CS-E4840
Information visualization D

Lecture 7: Human perception, cognitive aspects
Mar 20, 2023

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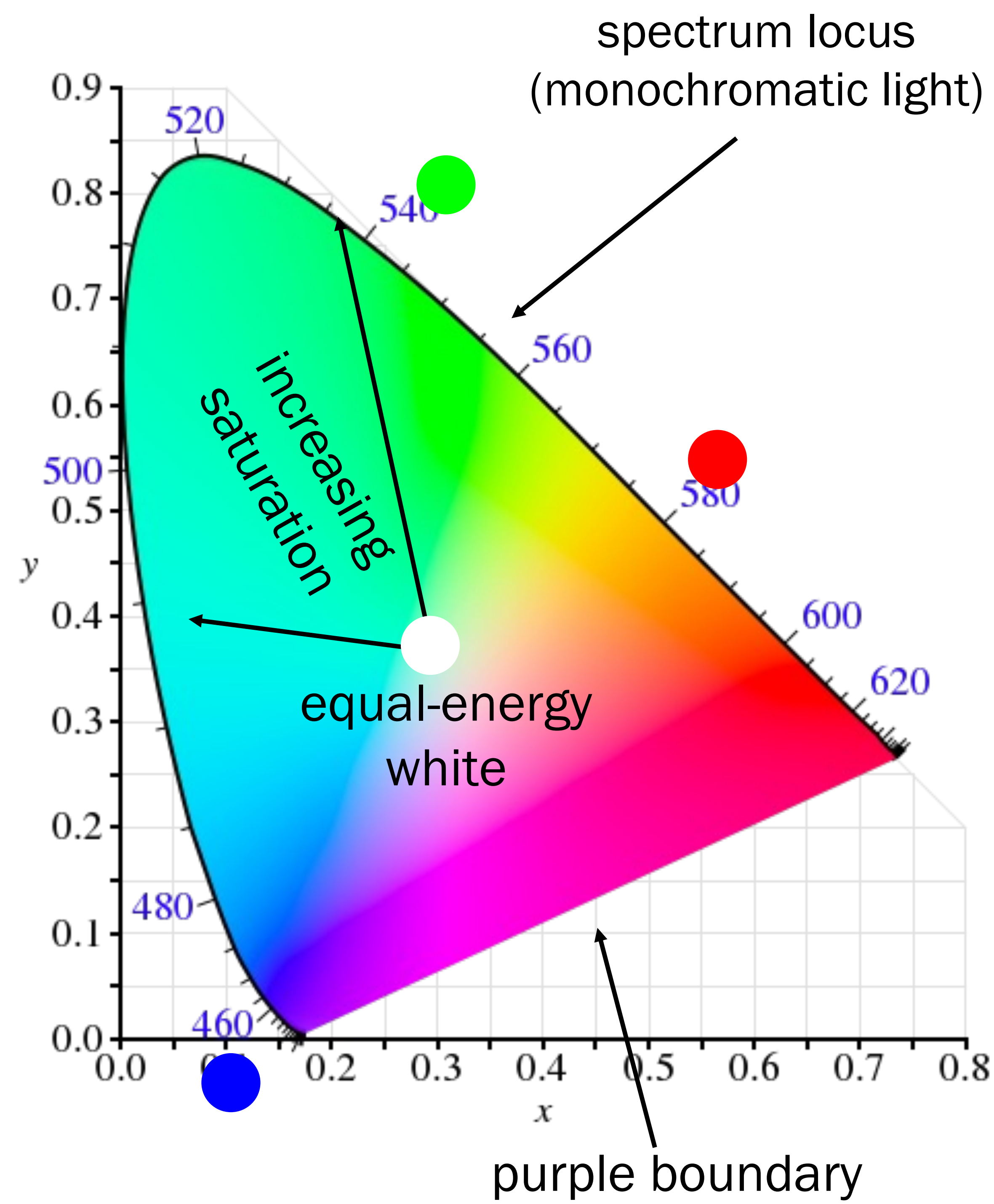
Recap

Last lecture: Colour

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).
- A *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



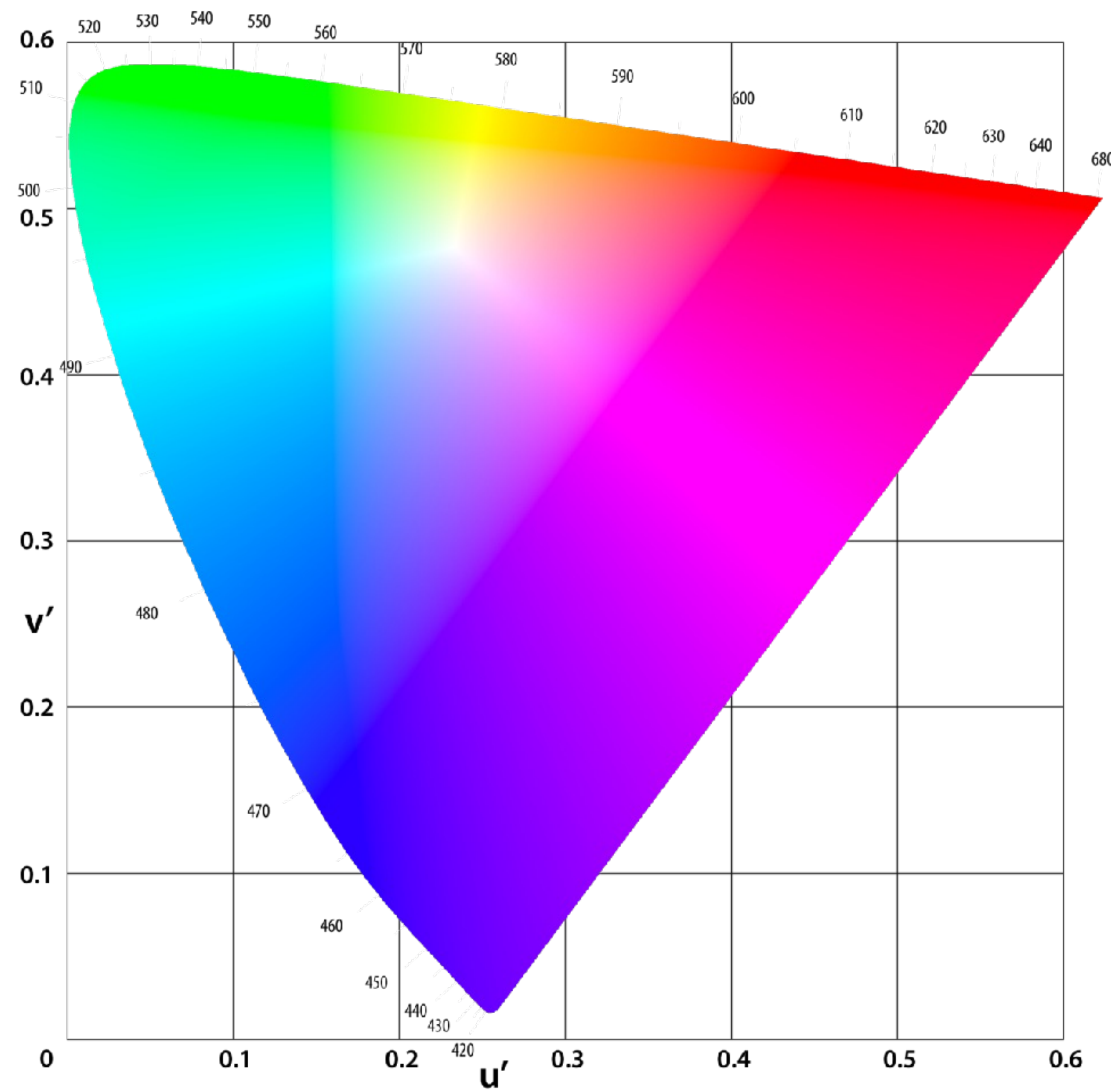
Perceptually more uniform CIELUV

- 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

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

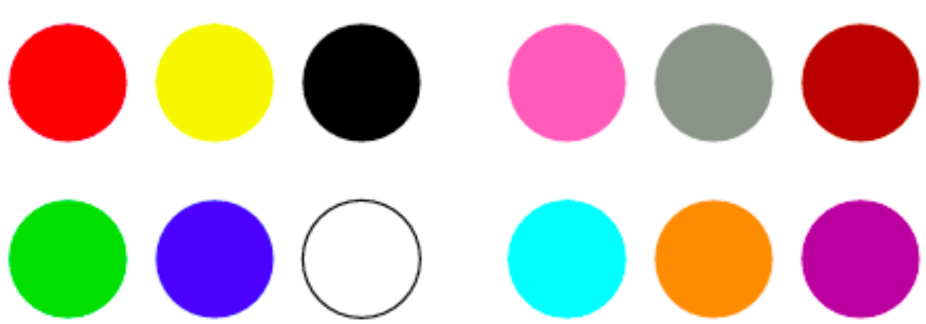
where 1 = approximately just noticeable difference

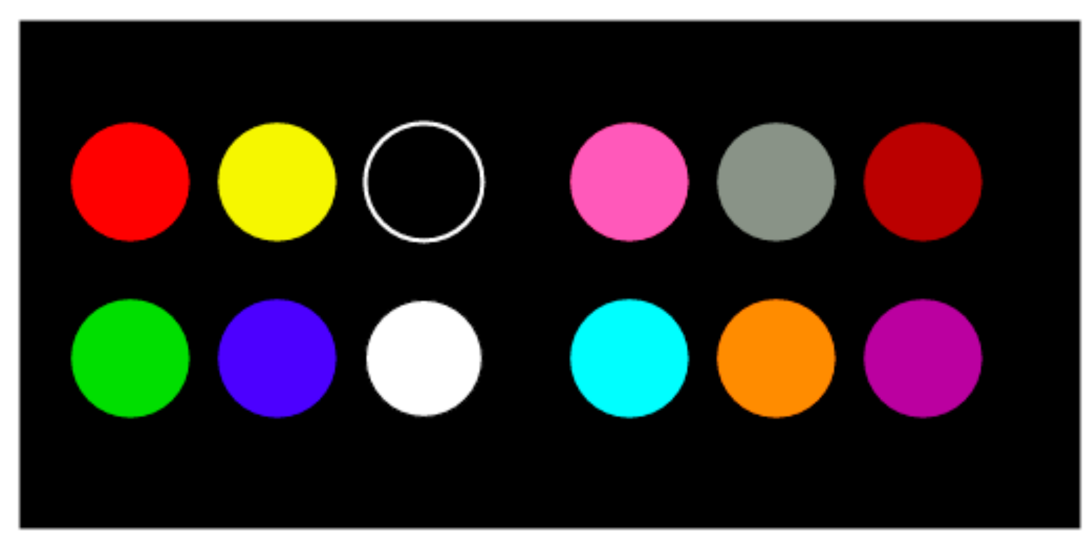


https://en.wikipedia.org/wiki/CIELUV#/media/File:CIE_1976_UCS.png

Color for labeling

- 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 color scans be rapidly distinguished)
  - field size
  - convention (in west: red = danger, hot; green = good, go etc)





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Color for labeling: palettes

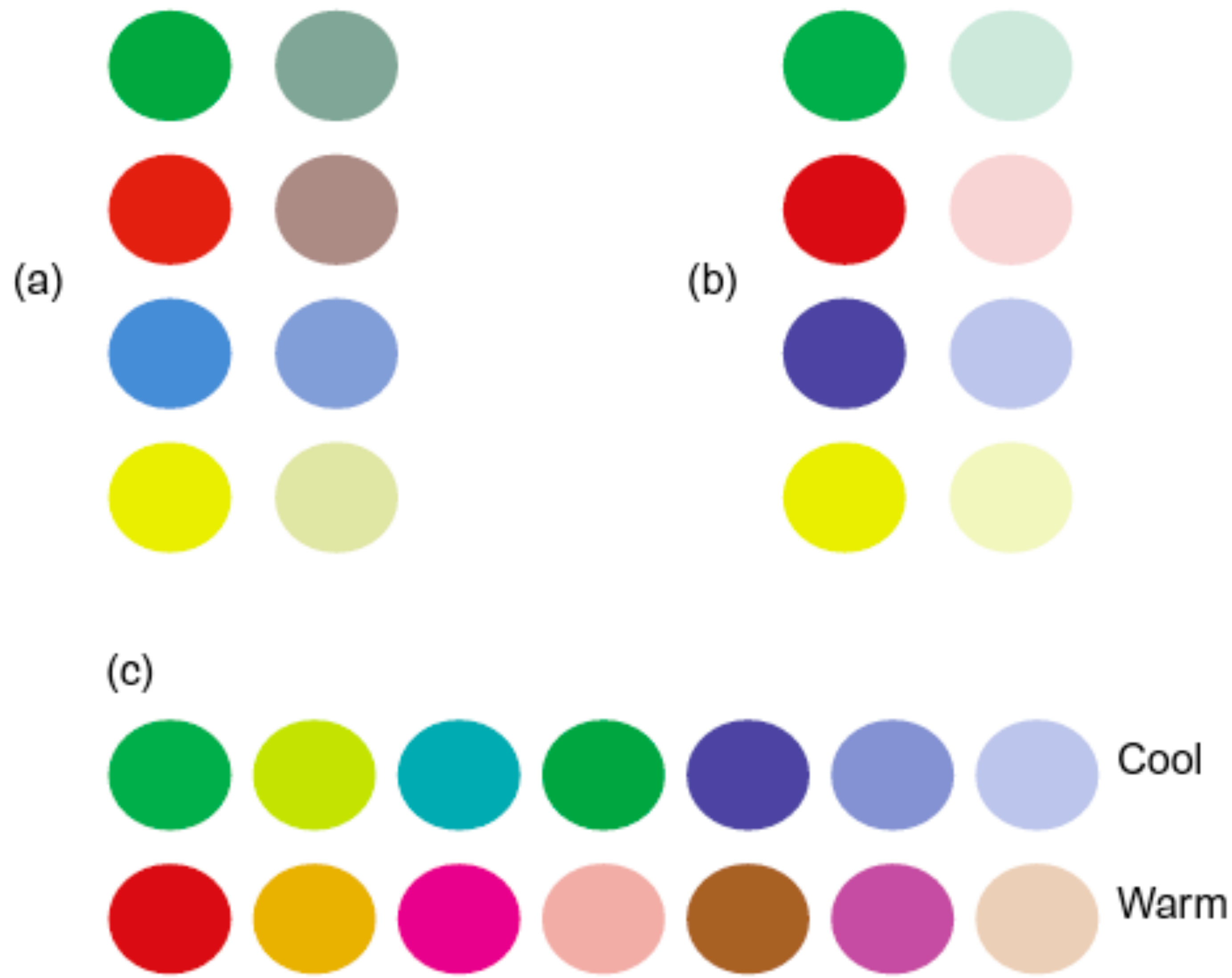

Figure 4.25 Families of colors. (a) Pairs related by hue; family members differ in saturation. (b) Pairs related by hue; family members differ in saturation and lightness. (c) A family of cool hues and a family of warm hues.

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Color for labeling: background

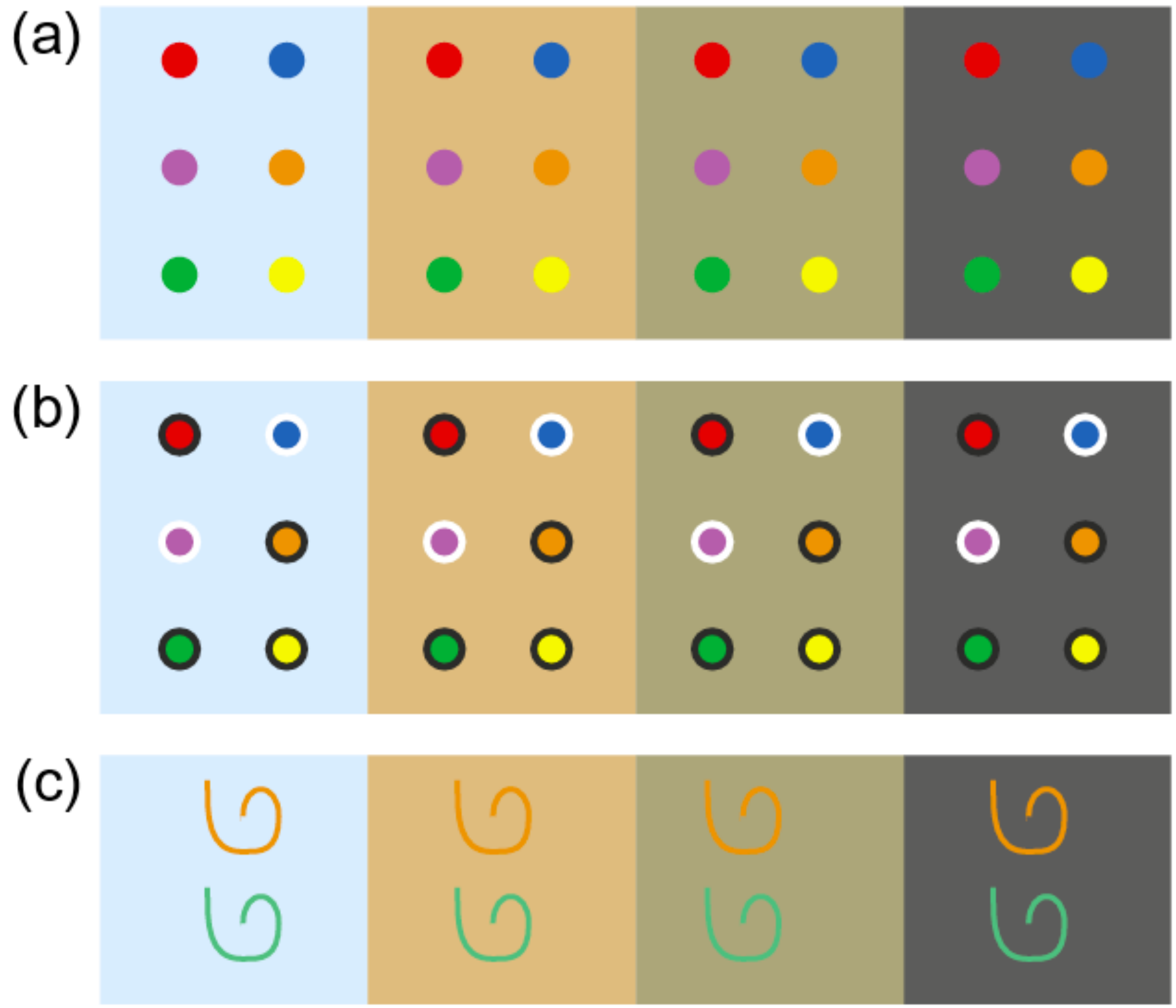

Figure 4.21 (a) Note that at least one member of the set of six symbols lacks distinctness against each background. (b) Adding a luminance contrast border ensures distinctness against all backgrounds. (c) Showing color-coded lines can be especially problematic.

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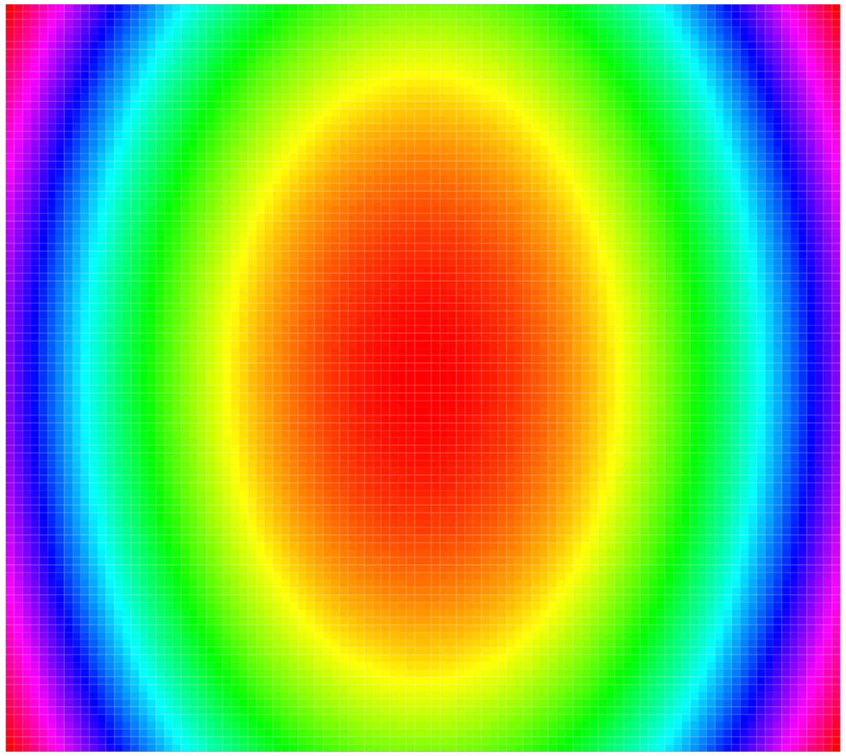
Color scales

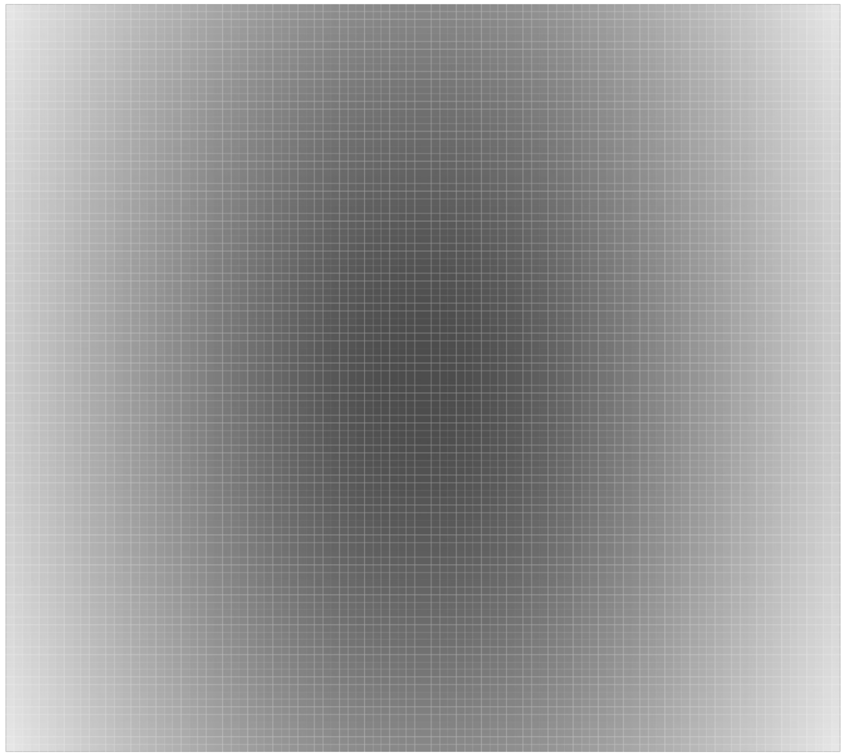
- Some differences are not perceived by the color blind (avoid red-green channel!)
- Perceptually **ordered channels** are, in general, formed from the six color opponent channels. Other ordering includes cold-hot and dark-light.
- **Level of detail:** luminance (e.g., grayscale) shows the highest level 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:** minimize 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

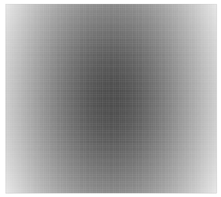
- **Spectrum (rainbow) scale**
  - perceptually very non-uniform and not ordered
  - can create “false contours”
  - good for reading back the values
  - should not be used if the shape of the data is important
- **Grayscale**
  - not good for reading back values
  - shows detail and shape of the data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

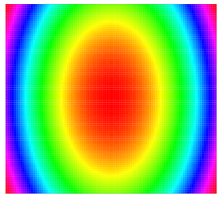
...but usually, you should use something else...





Color scales





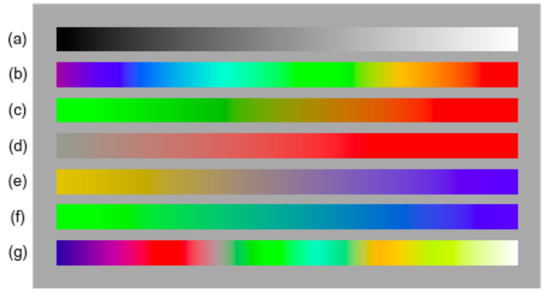


Figure 4.27 Seven different color sequences: (a) Grayscale. (b) Spectrum approximation. (c) Red–green. (d) Saturation. (e, f) Two sequences that will be perceived by people suffering from the most common forms of color blindness. (g) Sequence of colors in which each color is lighter than the previous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

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

Color scales

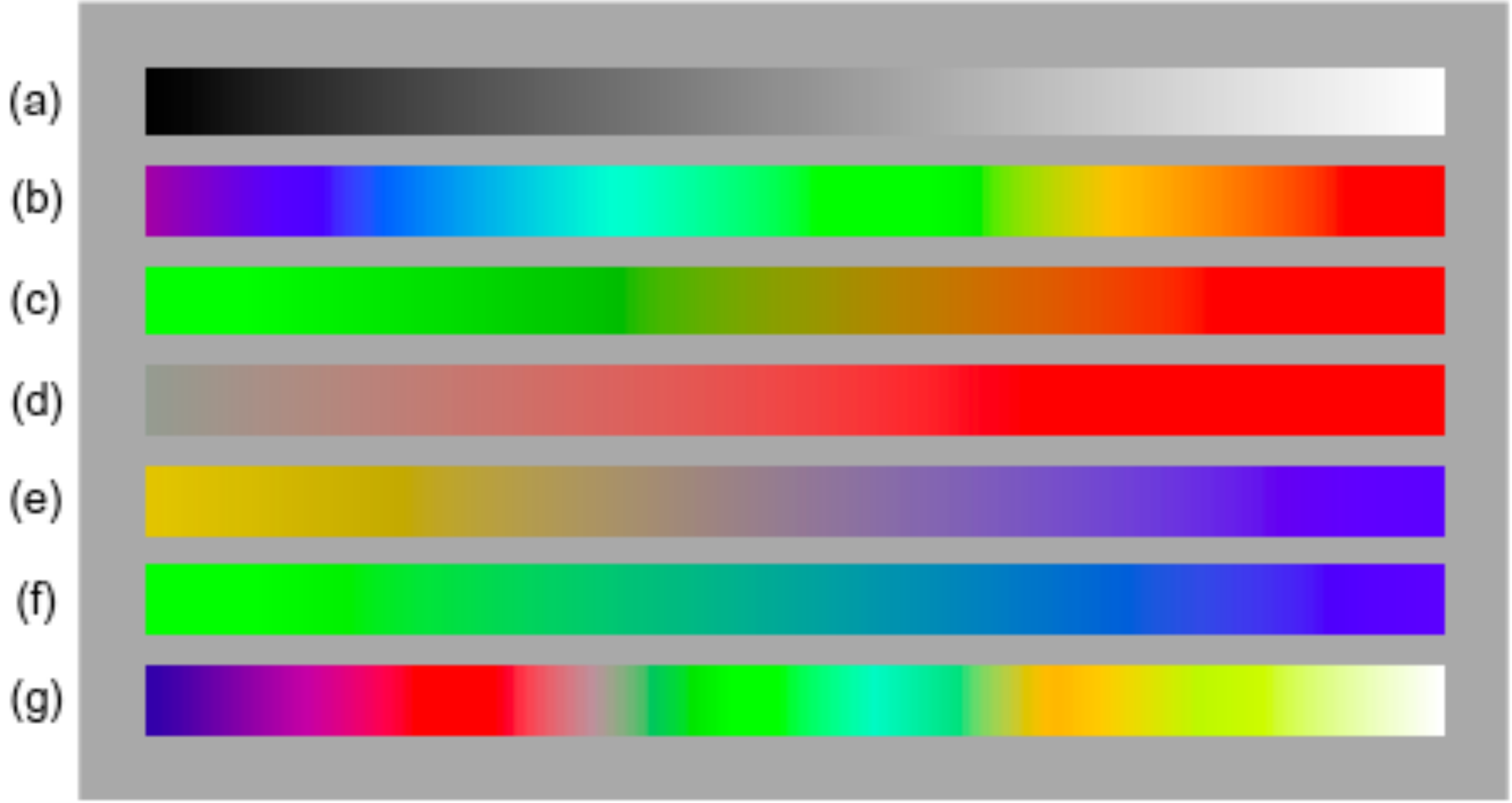


Figure 4.27 Seven different color sequences: (a) Grayscale. (b) Spectrum approximation. (c) Red–green. (d) Saturation. (e, f) Two sequences that will be perceived by people suffering from the most common forms of color blindness. (g) Sequence of colors in which each color is lighter than the previous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

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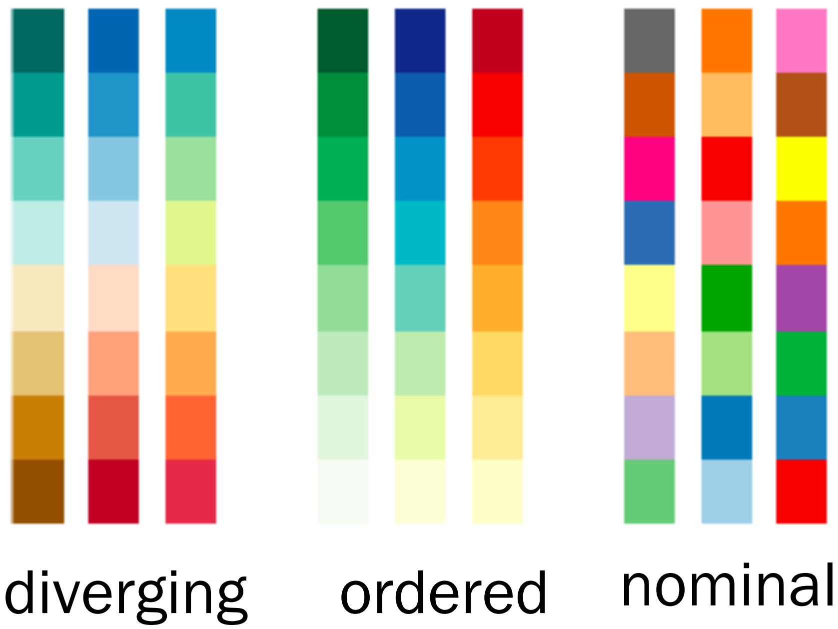
Color scales

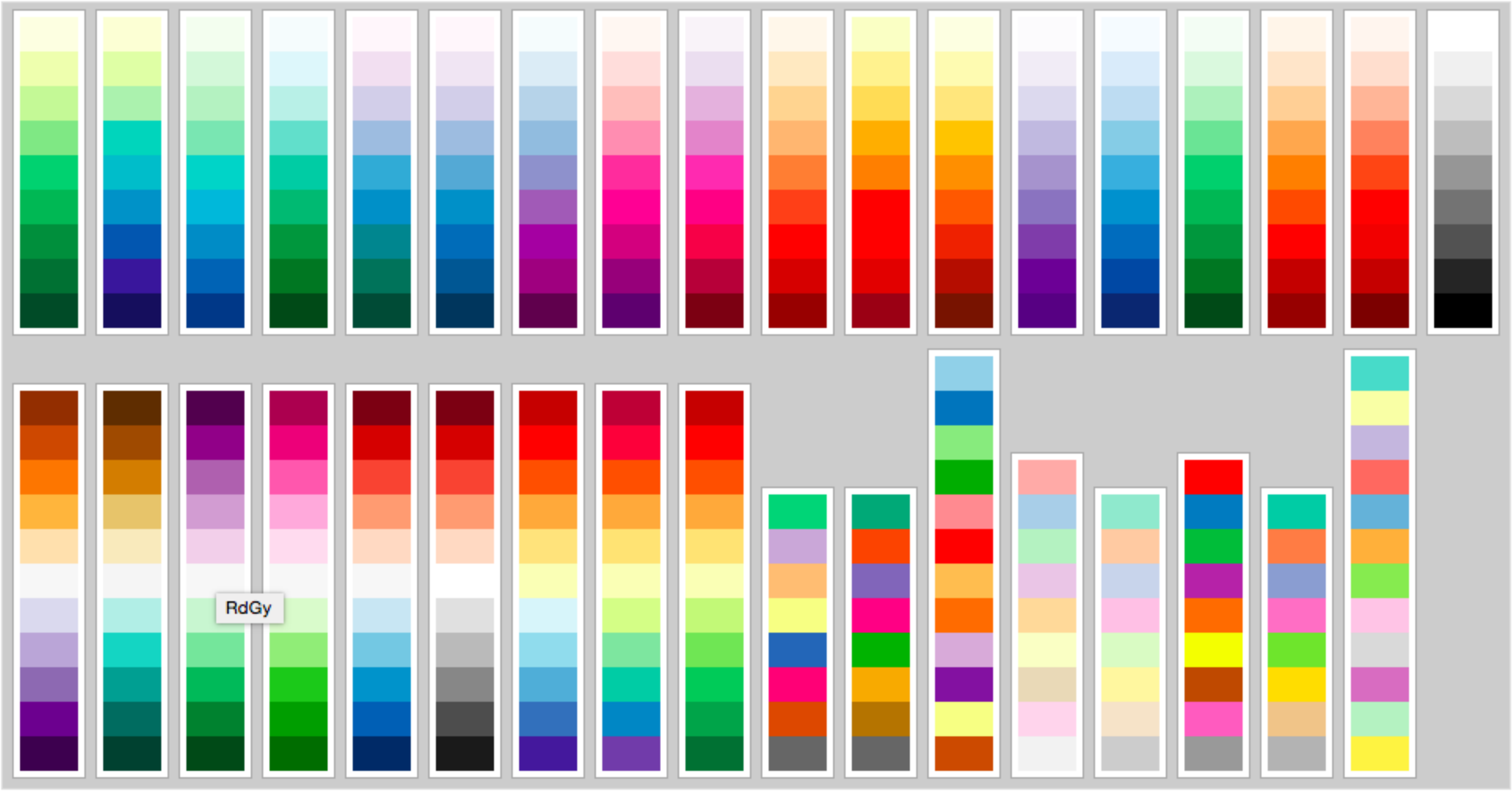
Some hints on selecting suitable color scale:

- **Nominal** (values have no order):
  - Same as using color for labeling. 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 a 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 (discretized) 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 the luminance channel to indicate order.



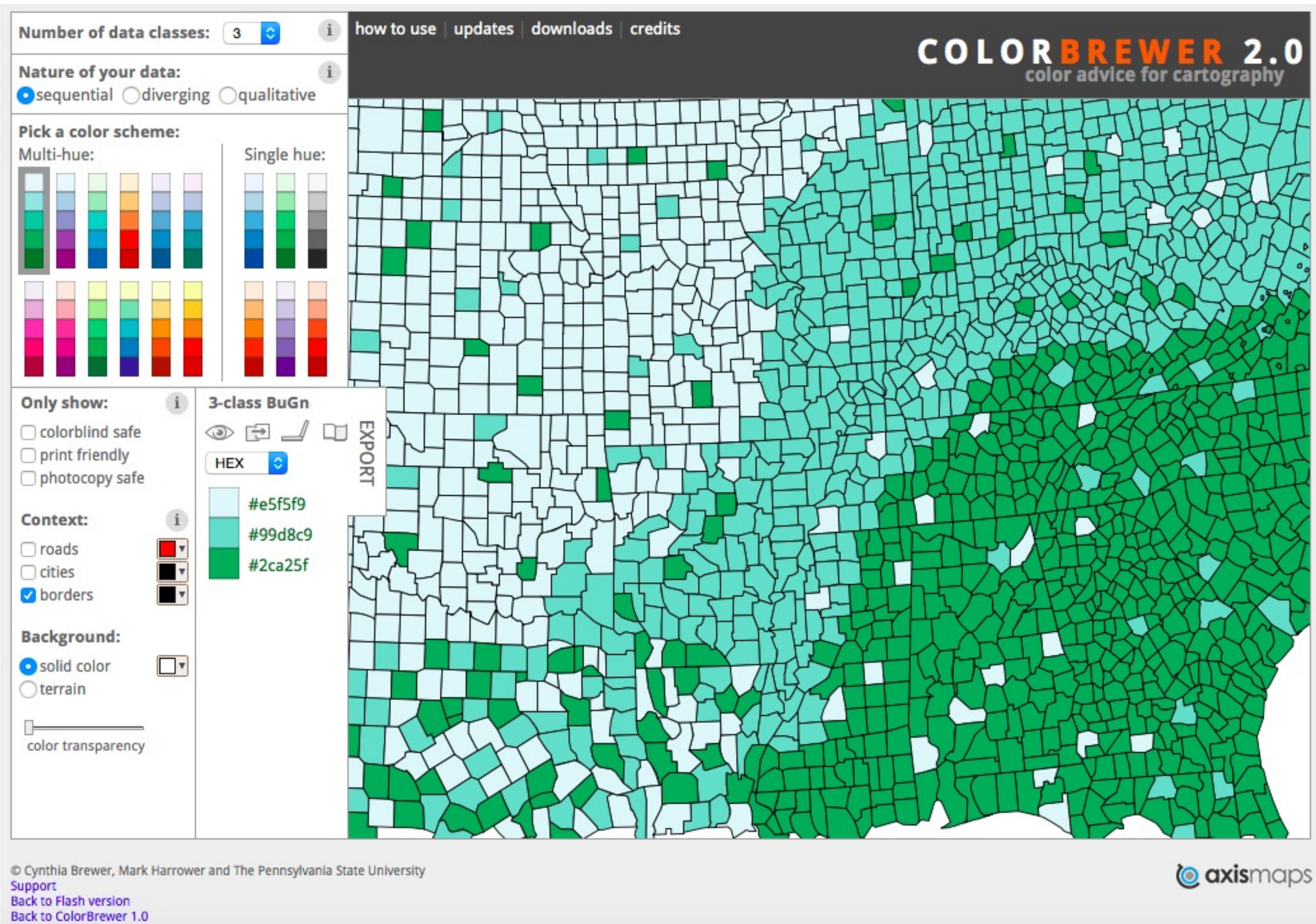
Color scales

RColorBrewer colour scales

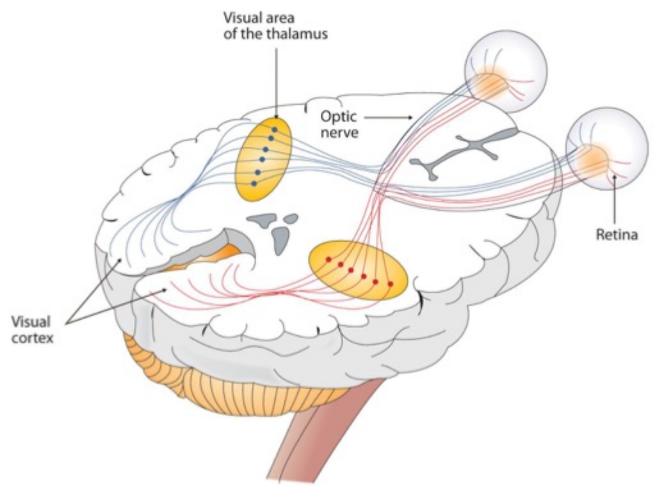


https://bl.ocks.org/mbostock/5577023

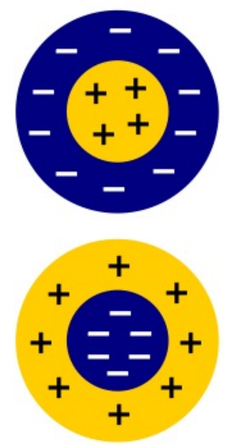
Color scales



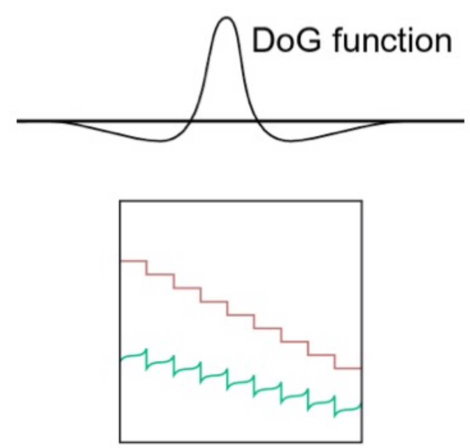
Harrower, Brewer. ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps, The Cartographic Journal, 40:1, 27-37, 2003. https://doi.org/10.1179/000870403235002042 from retina to brain



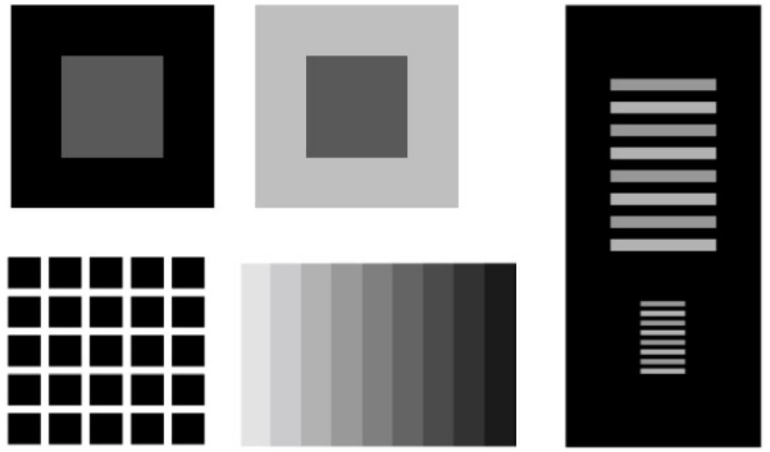
receptive field

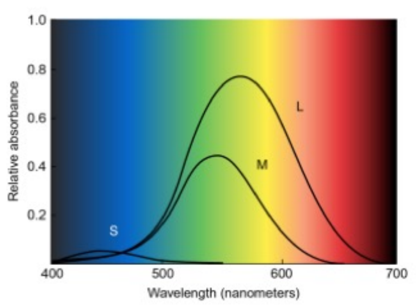


Difference of Gaussians



contrast illusions and crispening

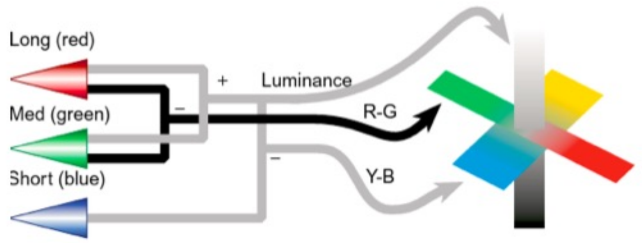




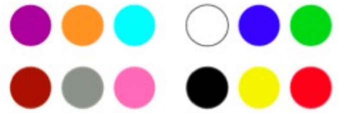
Trichromacy theory

colour blindness

colour spaces



opponent colour theory



colour for labels, scales, multidimensional data, reproduction

NEW IN THIS LECTURE

Visual salience and finding information

(Ware Ch 5)

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/

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

Query: how many 3s?

455865876864565749286555584765298742309847249473247
324879427149572389742982479280742938742564875647654
902842968476745464274784674573847648562484789847985

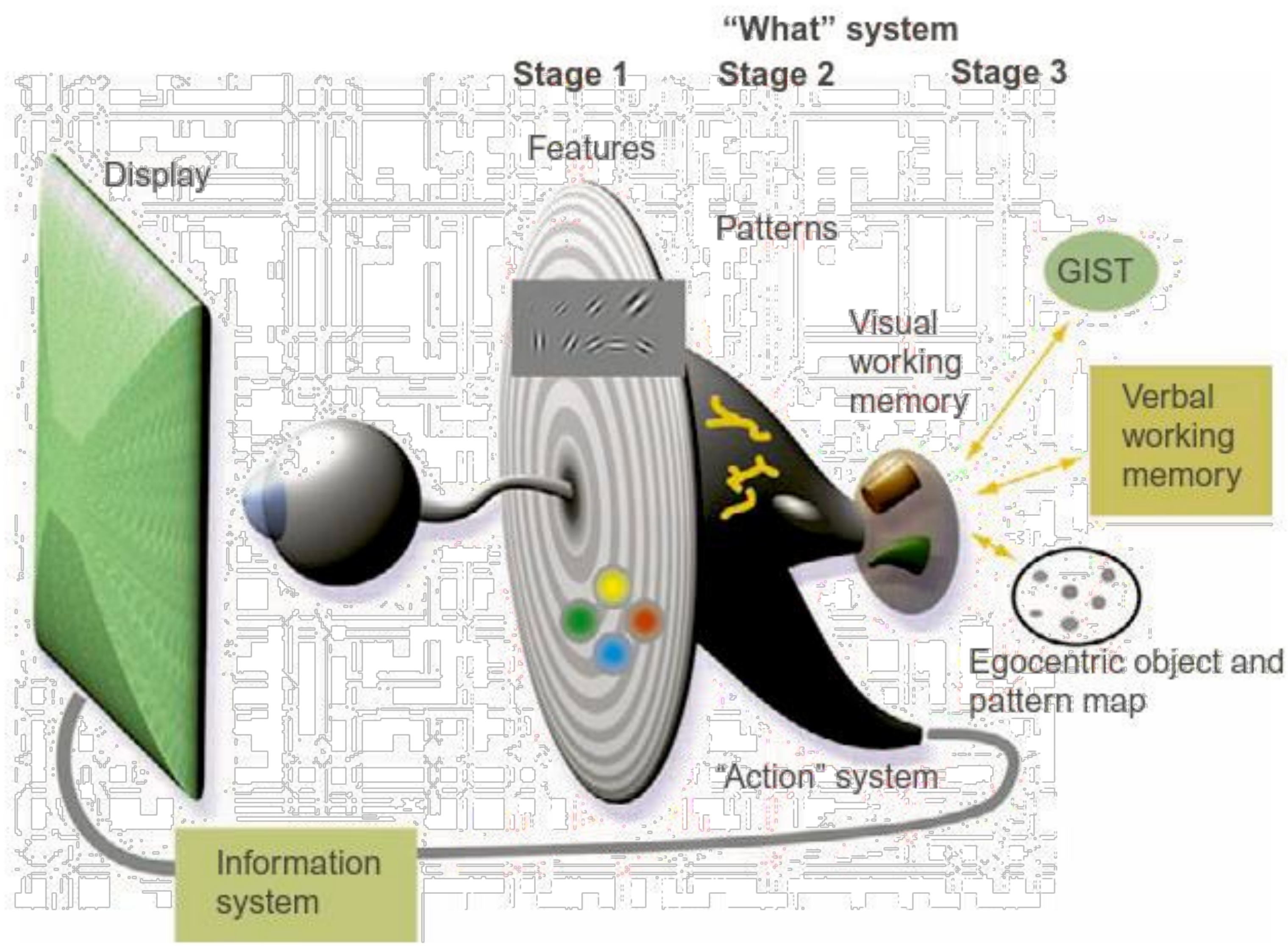
45586587686456574928655558476529874 2**3**0984724947**3**247
324879427149572**3**8974298247928074 29**3**8742564875647654
9028429684767454642747846745 7**3**847648562484789847985

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, color, 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



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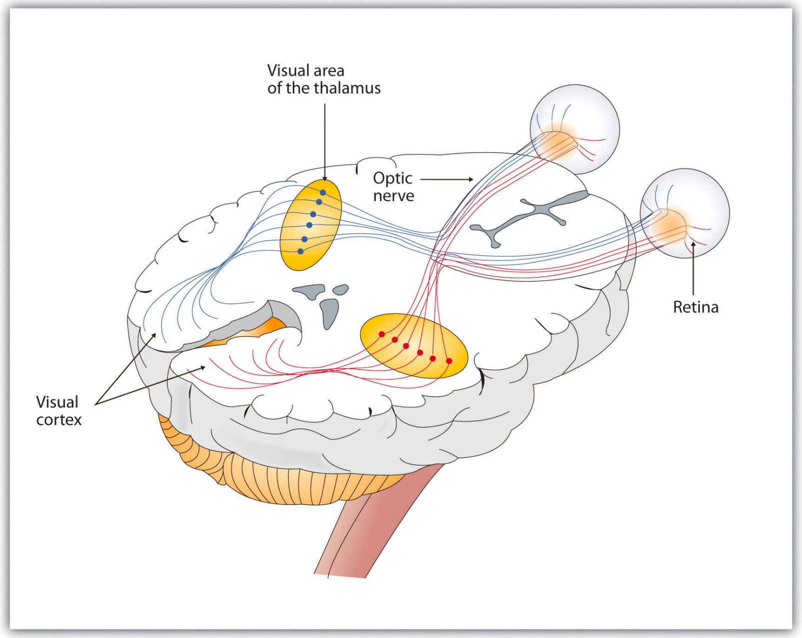
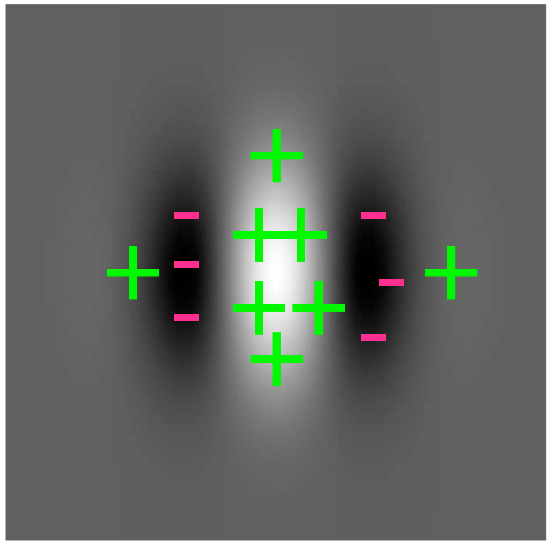
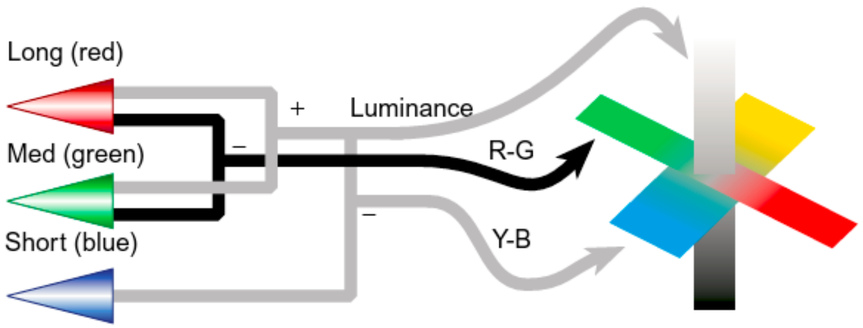
Visual cortex



- V1 (primary visual cortex) and V2 (secondary visual cortex) of the visual cortex together make up to 40% of vision processing

- V1 and V2 are tuned to these properties
  - Elements of **form**
    - orientation and size (with luminance)
    - via the Gabor processor (explained later)
  - **Color** (two types of signals)
    - Via the opponent color processing
  - Elements of local **stereoscopic depth**
  - Elements of local **motion**





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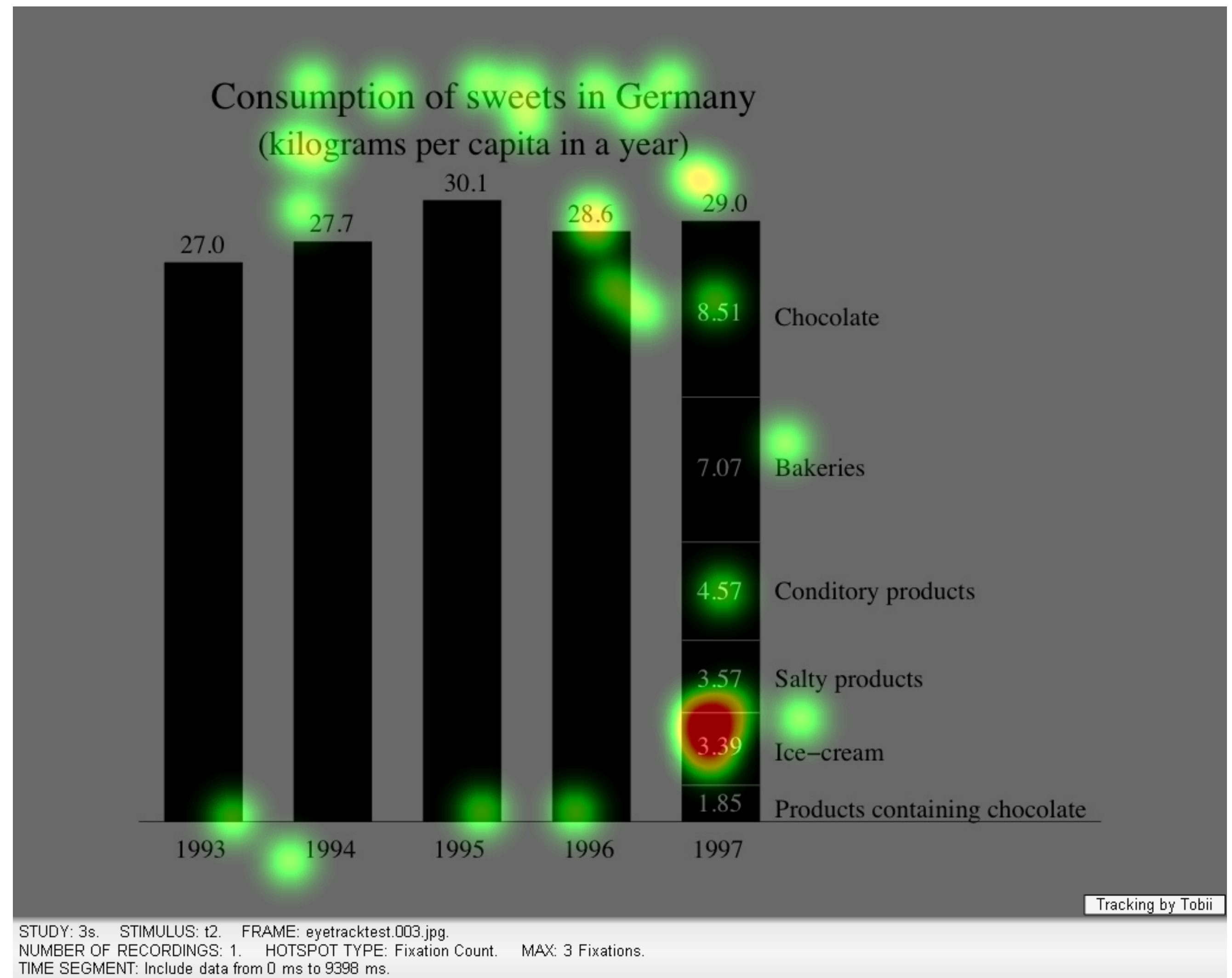
Visual channels

- The previous properties are processed separately, in parallel on different channels,
  - Color, form (orientation and size), motion
- The information expressed in one channel (e.g., the color of a symbol) does not interfere (much) with the information expressed in another channel (e.g., the orientation of a symbol), and properties on different channels (e.g., color and orientation) are visually distinct
- Different visual channels should be used to display aspects of data

Eye movements

- The eye moves according to three basic strategies:
  - **Saccadic movements**. Eye movements consist of fixations (duration 0.2-0.6 s), during which the eye is relatively stable. The eye moves from fixation to fixation with saccades (duration 0.02-0.1 s, velocities up to 900°/s). Saccadic movements are pre-programmed (ballistic). We are practically blind during the saccade (saccadic suppression). Refocusing (accommodation) takes about 0.2 s.
  - **Smooth-pursuit movements**. We can track smoothly moving visual objects (and static objects while moving ourselves)
  - **Convergent movements**. When objects move closer or further away, our eyes converge or diverge.
- During this lecture, we only consider saccadic movements and make (over?)simplification: information comes into the visual system as a series of discrete snapshots.

Where did they look?



The heatmap shows the time spent at looking (fixations) at different parts of an image.

What do we really see?

- Higher frequency components off-visual axis are blurred (foveation)
- The foveated video (right) is what the test subject really saw (keep your gaze fixed to the center, you do not need to move your eyes)

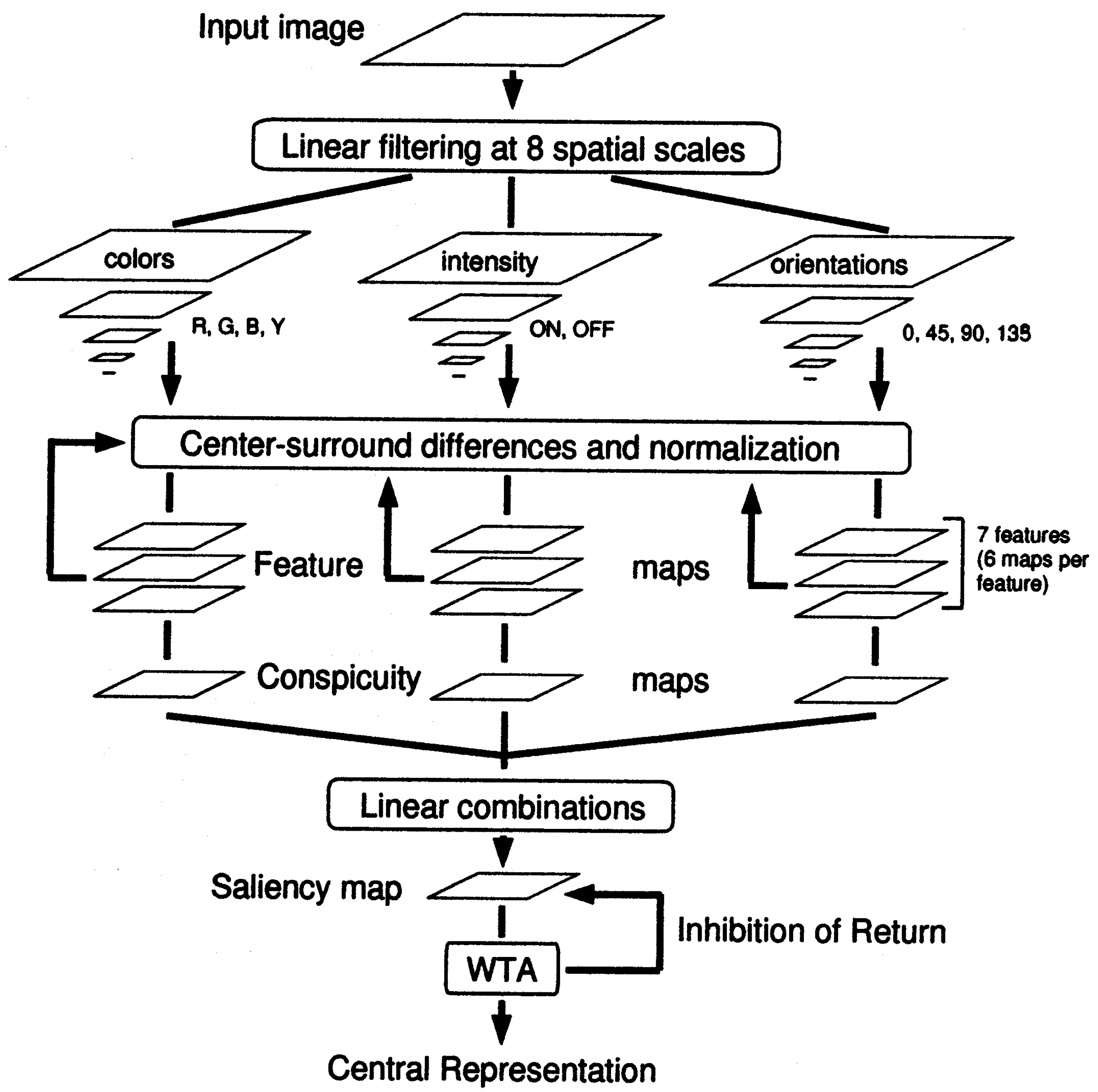
Videos by USC iLab, http://ilab.usc.edu/bu/

Guiding gaze

- Bottom-up: salient features
- Top-down: attention

Computational model for visual attention: saliency map

- Loosely based on Treismann's feature integration theory
- First, low-level visual features are extracted (color channels, orientation, brightness), preprocessed with the difference of Gaussians (DOG) models (winner-take-all-training, resulting in a sparse distribution of winners, or peaks, on the maps), presented on 42 separate maps
- The maps are summed linearly to form the saliency map
- The gaze is then directed to the point of maximum saliency
- In the case of static images, the saliency of the viewed parts is suppressed



Itti, Koch, Vision Research 2000, https://doi.org/10.1016/S0042-6989(99)00163-7

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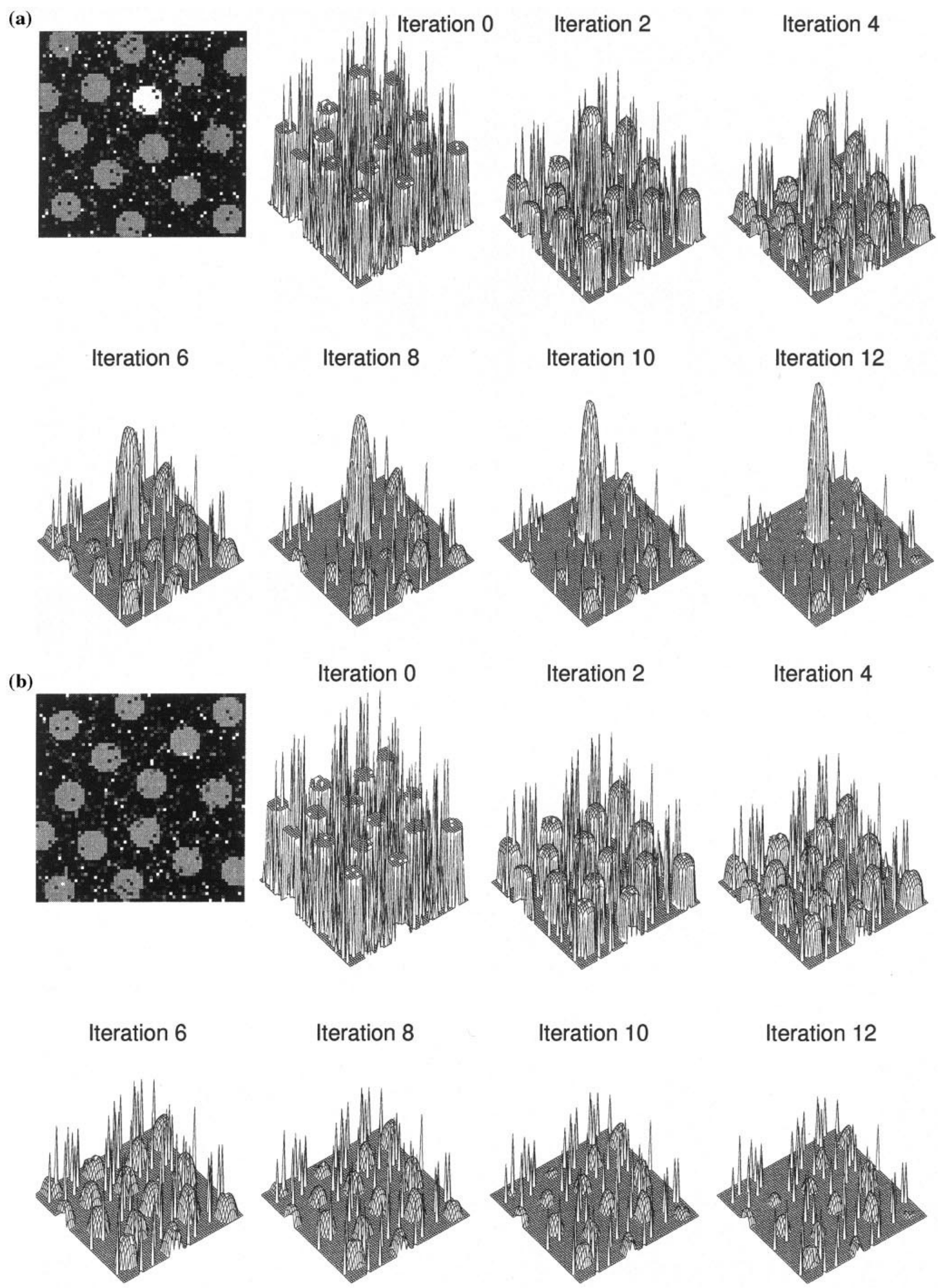

Itti, Koch, Vision Research 2000, https://doi.org/10.1016/S0042-6989(99)00163-

Computational model for bottom-up visual attention: saliency map

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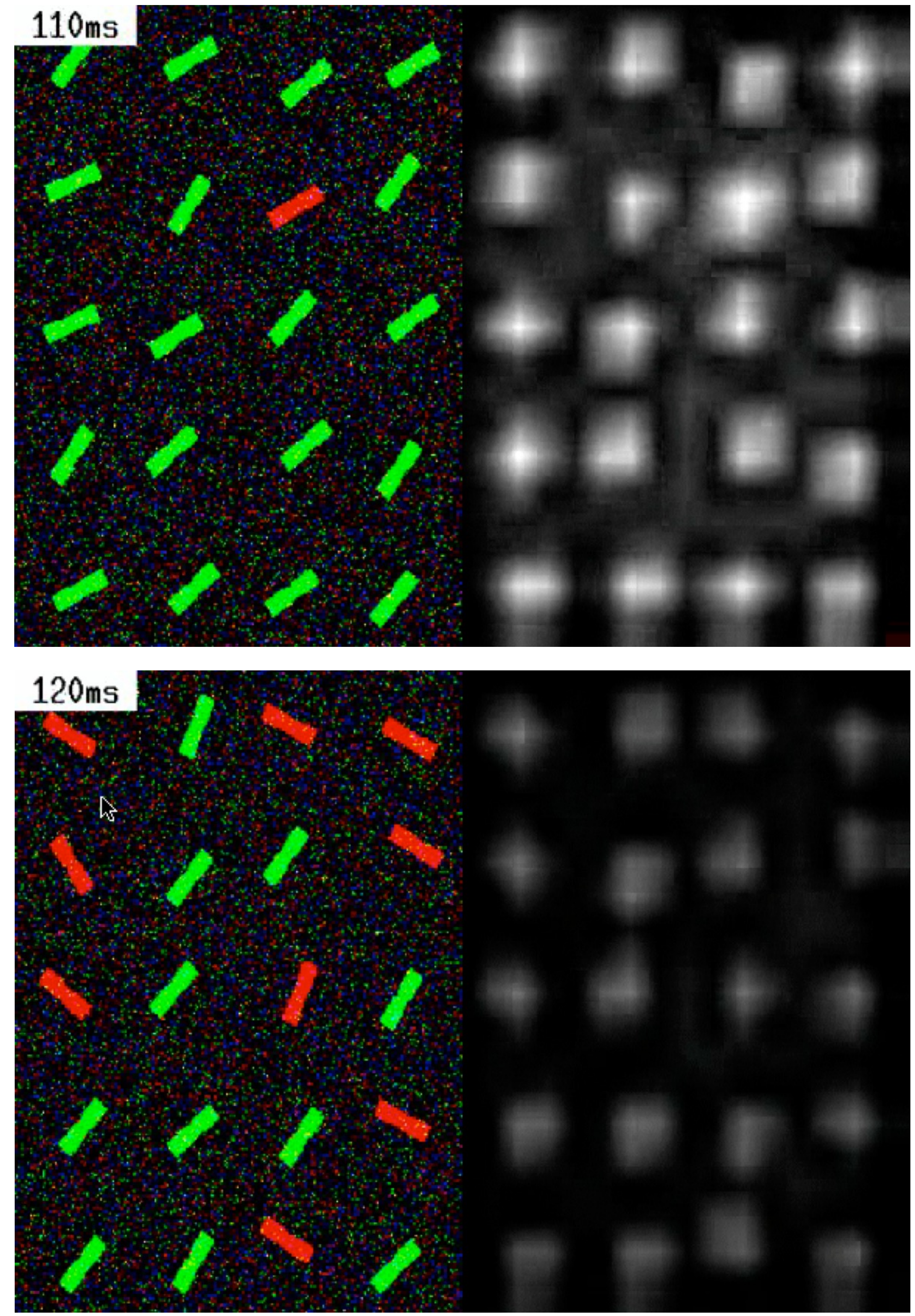
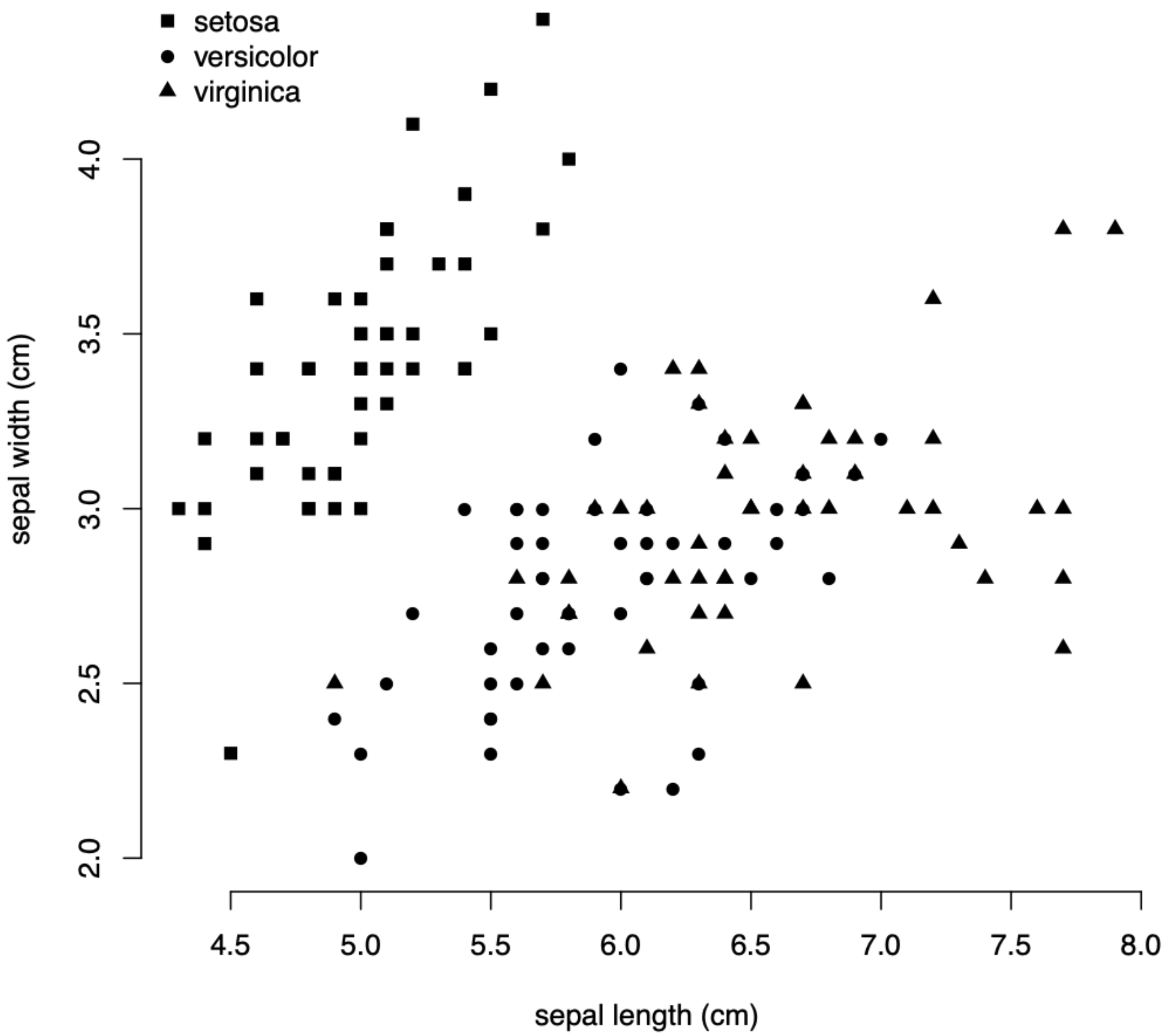
Itti, Koch, Vision Research 2000.

Some of the pre-attentive pop-up explained

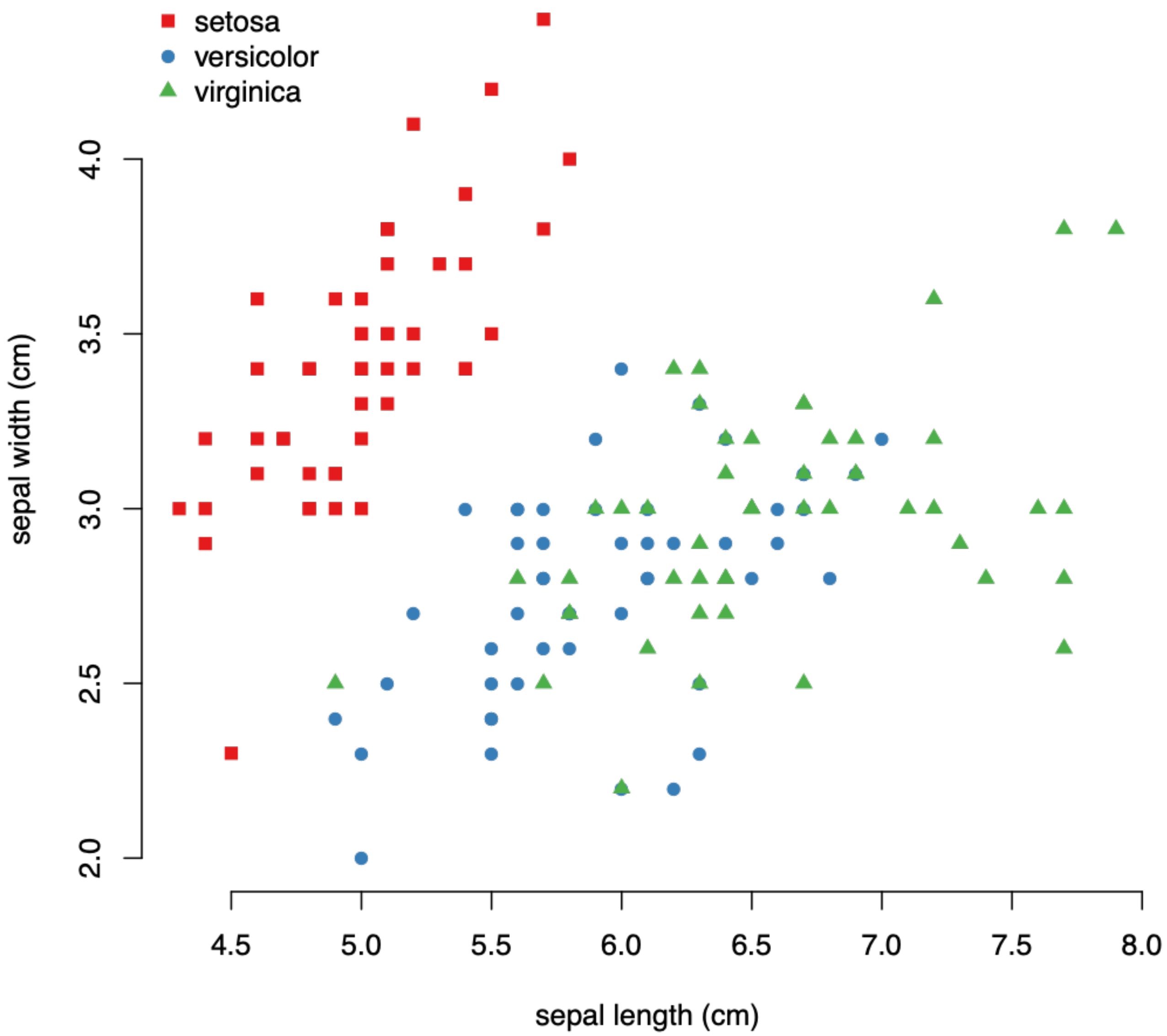
- The model reproduces some of the pre-attentive pop-out phenomena (Itti, Koch 2000)
- Search-time of a pop-out task is independent of the number of distractors (pre-attentive search)
- Search-time of conjunction tasks increases linearly with the number of distractors (conjunction searches are usually non-pre-attentive). (Why?)



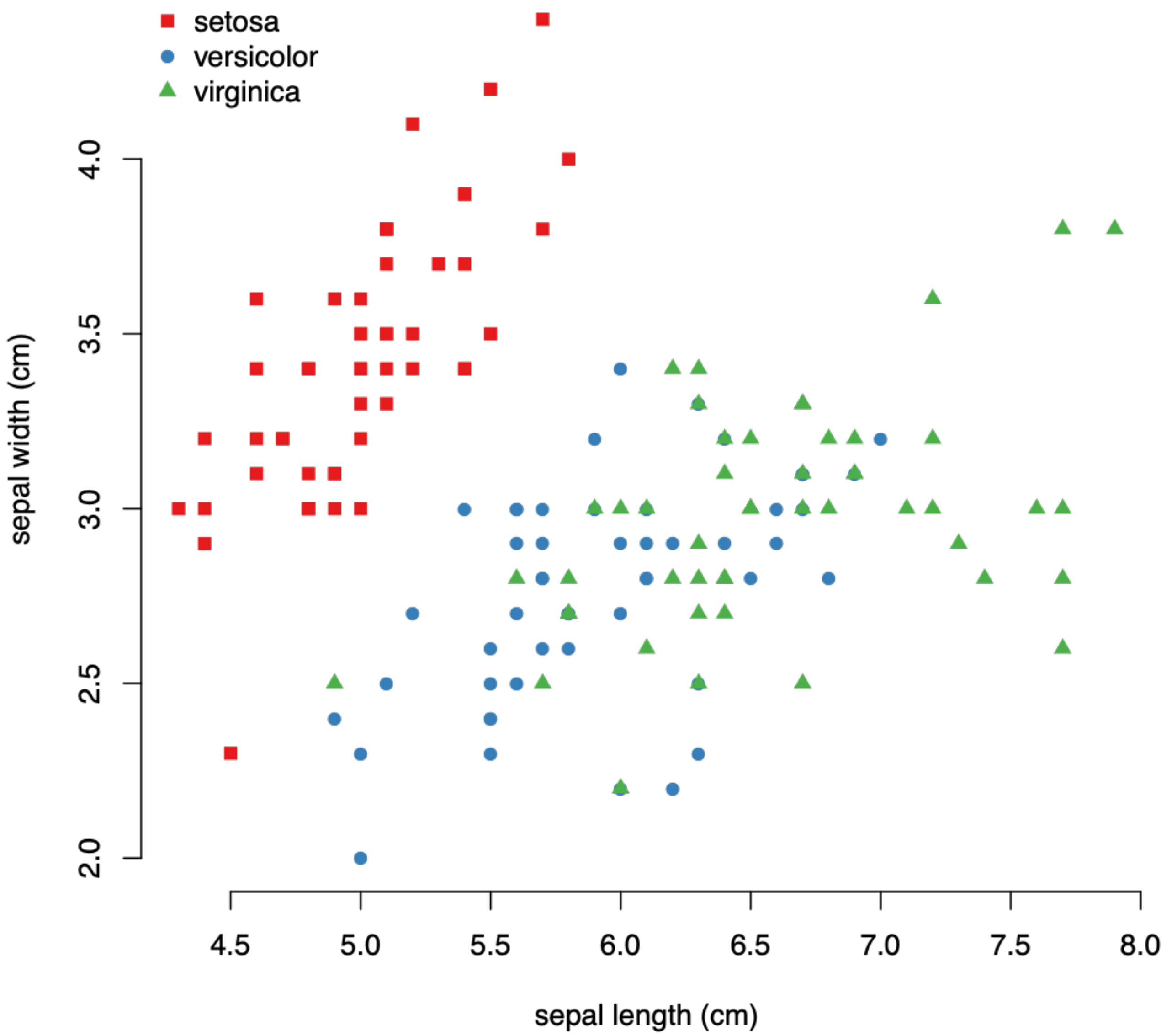
Saliency map on the right.



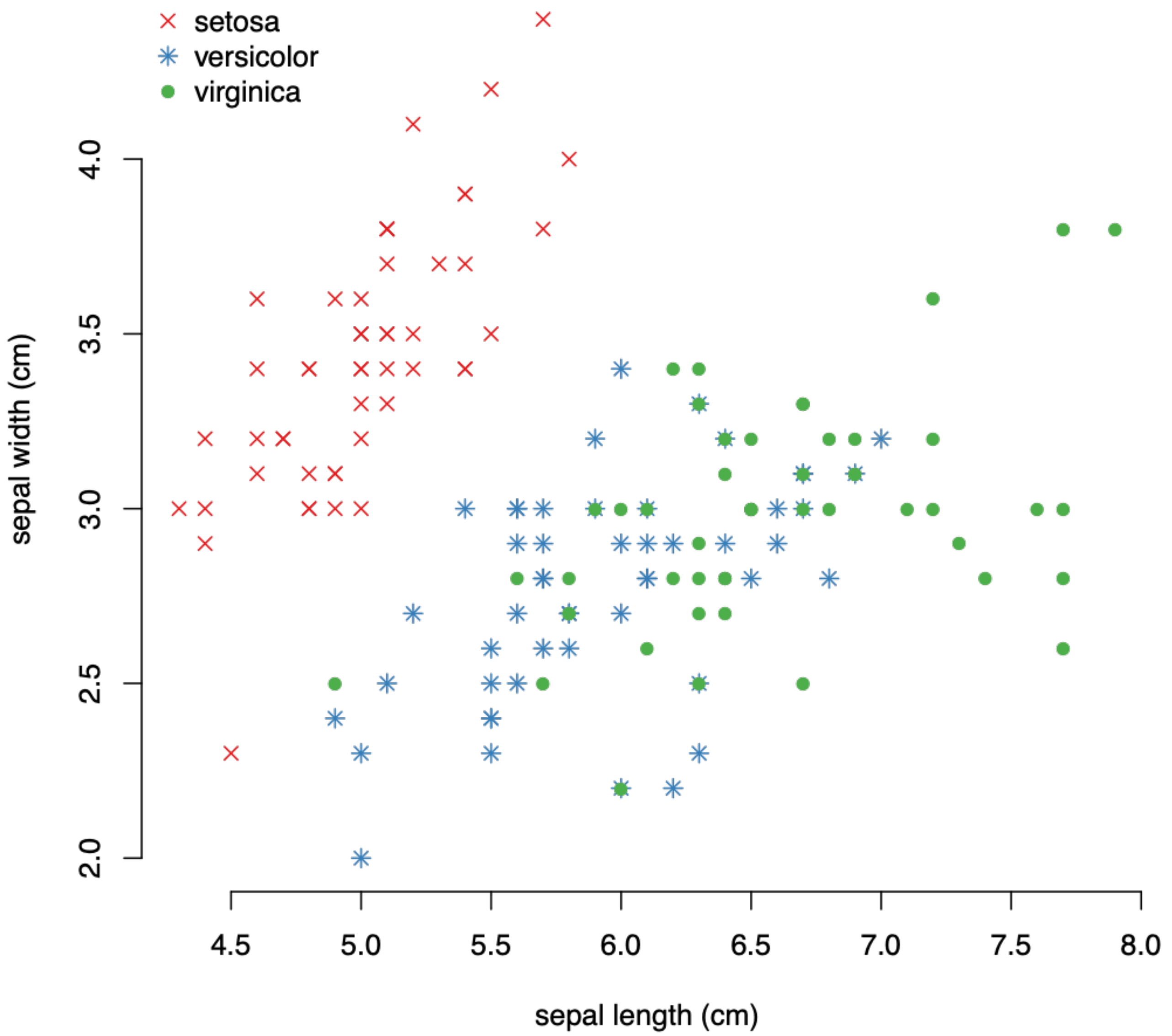
shape



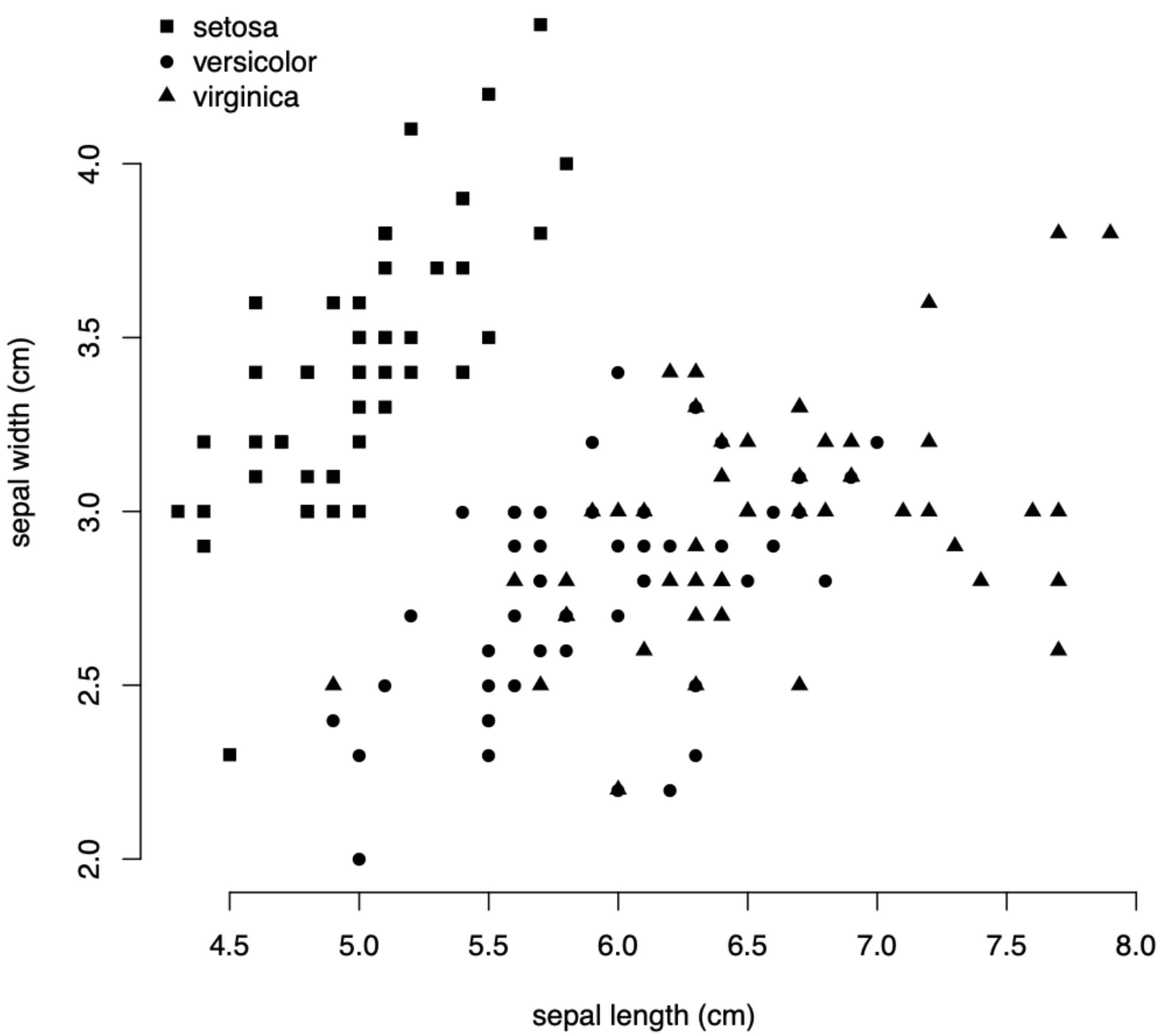
shape + colour



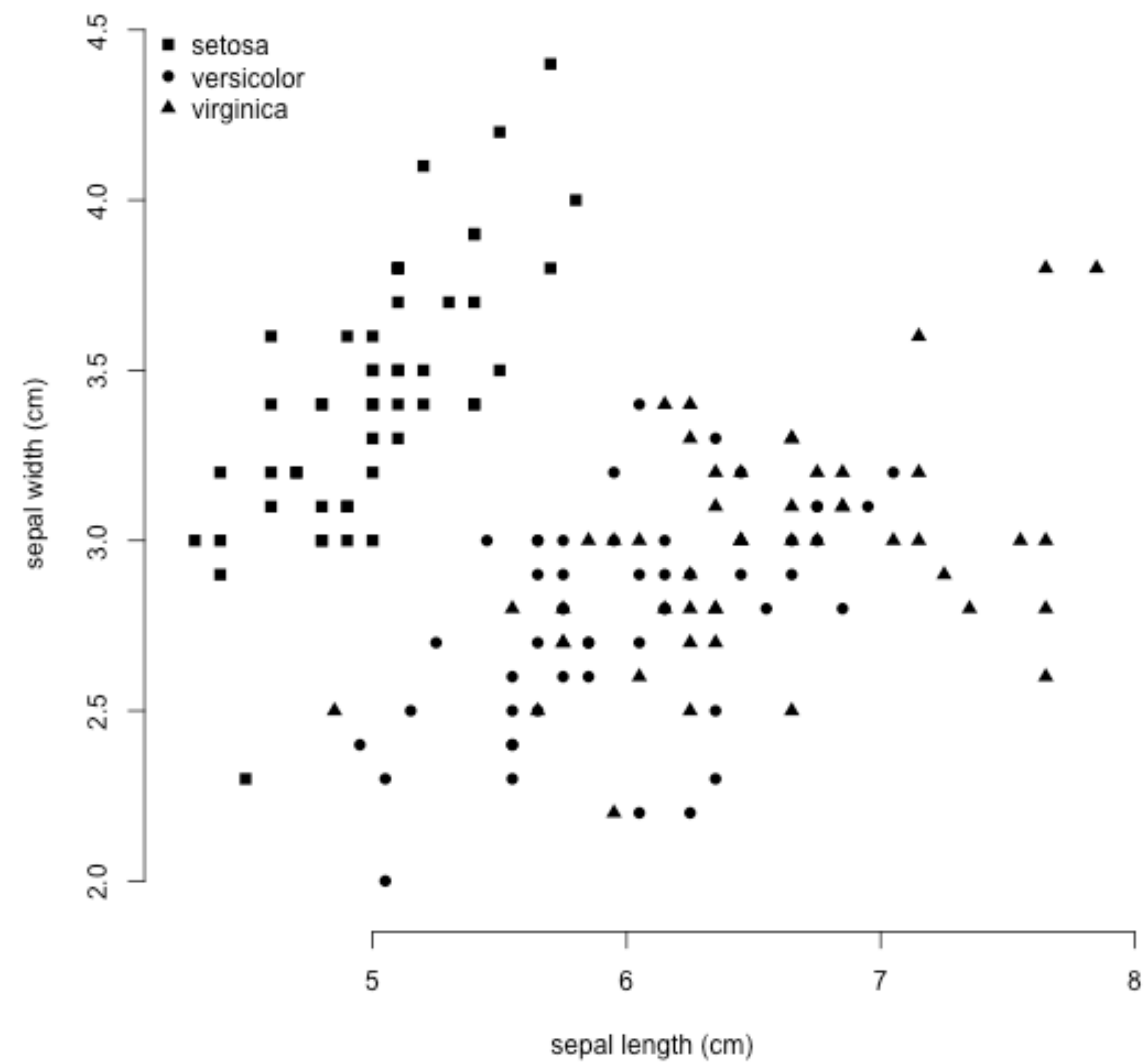
shape + colour



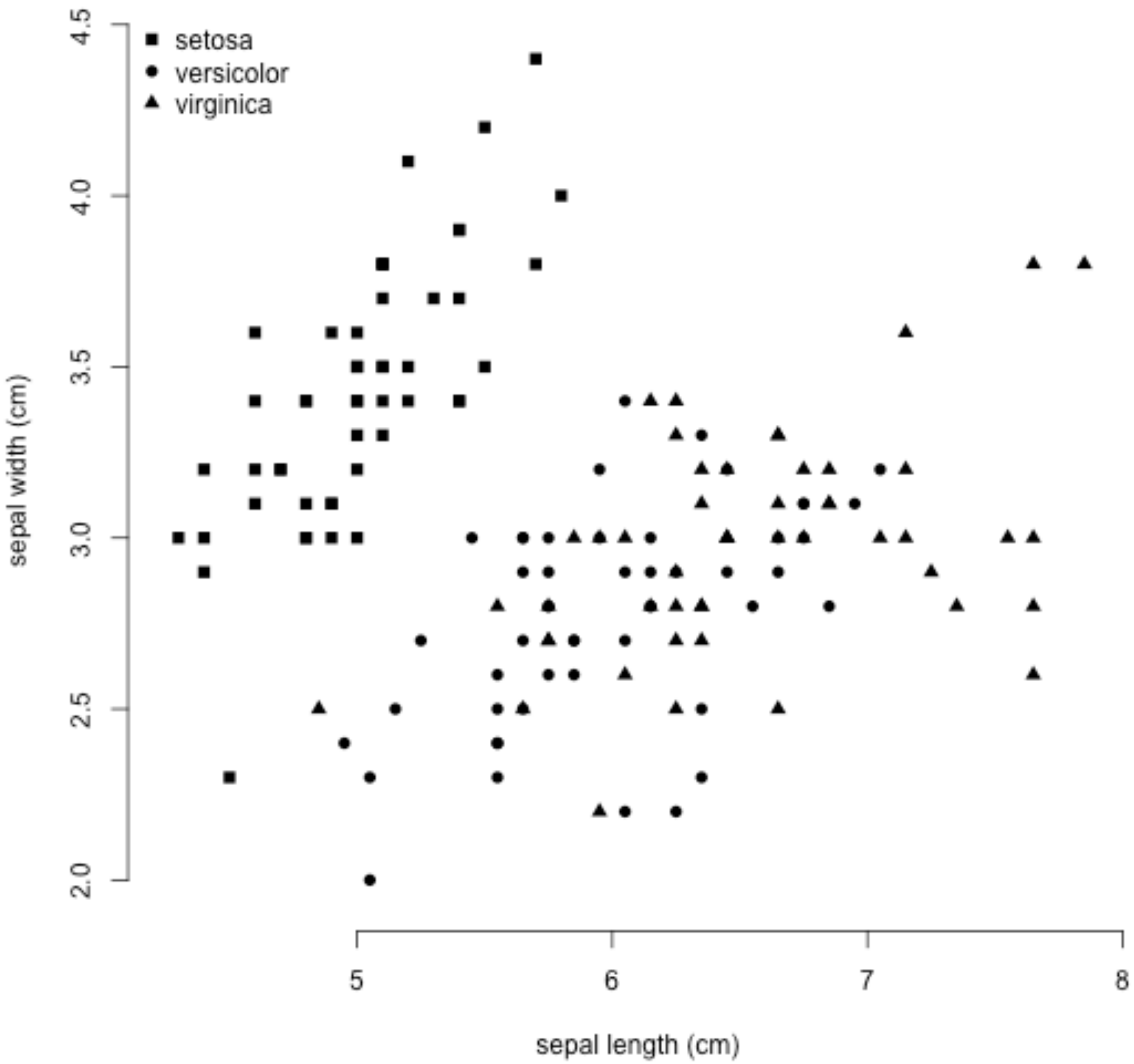
shape + orientation + colour



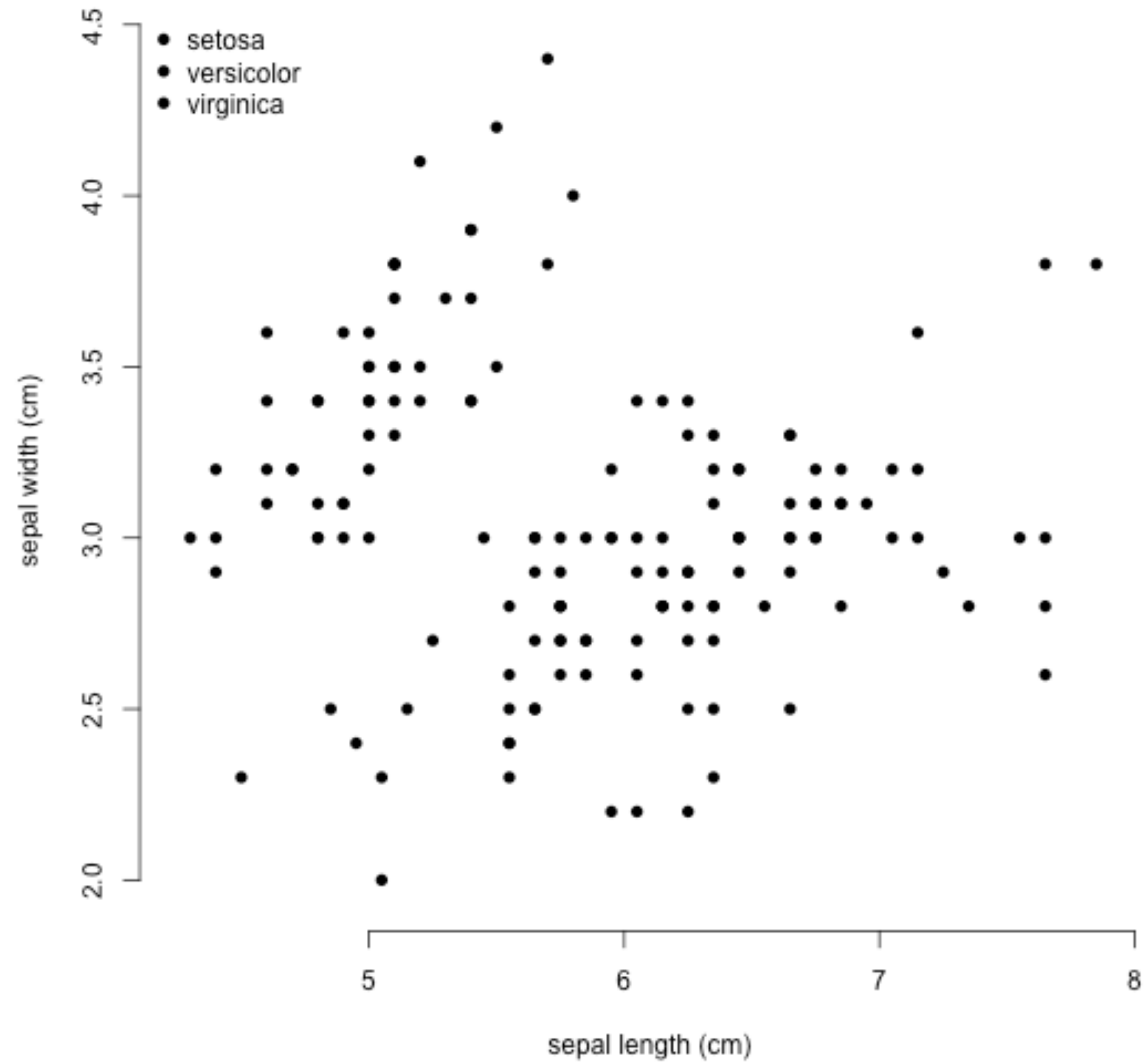
shape



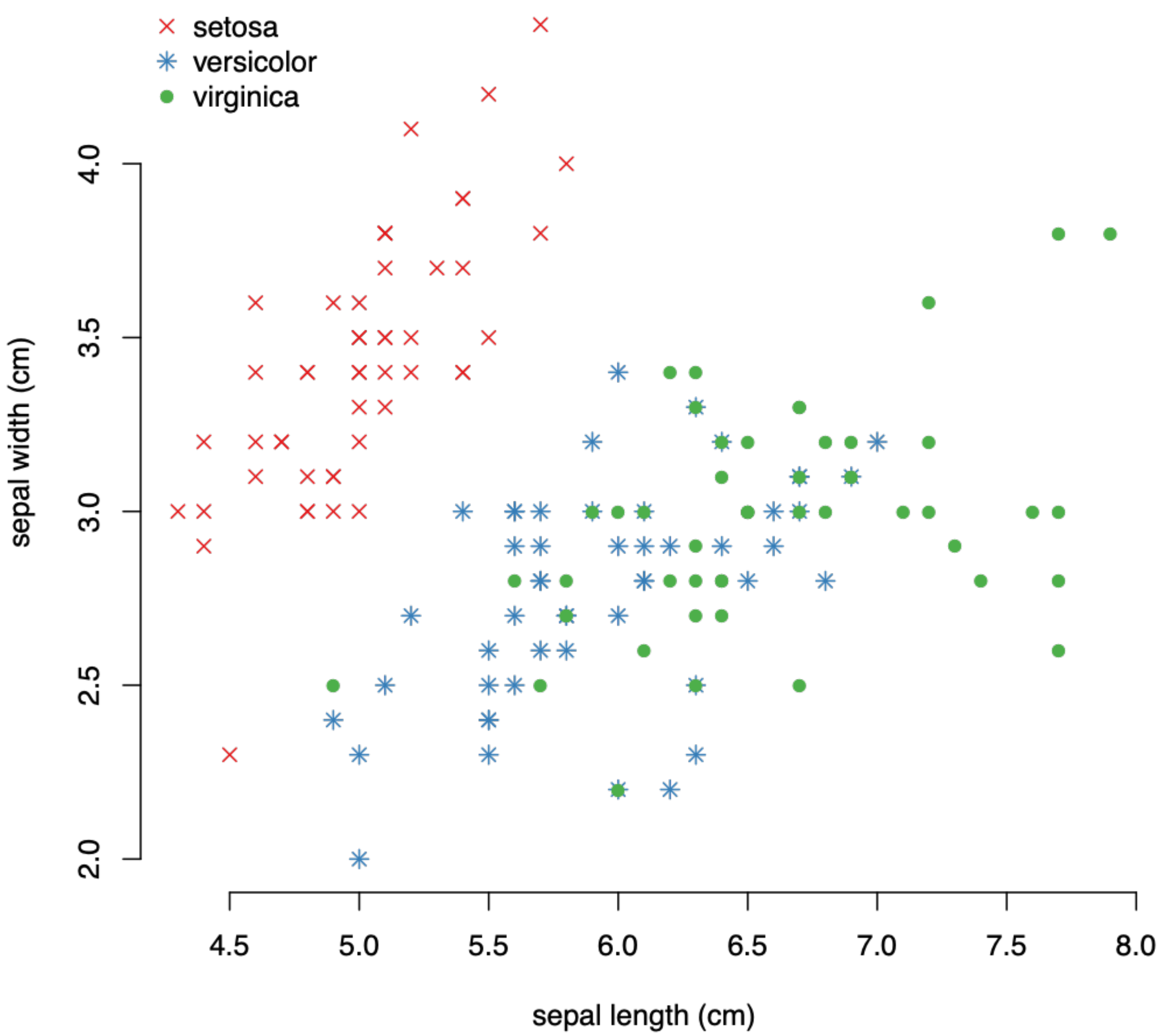
shape + animation



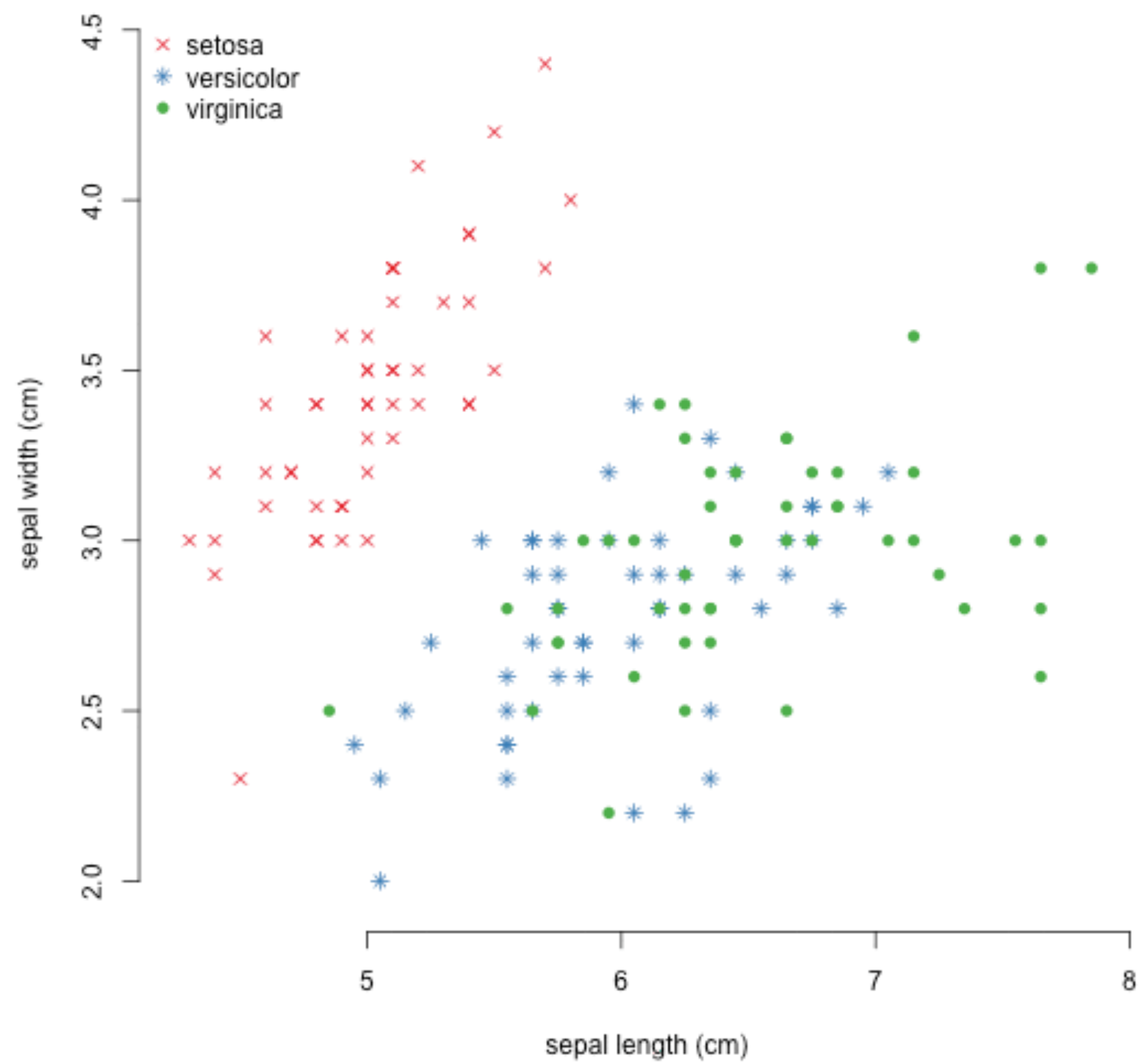
shape + animation



animation



shape + orientation + colour



shape + orientation + colour + animation

How many 3s?

455865876864565749286555584765298742309847249473247

324879427149572389742982479280742938742564875647654

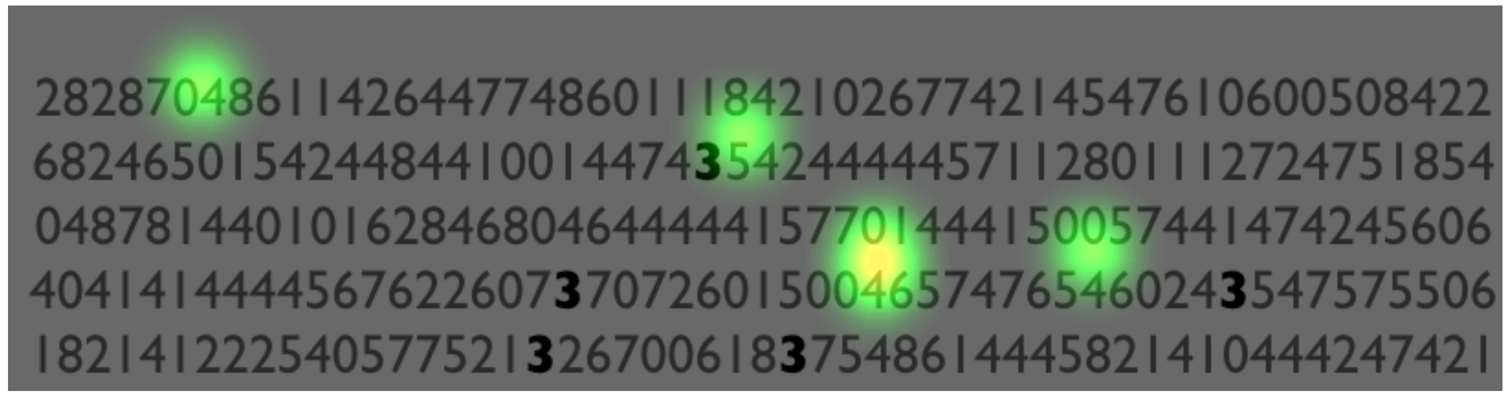
902842968476745464274784674573847648562484789847985

455865876864565749286555584765298742**3**0984724947**3**247

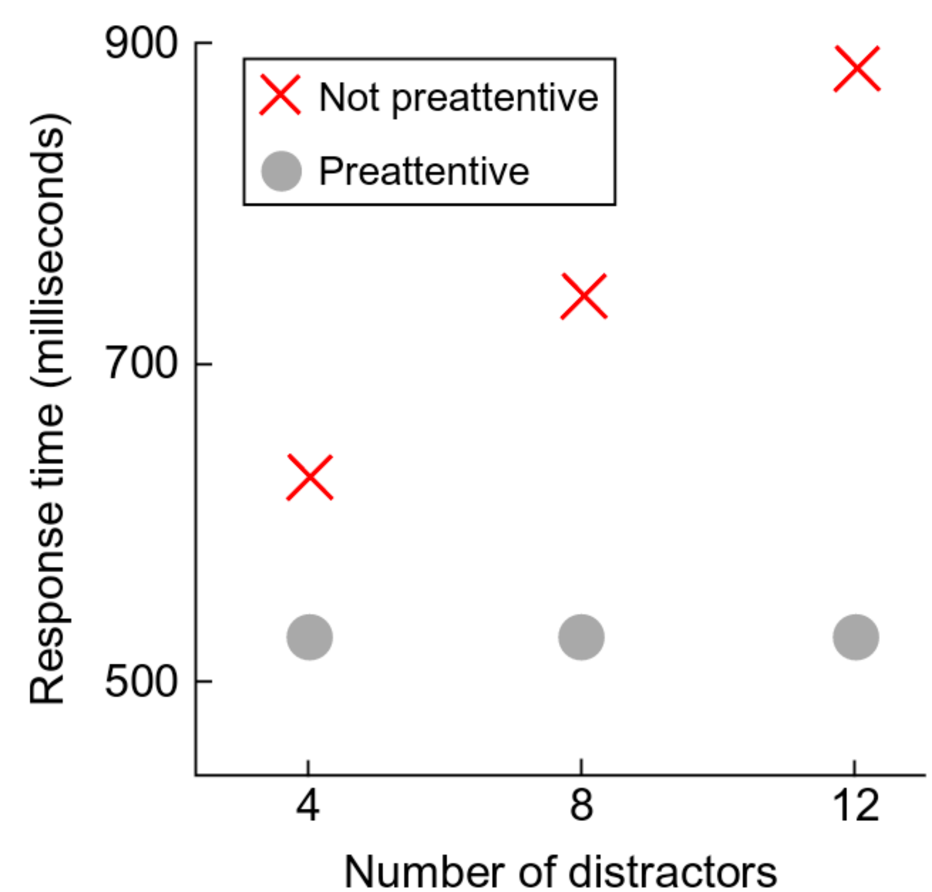
324879427149572**3**89742982479280742**9**38742564875647654

90284296847674546427478467457**3**847648562484789847985

Pre-attentive processing

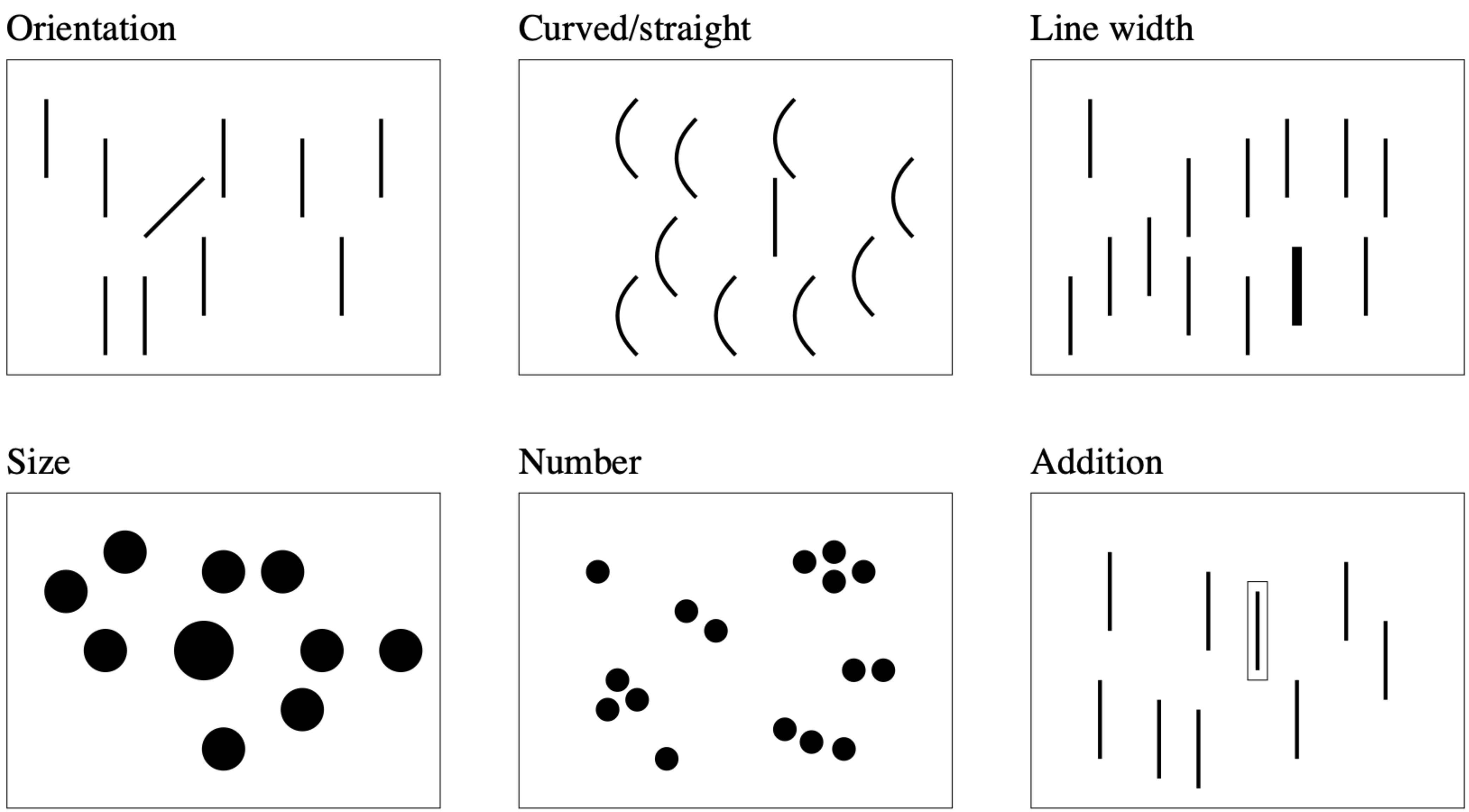


- Some visual objects are processed pre-attentively, before the conscious attention
- Pre-attentive features "pop out"
- Pre-attentive processing speed is independent of the number of distractors
- Processing speed of non-pre-attentive features is slower and the speed decreases as the number of distractors increases (i.e., you must go through all numbers to find 3s)



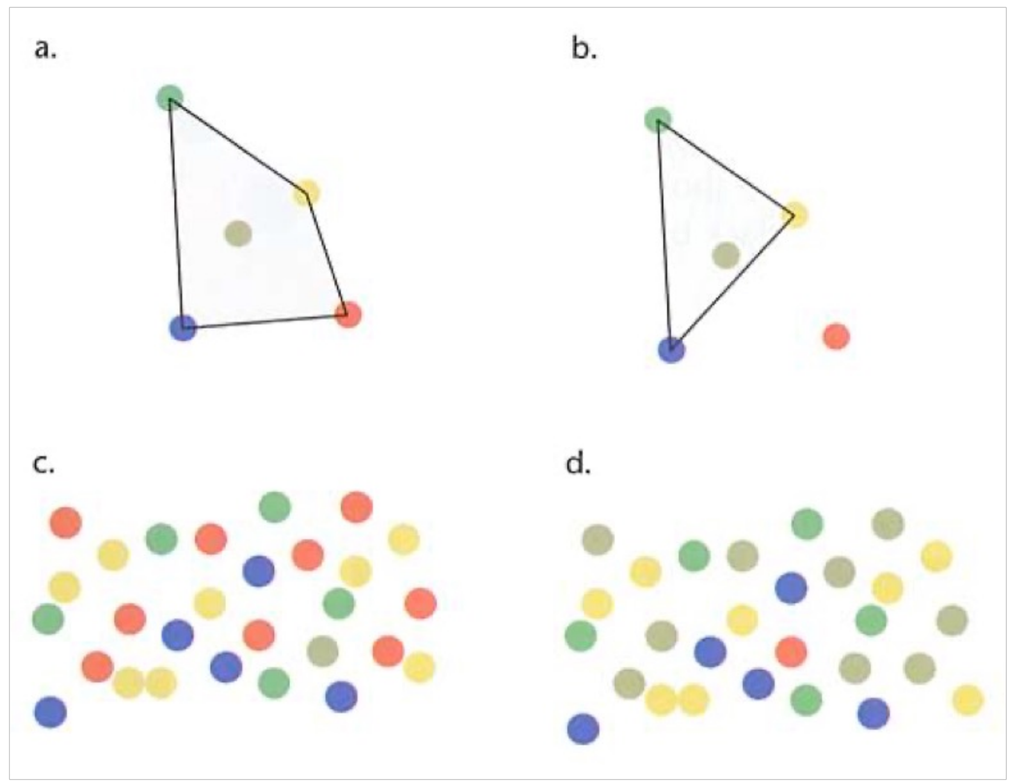
Pre-attentively distinct properties

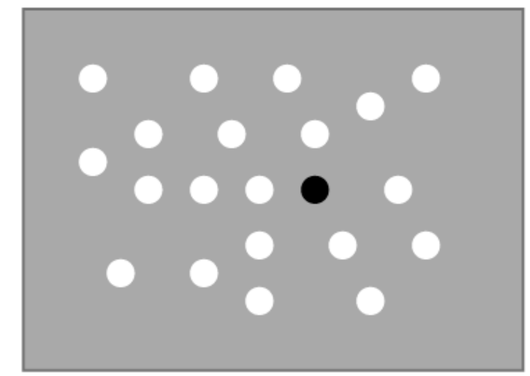
- **Form** (Line orientation, length, width and collinerity, size, curvature, spatial grouping, added marks, numerosity [up to four])

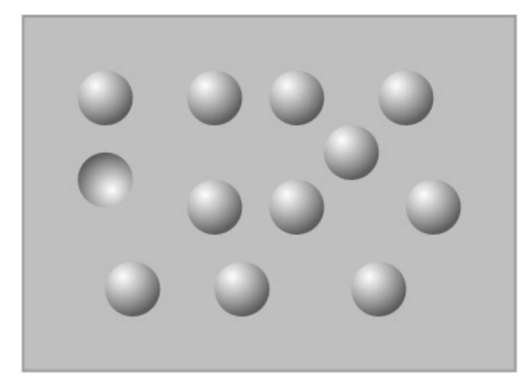


Pre-attentively distinct properties

- **Color** (hue, intensity [if outside CIE convex defined by other colors])

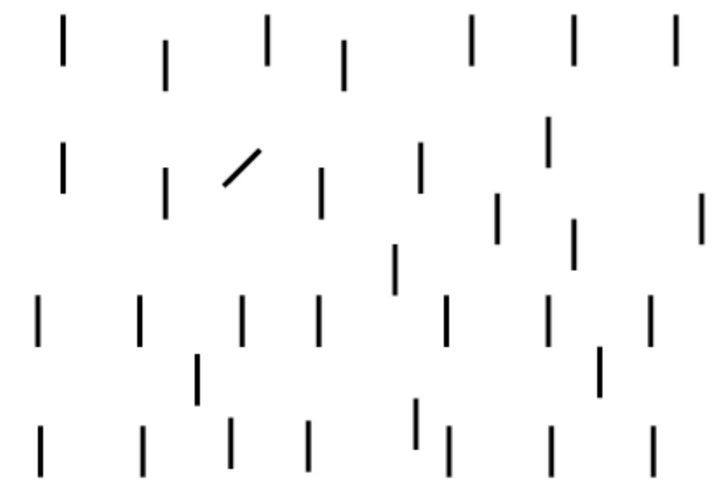




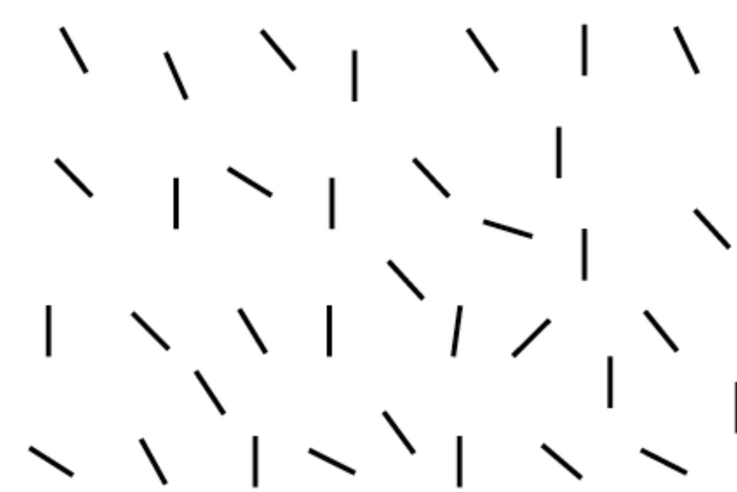


- **Motion** (flicker, direction of motion)
- **Spatial position** (2D position, stereoscopic depth, convex/concave form from shading)

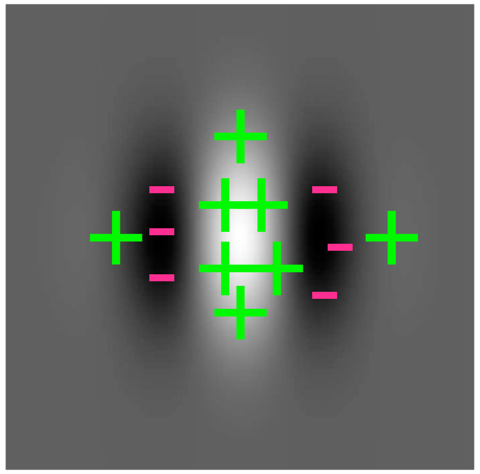
Pre-attentively distinct properties



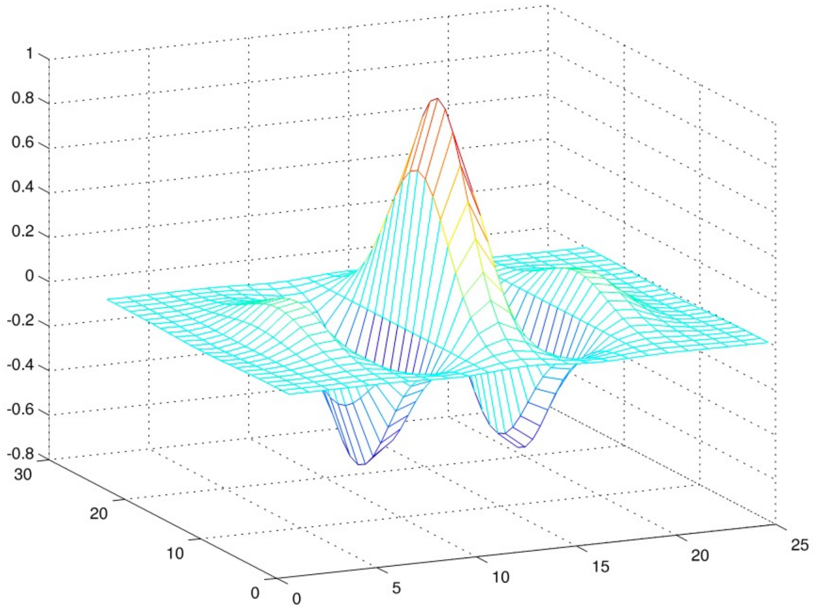
- Try to find the right-slanted line on the right
- Pre-attentive symbols become less distinct as the variety of distractors increases
- For maximum pop-out, a symbol should be the only object in a display that is distinctive on a particular feature channel
  - e.g., it might be the only item that is colored in a display where everything else is black and white



The Gabor model



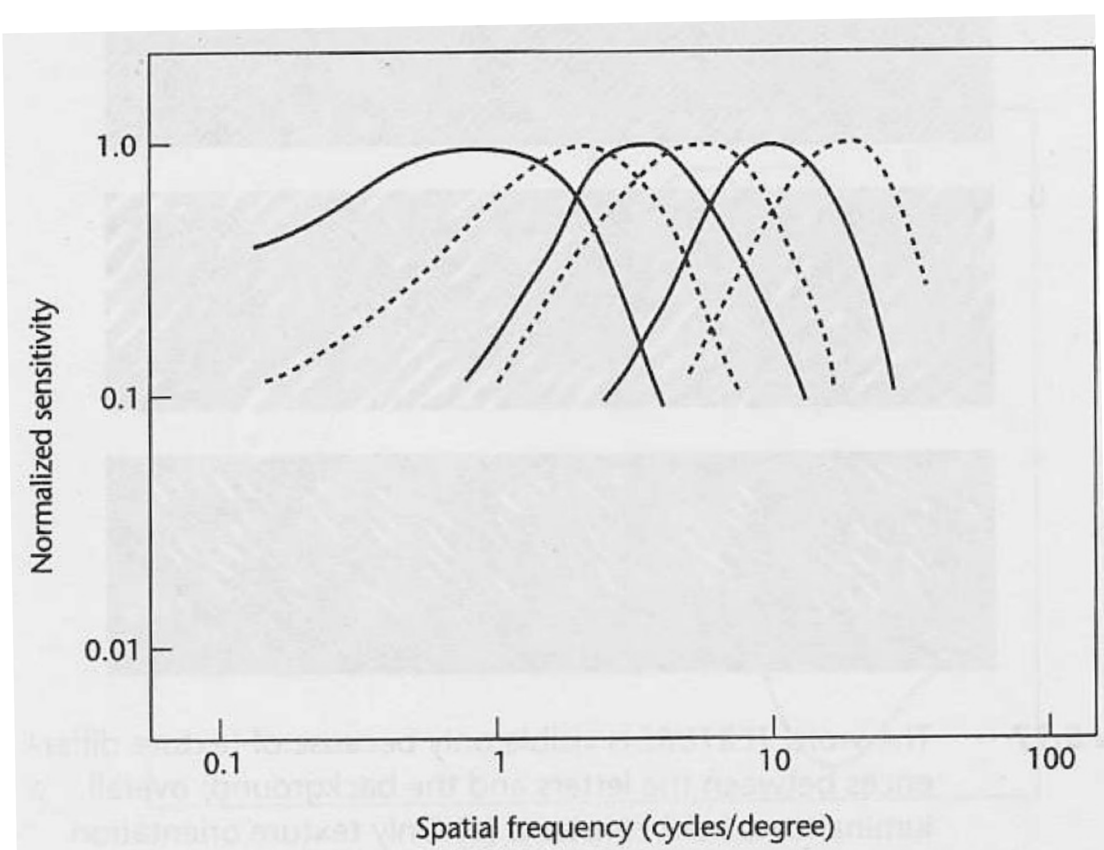
- V1 and V2 contain neurons that can filter **orientation** and **size** information
  - these neurons are tuned to respond best to a specific orientation and size
  - luminance patterns only, no color!
- The receptive field widths are around two cycles
- Ideal Gabor model has three parameters: contrast (C), orientation (O), and size (S) (or frequency 1/S).



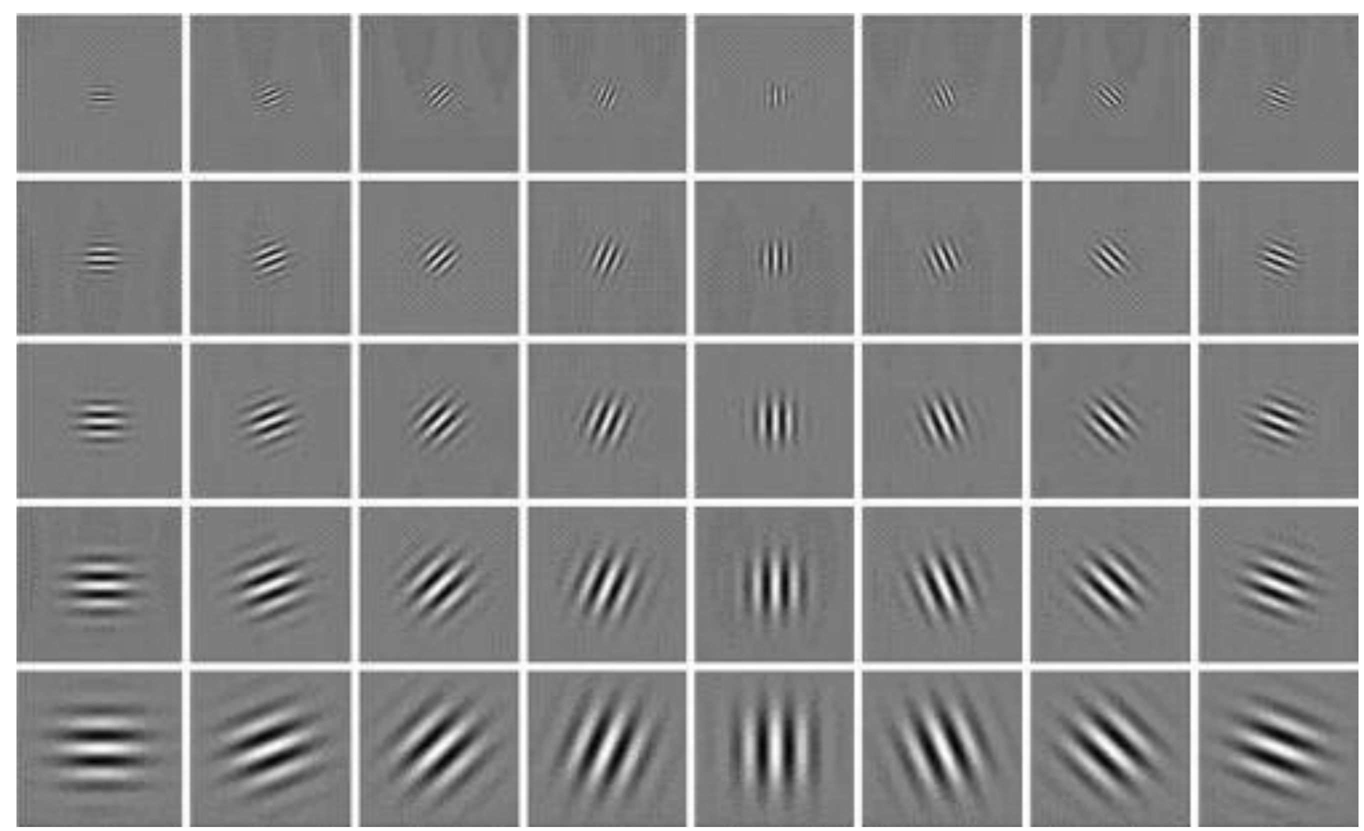
$$\text{Response} = C\cos\left(\frac{\pi}{\sqrt{2}}\frac{Ox}{S}\right)\exp\left(-\frac{1}{2}\frac{\|x\|^2}{S^2}\right)$$

Gabor model

- The parameters scale as follows:
  - **Size (1/frequency).** Exponential in range 1/16°–1/2°, c. 4 pre-attentively separable sizes.
  - **Orientation.** Linear in range 0°–180°, pre-attentive accuracy is ~ 30°.
  - **Contrast (amplitude).**



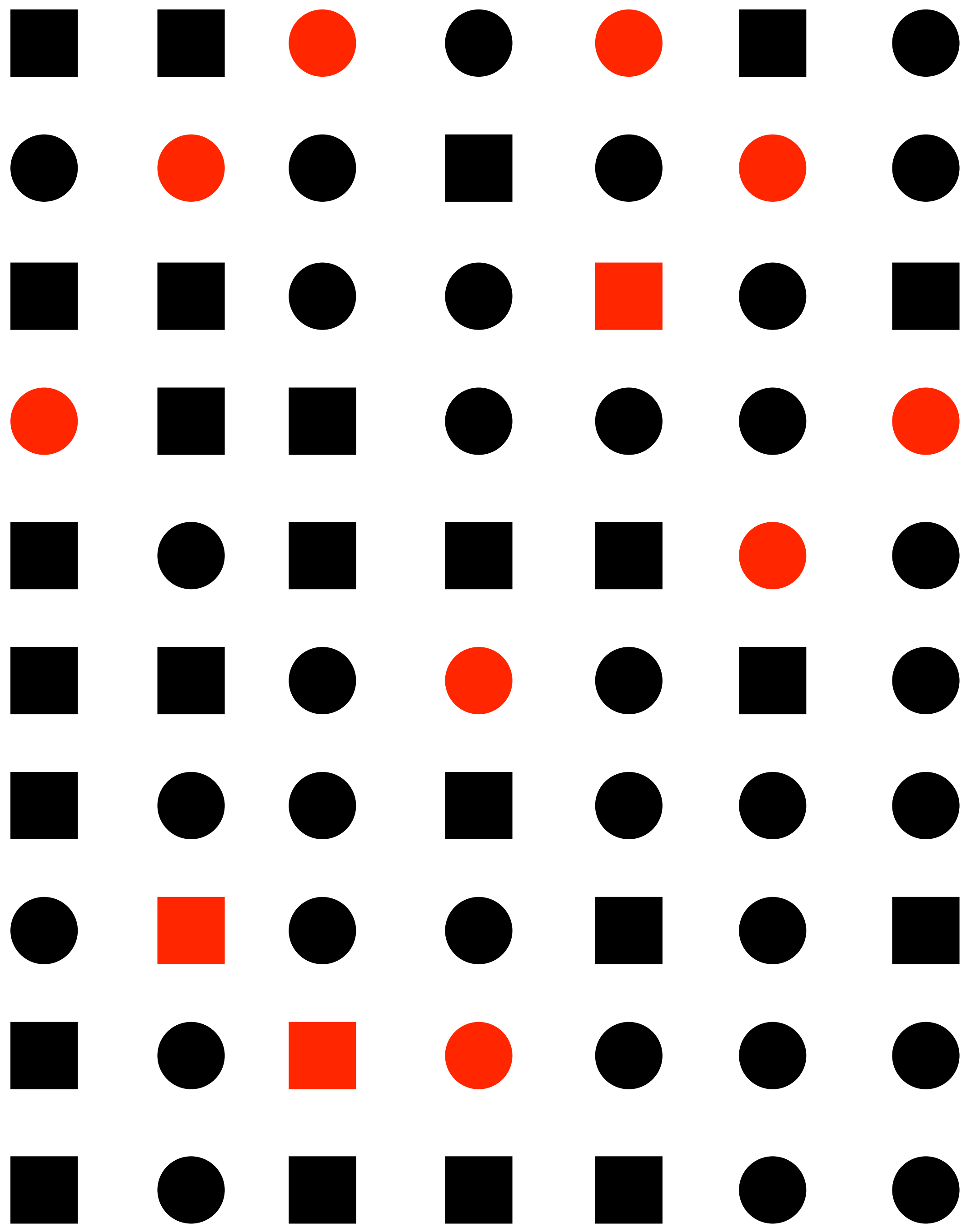
Wilson and Bergen (1983) [W 5.16]



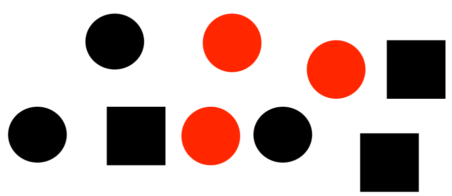
Conjunction searches

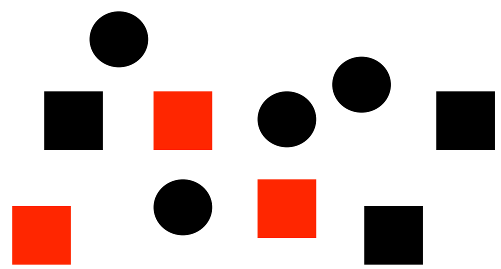
- **Conjunction search** is a visual search that involves searching a specific conjunction of several (2 or more) visual attributes
- Conjunction searches are usually not pre-attentive, even if the individual features are
- Examples:
  - “Find red and square objects” is not pre-attentive search (conjunction search)
  - “Find red objects” is pre-attentive search
  - “Find square objects” is pre-attentive search

How many red squares?

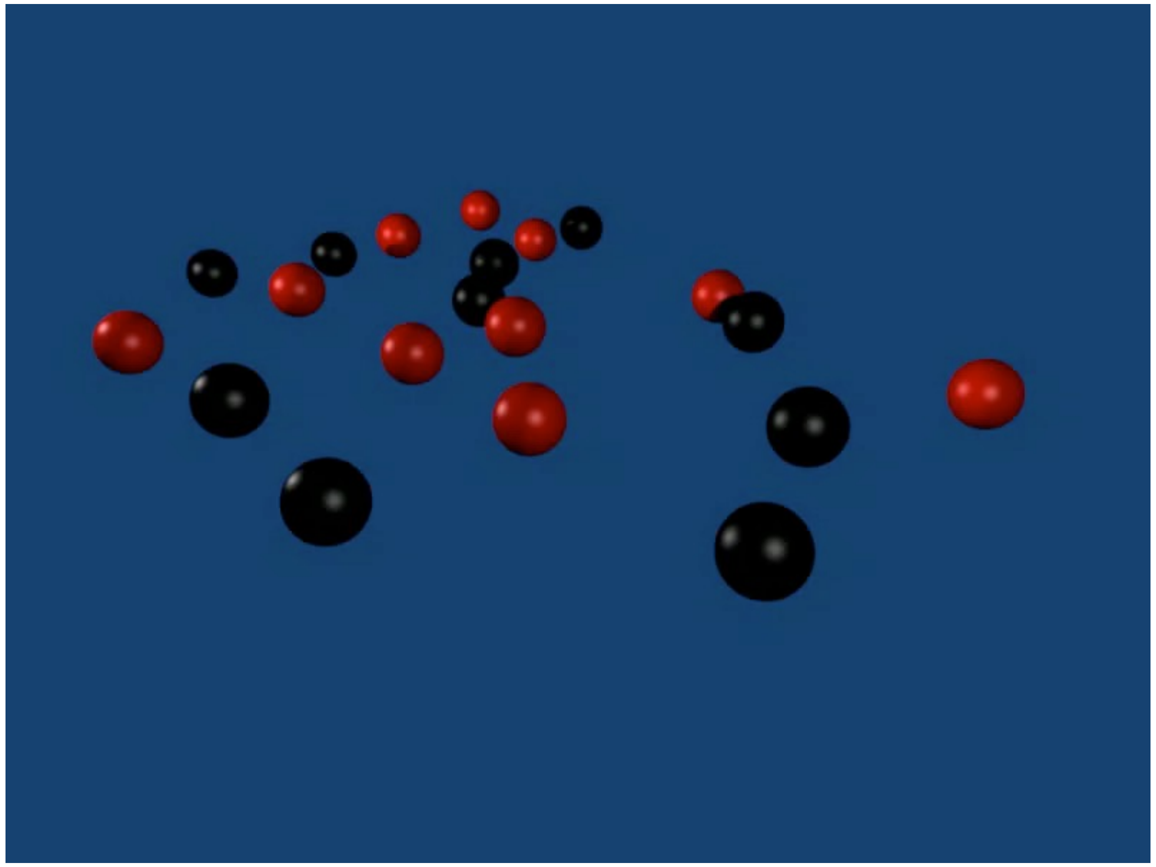


Conjunction searches





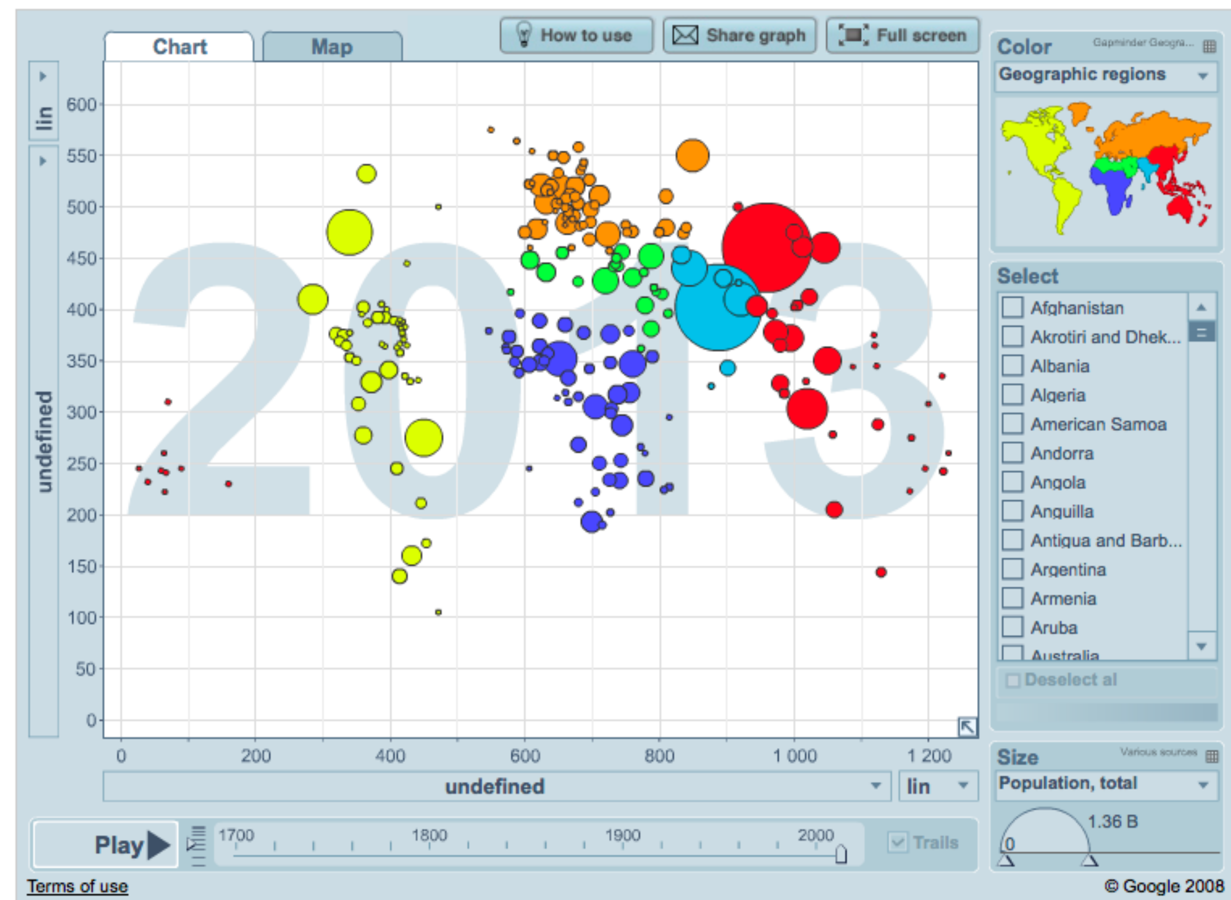
- Conjunction searches are usually not pre-attentive
- Some exceptions:
  - spatial grouping on the XY plane (“find red circles”)
  - motion (“find red moving things”)
  - stereoscopic depth
  - combination of convexity/concavity and colour



Glyph design

- Glyphs are symbols used to represent multivariate data
- A single glyph corresponds to one sample in a data set
- Data values are mapped to the visual properties of the glyph

- **How to design a glyph so that the data values can be perceived pre-attentively?**



www.gapminder.org

Glyph design

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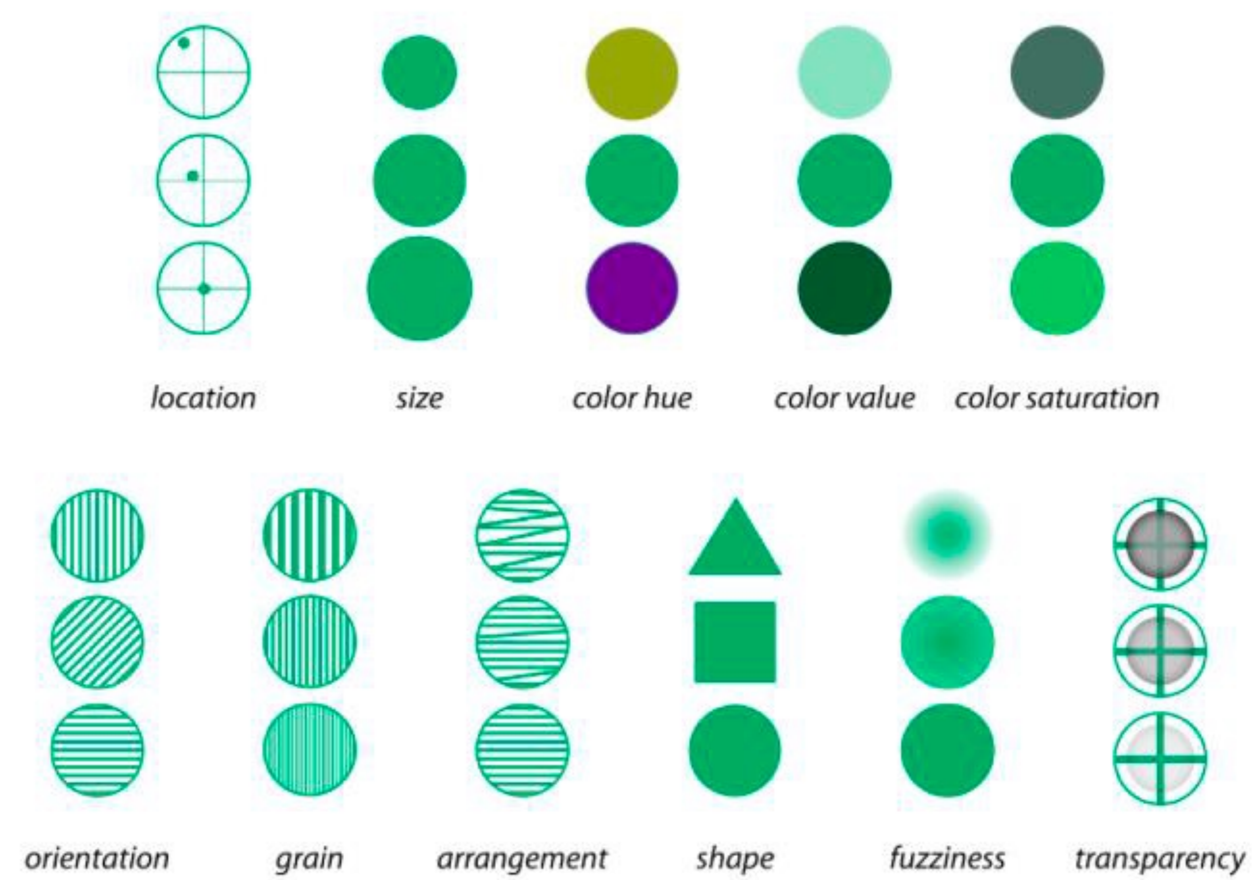
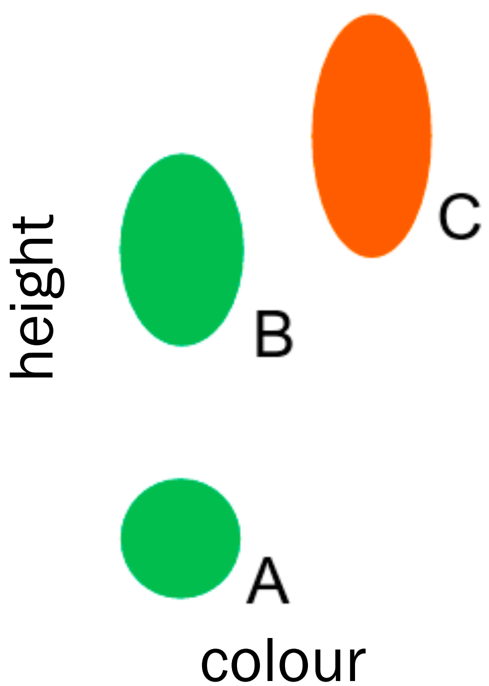


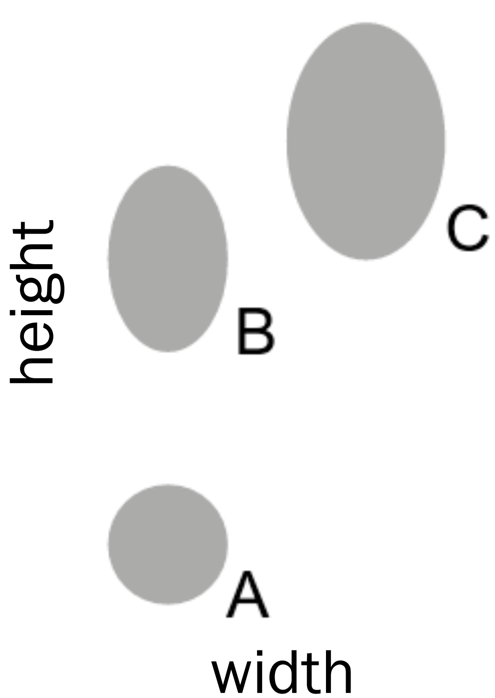
Mackinlay 1986,
https://doi.org/10.1145/22949.22950

Integral and separable dimensions

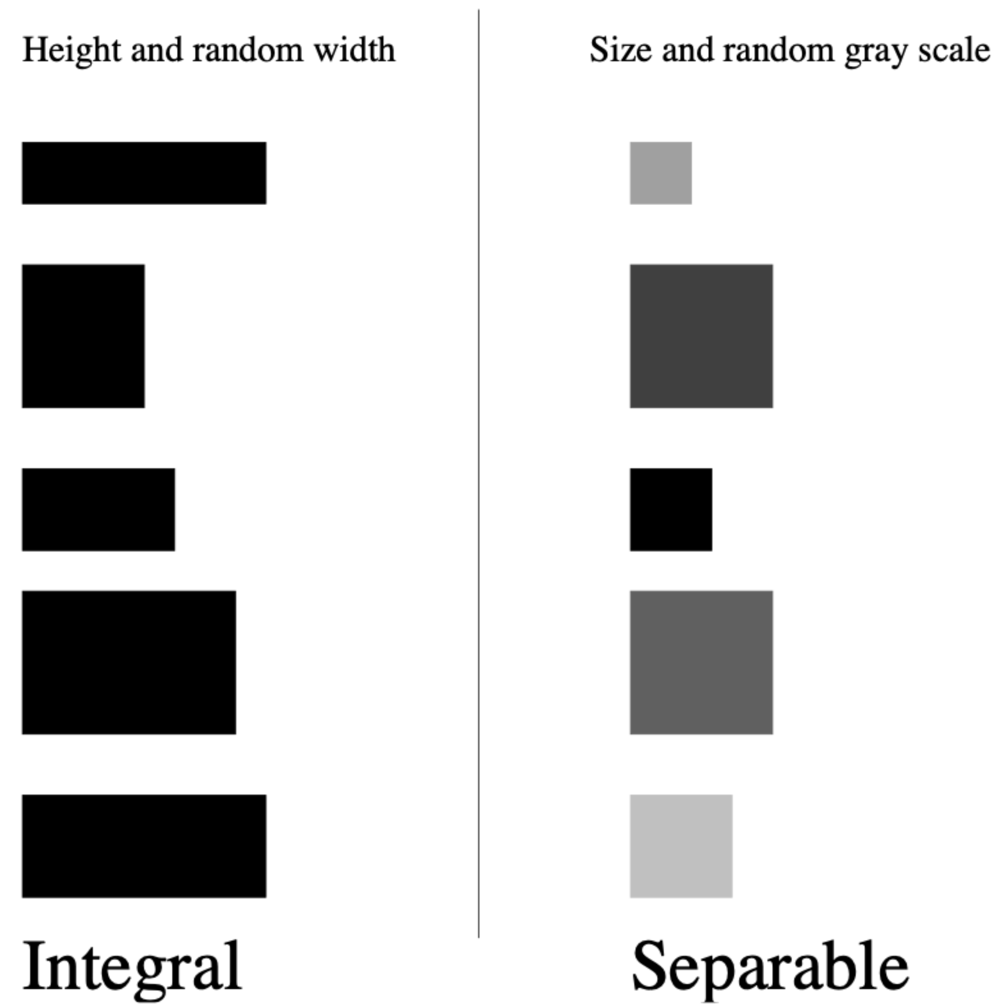
Which two glyphs go best together (restricted classification task)?



separable features are perceived independently of each other (e.g., size and color)

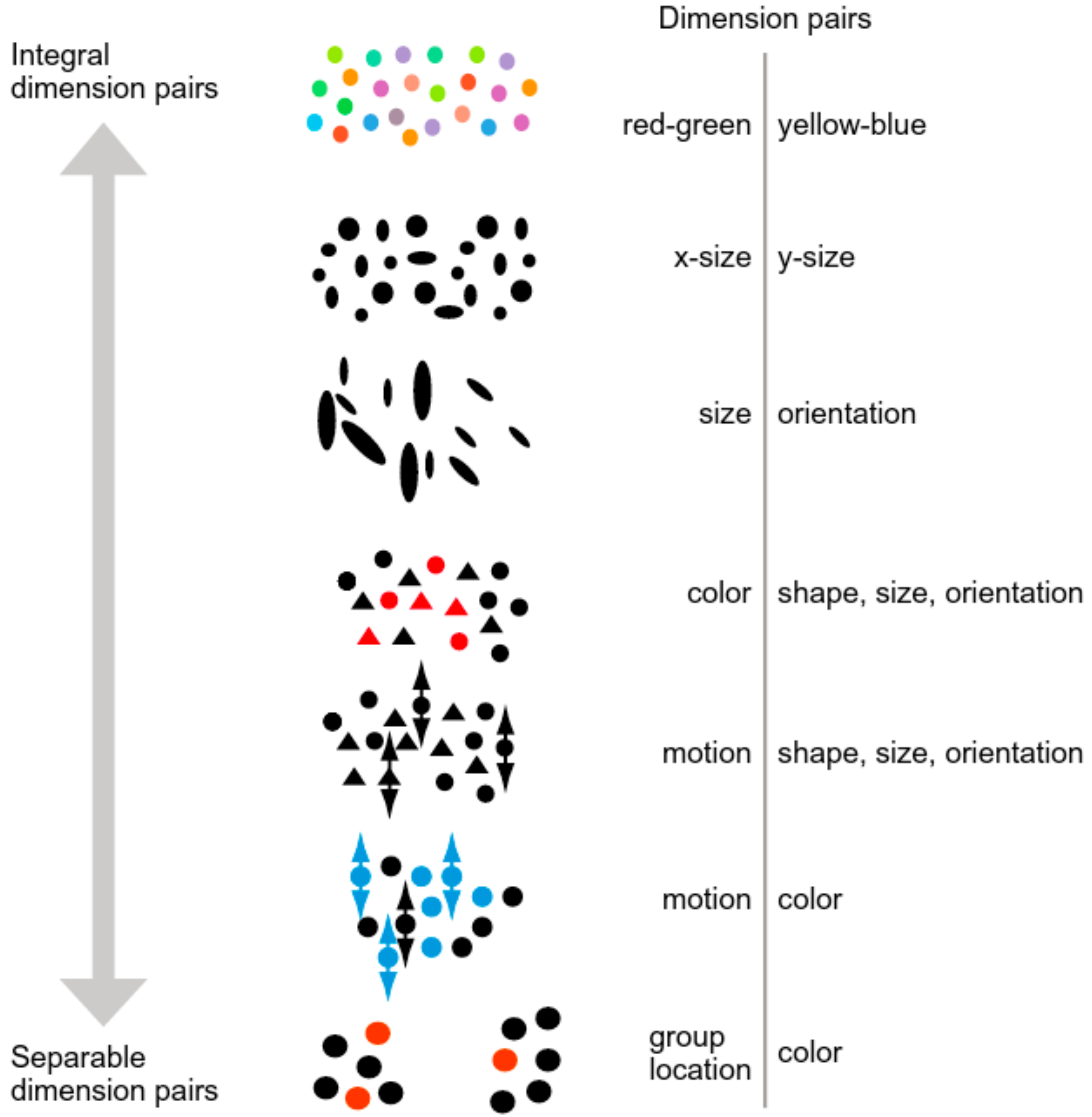


integral features are perceived holistically (e.g., a width and height)



Find this high rectangle.

Speeded classification task faster for separable features. Use separable dimensions to encode different variables in glyphs!


Dimension pairs
Integral dimension pairs
Separable dimension pairs
red-green
yellow-blue
x-size
y-size
size
orientation
color
shape, size, orientation
motion
shape, size, orientation
motion
color
group location
color

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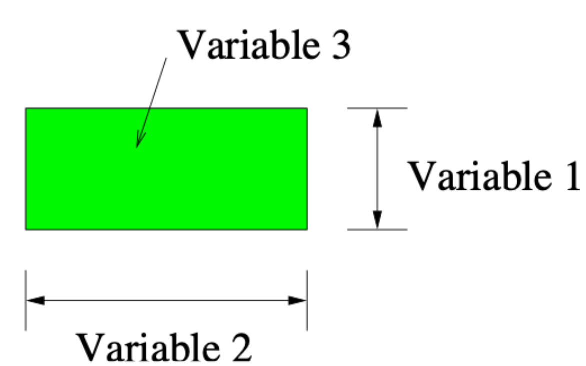
Glyph design: some rules of thumb

- All channels are not independent
  - try to use separable channels
  - in practice the number of channels to be used at once is limited
- If we want pre-attentive processing, we typically have 4-8 resolvable steps in each dimension (e.g., the number of size steps we can easily distinguish is ~4)

Visual variable	Dimensionality
Spatial position	3 (X, Y, Z)
Color of glyph	3
Shape	2-3?
Orientation	(1-)3
Surface texture	3
Motion coding	2-3?
Blink coding	1

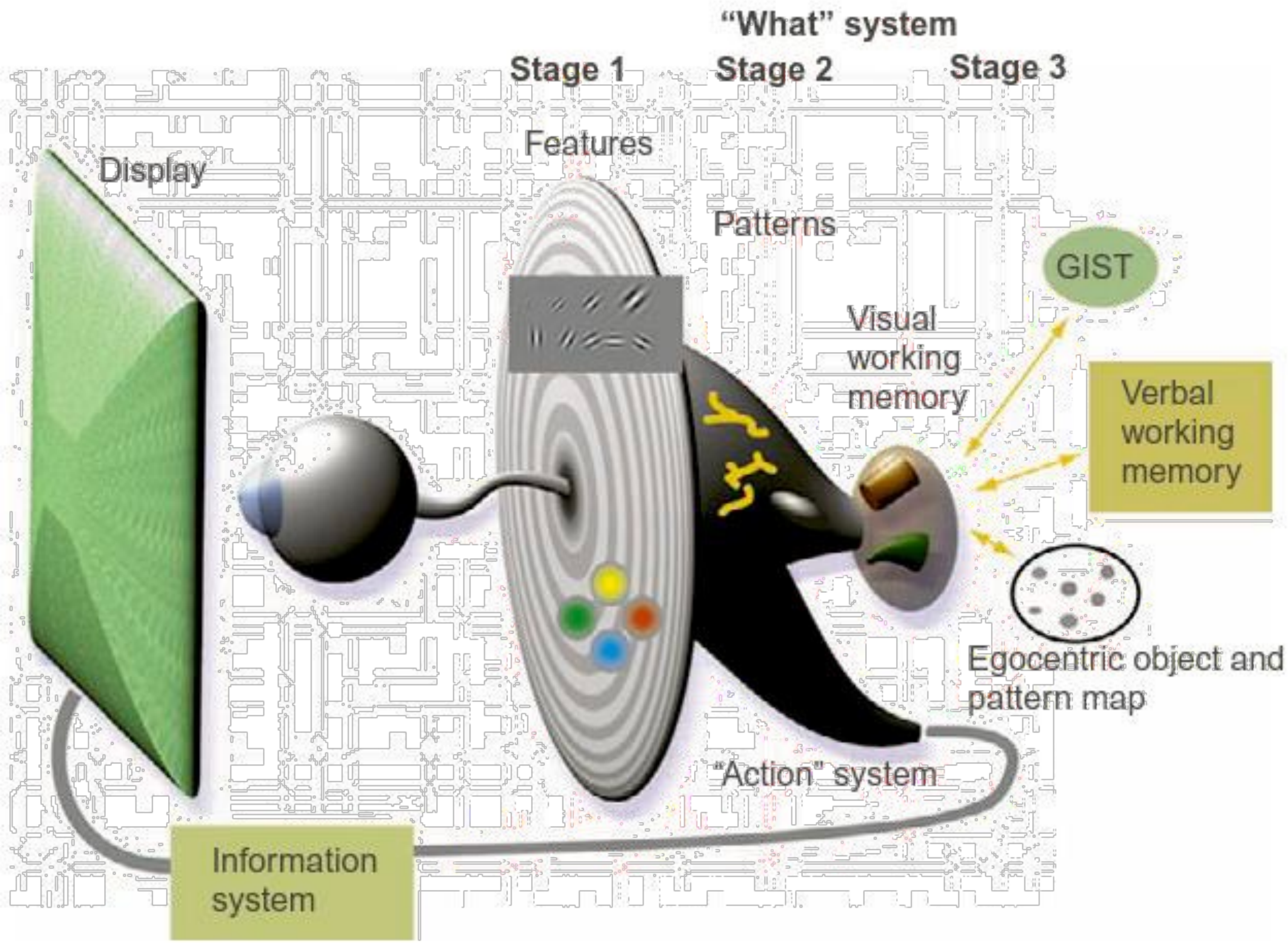


Summary of glyph design

- Certain visual features "pop out" (pre-attentive features)
- Data variables should (usually) be mapped to pre-attentive features (they are processed fast)
- Restrictions (if you want pre-attentive design):
  - conjunction searches are usually not pre-attentive
  - one can effectively display only limited number of visual variables, with limited accuracy
  - integral visual dimensions interfere with each other: you should use separable dimensions instead

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



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Patterns in 2D data

- Exploratory visualization is based on finding patterns from data
- Oversimplification: the patterns are recognized between pre-attentive processing and higher level object perception

- Relevant questions:
  - How do we see groups?
  - How can 2D space be divided into perceptually distinct regions?
  - When are two patterns similar?
  - When do two different elements appear to be related?

- Patterns may be perceived even where there is only visual noise

Gestalt laws

- **Gestalt** is form in German
- The Gestalt School of Psychology (1912 onwards) investigated the way we perceive form
- They produced several Gestalt laws (laws of organisation) of pattern perception
- The Gestalt laws translate directly into design principles of visual displays
- Many of the rules seem obvious, but they are violated often

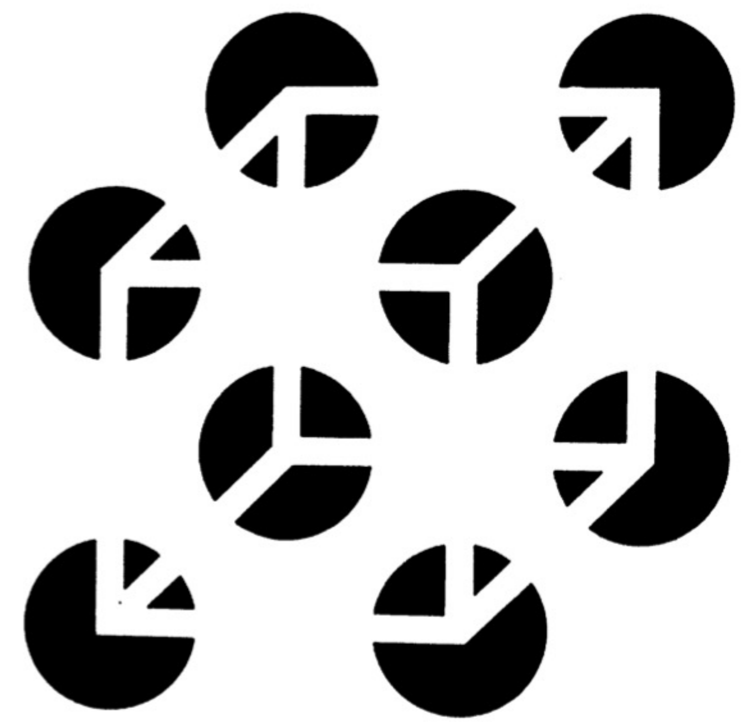


Figure 1. The subjective Necker cube. A phenomenally complete Necker cube can be seen overlying a white surface and eight black discs; so viewed, illusory contours corresponding to the bars of the cube can be seen extending between the discs. The illusory bars of the cube disappear when the discs are seen as 'holes' in an interposing surface, through which the corners of a partially occluded cube are viewed; curved subjective contours are then seen demarcating the interior edges of the 'holes'

Bradley and Petry 1977

Gestalt laws

- Similarity
- Good continuation
- Proximity
- Symmetry
- Closure
- Relative size
- Common fate

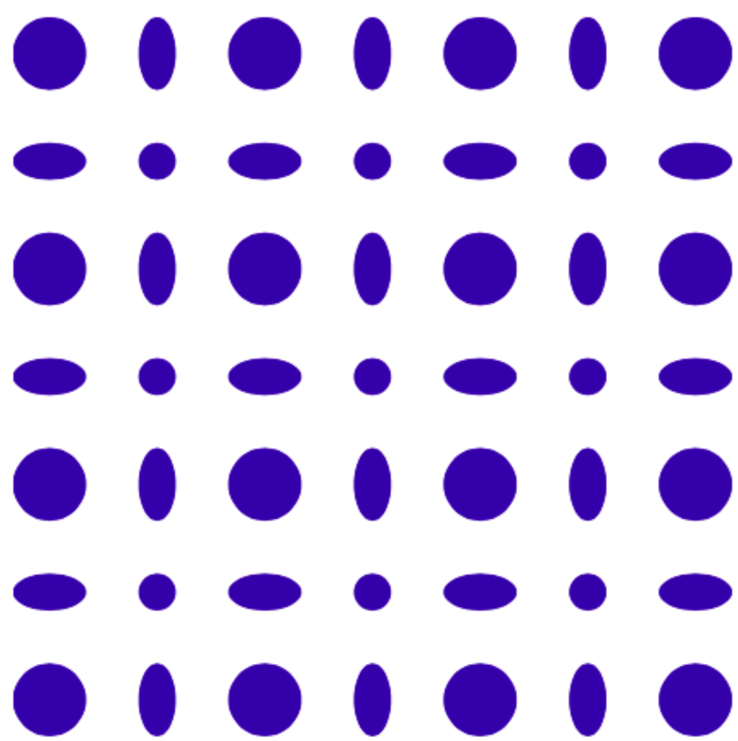
[there are various different lists]

e.g. https://www.usertesting.com/blog/gestalt-principles

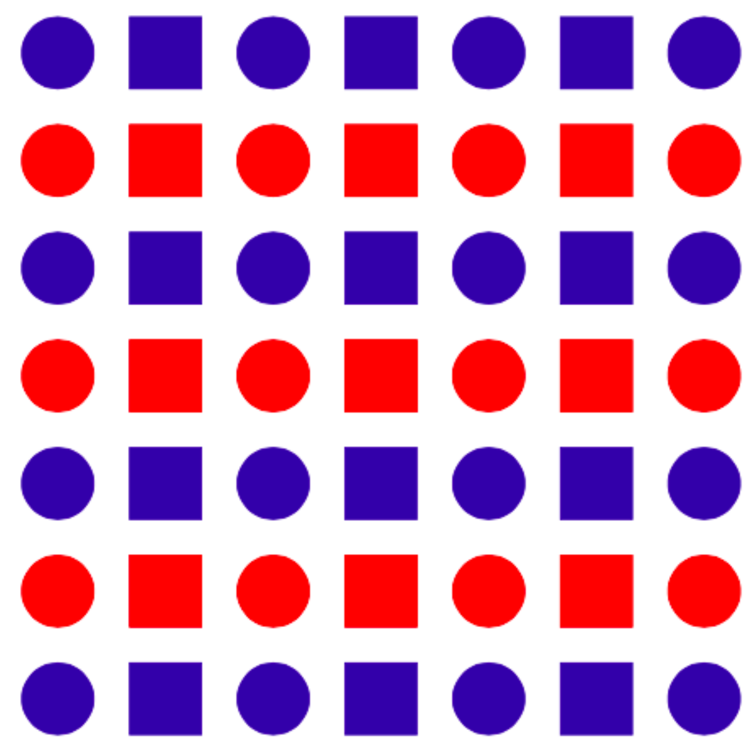
- some “new” motion-based Gestalt(-like) laws:
    - Patterns from motion
    - Animation and perception of shapes
    - Causality

Similarity

- Similar objects appear to be grouped together
- When designing a grid layout of a data set, code rows and/or columns using low-level visual channel properties, such as colour and texture



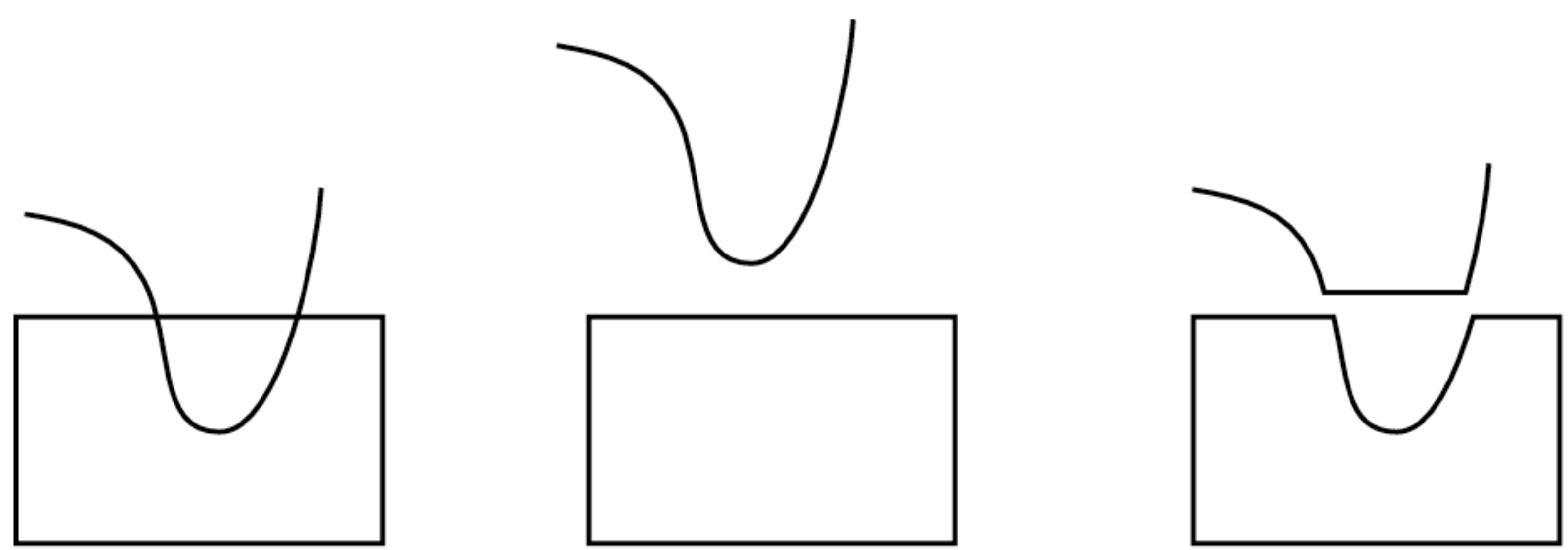
integral dimensions
emphasize overall pattern



separable dimensions
segment rows and columns

Good continuation

- Visual complete objects are more likely to be constructed from visual elements that are smooth and continuous, rather than ones that contain abrupt changes in direction



The pattern on the left is perceived as a curve overlapping a rectangle (centre) rather than 2 irregular shapes touching (right).

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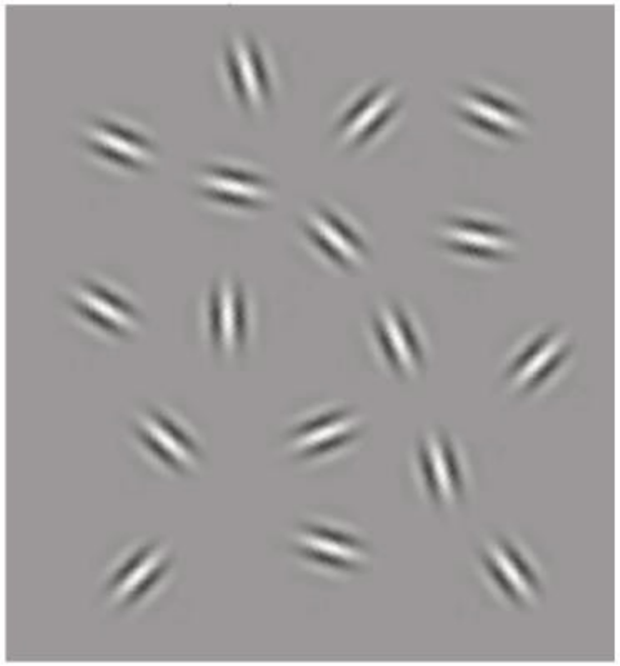
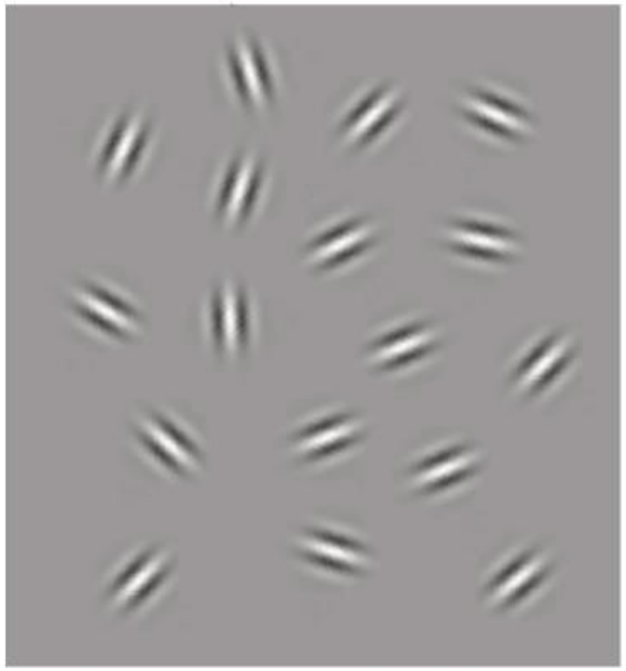
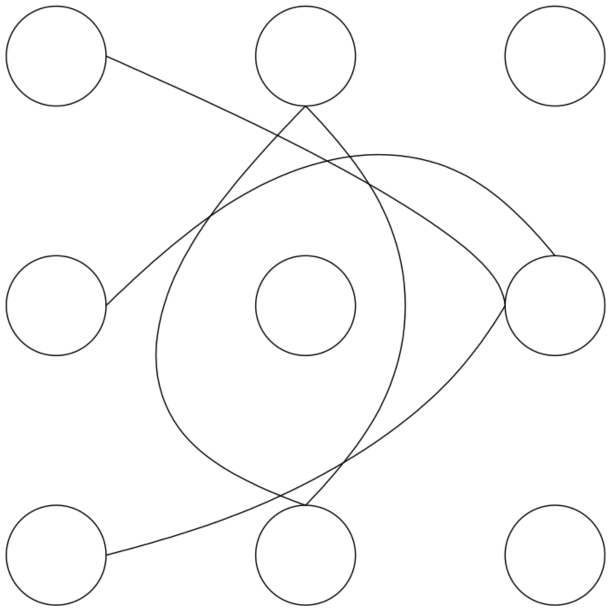
Good continuation

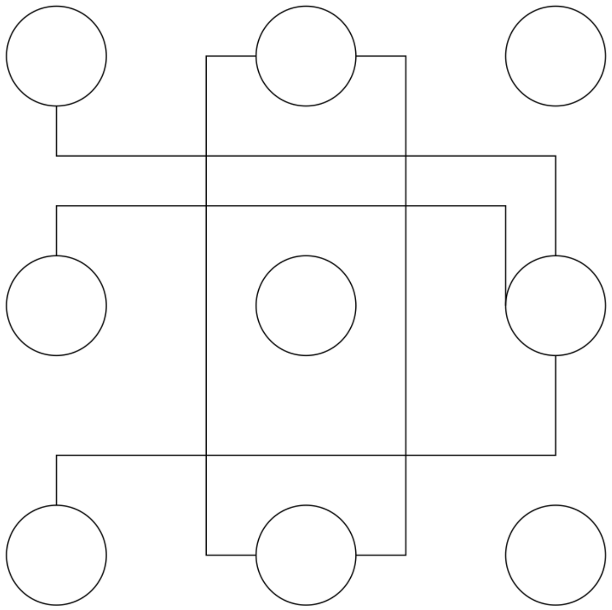
- Connectedness is one of the most powerful grouping principles
- It is easier to perceive connections when contours run smoothly
- In networks, lines connecting nodes should be smooth and continuous, so they are easier to follow

follow the path:









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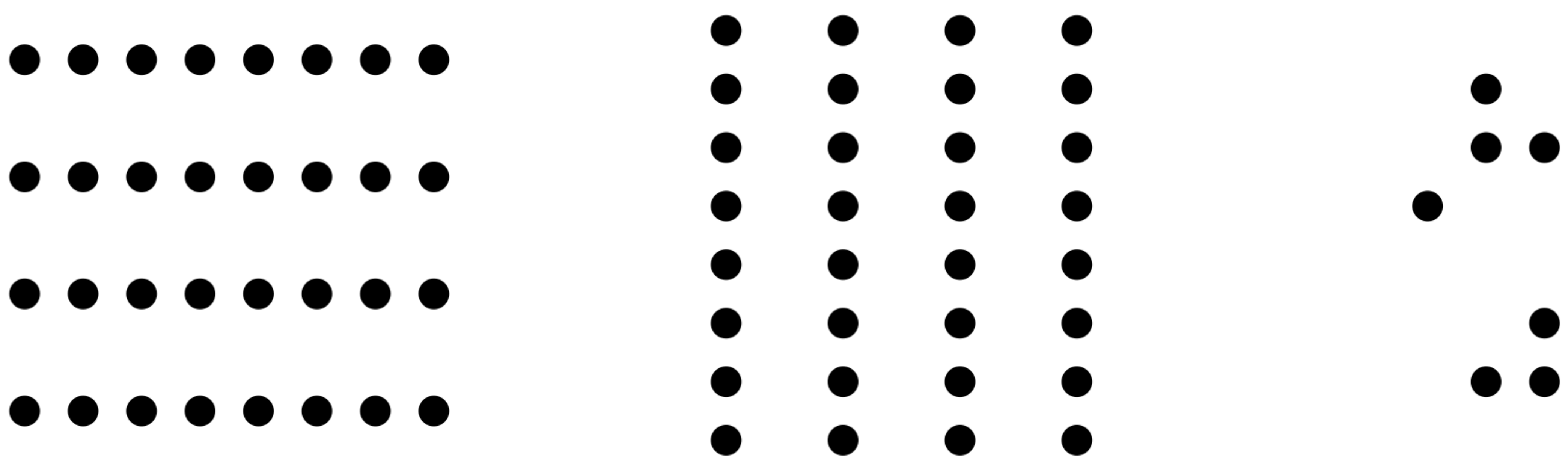
Proximity

- Things that are near to each other appear to be grouped together
- Proximity is one of the most powerful gestalt laws

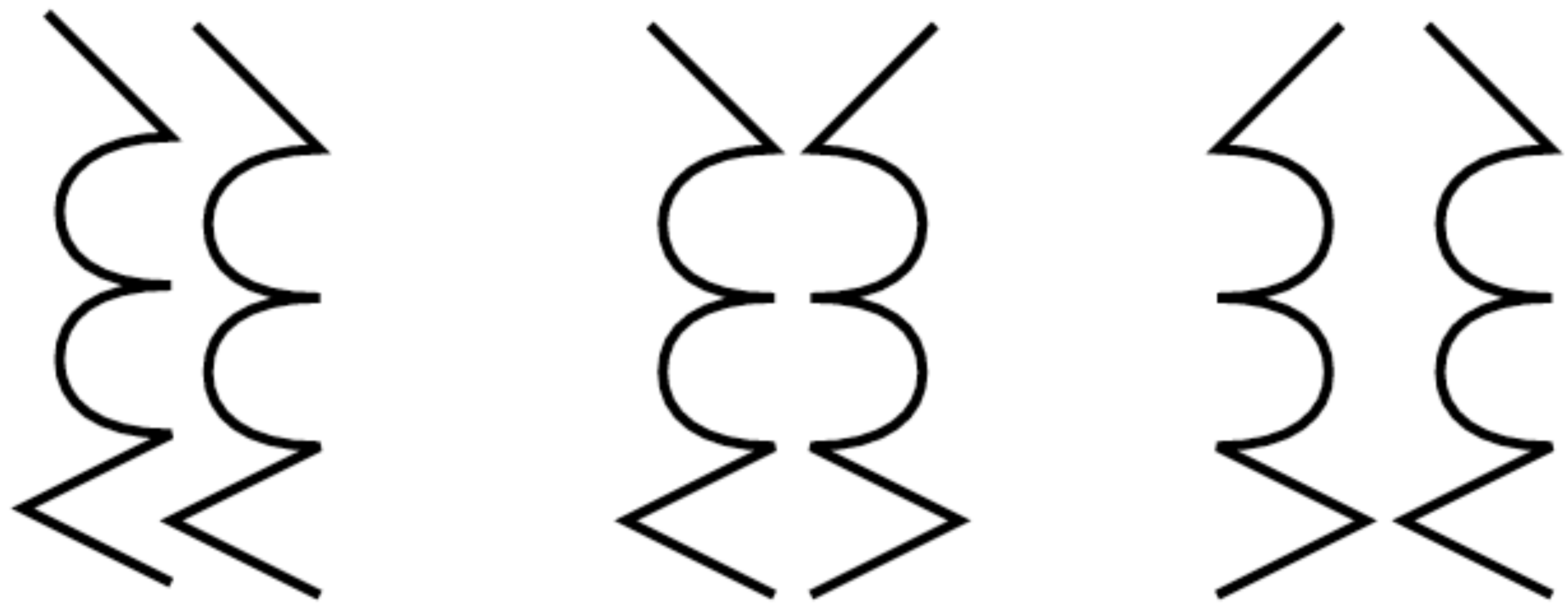
- Place the data elements into proximity to emphasise connections between them

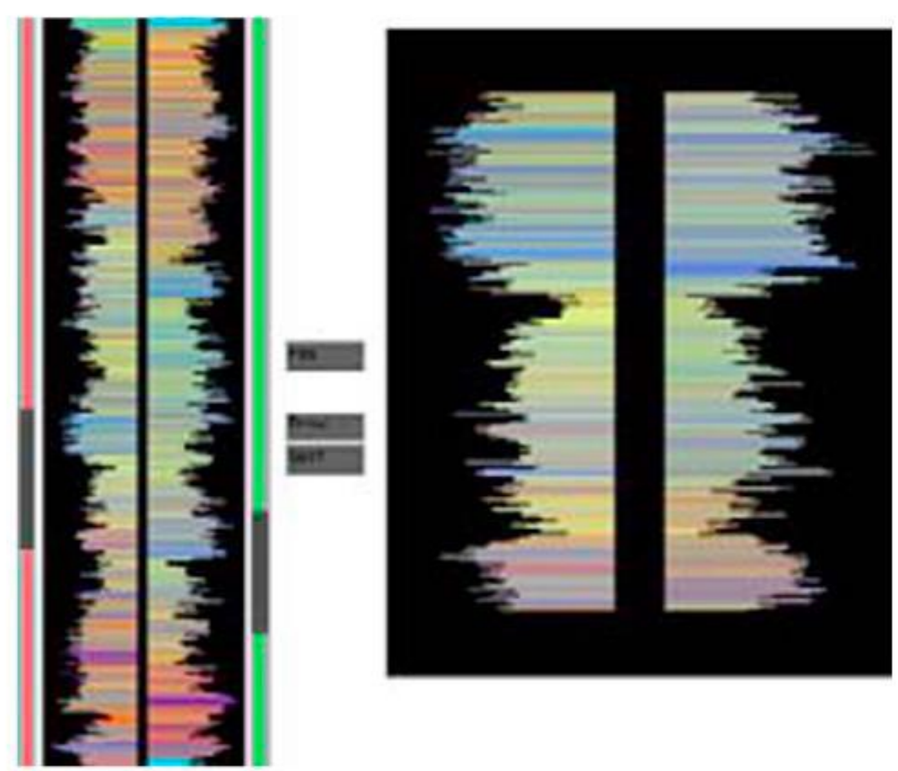


Symmetry

- Symmetrically arranged pairs of lines are perceived together

- Use symmetry to make pattern comparisons easier
- Symmetrical relations should be arranged on horizontal or vertical axes (as symmetries are more easily perceived), unless a framing pattern is used





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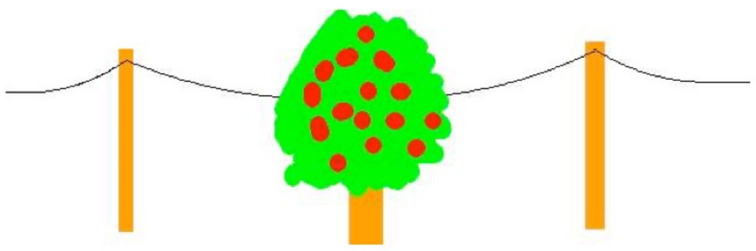
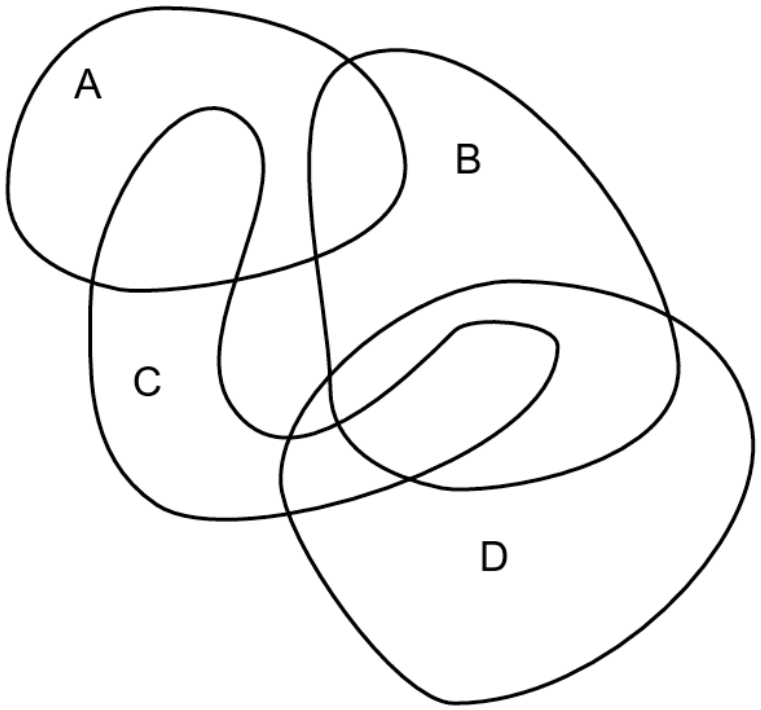
Closure

- A closed contour tends to be seen as an object
- There is a perceptual tendency to close contours that have gaps in them
- When a closed contour is seen, there is a very strong perceptual tendency of dividing space into a region enclosed by the contour (a common region) and a region outside the contour
- In window-based interface strong framing effects inhibit between-window comparisons: related items should not reside in separate windows

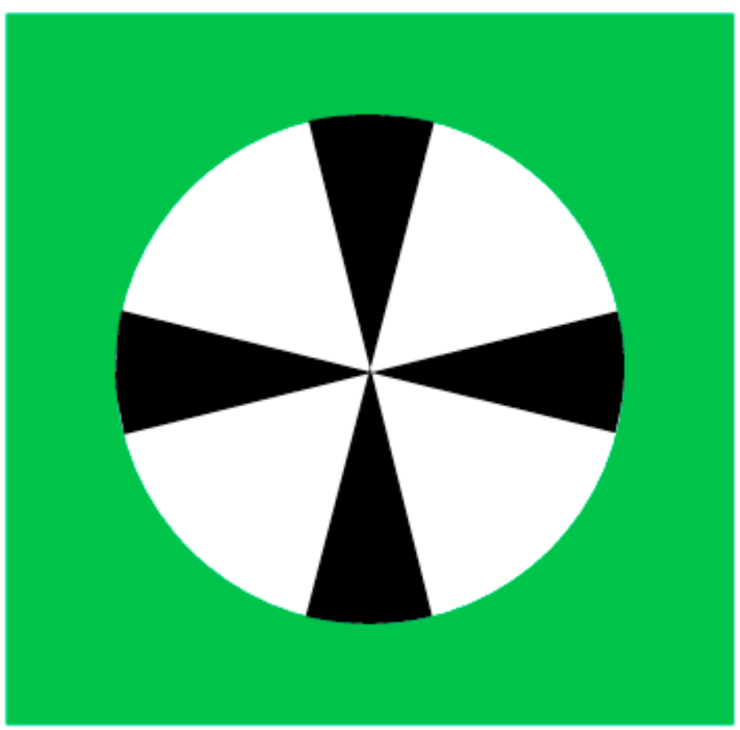




What do you see in this image?
(a famous example of closure)

Relative size, figure/ground

- Smaller components tend to be perceived as an object
- Groupings perceived as overlapping objects



black propeller on
white background

Rubin's reversible
face-vase figure
(multistability)

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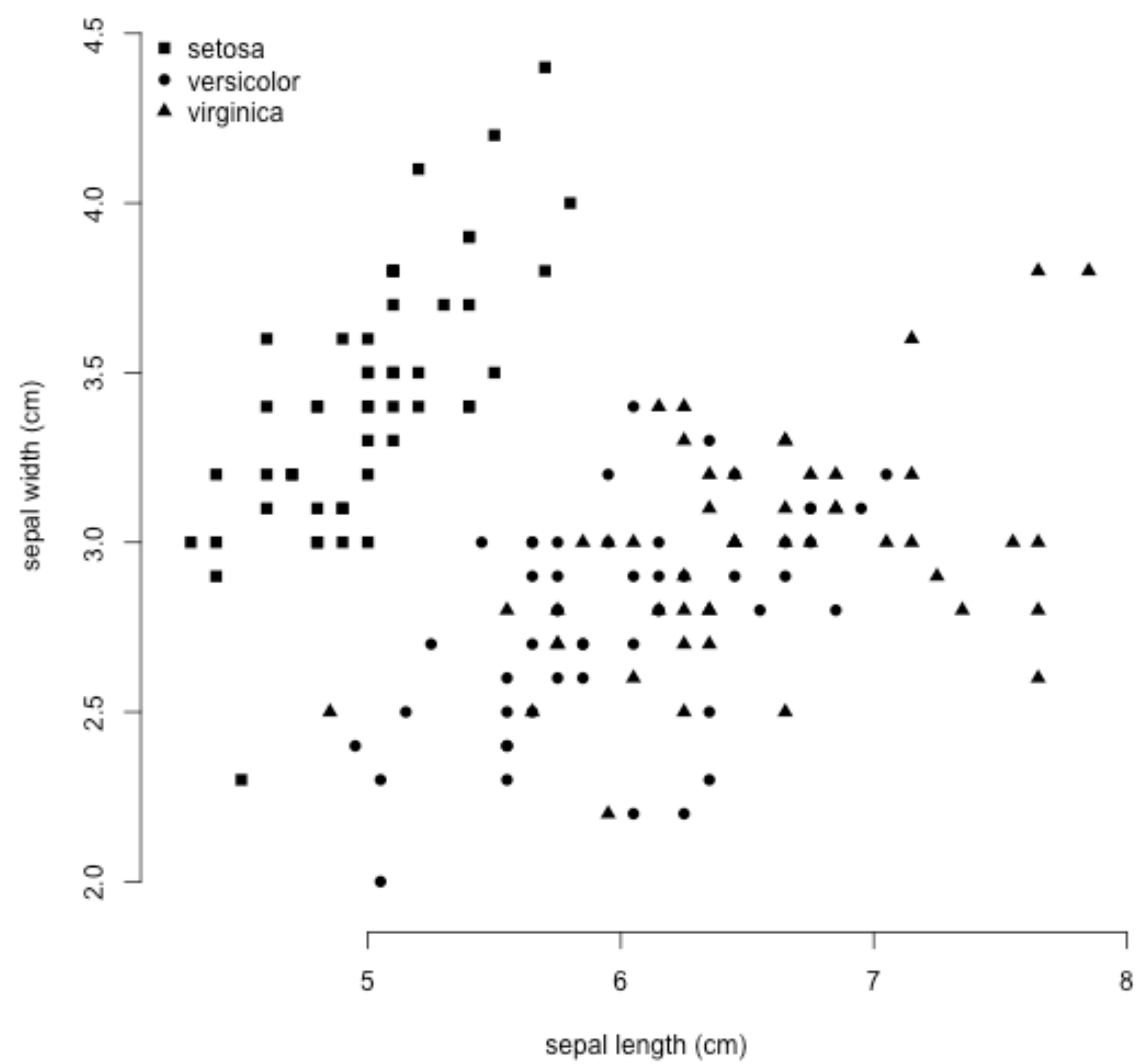
Common fate

- Relative motion is an extremely efficient method of showing patterns from data
- Data points oscillate around center point
  - Variables: frequency, phase, amplitude of motion
  - Phase is the most effective variable



Animation and perception of shape

- Gestalt laws also work for animated images: structures and patterns are seen from partial data (as with static images)
- Mystery lights in the dark:

Another example

- There is a specific area in human brain for detecting biological motion

See also: https://www.biomotionlab.ca/html5-bml-walker/

No delay

Causality

- *Launching:* an object is perceived to set another into motion
- Perception of launching requires precise timing (delays less than 0.07-0.16 s)
- Already infants can perceive causal relations, such as launching

Delay of 0.2 s

Next lecture

- Interacting with visualisations (Ware Ch 10 + other)
- (tentatively) Introduction to dimension reduction