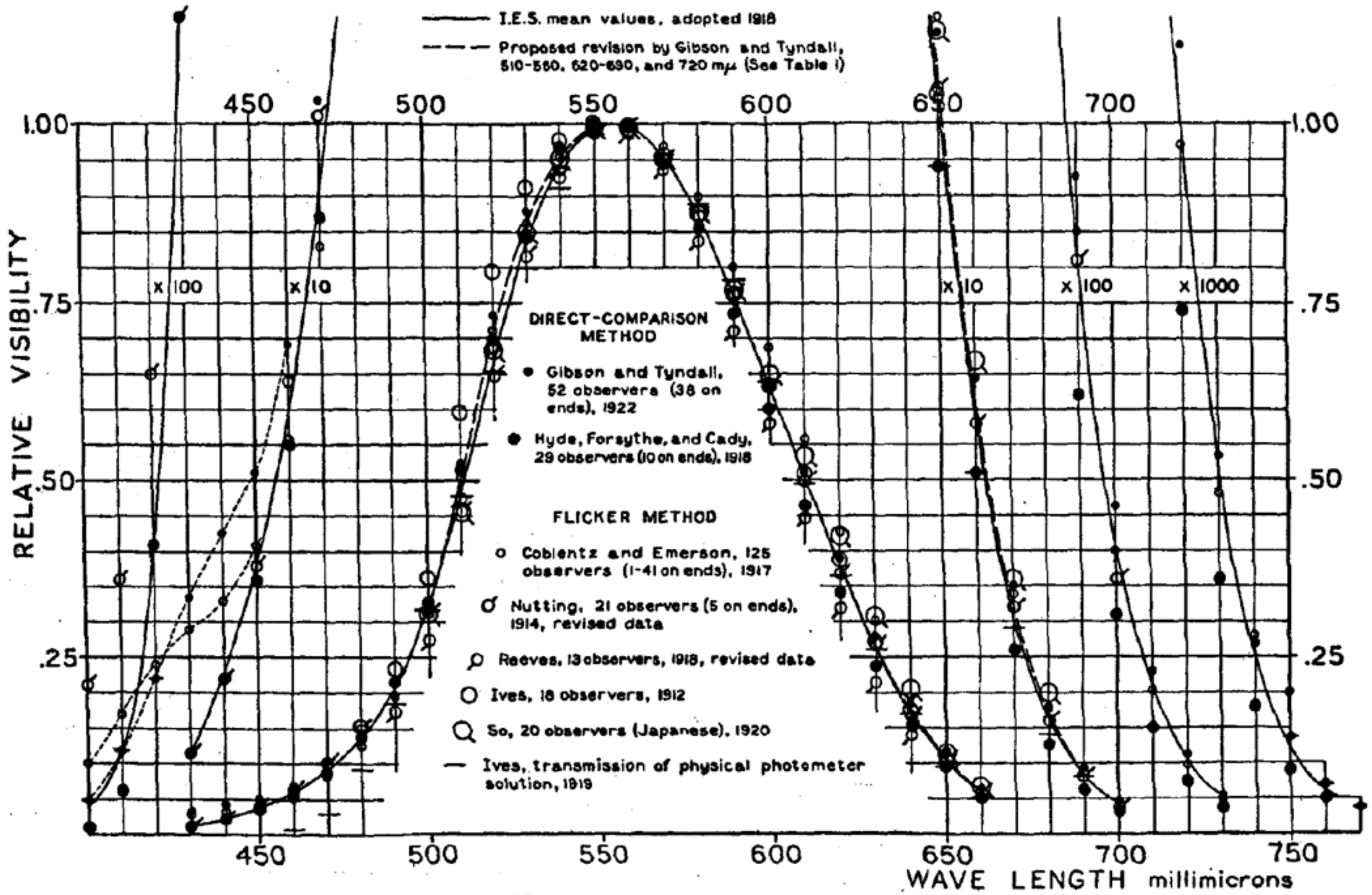


Fig. 1. Values of Relative Visibility.

From CIE 1924 proceedings

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.
- Adaptation & lateral inhibition