CMU 05-899, Fall 2025

Perception + Accessibility

Data Visualization

Frank Elavsky, slides built on by Adam Perer and Dominik Moritz

dig.cmu.edu

What you will learn today

- Why Perception is important for Visualization
  - How to show relationships
  - How to draw attention
  - How to minimize risk of overlooking
  - Different ways that people perceive

PERCEPTION

Identification and interpretation of sensory information

From the physical stimulus to recognizing information

Shaped by learning, memory, expectation

COGNITION

The processing of information, applying knowledge

Hear someone speak: Perception

Understand the language and the words: Cognition

PERCEPTION VS. COGNITION

Perception

Eye, optical nerve, visual cortex

Basic perception

First processing

(edges, planes)

Not conscious

Reflexes

Cognition

Recognizing objects

Relations between objects

Conclusion drawing

Problem solving

Learning

…

PERCEPTION VS. COGNITION

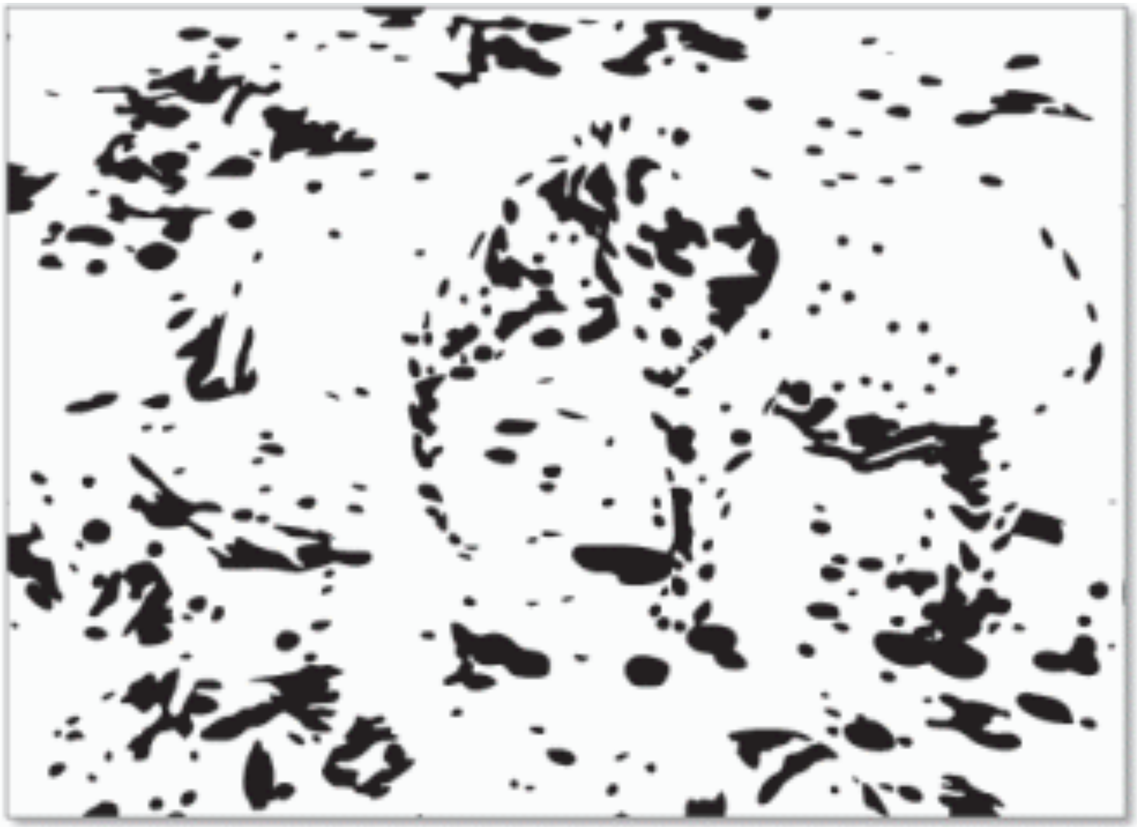
(Research has been visually-biased for 100+ years!)

Perception	Cognition
Eye, optical nerve, visual cortex	Recognizing objects
Basic perception	Relations between objects
First processing	Conclusion drawing
(edges, planes)	Problem solving
Not conscious	Learning
Reflexes	…


RED GREEN BLUE YELLOW PINK
ORANGE BLUE GREEN BLUE WHITE
GREEN YELLOW ORANGE BLUE WHITE
BROWN RED BLUE YELLOW GREEN
PINK YELLOW GREEN BLUE RED

LOOKING VS. SEEING

Emergence Images - Perceptual Hysteresis



Looking only at patches doesn’t work

http://graphics.stanford.edu/~niloy/research/emergence/emergence_image_siga_09.html


© EDGAR MUELLER - METANAMORPH.COM
we rely on priors
RIVER STREET
24 and more flavors of soft serve
www.icecreamflavors.com 1-800-392-3336
RIVER STREET

3d illusion street art

Google

3d illusion street art

amazing | cool | wall | murals | sidewalk | chalk | edgar mueller | mind blowing | pavement | spray paint | julian beever

Free shipping | Free shipping | Free shipping | Free shipping

20+ Amazing 3D Street...
mymodernmet.com

3D street art photos: What's the secret ...
cnn.com

50 Absolutely Stunning 3...
hongkiat.com

3D Street Art Illusion - Making of and ...
youtube.com

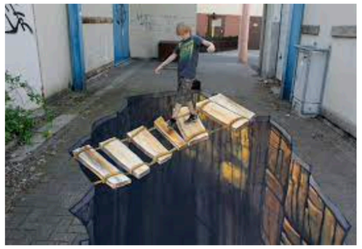
Amazing 3D Street Art Illusion ...
youtube.com

street murals with optical illusions
matadornetwork.com

optical illusion | 3d street art ...
pinterest.com

Talented Mexican Street Artist ...
boredpanda.com

Optical illusion 3D stre...
pinterest.com



20+ Amazing 3D Street Art Illusions ...
mymodernmet.com

Optical Illusions: Amazing 3D ...
geeks3d.com

3D Street Art - Amazing Optical Illusions
flixxy.com

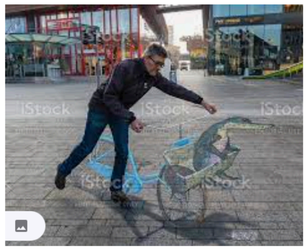
Street art illusions ...
pinterest.com

25+ Amazing Images of 3D Street Art
interestingengineering.com

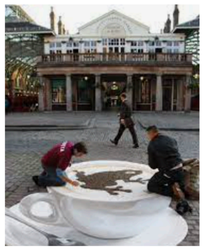
3D street art: a question of ...
theguardian.com

Graffiti artist creates mind-b...
thesun.co.uk

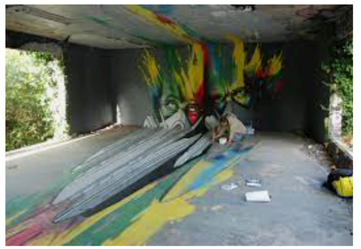
3D Illusions Street Art 1 | St...
pinterest.com



Street Art Showing Optical Illusion ...
istockphoto.com

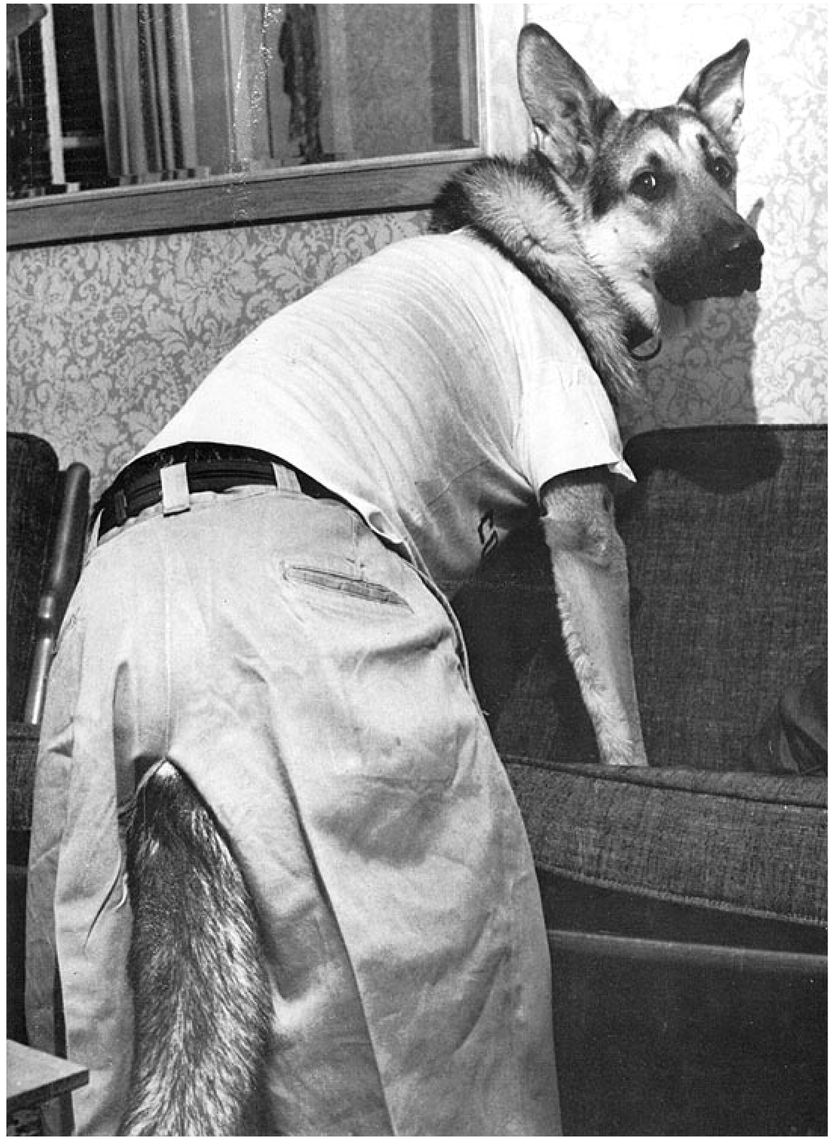


3d Street Art- Everythin...
streetadvertisingservices...



3D street art photos: What's the secret ...
cnn.com

Step into 3D street art | Widewalls
widewalls.ch



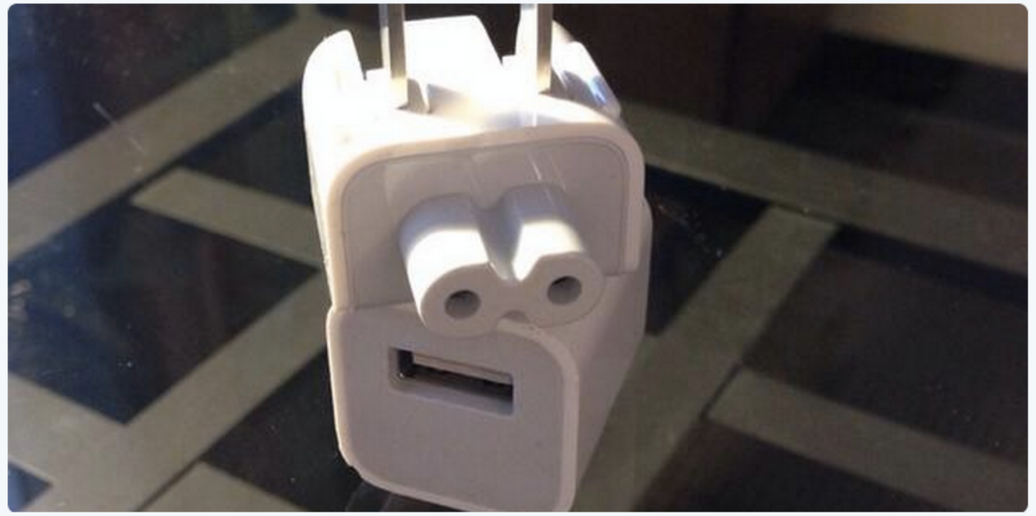

dribbleglass.com

PAREIDOLIA

Faces in Things @FacesPics · Mar 9
These chairs have seen some terrible things pic.twitter.com/GjIc9wuP47

Faces in Things @FacesPics · Feb 14
Deep in thought Deep Fryer pic.twitter.com/1Qyqjmslka

Faces in Things @FacesPics · Mar 22
Hey little guy! pic.twitter.com/nt2BgwZeTR



Faces in Things @FacesPics · Mar 10
A terrified pickle pic.twitter.com/Ffph1wzTyv

TAKE HOME POINT

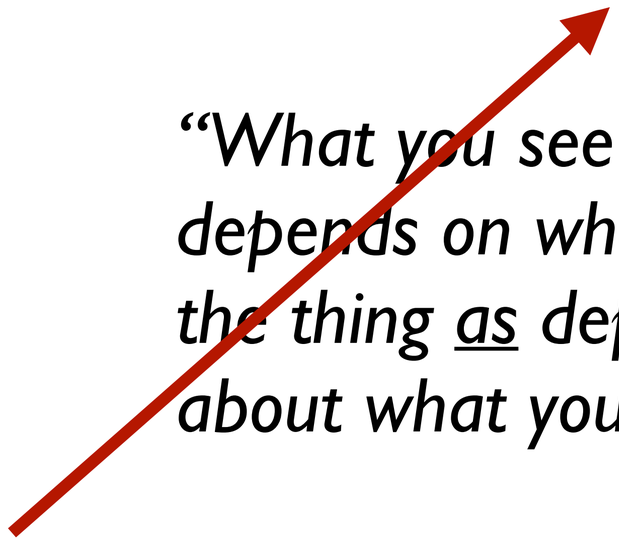
Vision is “constructed” top down from the input

“What you see when you see a thing depends on what the thing <u>is</u>. What you see the thing <u>as</u> depends on what you know about what you are seeing.”

Zenon Pylyshyn
Cognitive Scientist and
Philosopher

TAKE HOME POINT

Vision is “constructed” top down from the input



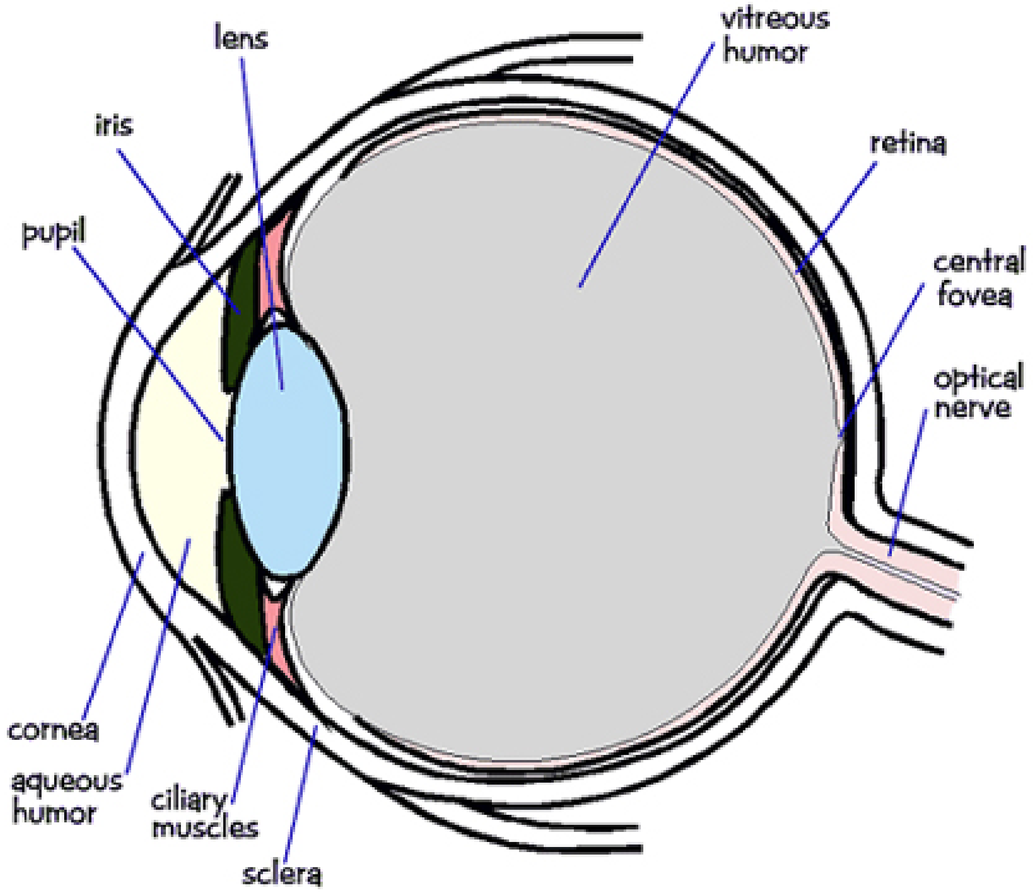
“What you see when you see a thing depends on what the thing <u>is</u>. What you see the thing <u>as</u> depends on what you know about what you are seeing.”

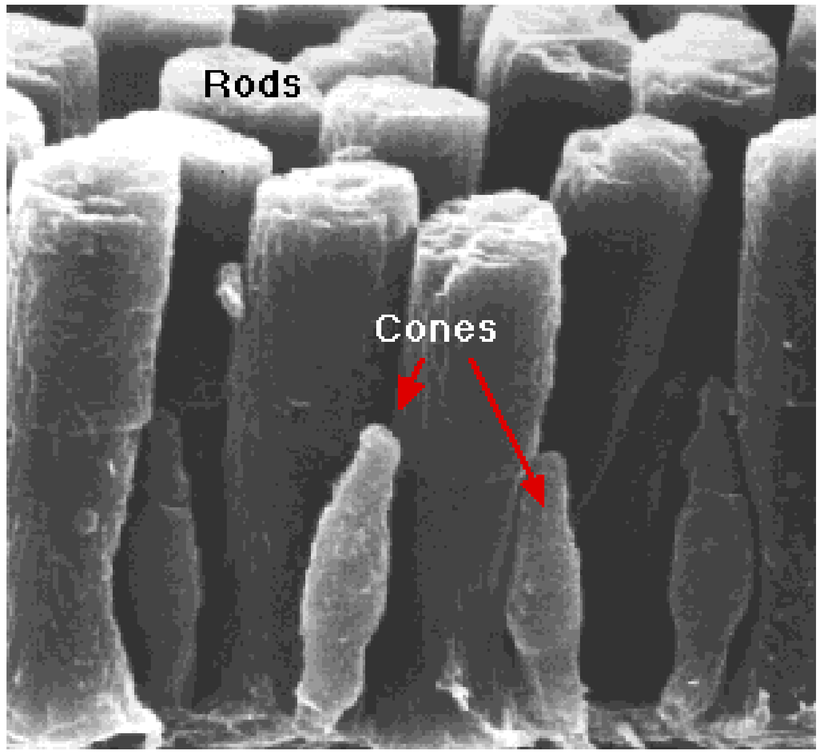
Zenon Pylyshyn
Cognitive Scientist and
Philosopher

Touch: **bottom-up**

Hearing: **serial** (yikes!)


THE EYE

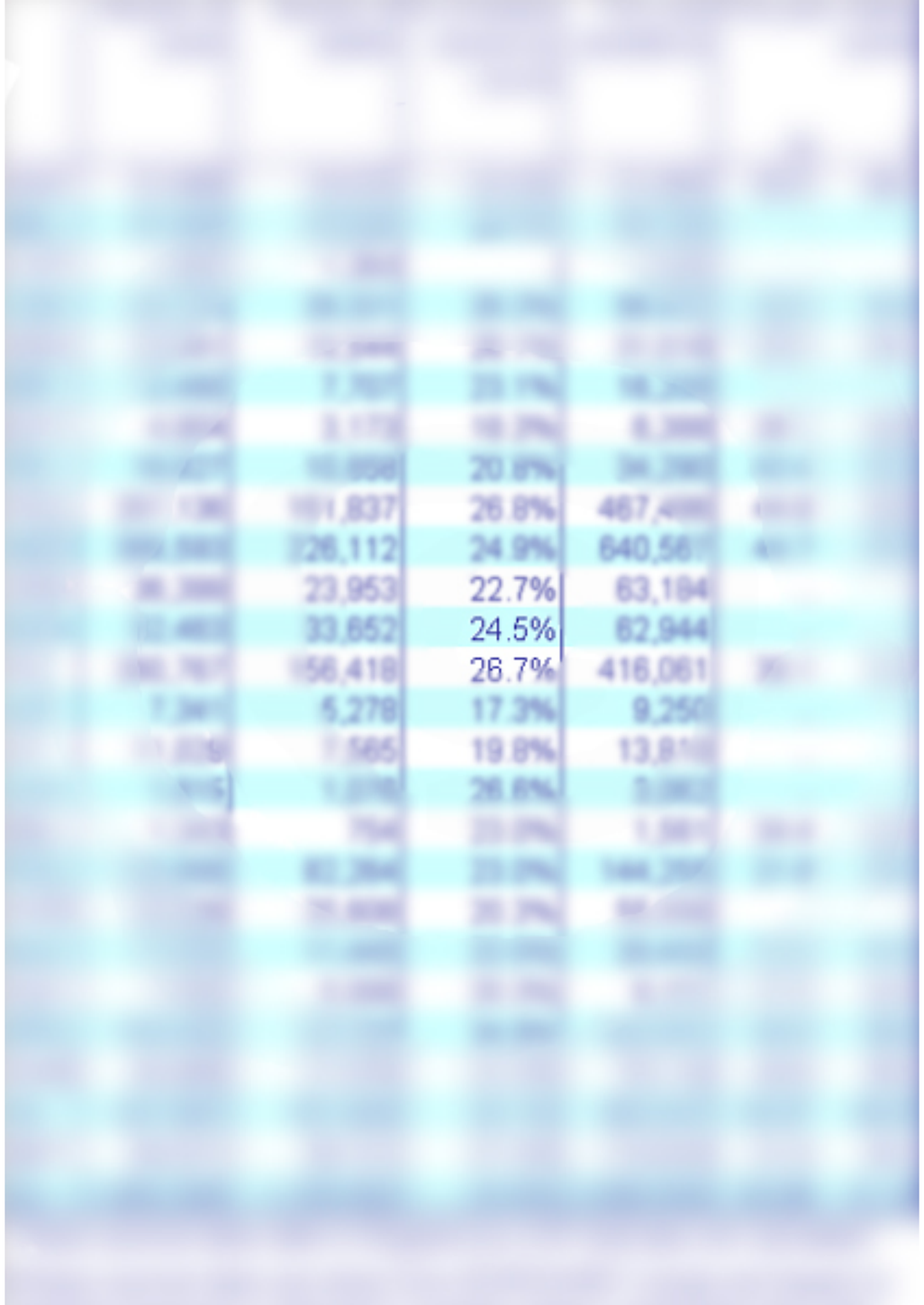

lens
vitreous humor
iris
retina
pupil
central fovea
optical nerve
cornea
aqueous humor
ciliary muscles
sclera



~120 million rods

~5-6 million cones

Wandell, "Foundations of Vision"



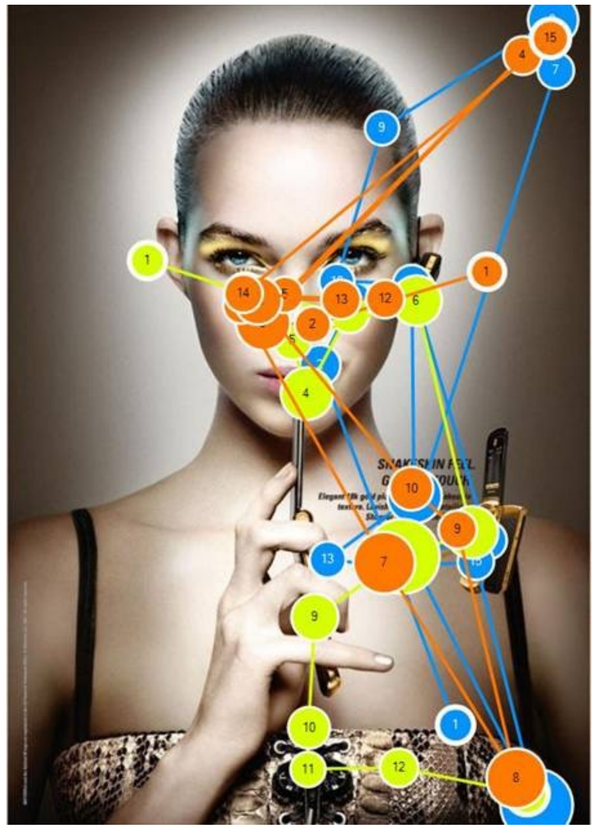
C. Ware, "Visual Thinking for Design"

HUMAN VISUAL SYSTEM

Vision works as sequence of fixations and saccades

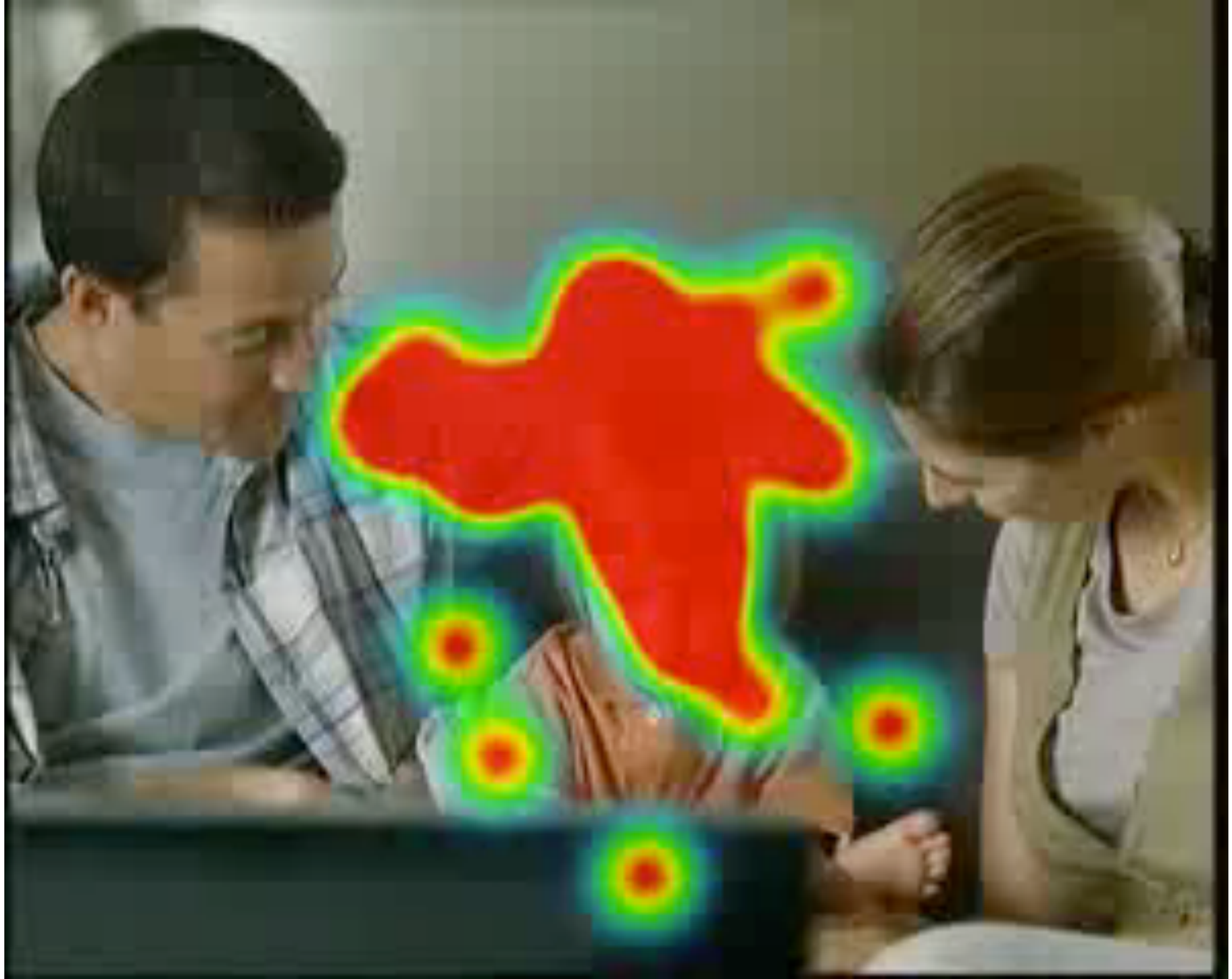
fixations: maintaining gaze on single location (200-600 ms)

saccades: moving between different locations (20-100 ms)



Vision not similar to a camera

More similar to a dynamic and ongoing construction project



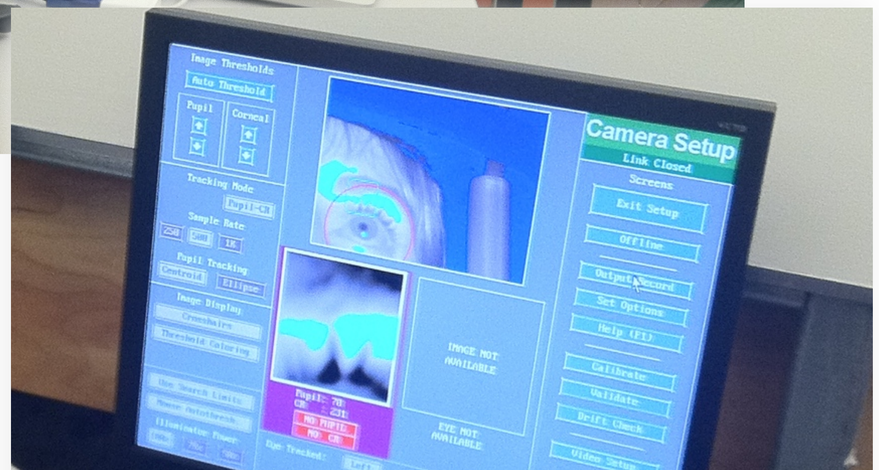
http://www.tobiipro.com/

EYE-TRACKING EXPERI

Eye-tracking control computer

Visualization display

Infrared camera



Video!

HUMAN VISUAL SYSTEM

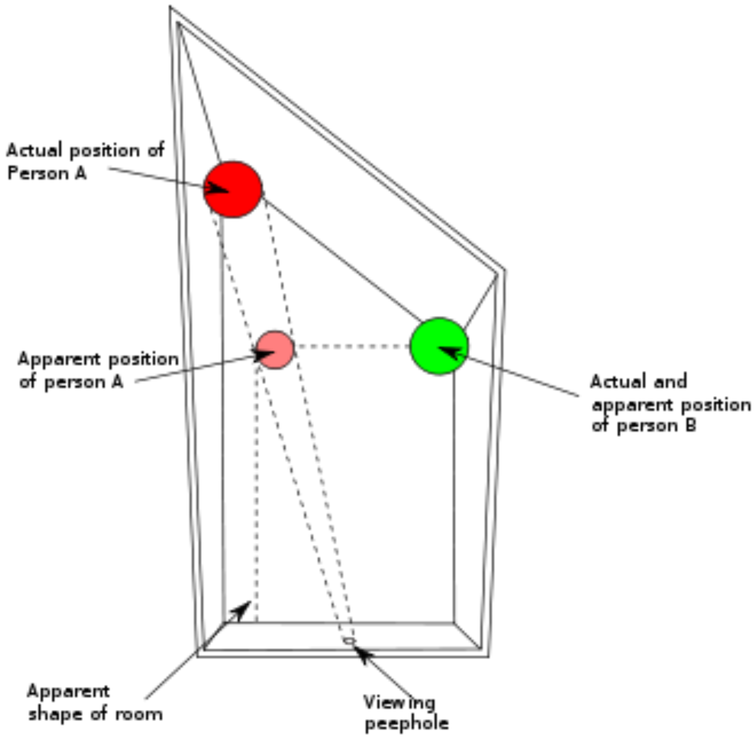
No general purpose vision

What we see depends on our goals and expectations

Relative judgments: strong

Absolute judgments: weak

Ames Room



POPOUT

POPOUT

Properties detected by the low-level visual system

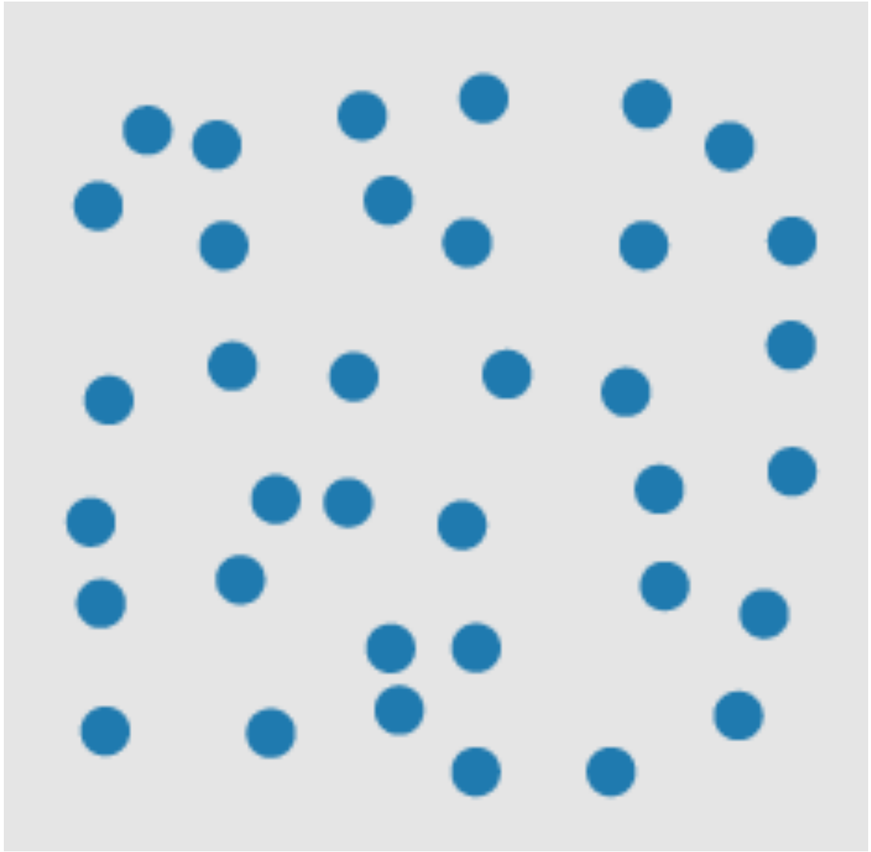
- very rapid - 200-250 milliseconds
- very accurate
- processed in parallel

happens before focused attention -> “pre”-attentive

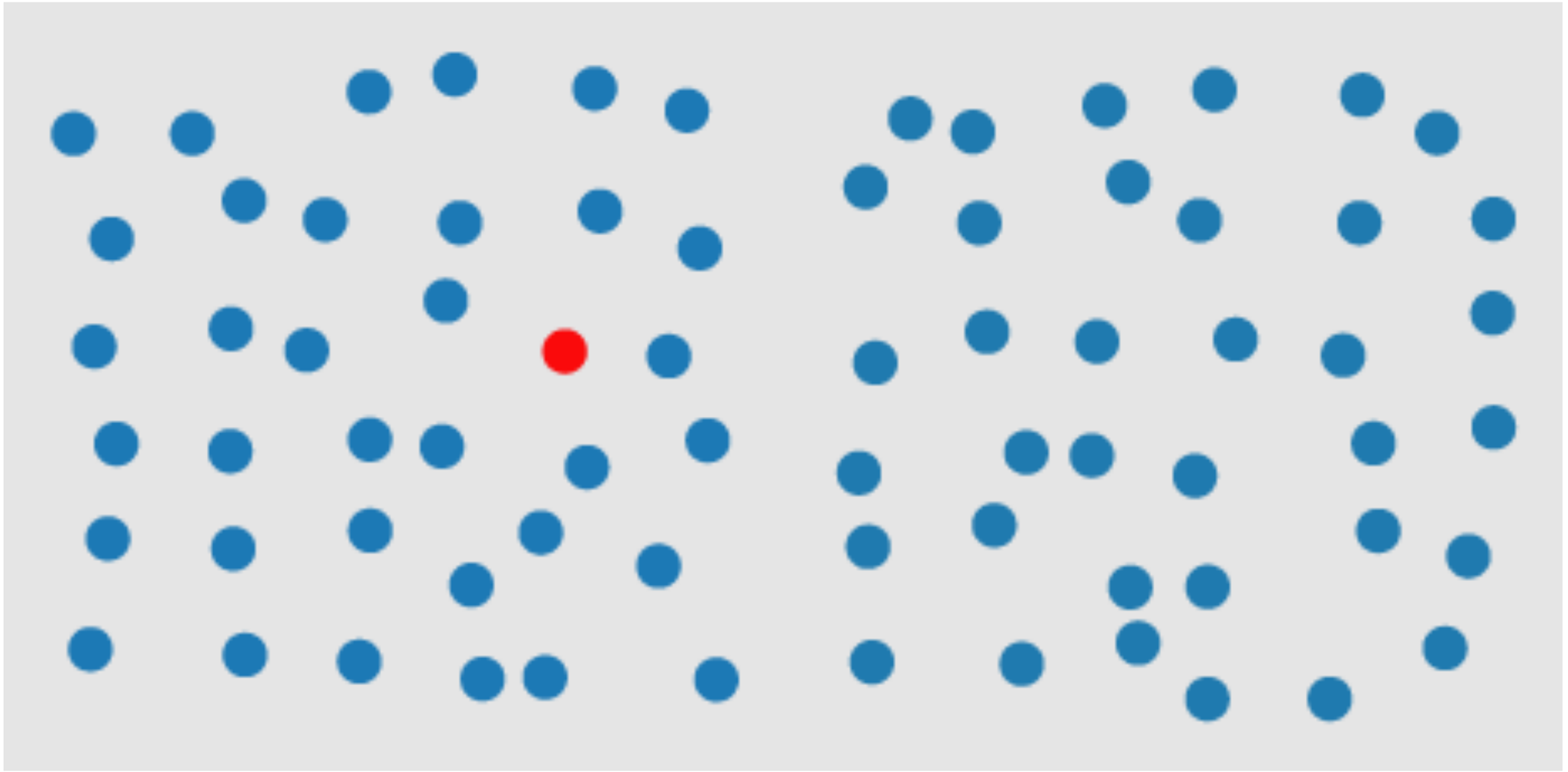
Independent of the number of distractors!

Opposite: sequential search (processed serially)

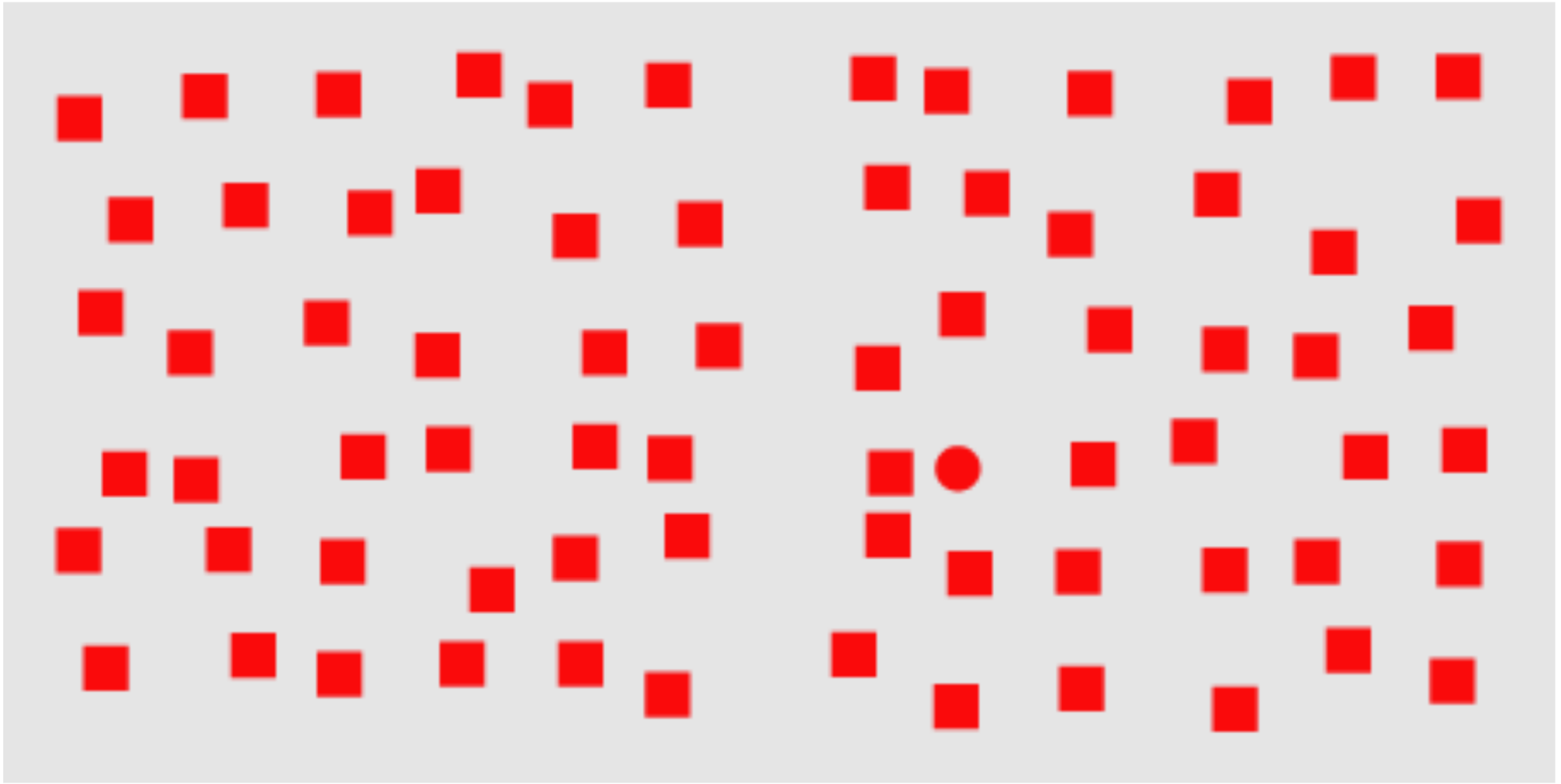
EXPERIMENT

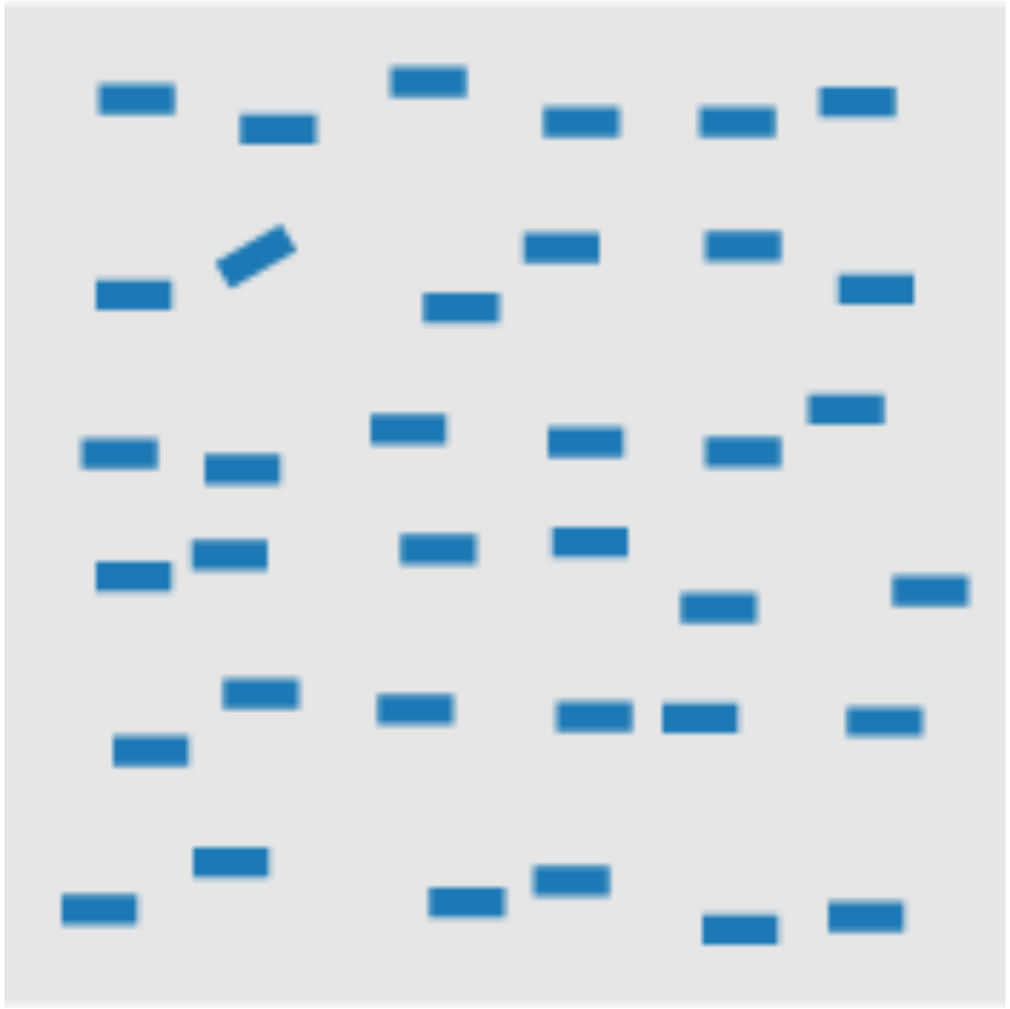


DIFFERENCE IN HUE

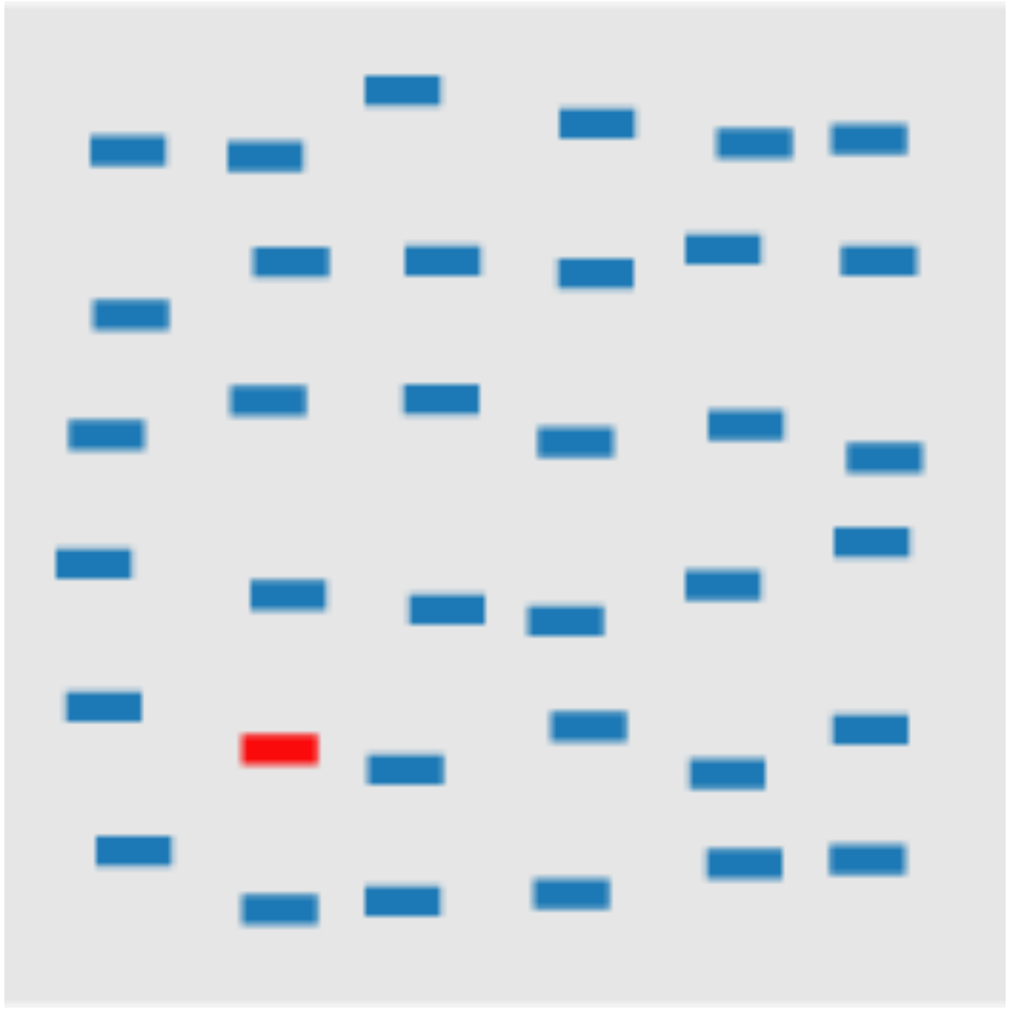


DIFFERENCE IN CURVATURE / FORM



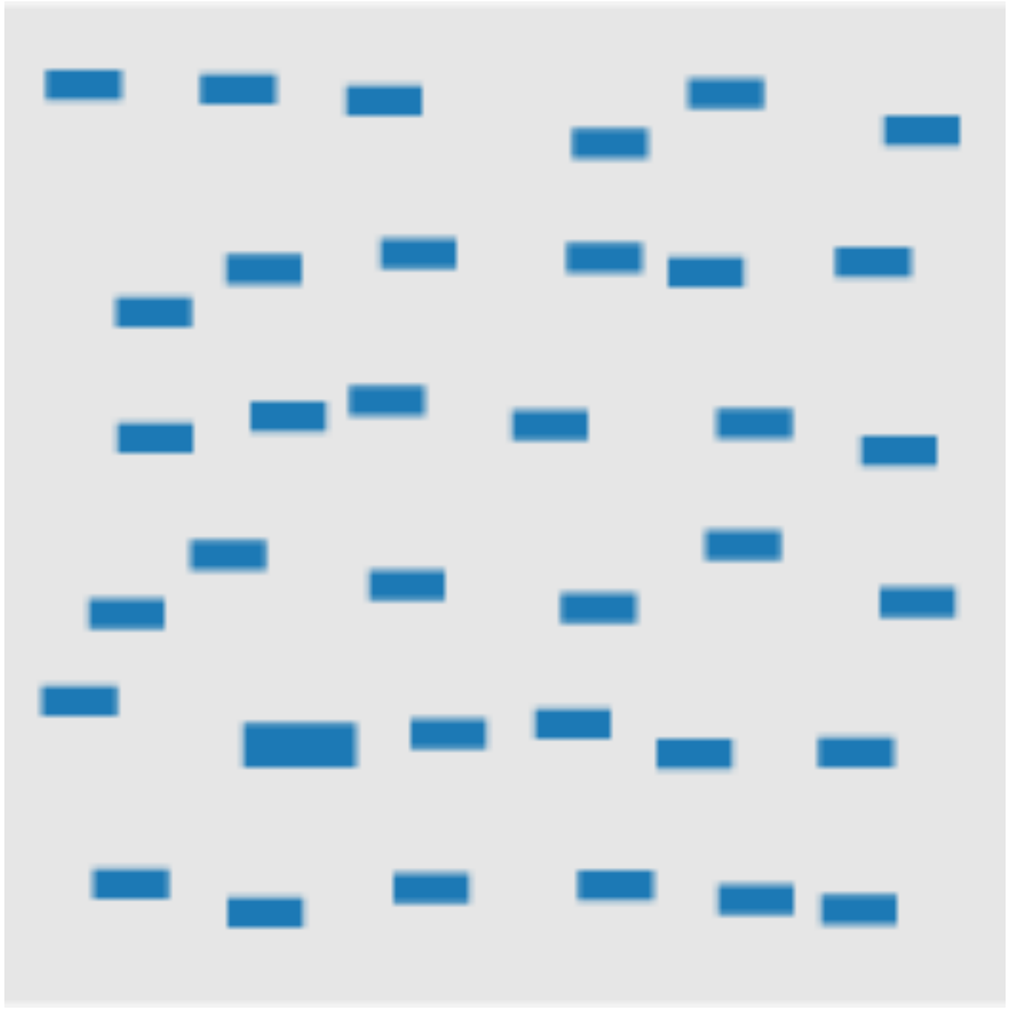


orientation



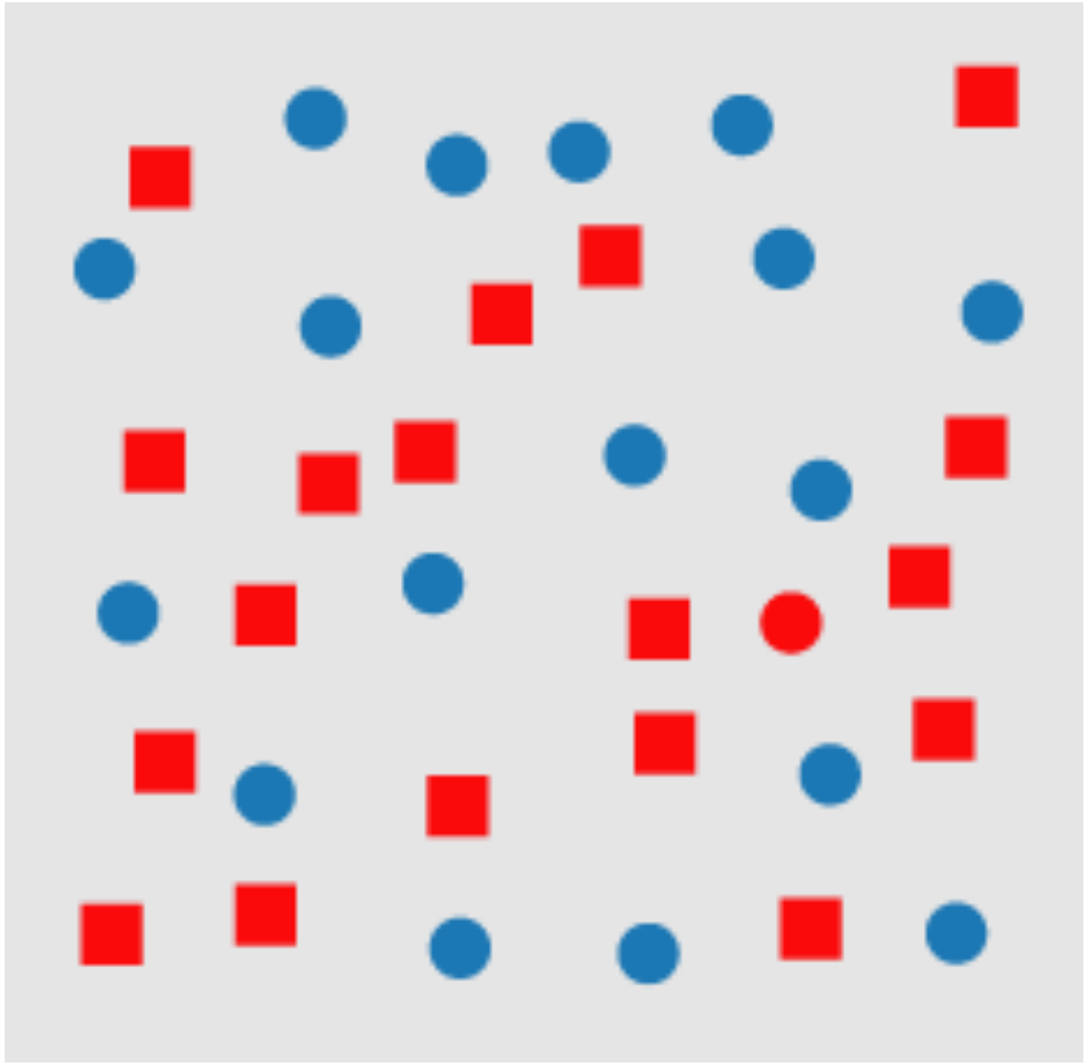
hue

closure



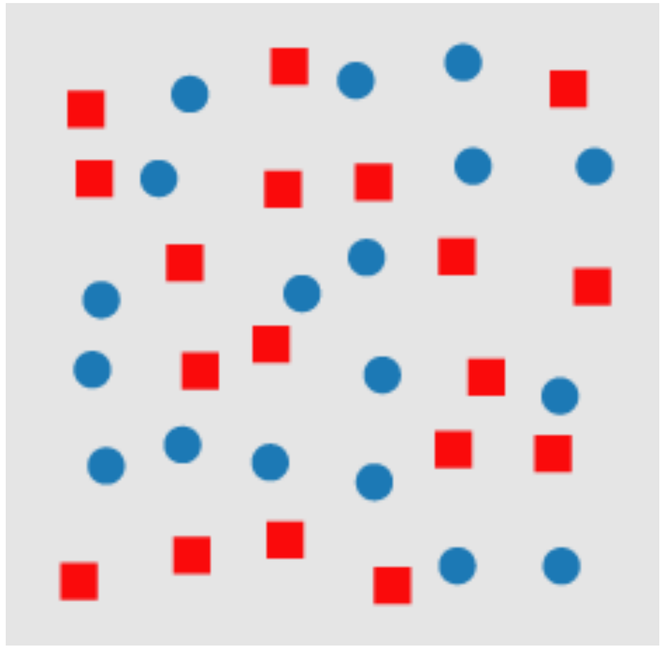
size

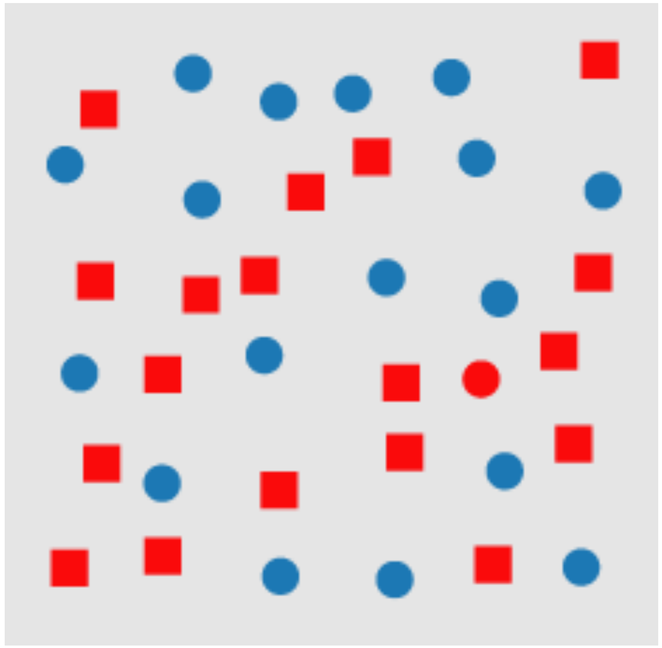
EXPERIMENT



?

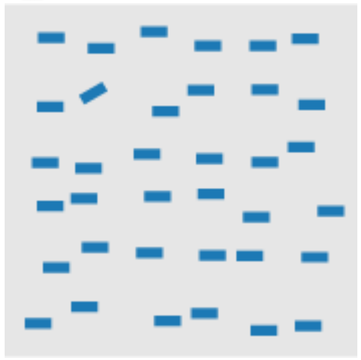
NOT VALID FOR COMBINATIONS



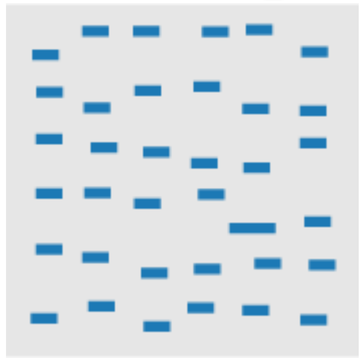


Conjunction Targets – no unique visual property
Target: red, circle
Distractor objects have both properties

SOME PREATTENTIVE PROPERTIES

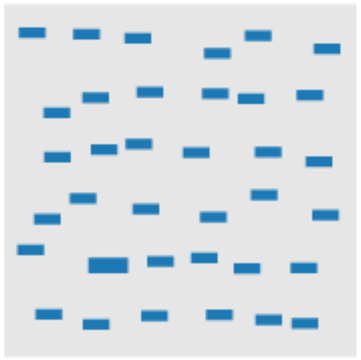


orientation

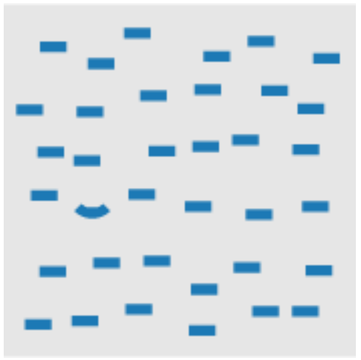


length

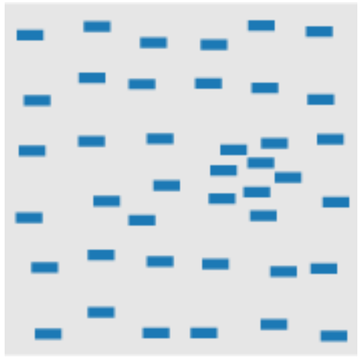
closure



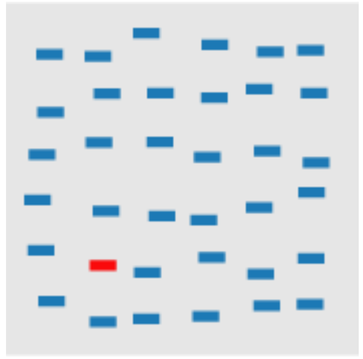
size



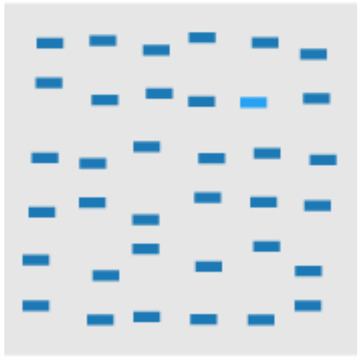
curvature



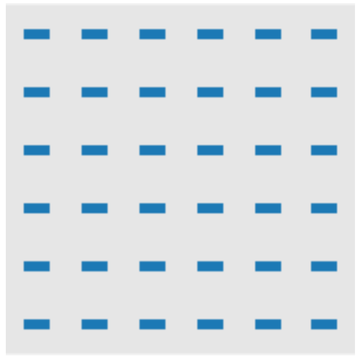
density



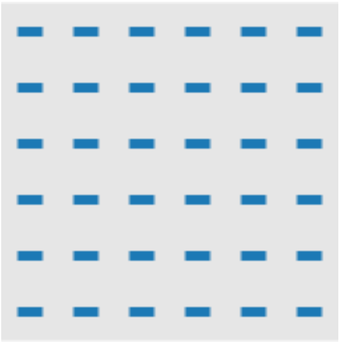
hue



hue



flicker



direction of motion

TASKS

target detection

detect the presence or absence of a target

boundary detection

detect a texture boundary between two groups of elements, where all of the elements in each group have a common visual property

region tracking

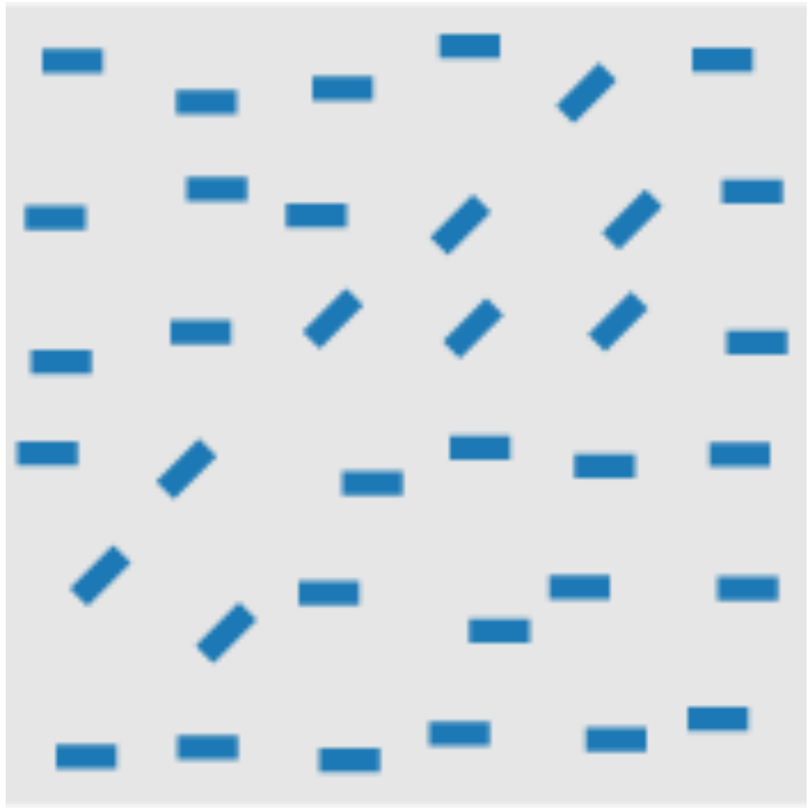
track one or more elements with a unique visual feature as they move in time and space

counting and estimation

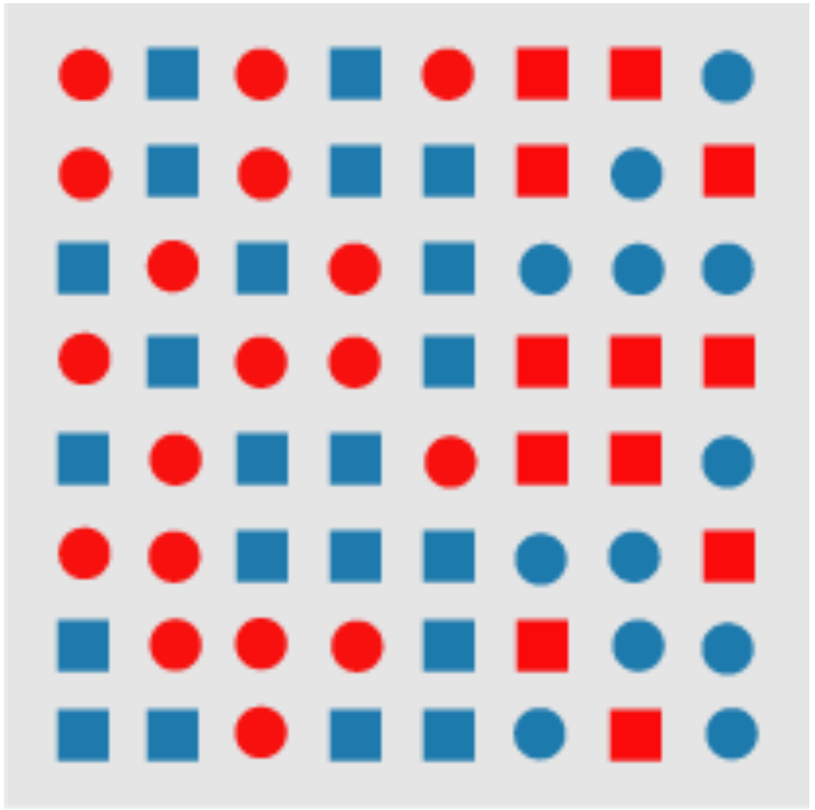
users count or estimate the number of elements with a unique visual feature.

TASKS

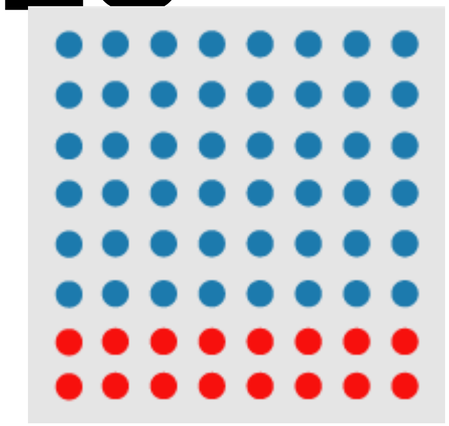
Number Estimation

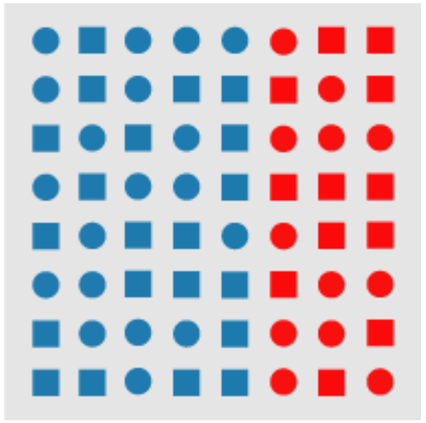


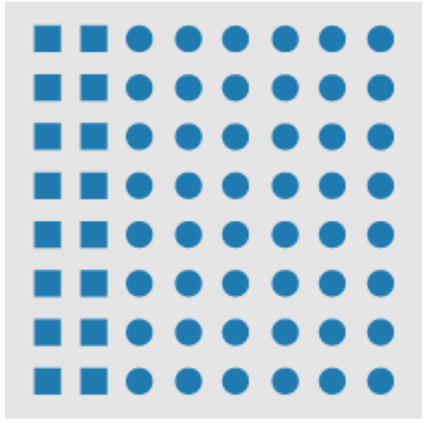
Boundary Detection

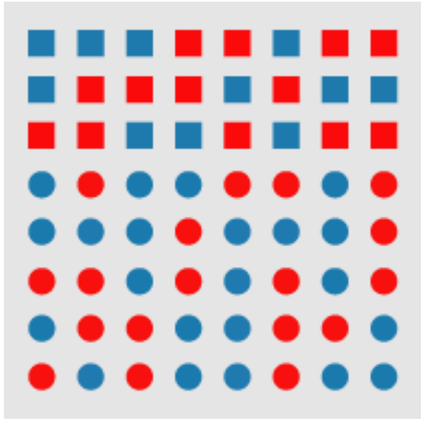


HIERARCHY OF PREATTENTIVE FEATURES









Examples online!

THEORIES OF PREATTENTIVE PROCESSING

Not known for sure how it works

Several theories:

http://www.csc.ncsu.edu/faculty/healey/PP/index.html

PREATTENTIVE PROCESSING IN VIS

Can be used to draw attention to areas of interest

Can be used to express similarity/group memberships

Visual features must be carefully designed

Conjunctions must be avoided

Examples are “Cues” (Focus and Context technique)

CHANGE BLINDNESS

CHANGE BLINDNESS

Details of an image cannot be remembered across separate scenes

- except in areas with focused attention

Interruption (e.g. a blink, eye saccade or blank screen) amplifies this effect

Not failure of vision system

failure due to inappropriate attentional guidance

Ron Rensink 2002

Ron Rensink 2002

Ron Rensink 2002

Ron Rensink 2002

CHANGE BLINDNESS

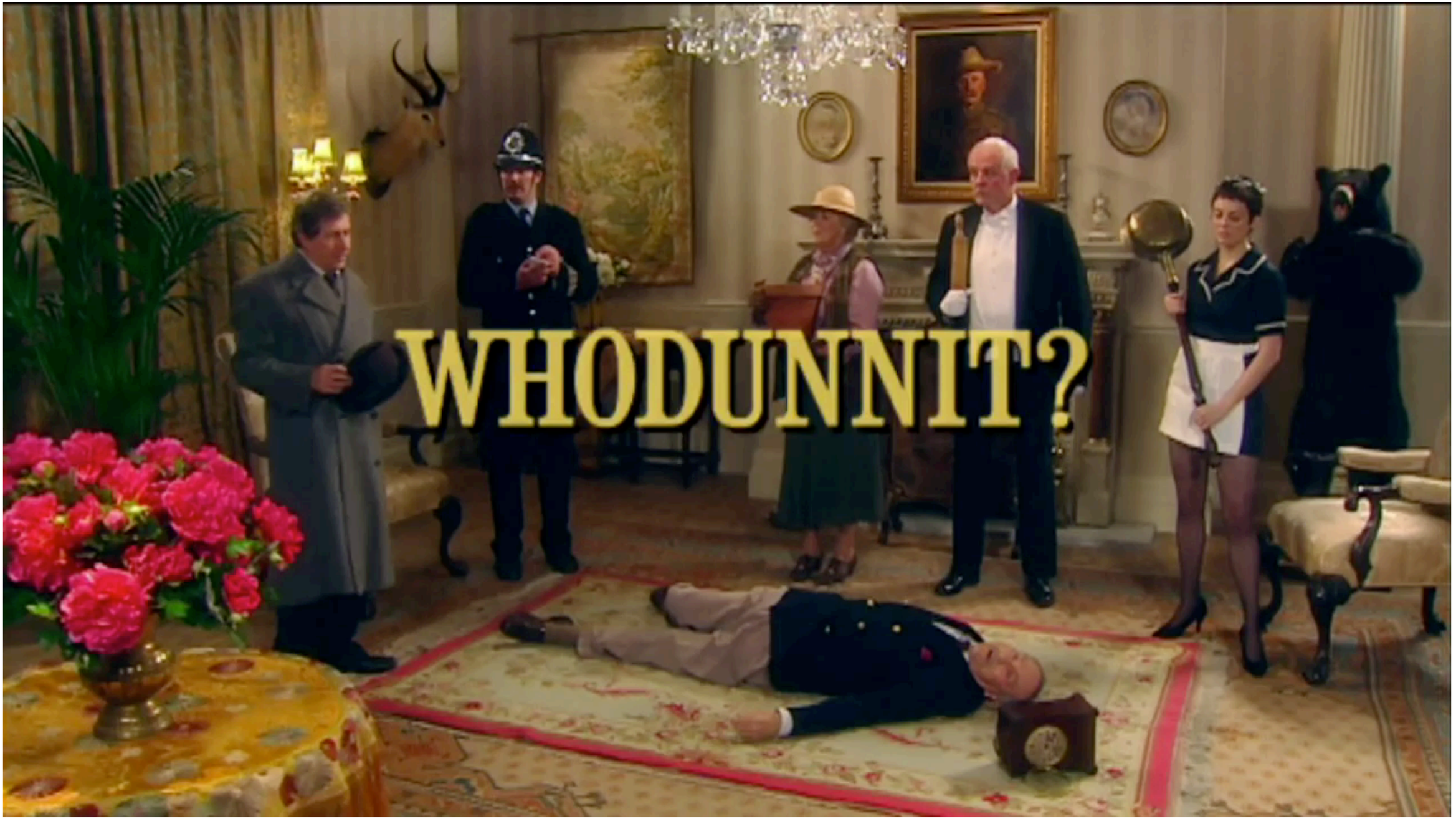
Various theories about causes

- Overwriting: Information that was not abstracted is lost
- First Impression: Only initial view is abstracted
- Nothing is Stored: Only abstract concepts are committed to memory
- Everything is Stored, Nothing is Compared: We compare only when we are forced to
- Feature Combination: scenes are combined as long as they make sense

Influencing factors

- attention
- expectation (knowing something will change)
- semantic importance of changed object
- low level object properties overlooked more easily

ATTENTION BLINDNESS


WHODUNNIT?

TAKE HOME POINTS

To find meaning in what we see **we must selectively pay attention** to what is important

Low-level vision is driven by object features rather than a conscious effort where to look (e.g., pre-attentive processing)

Attention is driven by preexisting knowledge, expectations, and goals stored in long-term memory

GESTALT PRINCIPLES

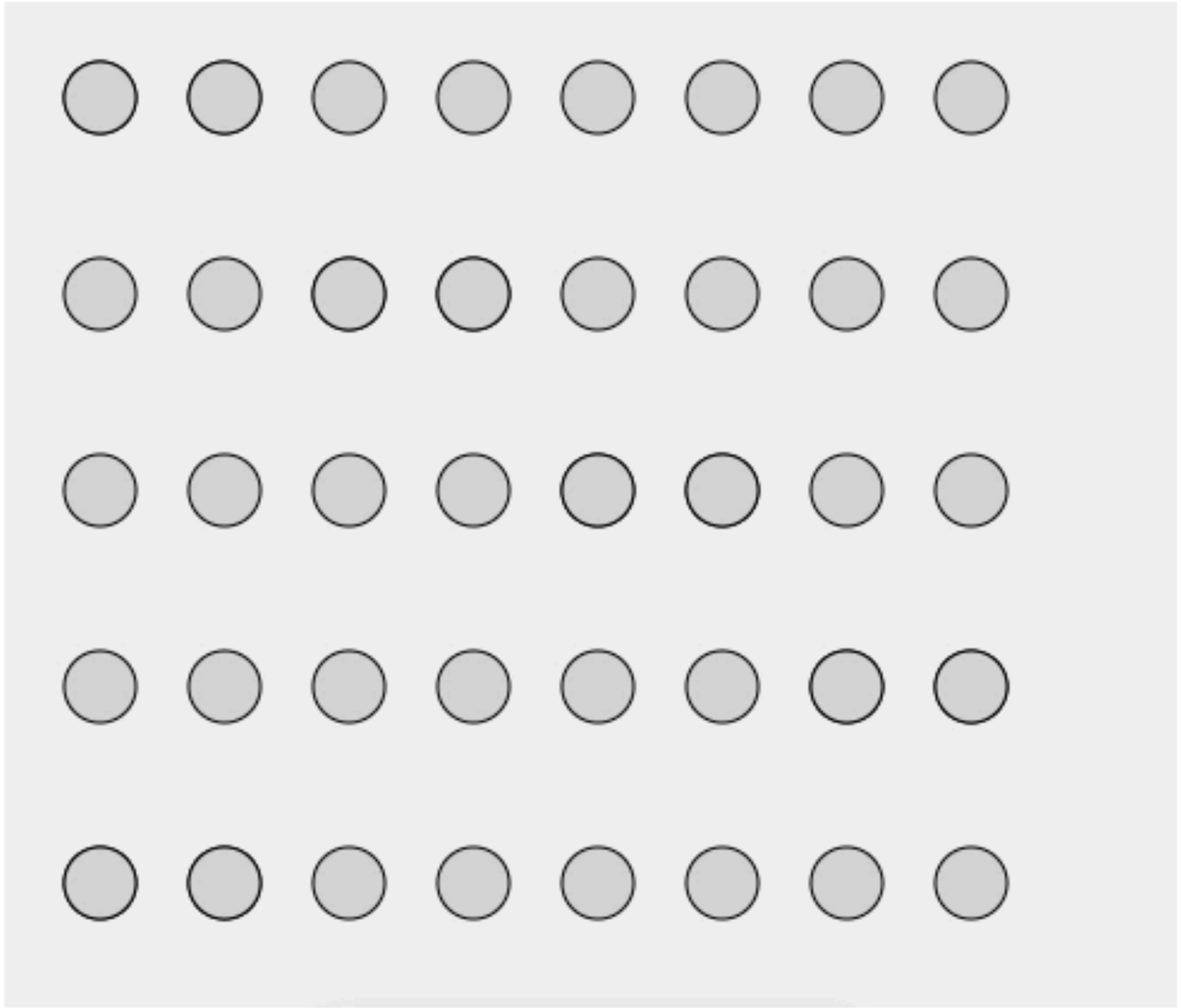
GESTALT PRINCIPLES

"Patterns that transcend the visual stimuli that produced them"

GESTALT PRINCIPLES

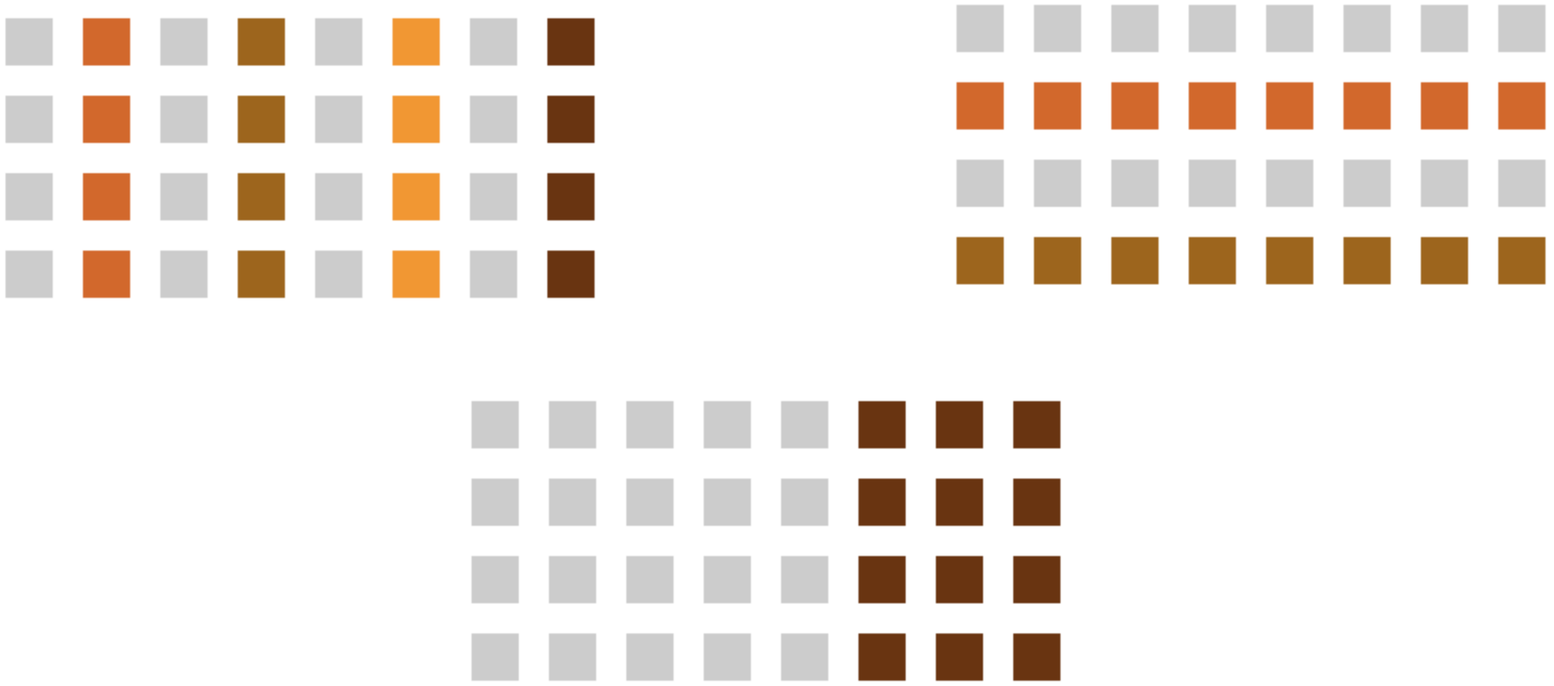
- Similarity
- Proximity
- Connectedness
- Enclosure
- Continuity
- Closure
- Symmetry
- Figure/Ground
- Common Fate

SIMILARITY



https://emeeks.github.io/gestaltdataviz/

SIMILARITY



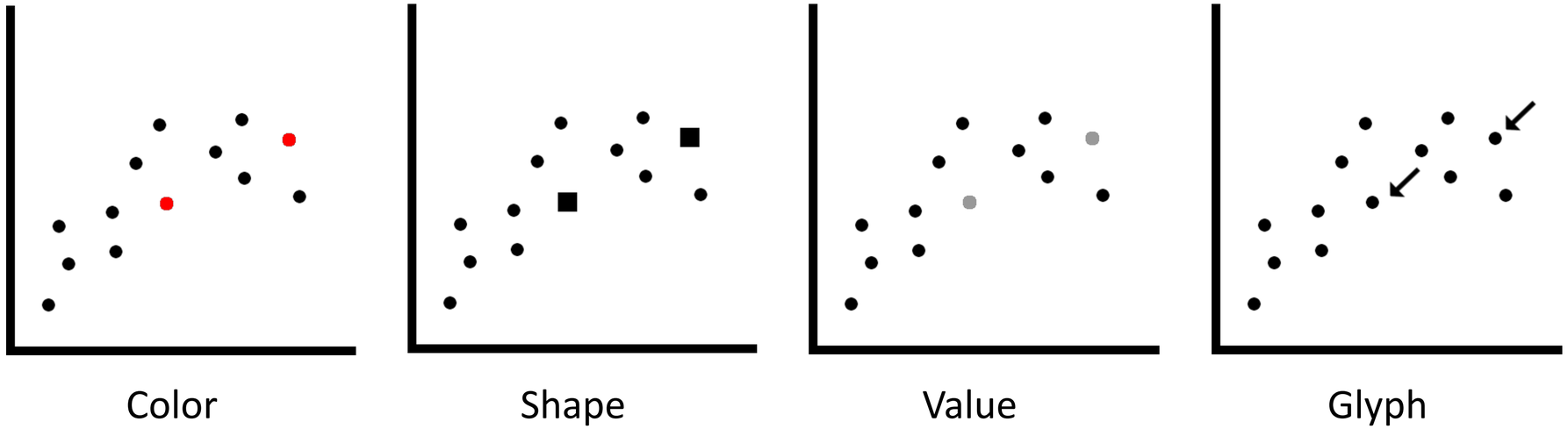
Andy Rutledge, “Gestalt Principles of Perception”

SIMILARITY

Co-modulation of a **channel**

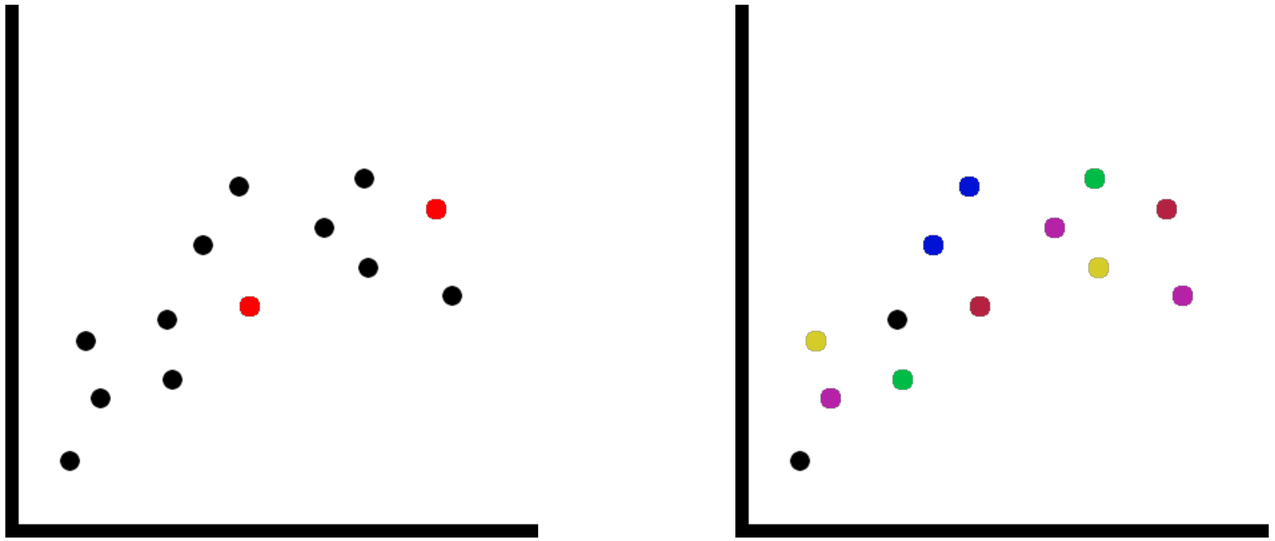
color, shape, size, value, orientation, texture, …

Adding a glyph, label, frame, background



COLOR – PERCEPTION ISSUES (1/2)

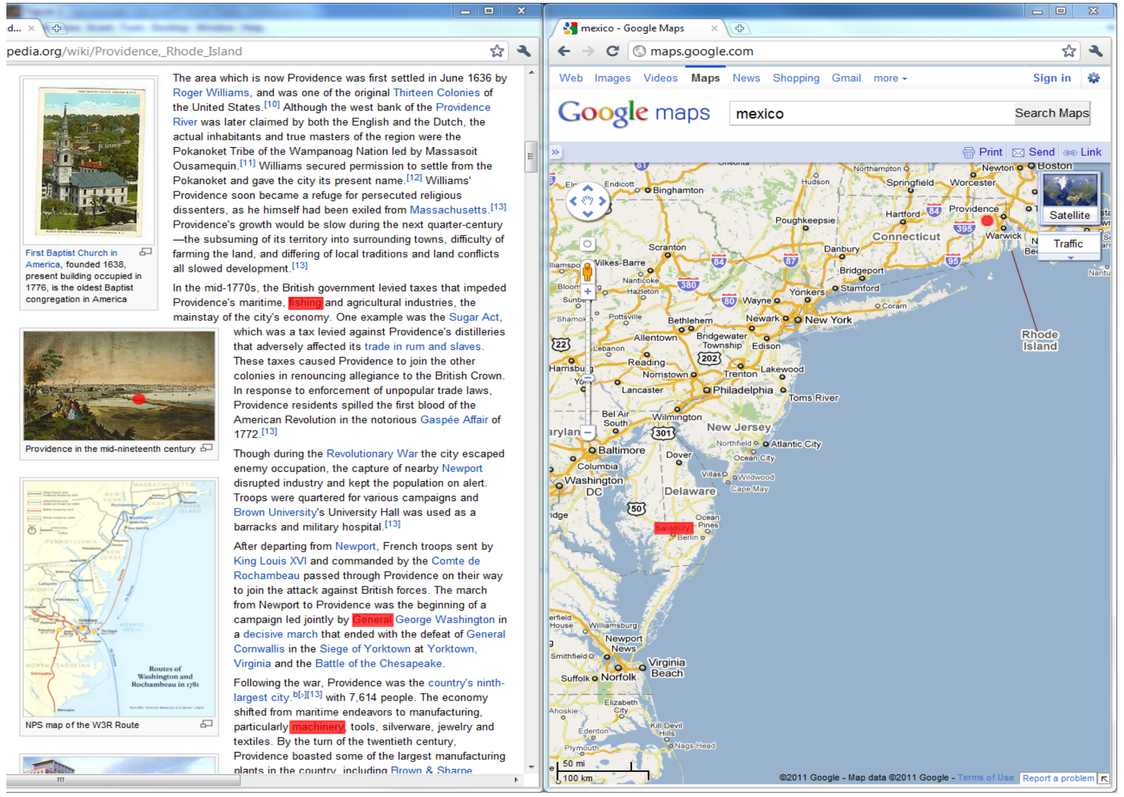
Preattentive properties: Very good for 1-2 simultaneous, serial search for more



COLOR – PERCEPTION ISSUES (2/2)

Slower in a cluttered environment

Size of colored object relevant.

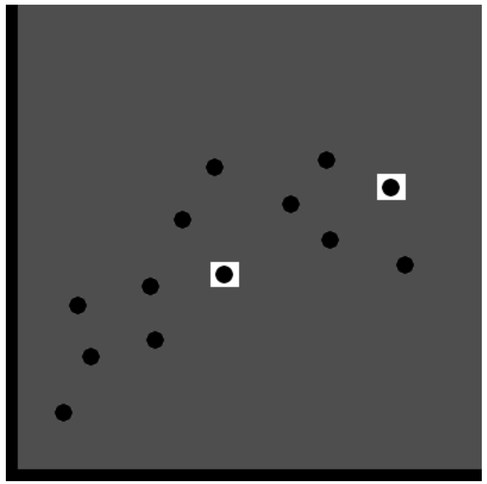


SIMILARITY

Modulate everything else

Blurring, darkening, desaturating, etc.

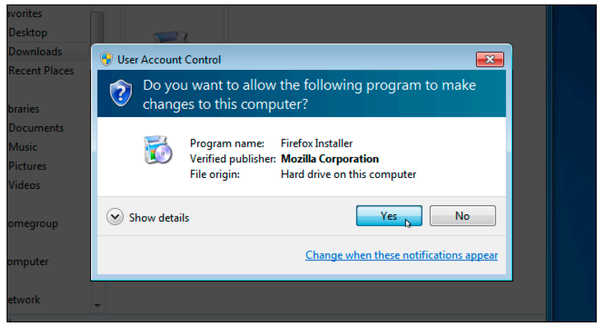
Blur



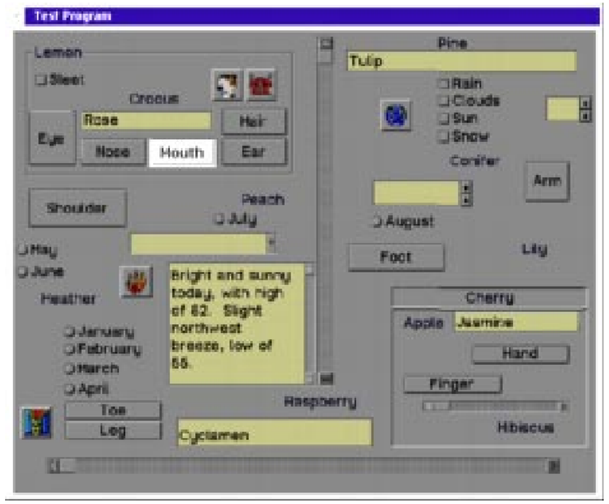
Darkening

MODULATING EVERYTHING ELSE: RECOMMENDATION, EXAMPLE

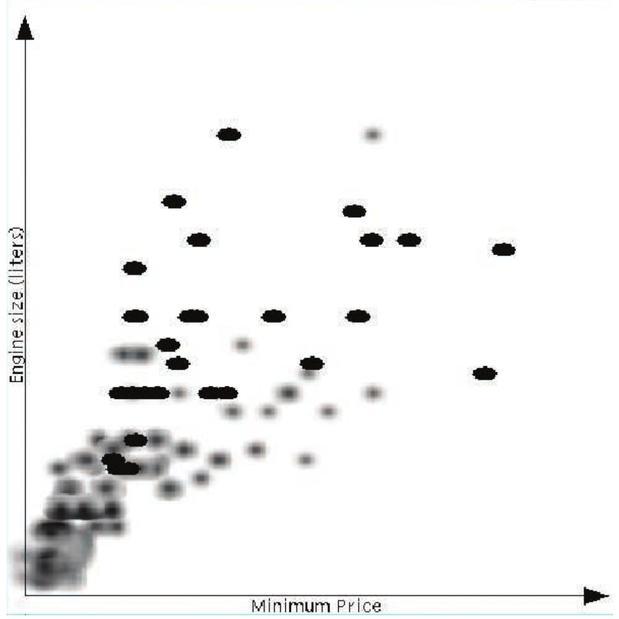
Don‘t use unless the **sole objective** is to guide attention toward one (set of) items



[MS Windows]

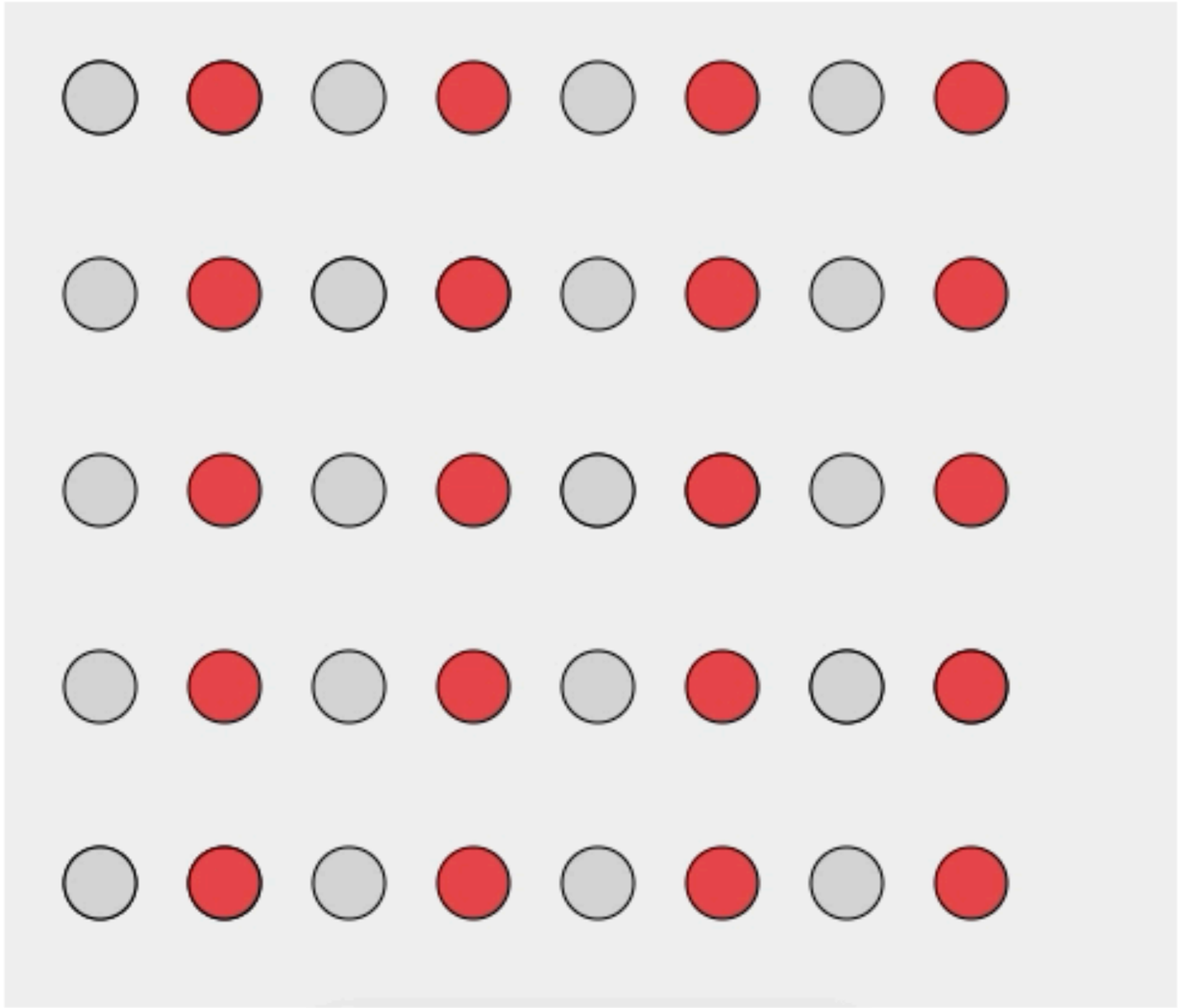


[Zhai et al., 1997]



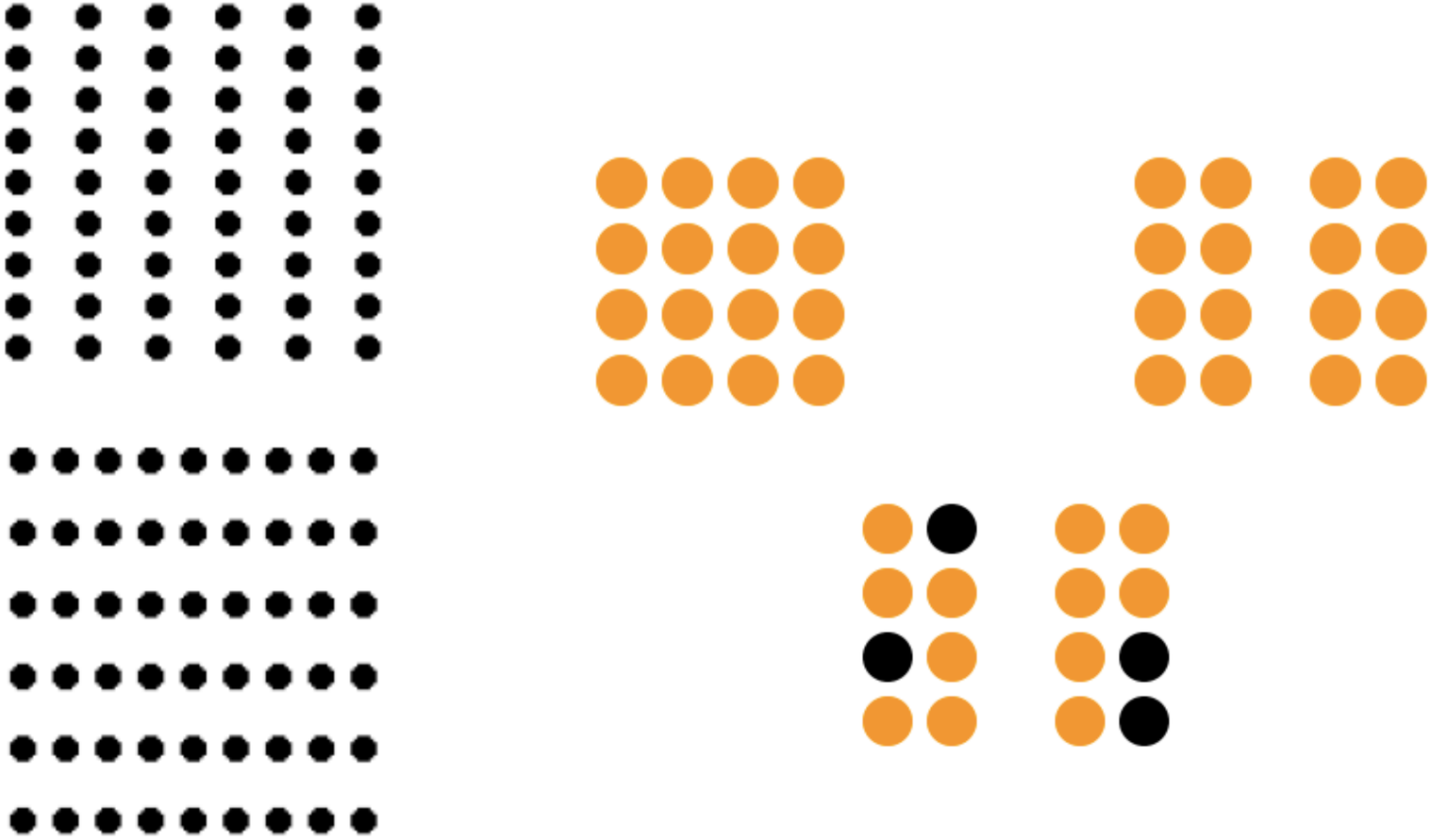
[Kosara et al., 2002]

PROXIMITY



https://emeeks.github.io/gestaltdataviz/

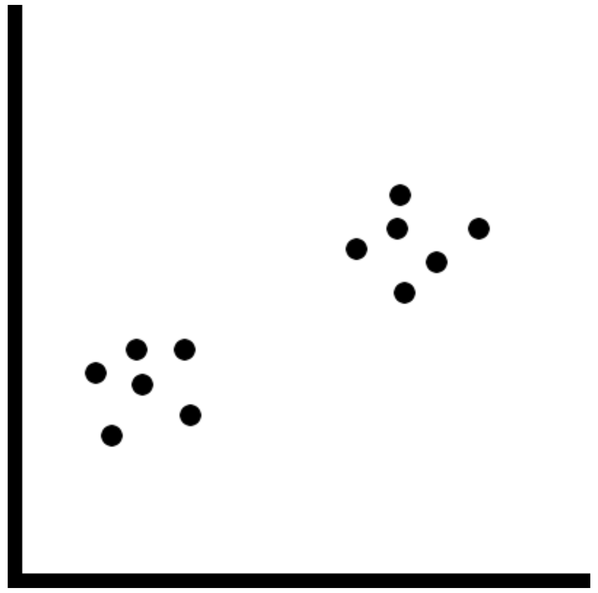
PROXIMITY



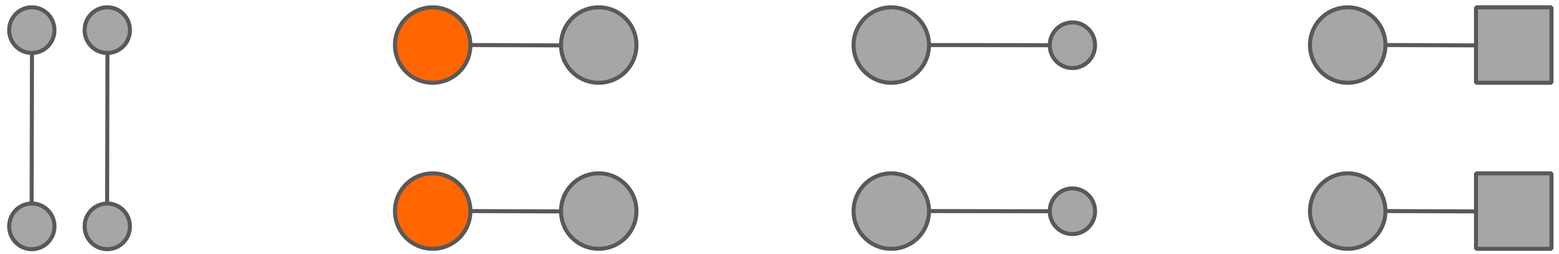
Andy Rutledge, "Gestalt Principles of Perception"

PROXIMITY

Grouping/linking by placing entities in close proximity



A LITTLE EXPERIMENT…

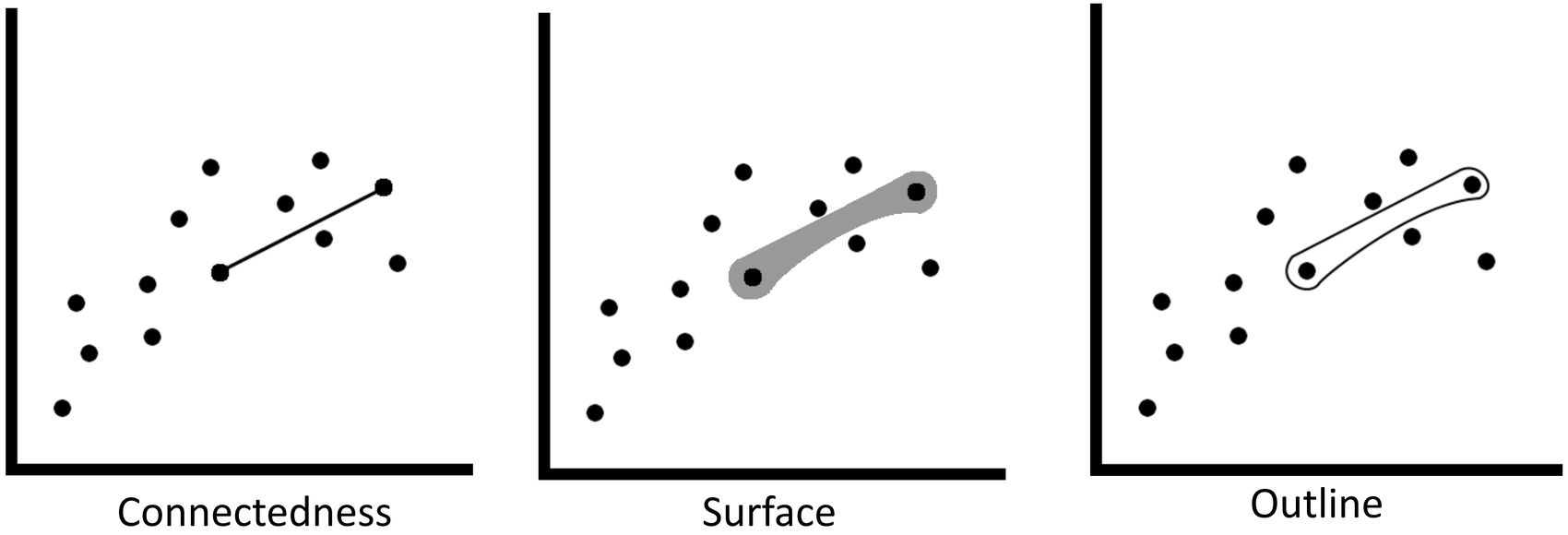


Proximity Color Size Shape

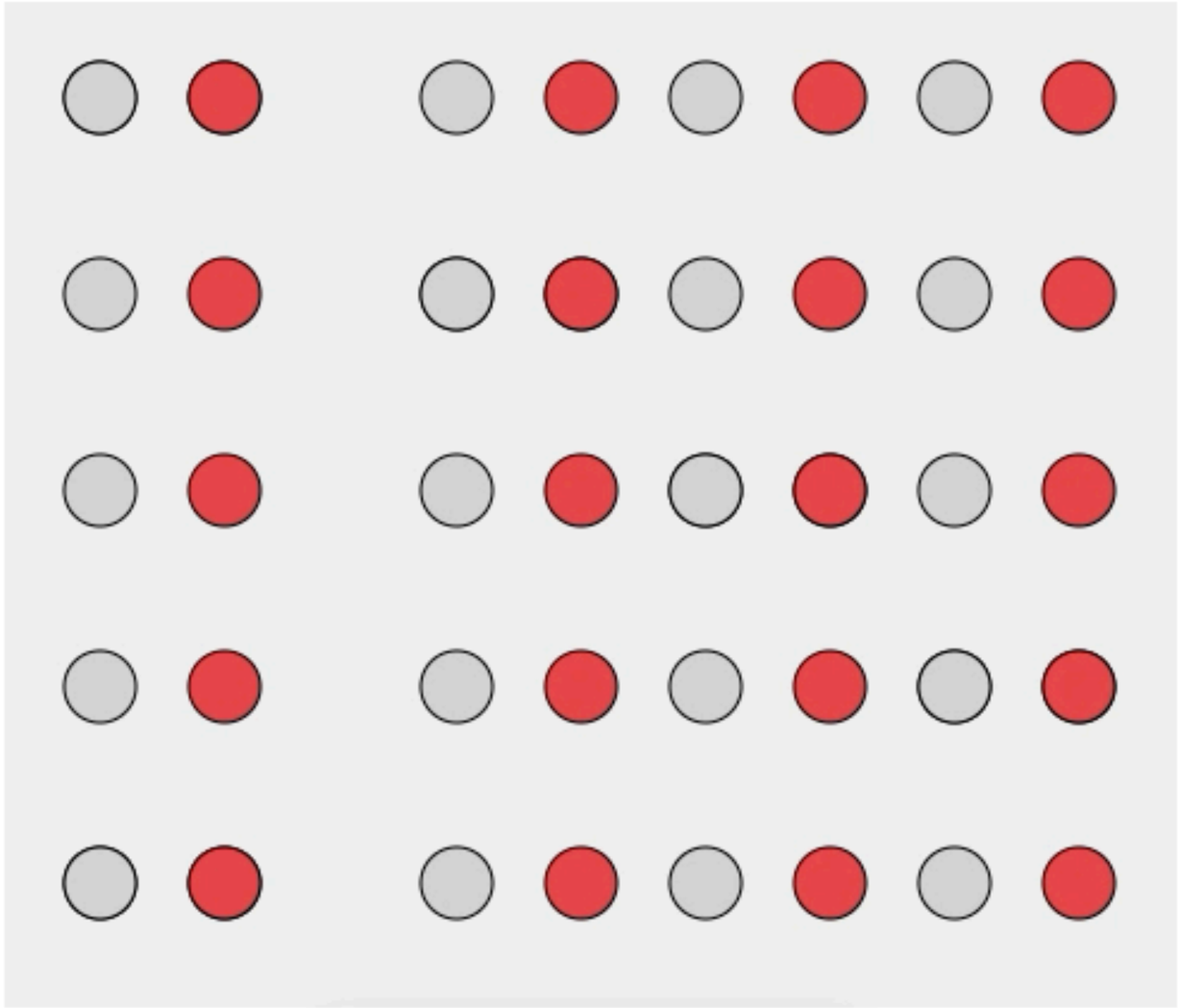
CONNECTEDNESS

Connected items with a line or curve

Surround items with a outline, surface, volume



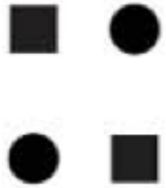
ENCLOSURE



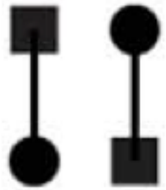
https://emeeks.github.io/gestaltdataviz/

ENCLOSURE

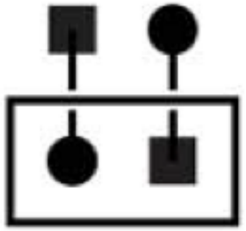
Similarity



Connection

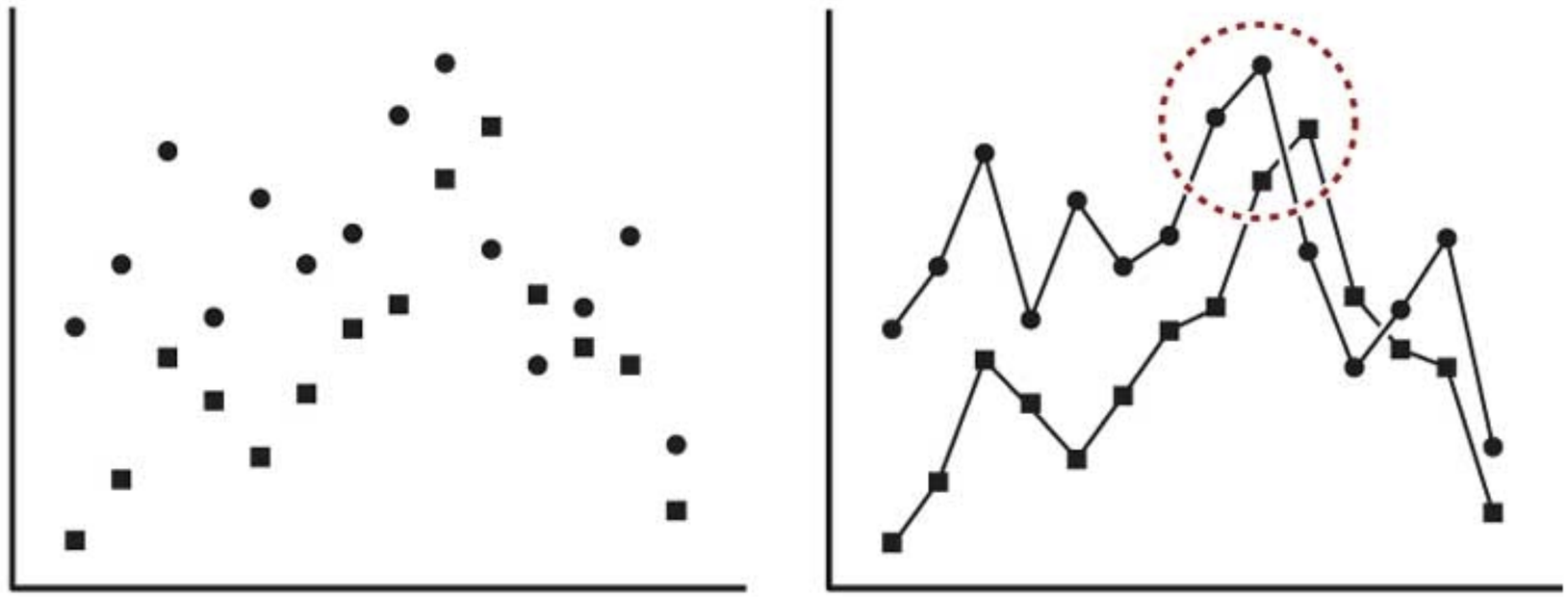


Enclosure



Bang Wong, "Gestalt Principles, 1", Nature Methods

ENCLOSURE



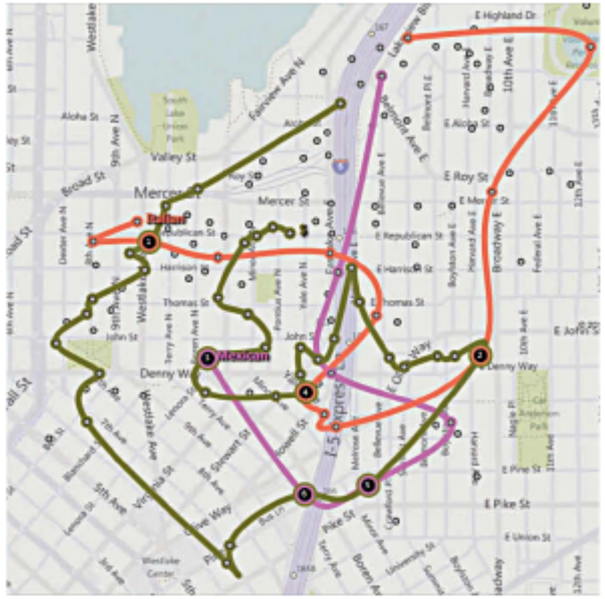
Bang Wong, "Gestalt Principles, 1", Nature Methods

CONNECTEDNESS VARIETIES

Bubble Sets

Image by [Dinkla et al., 2011]
Technique by [Collins et al.,2009]

Line Sets

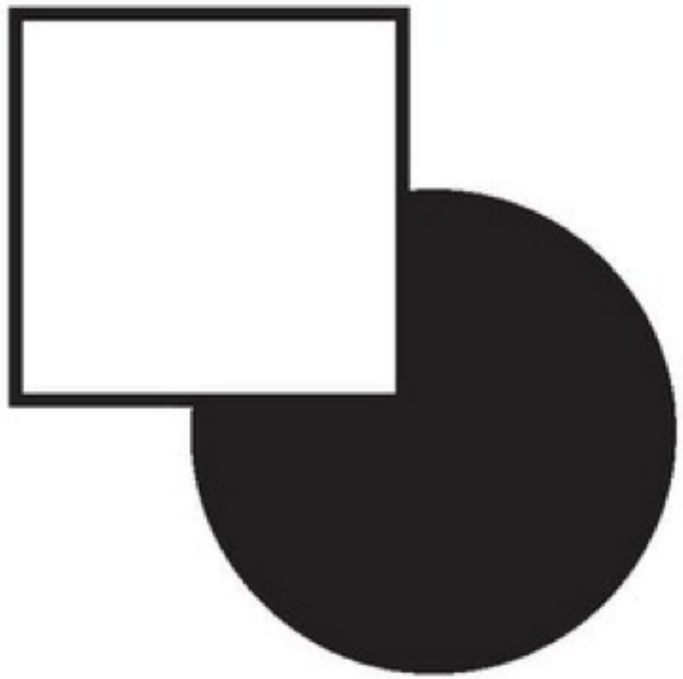


[Alper et al., 2011]

Kelp Diagrams

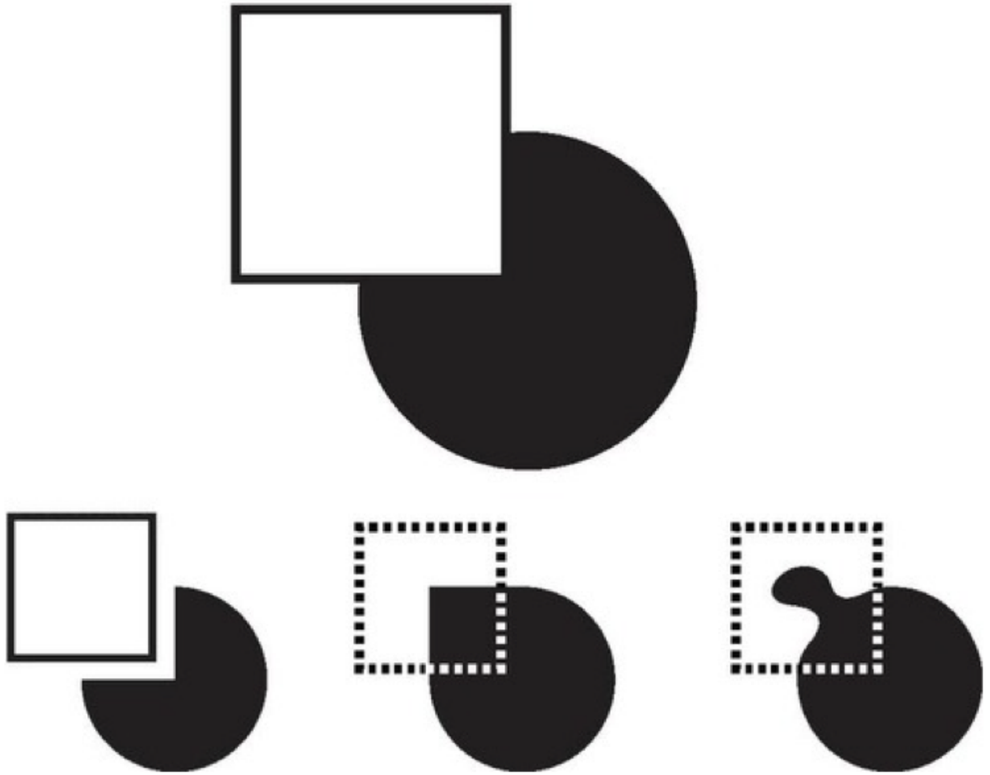
[Dinkla et al., 2012]

CONTINUITY



Bang Wong, “Gestalt Principles, II”, Nature Methods

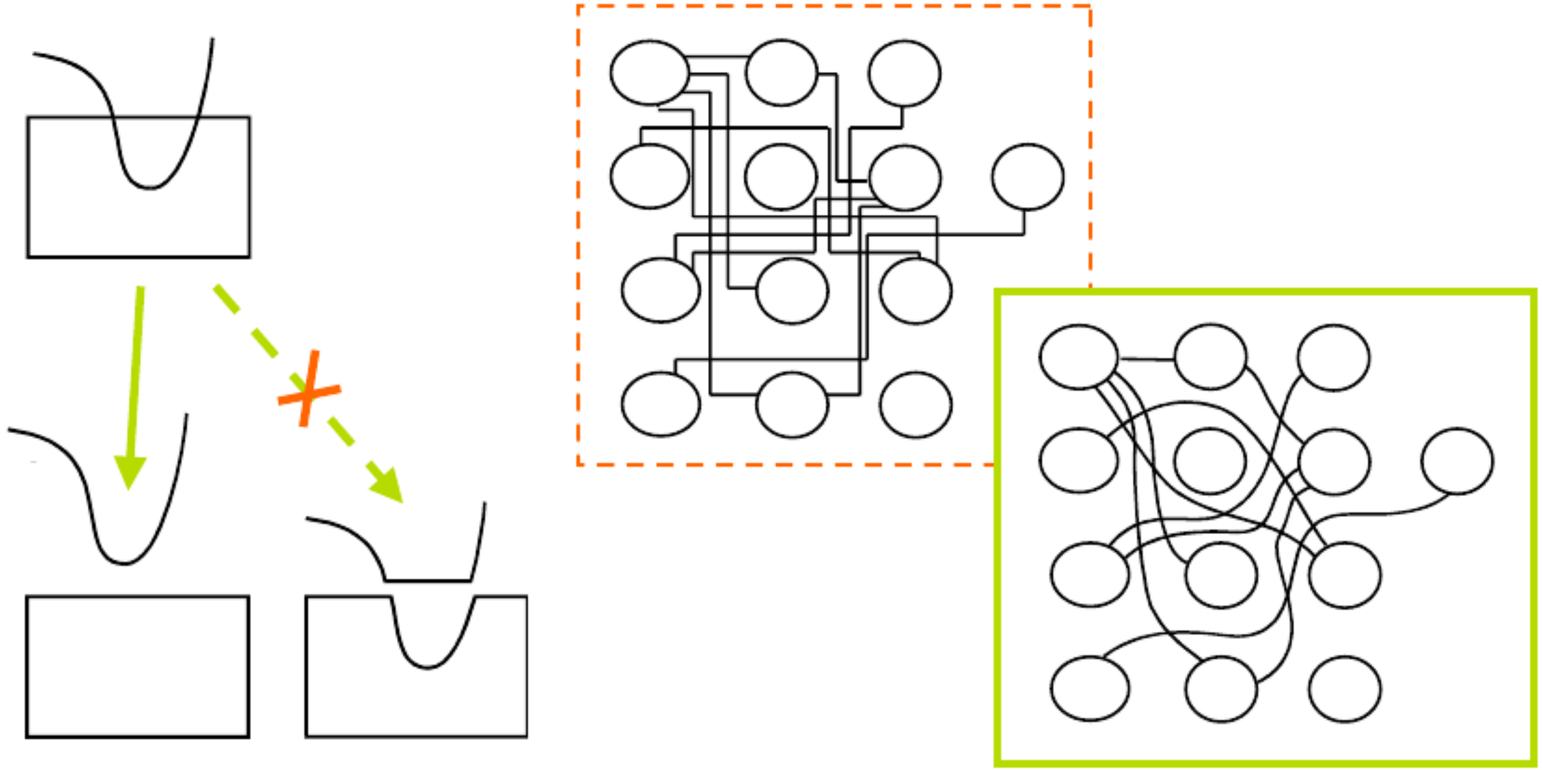
CONTINUITY



Bang Wong, "Gestalt Principles, II", Nature Methods

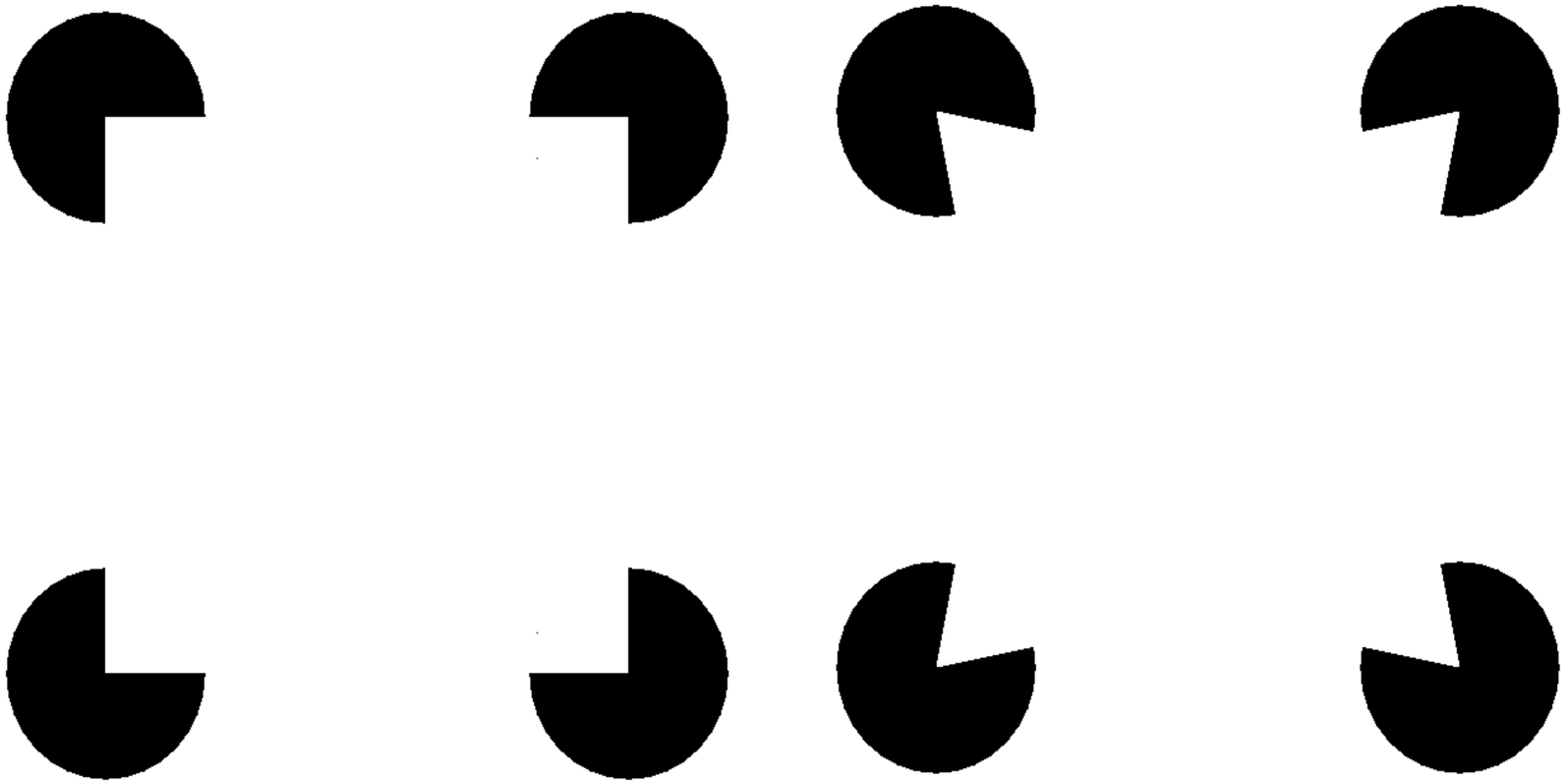
CONTINUITY

Things: smooth & continuous



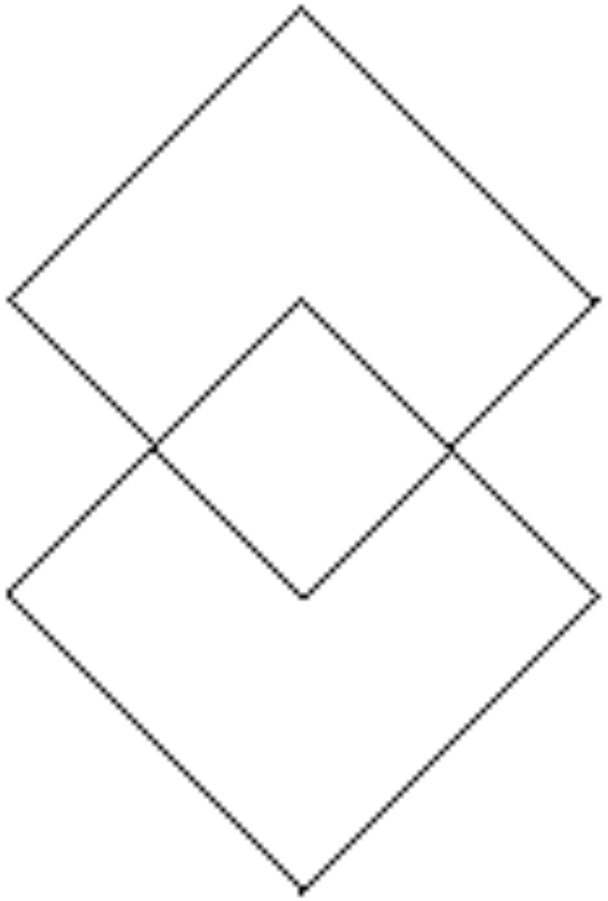
CLOSURE

CLOSURE



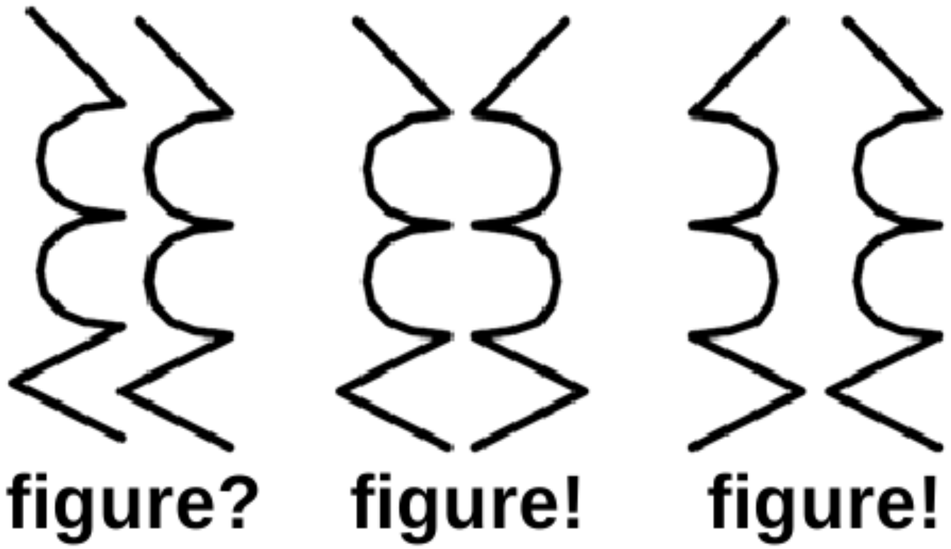
CLOSURE

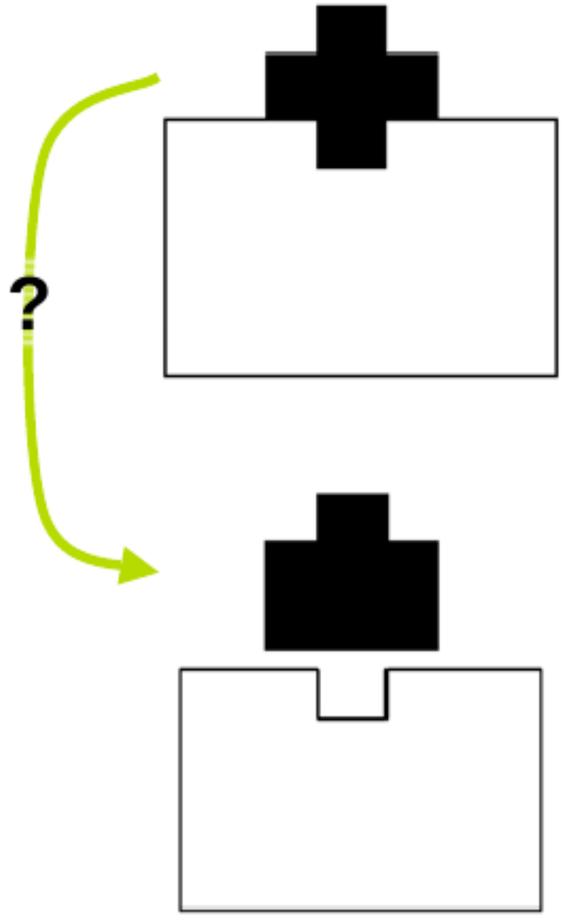
SYMMETRY



SYMMETRY

Things: symmetric





POPULATION PYRAMID:

FINLAND

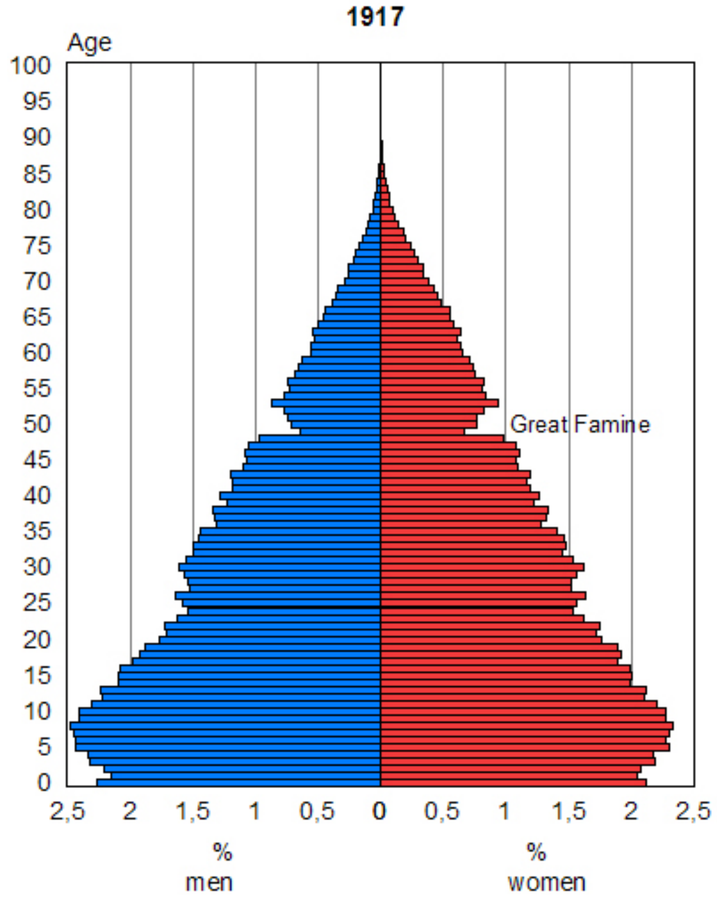
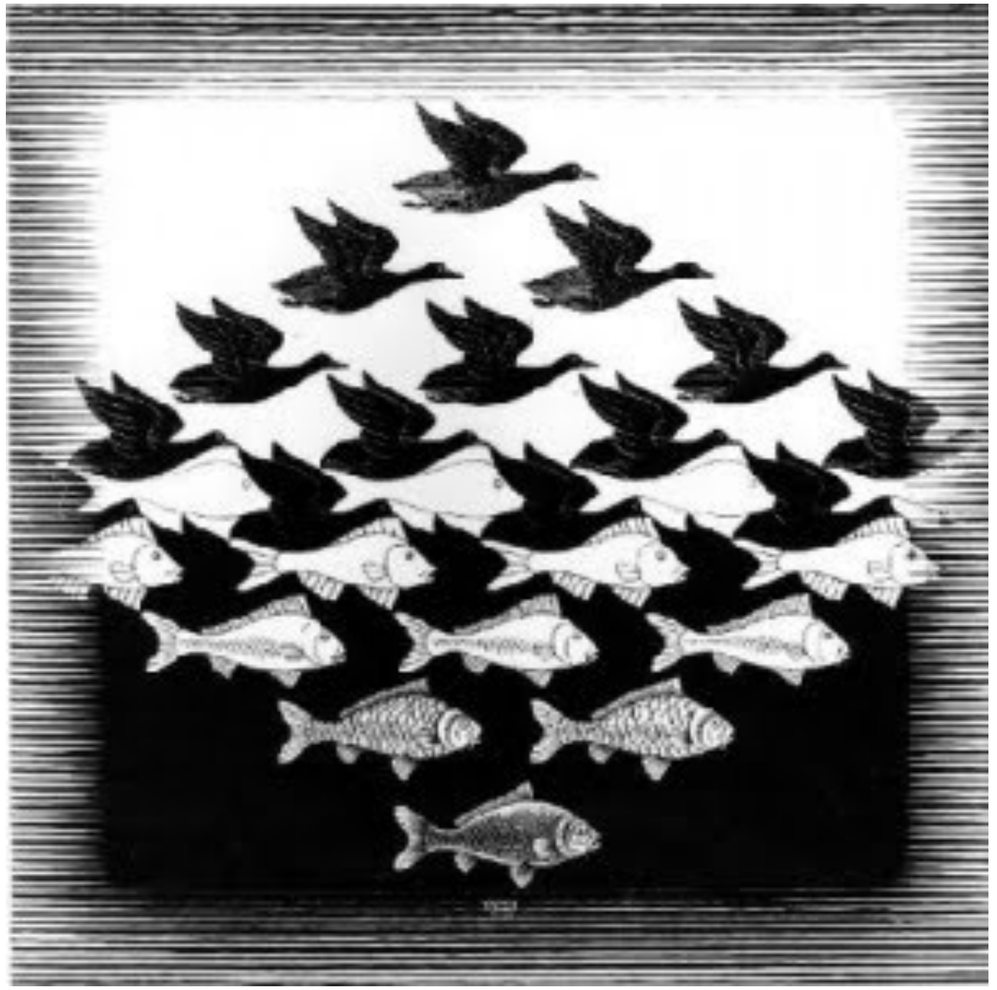


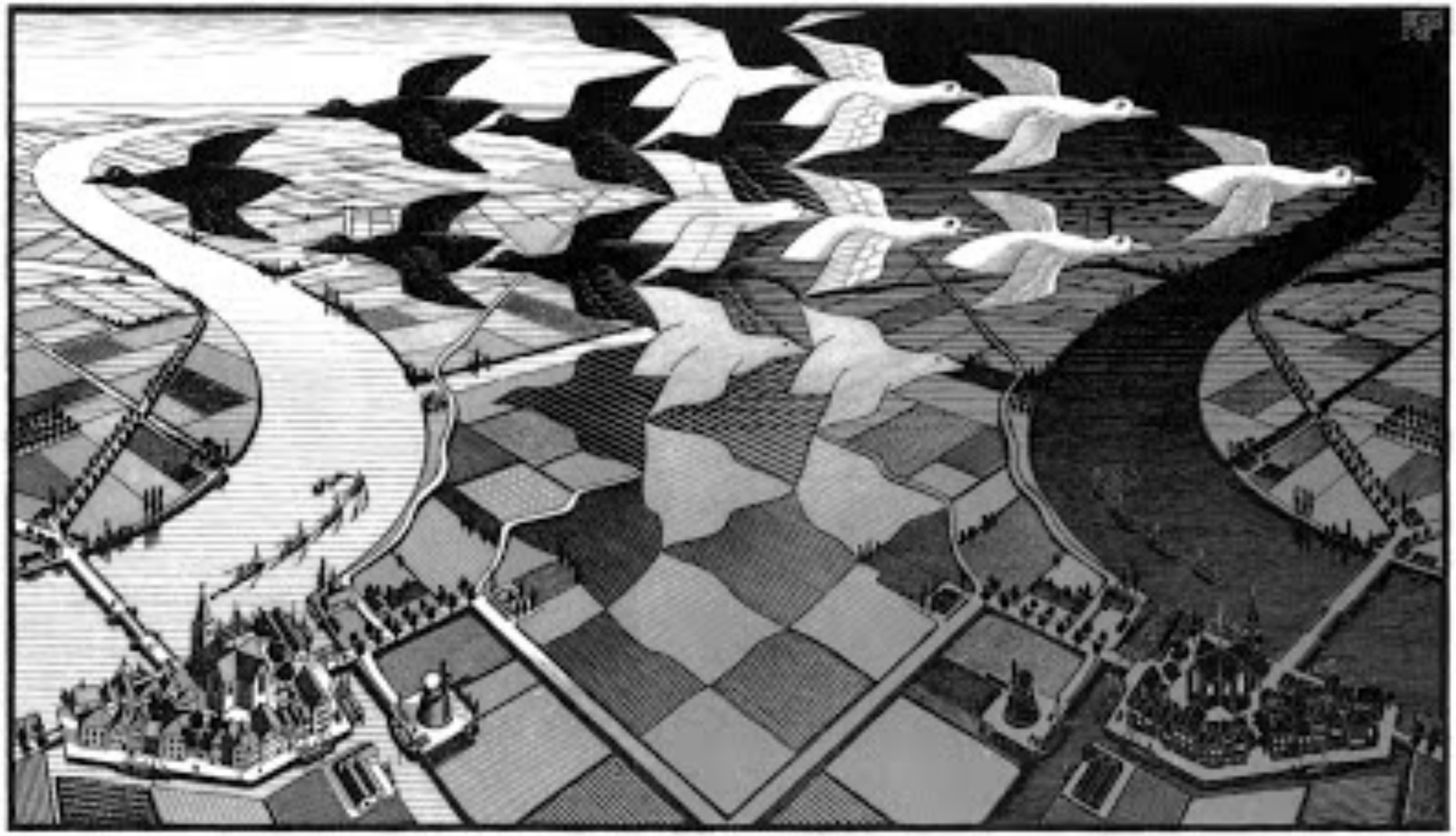
FIGURE / GROUND

FIGURE / GROUND



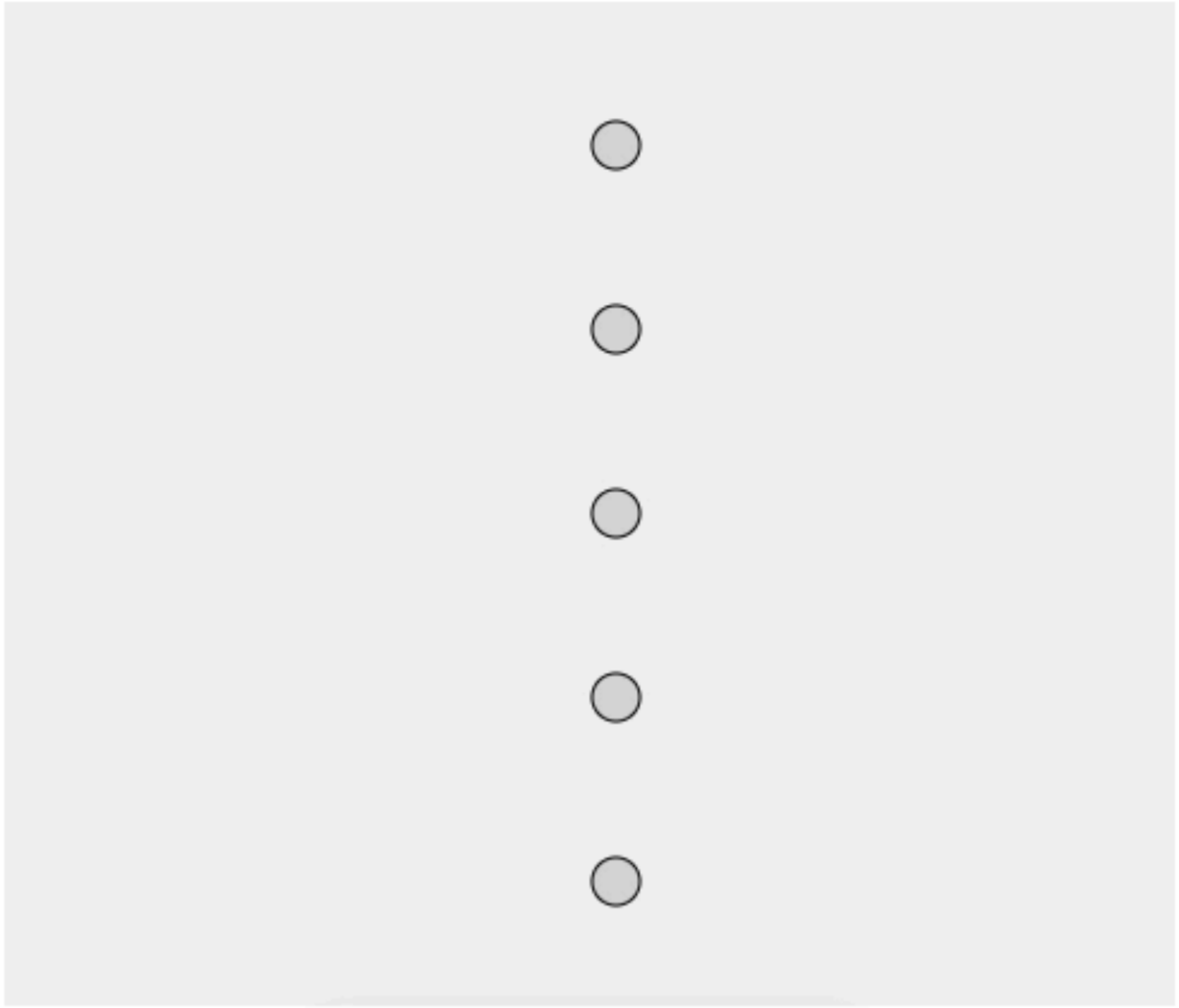
Sky and Water. M.C. Escher 1938 woodcut.

FIGURE / GROUND



Day and Night. M.C. Escher 1938 woodcut

COMMON FATE



https://emeeks.github.io/gestaltdataviz/

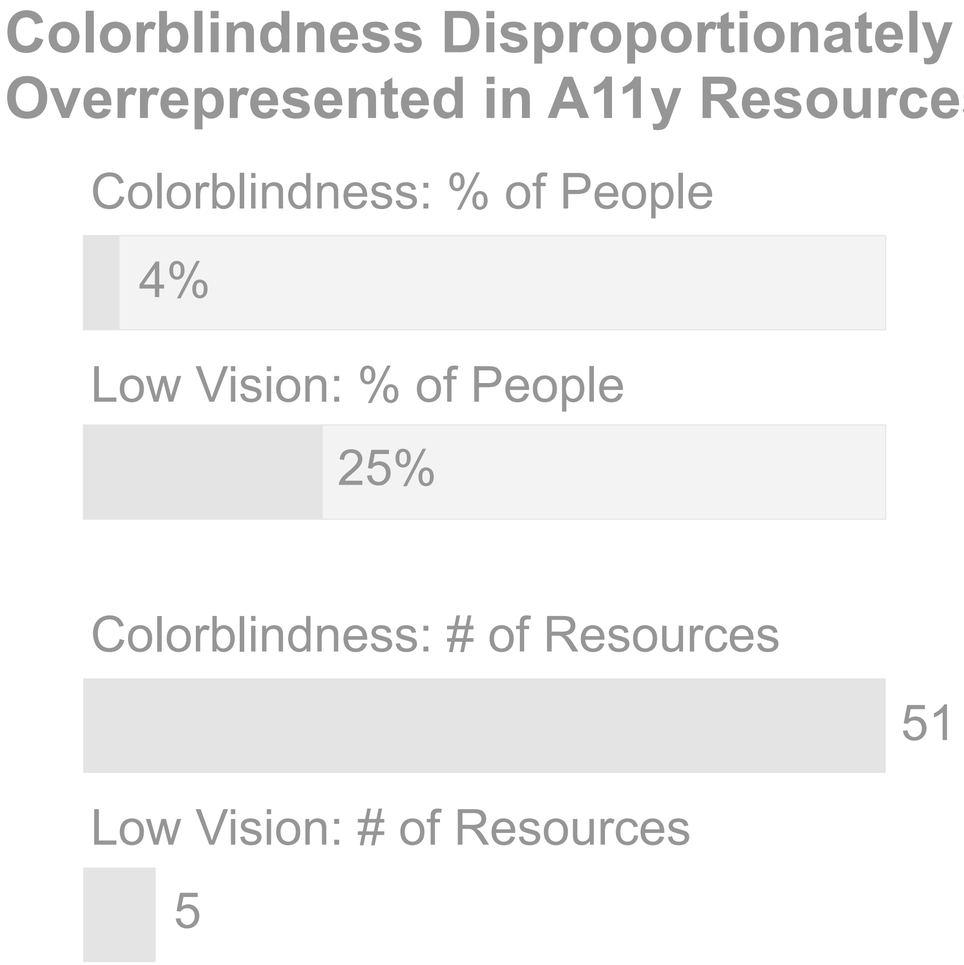
Perceivable

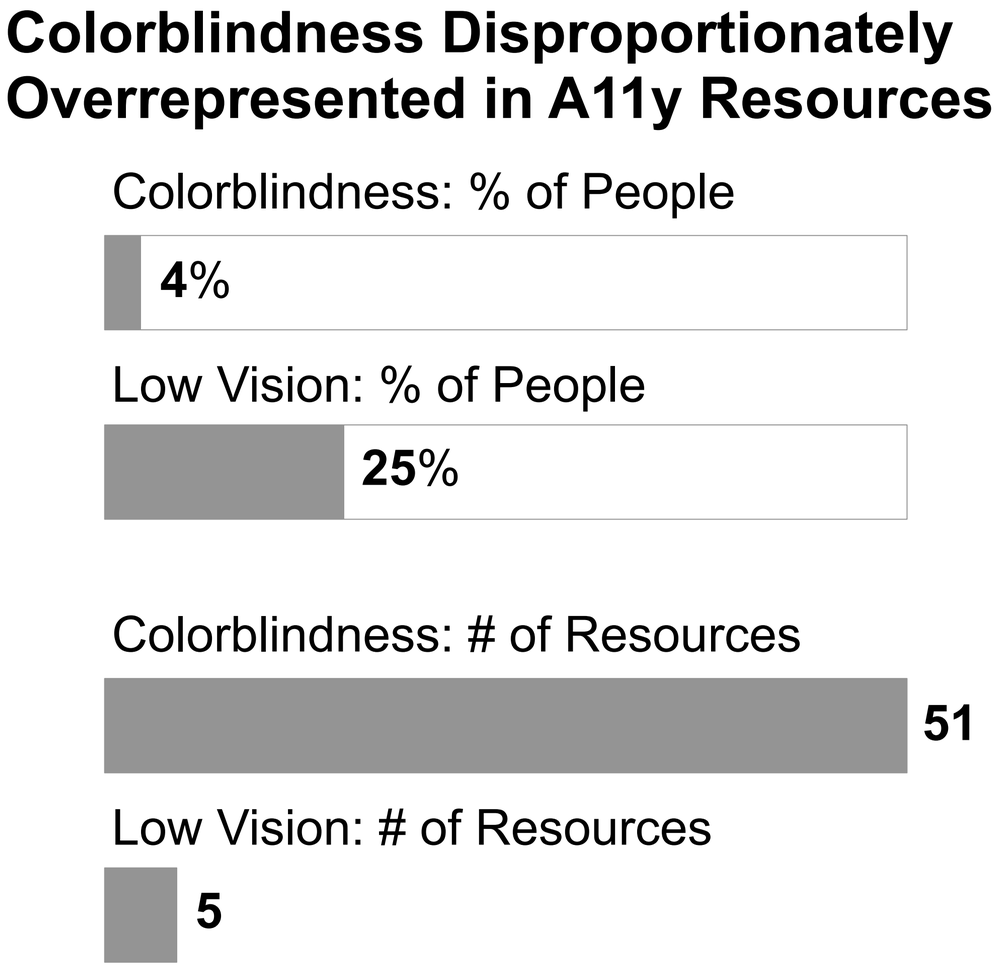
Can someone perceive this in multiple ways? Is each way easy?

Perceivable Checklist:

1. High Contrast
2. Colorblind-Safe + Redundant Encoding
3. Alt Text

Design with high contrast

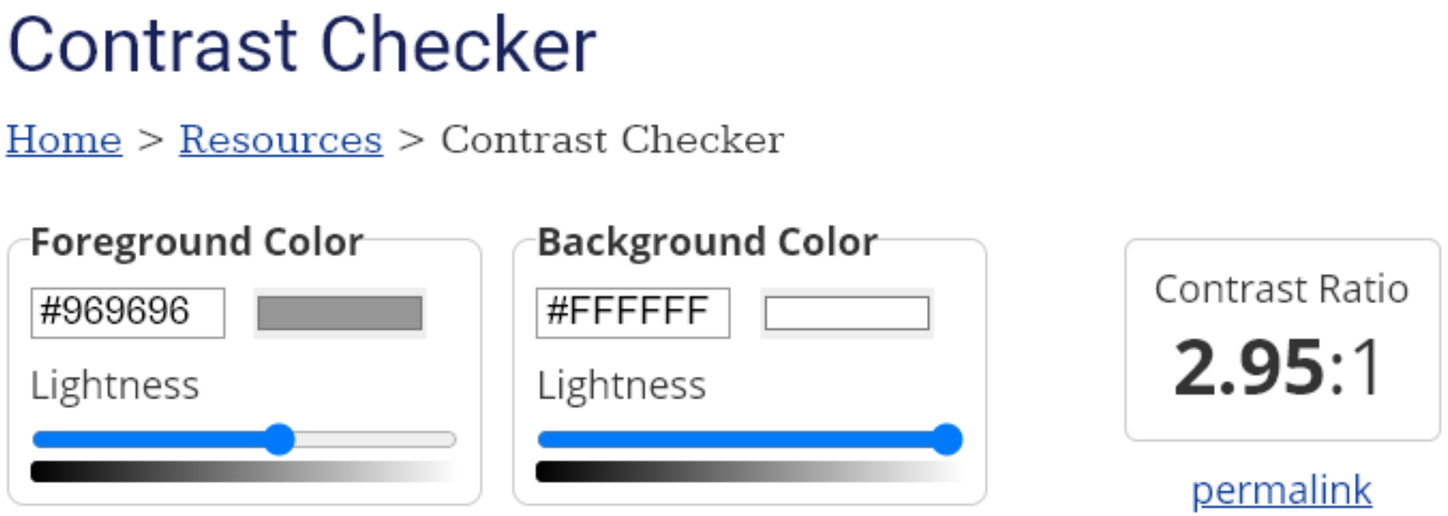




Use High Contrast Text

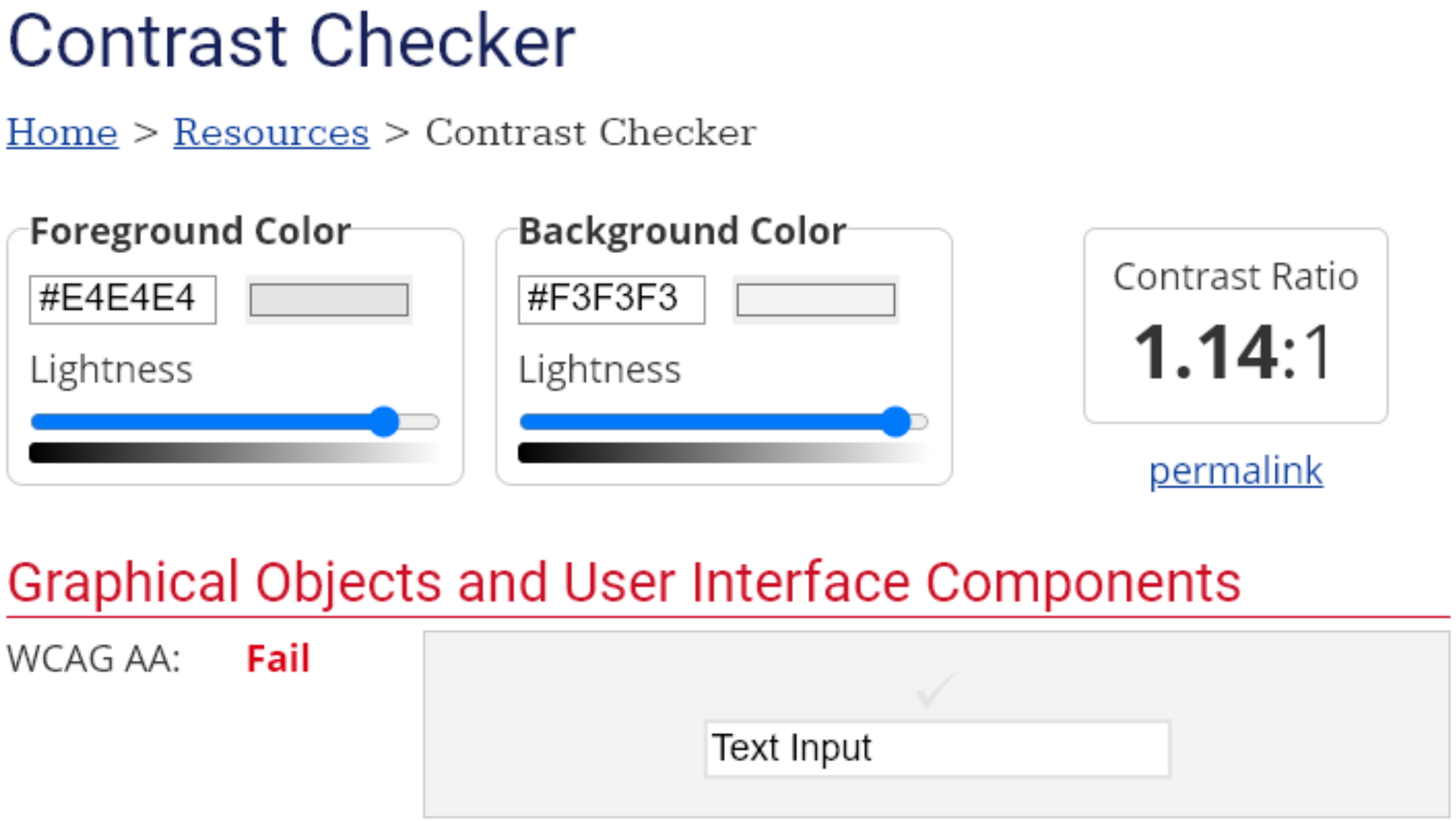
Text needs at least 4.5:1 contrast against its background.

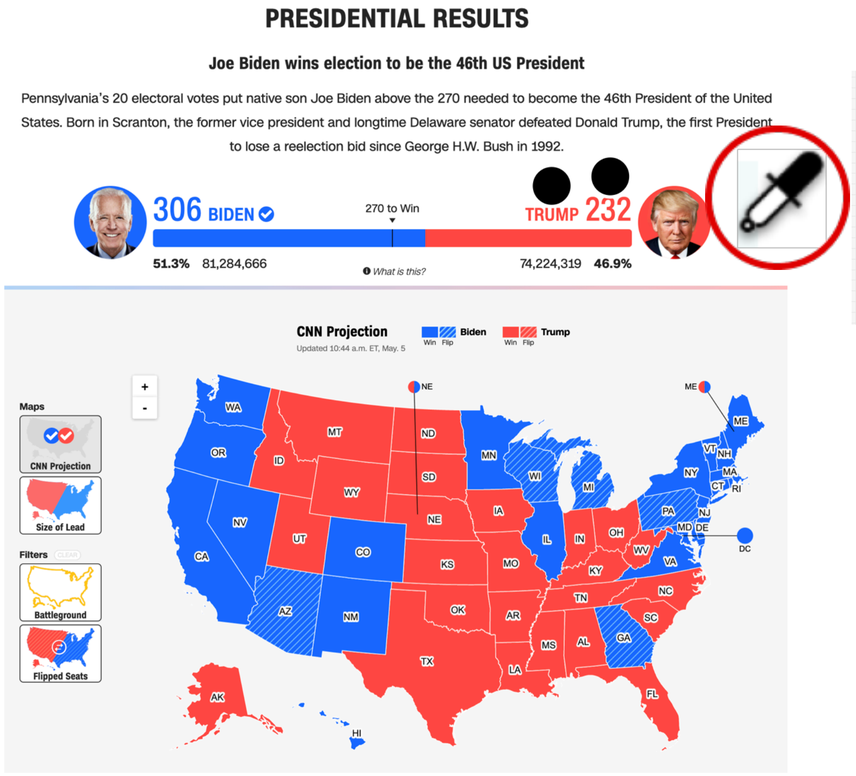
Large text (bold and 16pt or larger) can be 3:1 or higher.

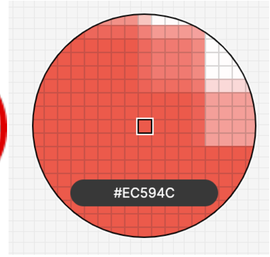


Use High Contrast Geometries

Chart elements need at least 3:1 contrast against their background.







Contrast Checker

Home > Resources > Contrast Checker

Foreground Color

#EC594C

Lightness

↔

Background Color

#FFFFFF

Lightness

Contrast Ratio

3.44:1

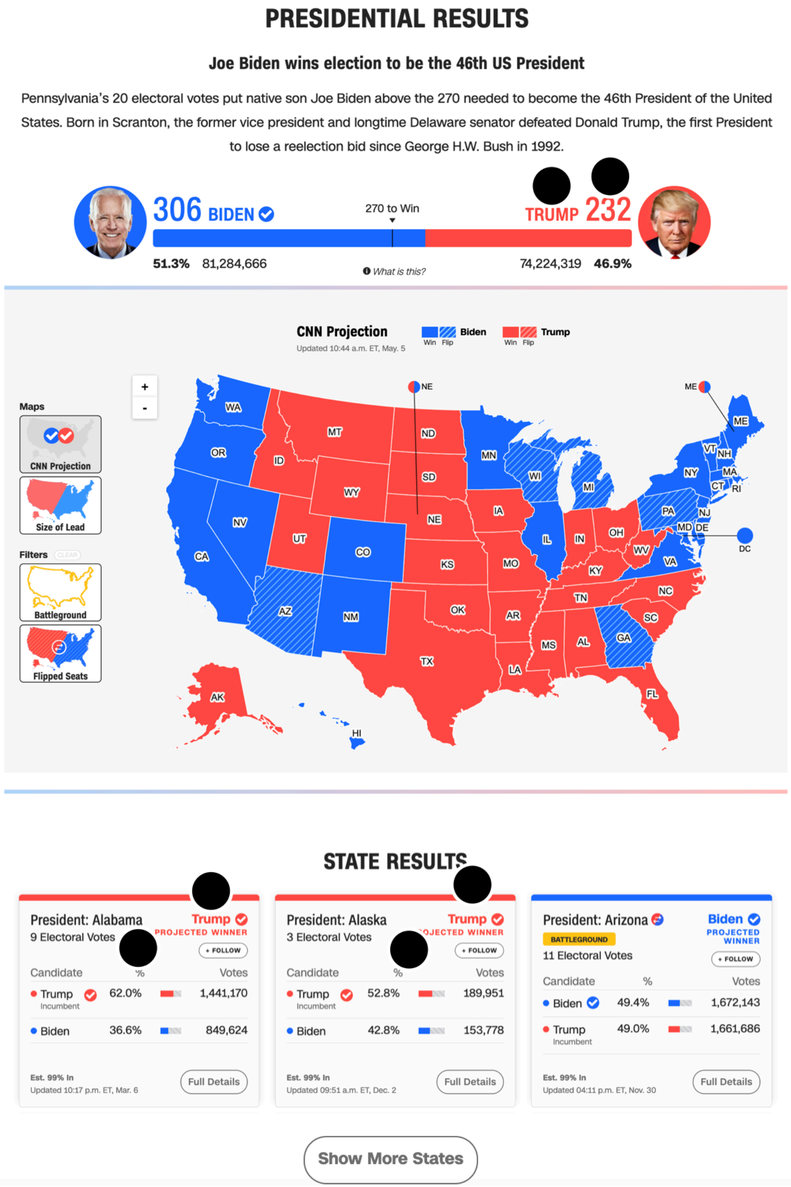
permalink

Normal Text

WCAG AA: **Fail**

WCAG AAA: **Fail**

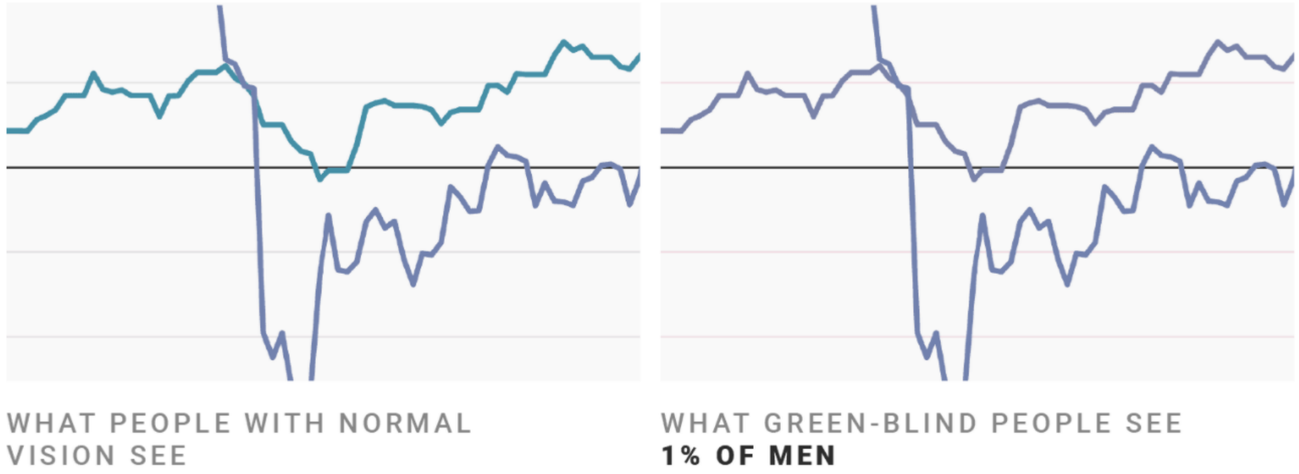
The five boxing wizards jump quickly.



6 instances of low contrast

Don’t rely on color alone!

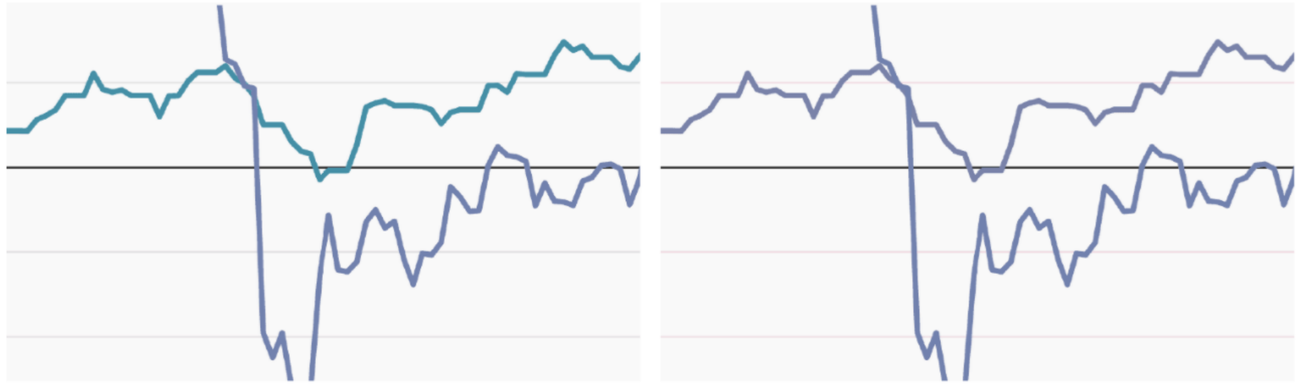
(Muth) https://blog.datawrapper.de/colorblindness-part2/



WHAT PEOPLE WITH NORMAL VISION SEE

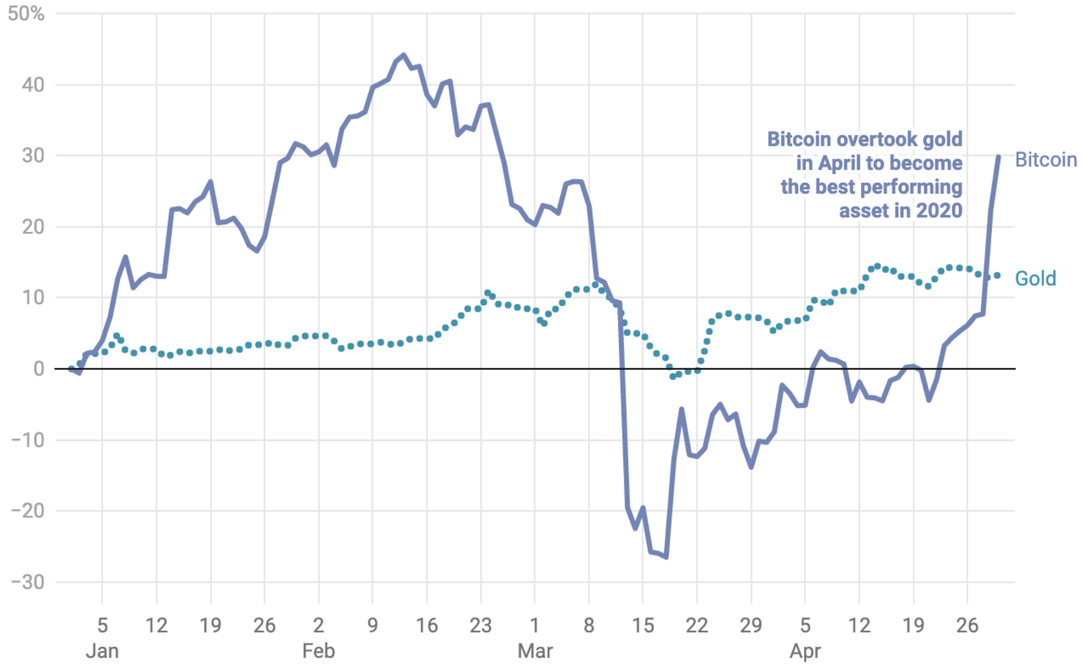
WHAT GREEN-BLIND PEOPLE SEE
1% OF MEN

“Redundant encoding” is one strategy



WHAT PEOPLE WITH NORMAL VISION SEE

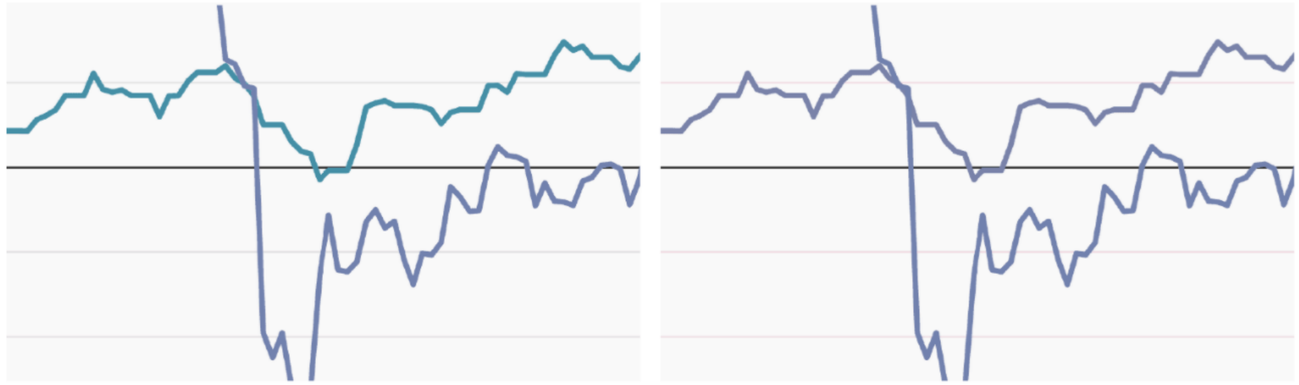
WHAT GREEN-BLIND PEOPLE SEE
1% OF MEN



Bitcoin and gold price change (%) between January and May 2020

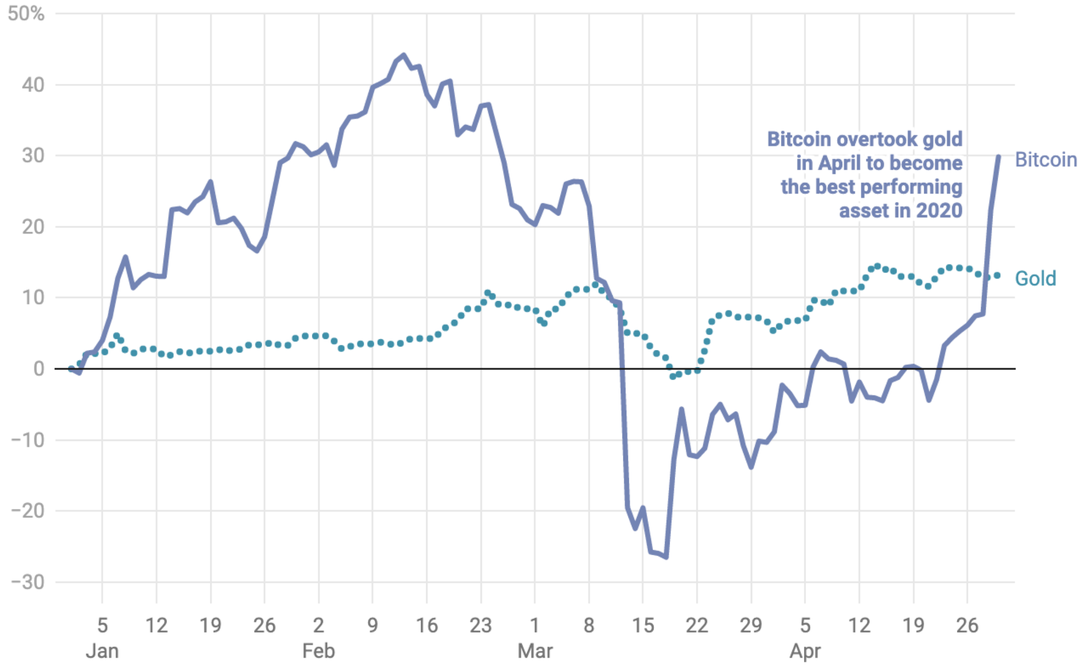
Chart: Based on Anthony Cuthbertson • Source: CoinMarketCap, Nasdaq, Gold Price • Get the data

A note: **“Color-vision deficiency”** and **“colorblindness”** refer to the same thing, both terms are fine to use.



WHAT PEOPLE WITH NORMAL VISION SEE

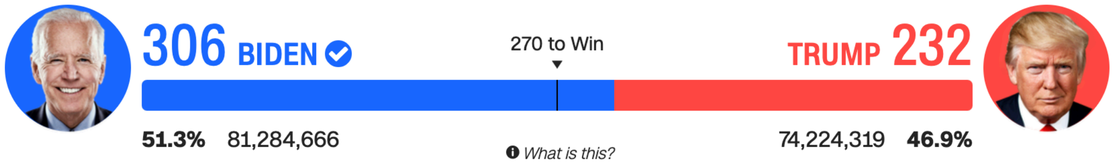
WHAT GREEN-BLIND PEOPLE SEE
1% OF MEN

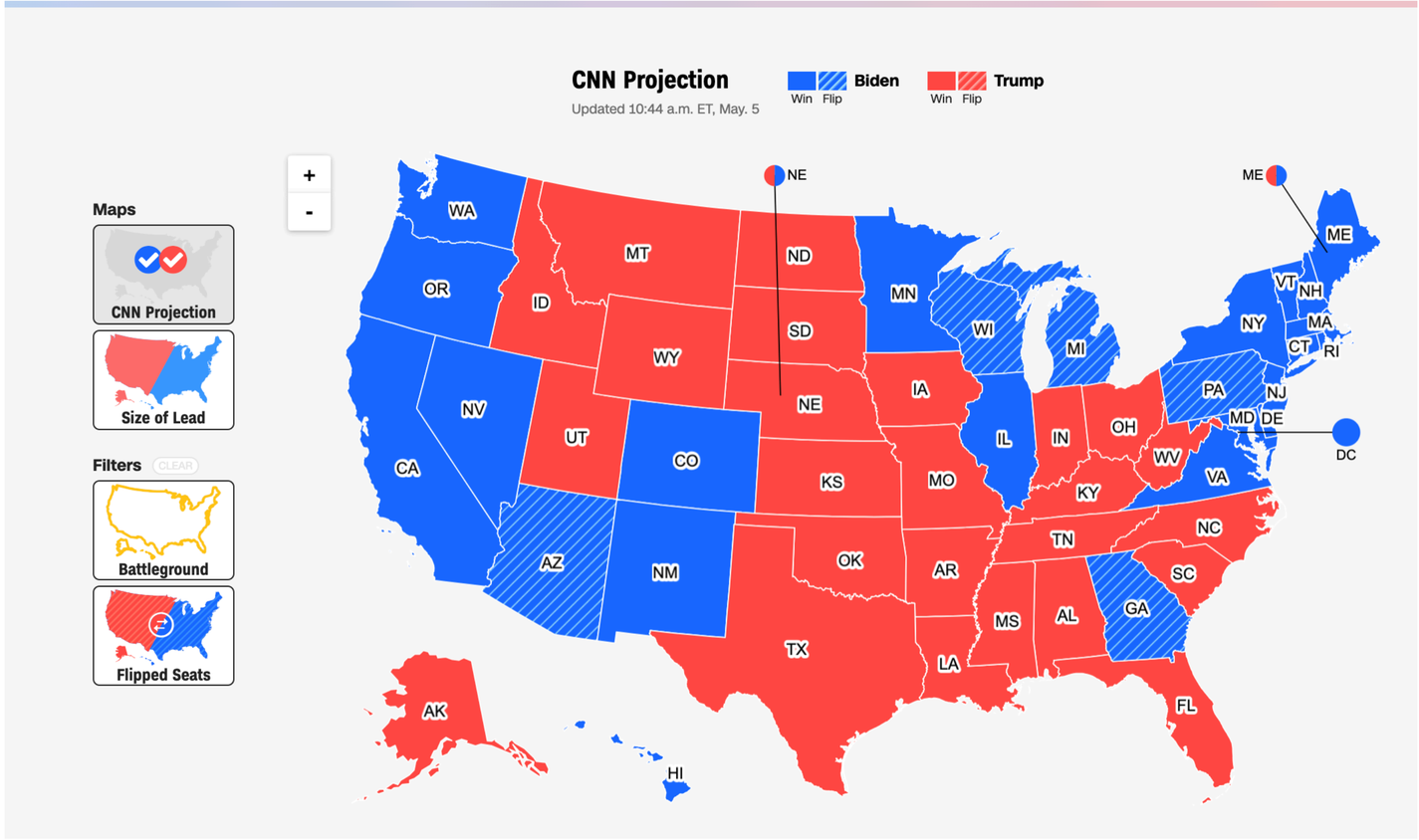


Bitcoin and gold price change (%) between January and May 2020

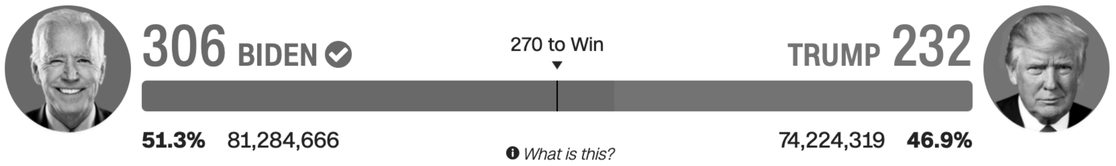
Chart: Based on Anthony Cuthbertson • Source: CoinMarketCap, Nasdaq, Gold Price • Get the data

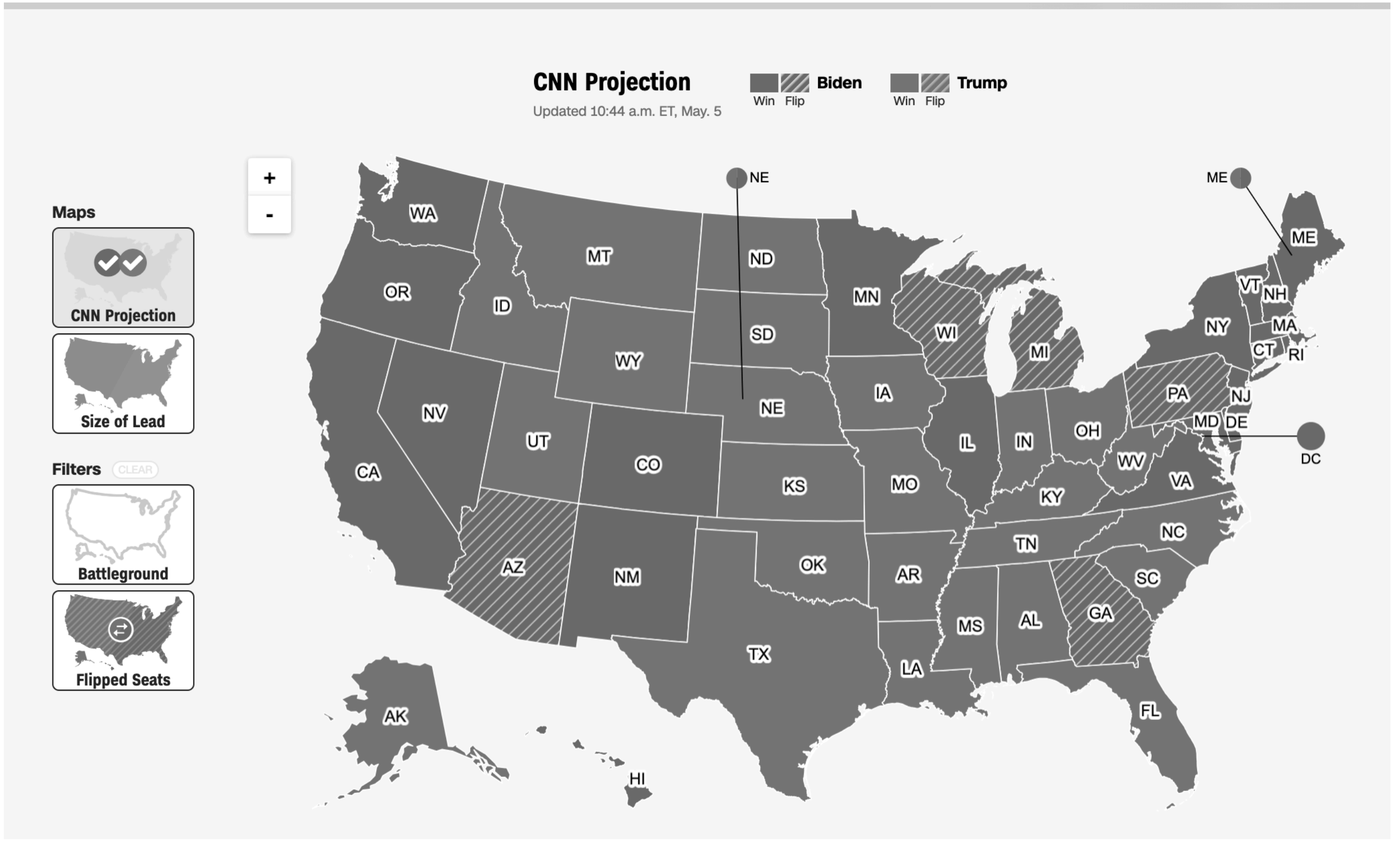
But sometimes you *can't* redundantly encode!



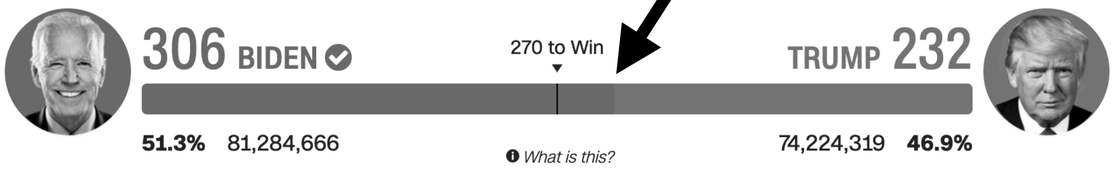


This map is trouble in greyscale

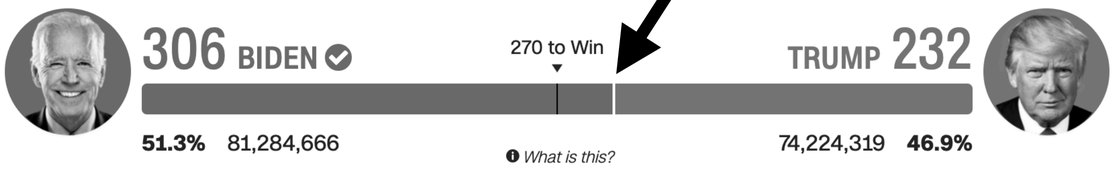


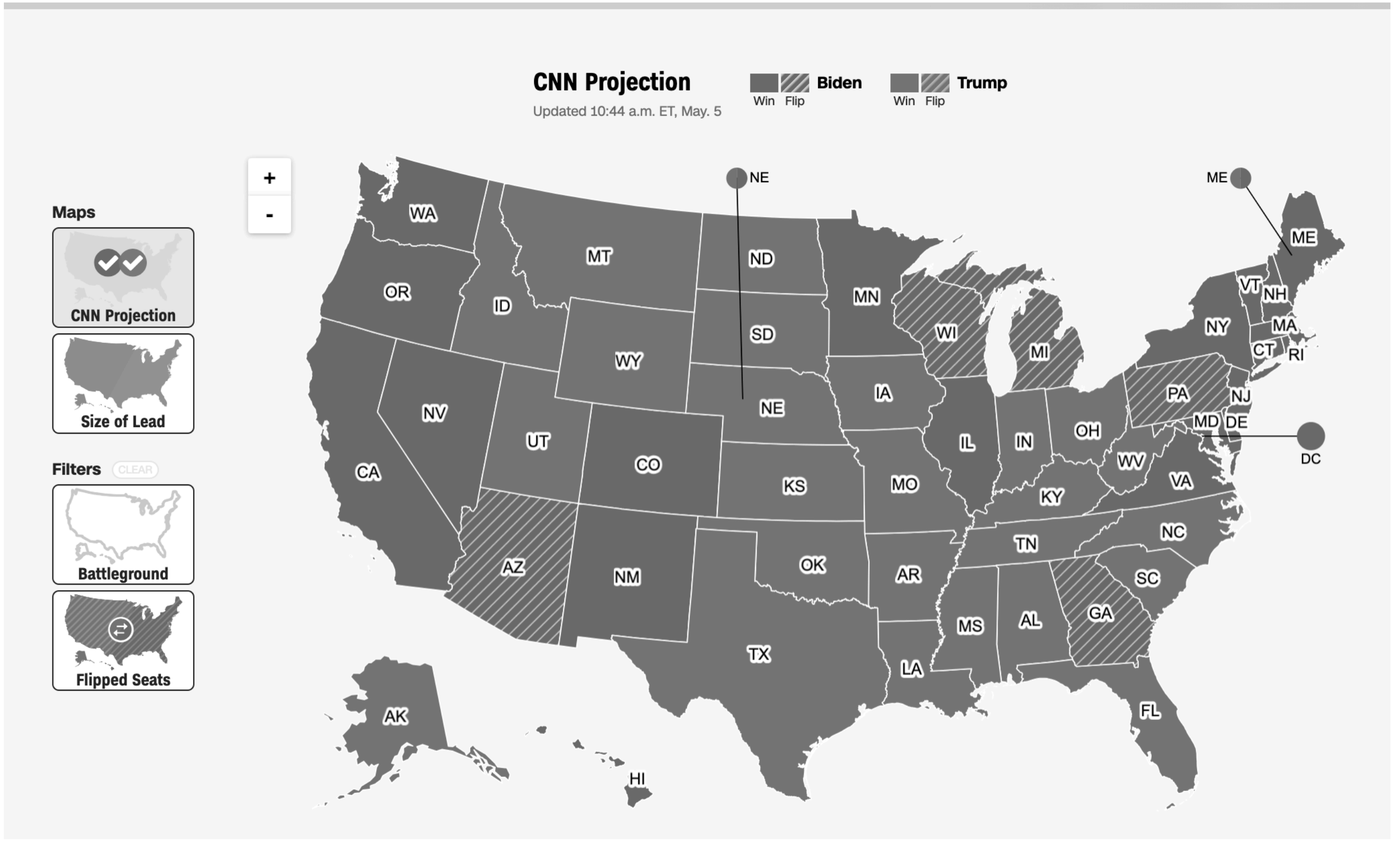


The division here matters!

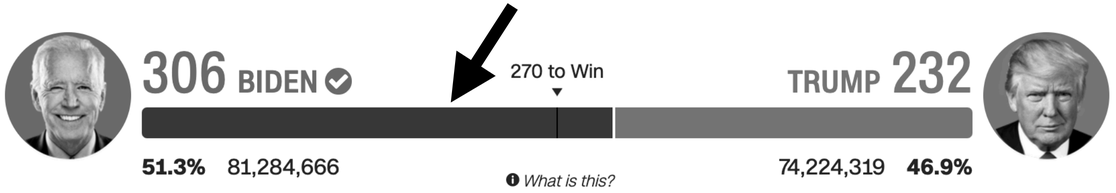


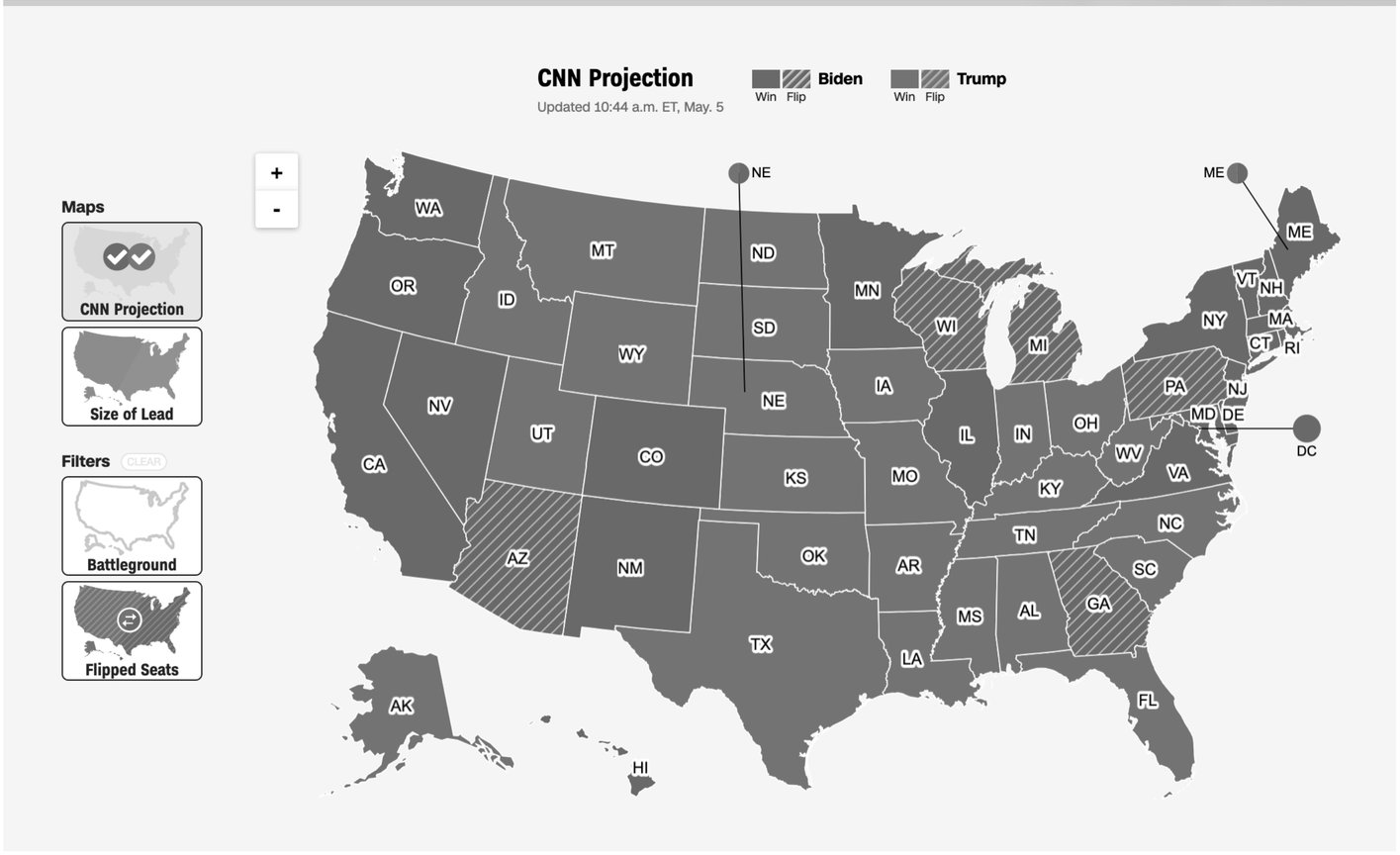
Maybe a small white divider, like the states?



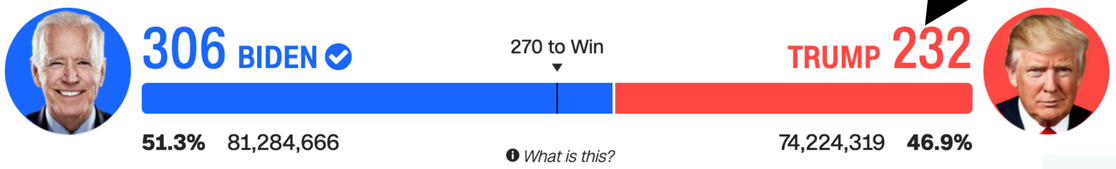


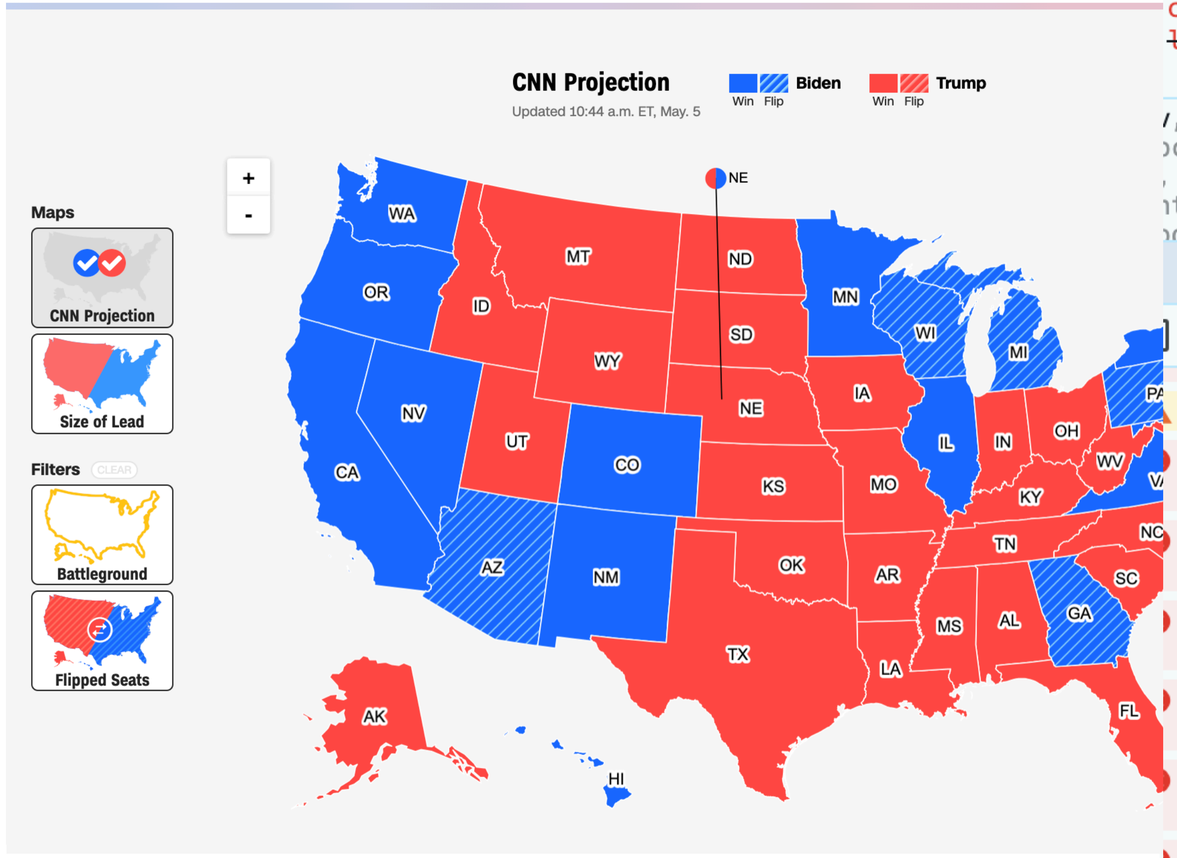
Perhaps test a darker blue too?

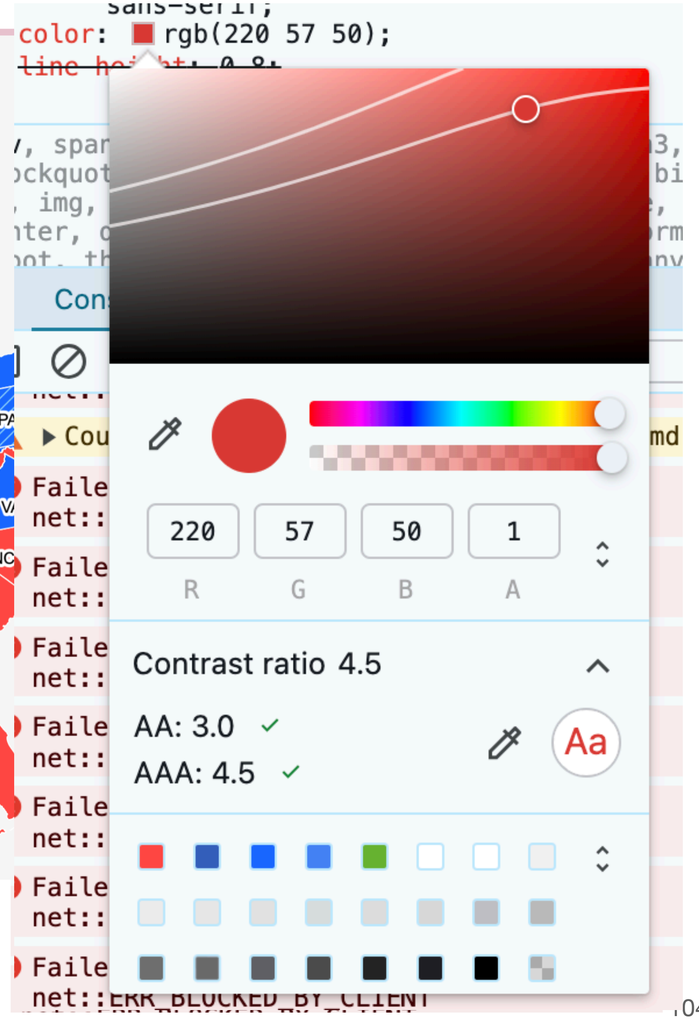




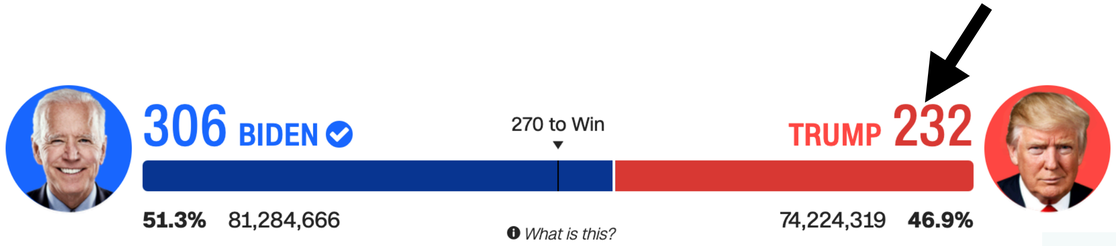
What if we fix the contrast failures at the same time?

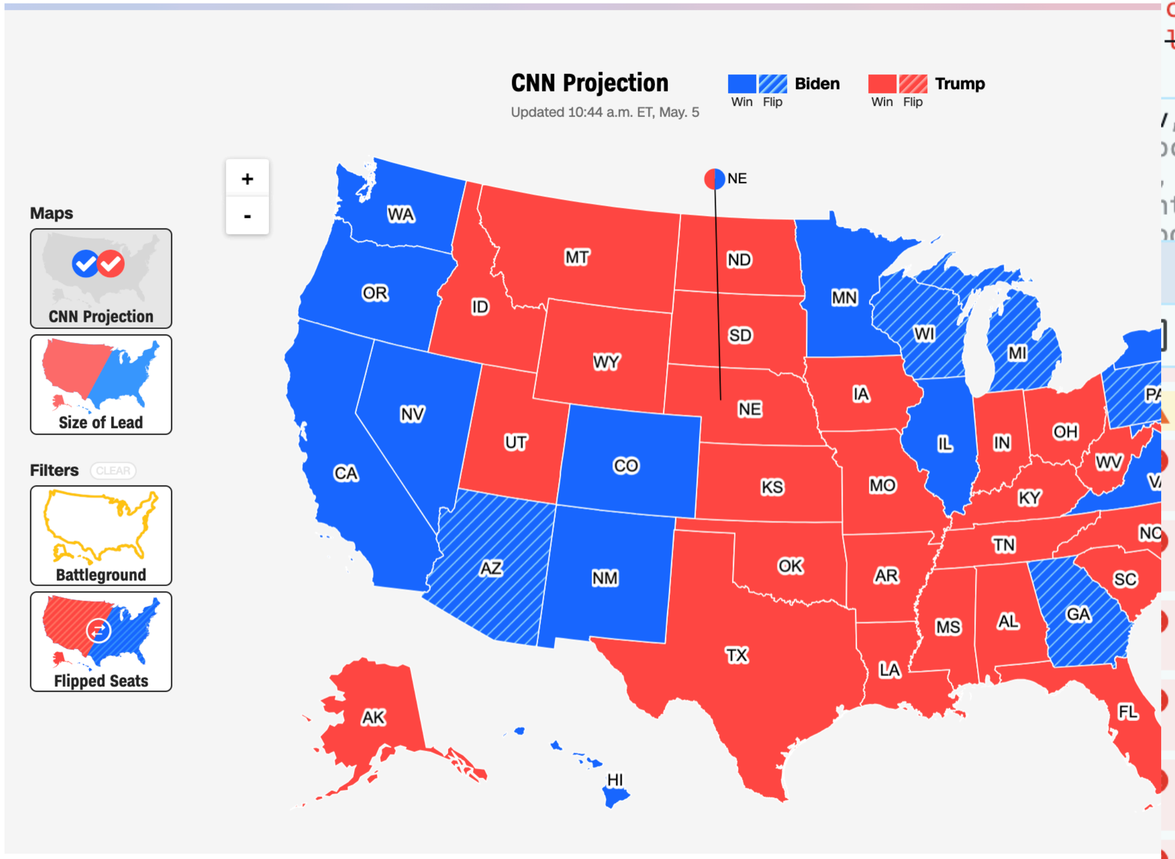


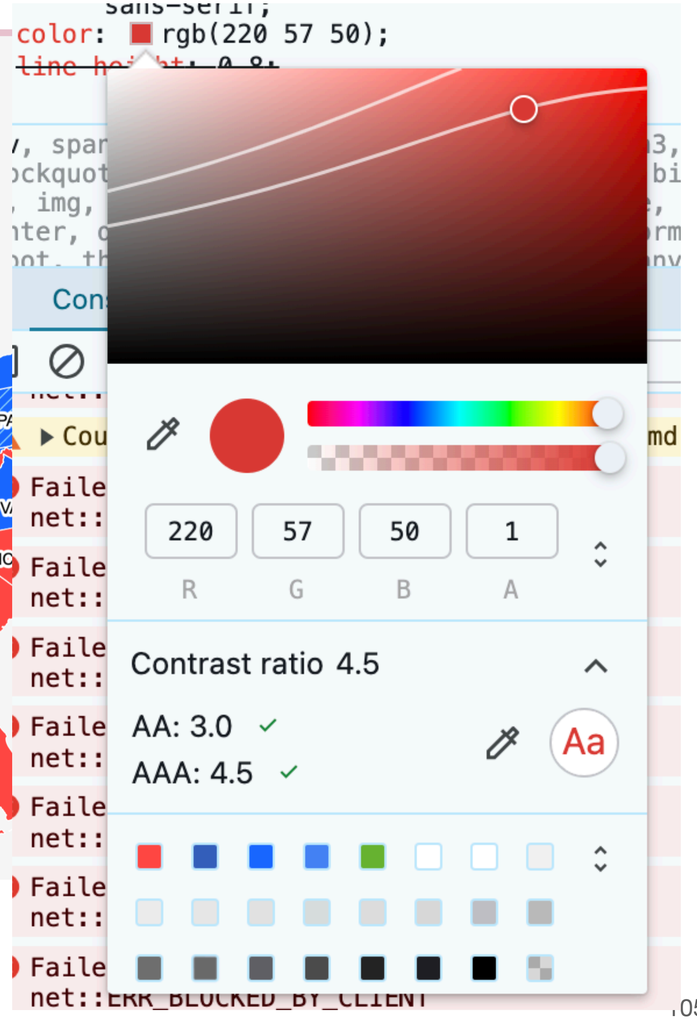




This text now passes!

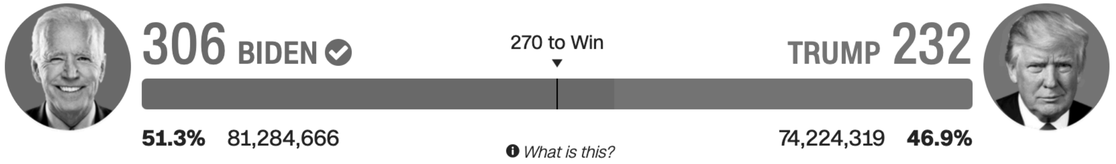


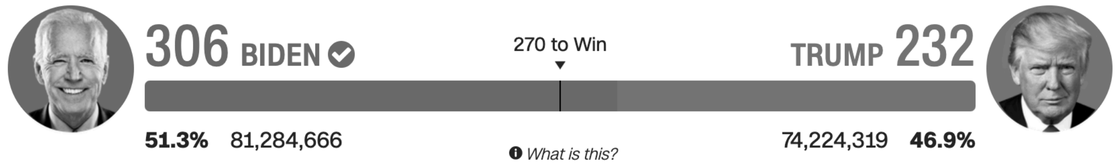




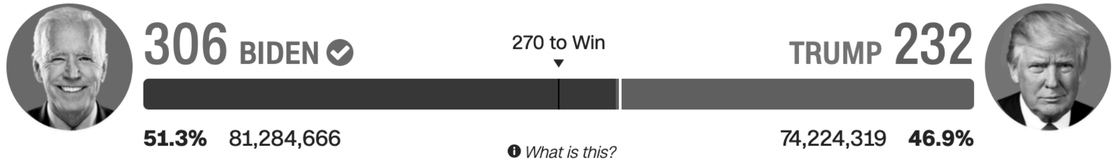
Let’s check that greyscale again…

Before

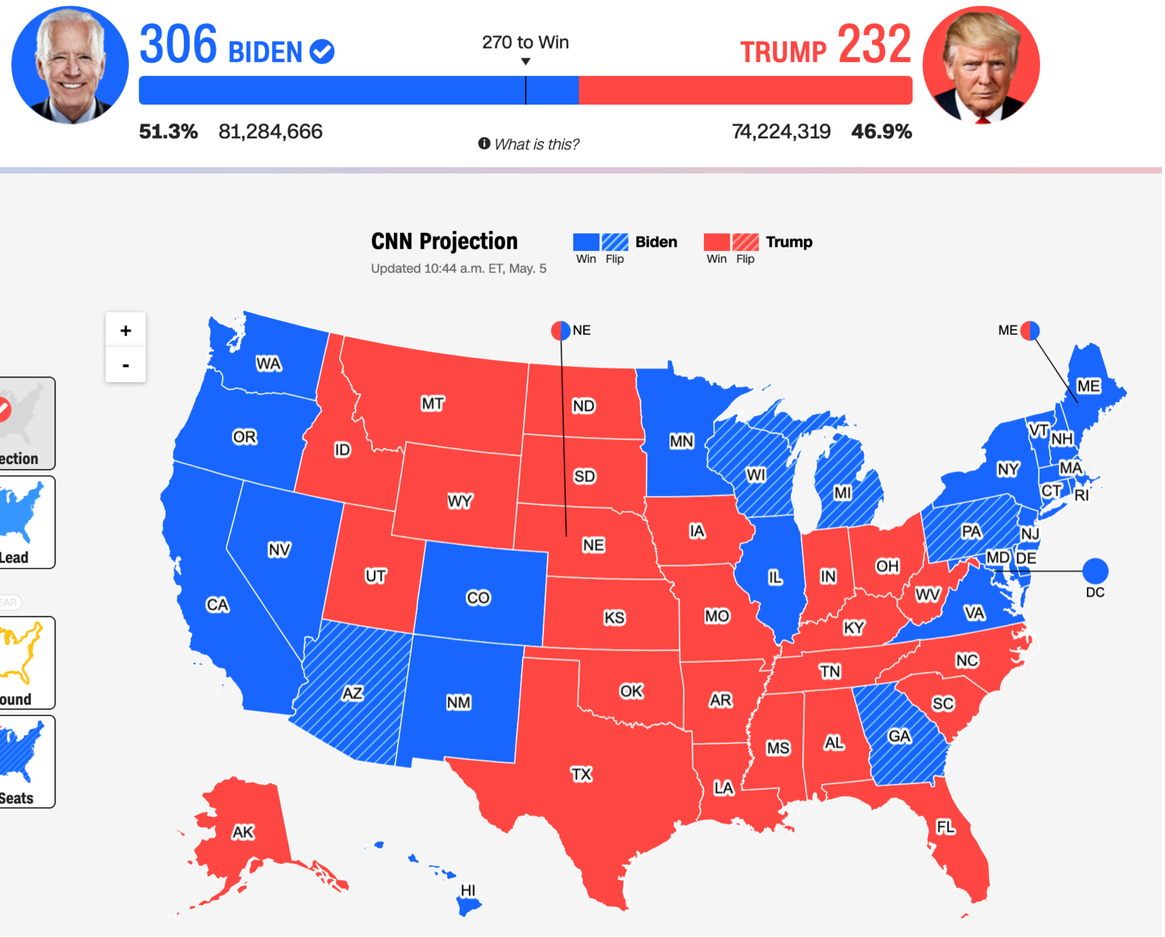

306 BIDEN
270 to Win
TRUMP 232
51.3% 81,284,666
What is this?
74,224,319 46.9%

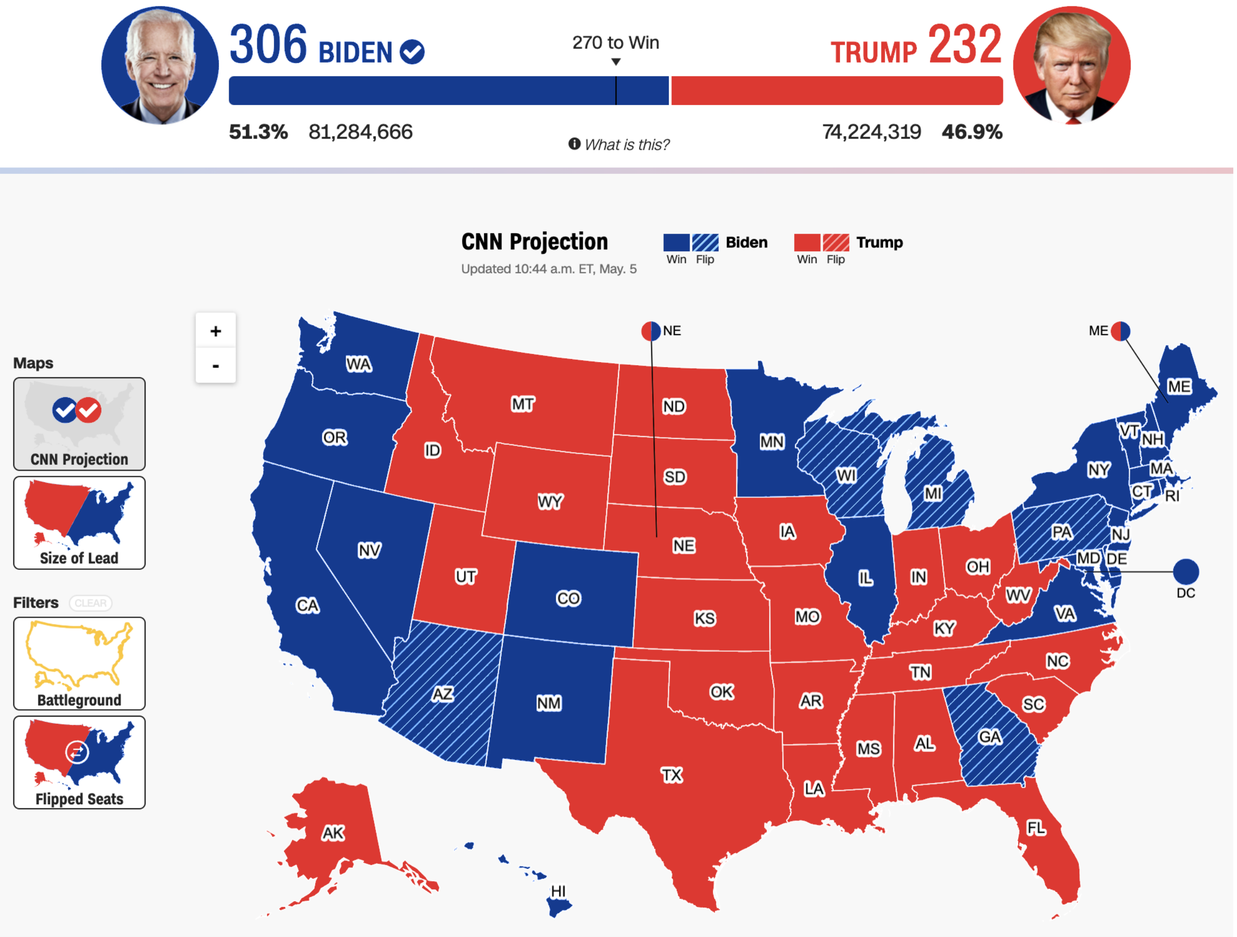

306 BIDEN
270 to Win
TRUMP 232
51.3% 81,284,666
What is this?
74,224,319 46.9%

And after!


306 BIDEN
270 to Win
TRUMP 232
51.3% 81,284,666
What is this?
74,224,319 46.9%

Sufficient contrast can help folks differentiate



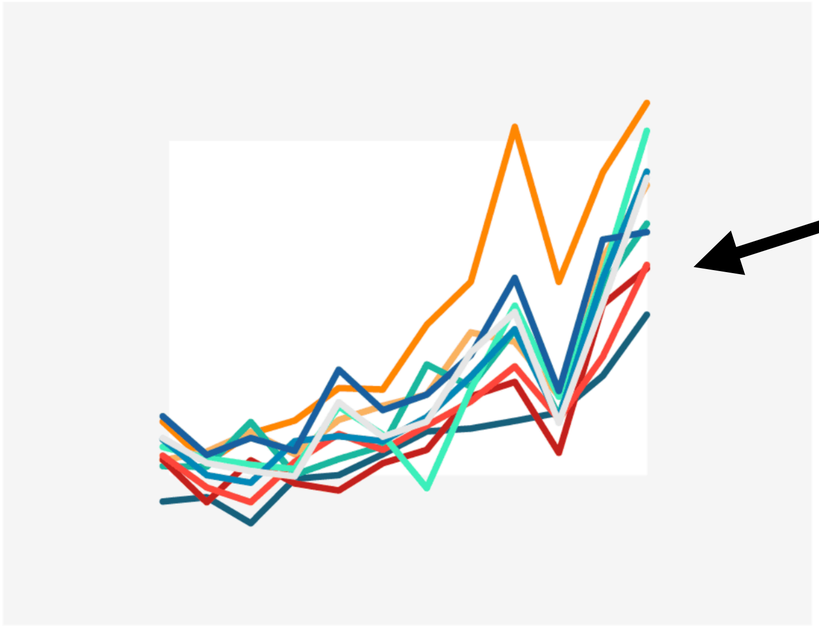


But what about more than 2 colors?

NOT IDEAL

Source: Datawrapper

But what about more than 2 colors?



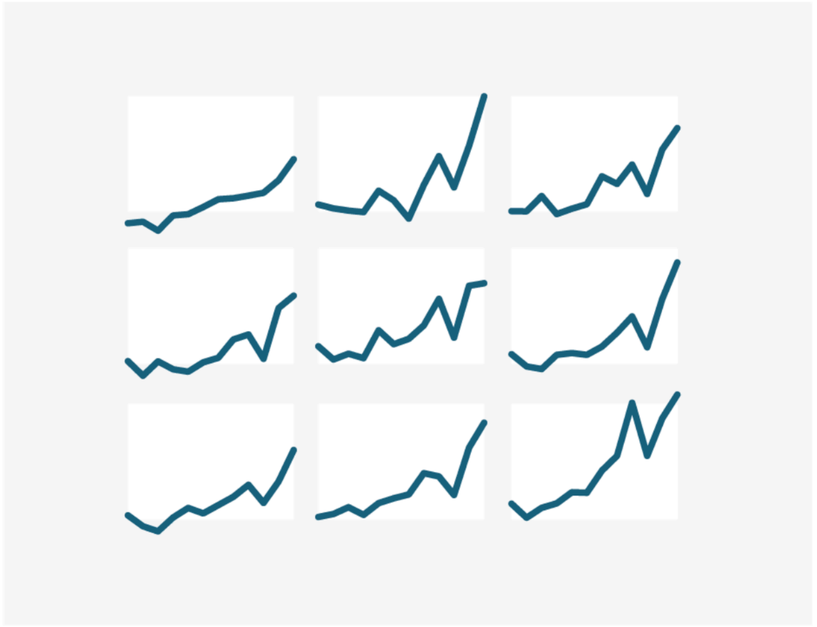
NOT IDEAL

Finding “pair” contrast gets really hard after 3+ colors…

Source: Datawrapper

Reduce your colors and redesign!

NOT IDEAL



BETTER

Source: Datawrapper

Reduce your colors and redesign!

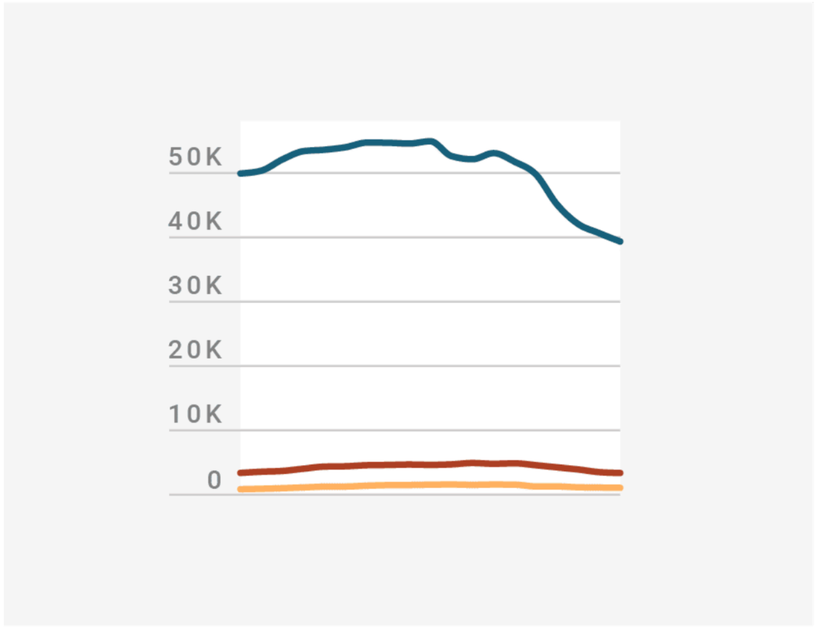
Using “small multiples” is an easy, powerful technique

NOT IDEAL

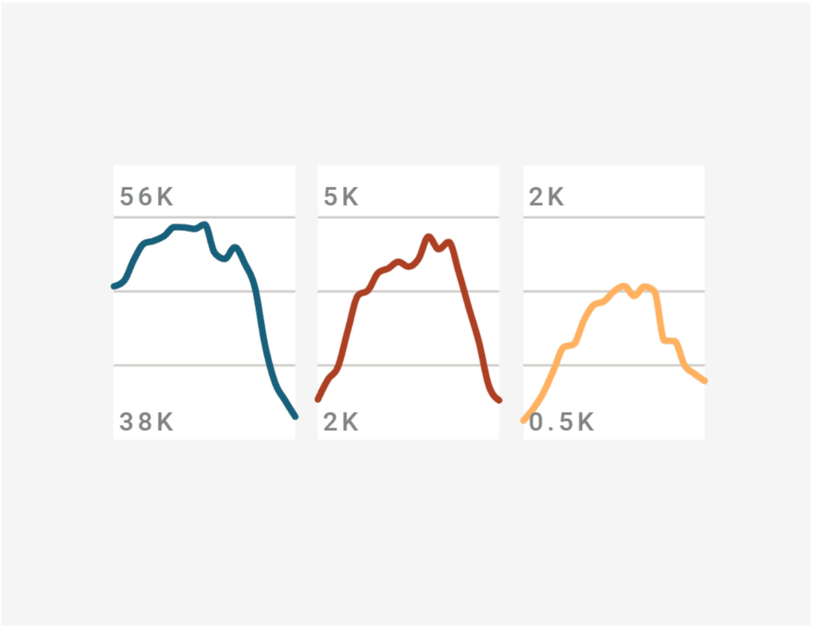
BETTER

Source: Datawrapper

Or simply separate your colors, if they matter



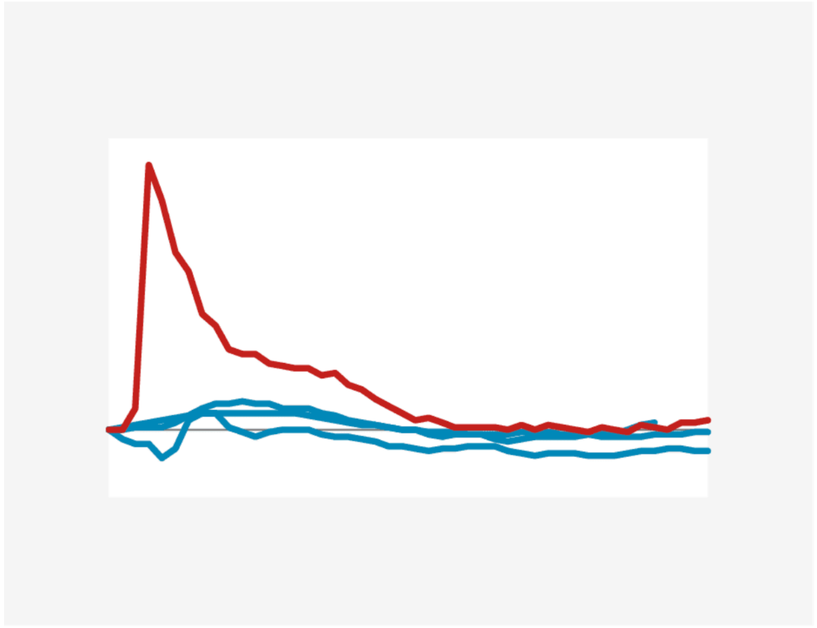
GOOD



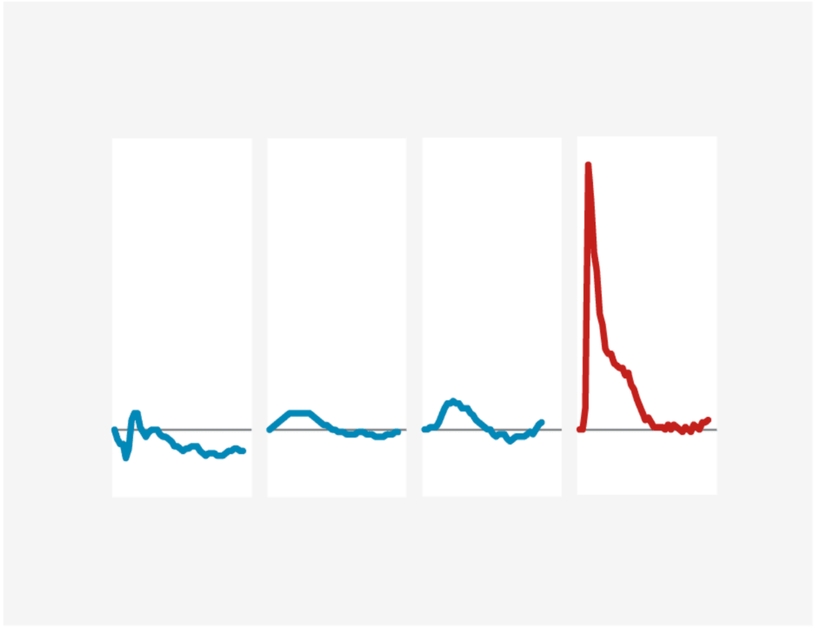
ALSO GOOD

Source: Datawrapper

My favorite use of color is to pick just one for *emphasis*



GOOD



BETTER

Source: Datawrapper

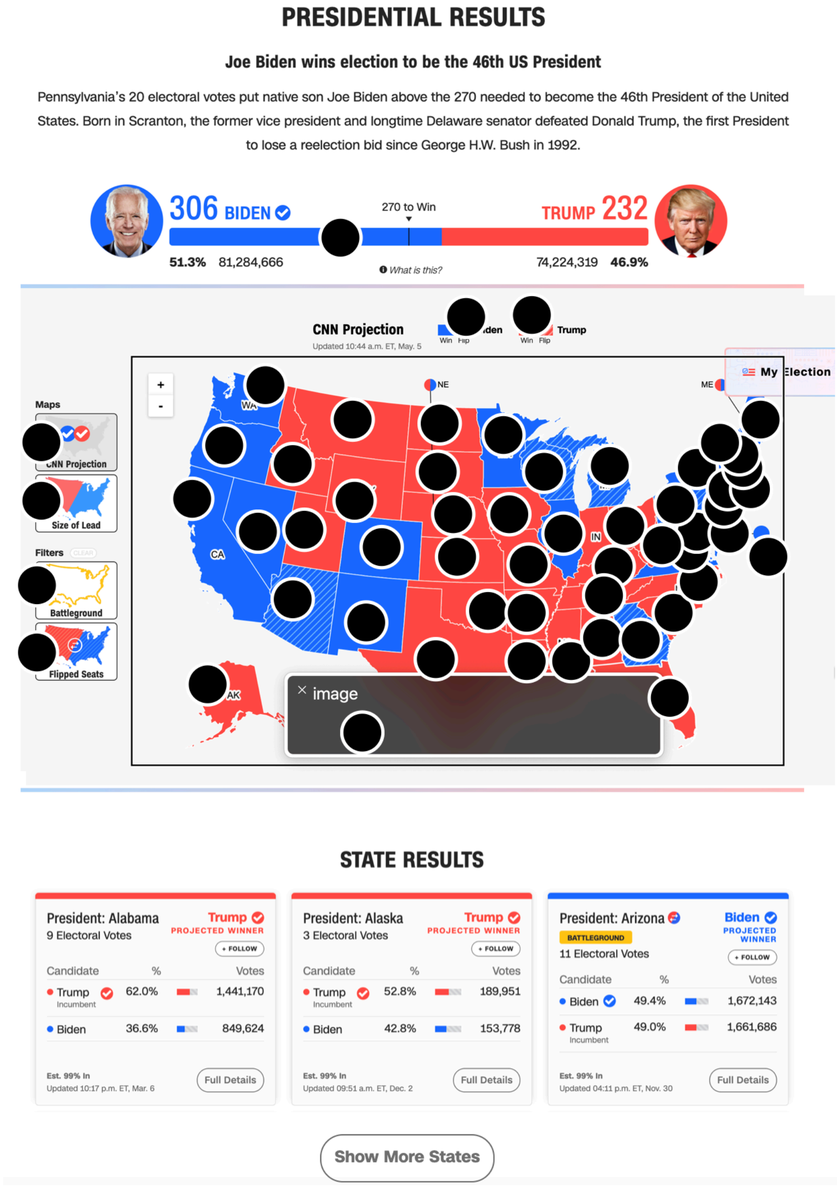
Add alt text

There is great research on alt text, but the most important thing to know is that you should add it to every image you post online (including twitter), in a document, or presentation.

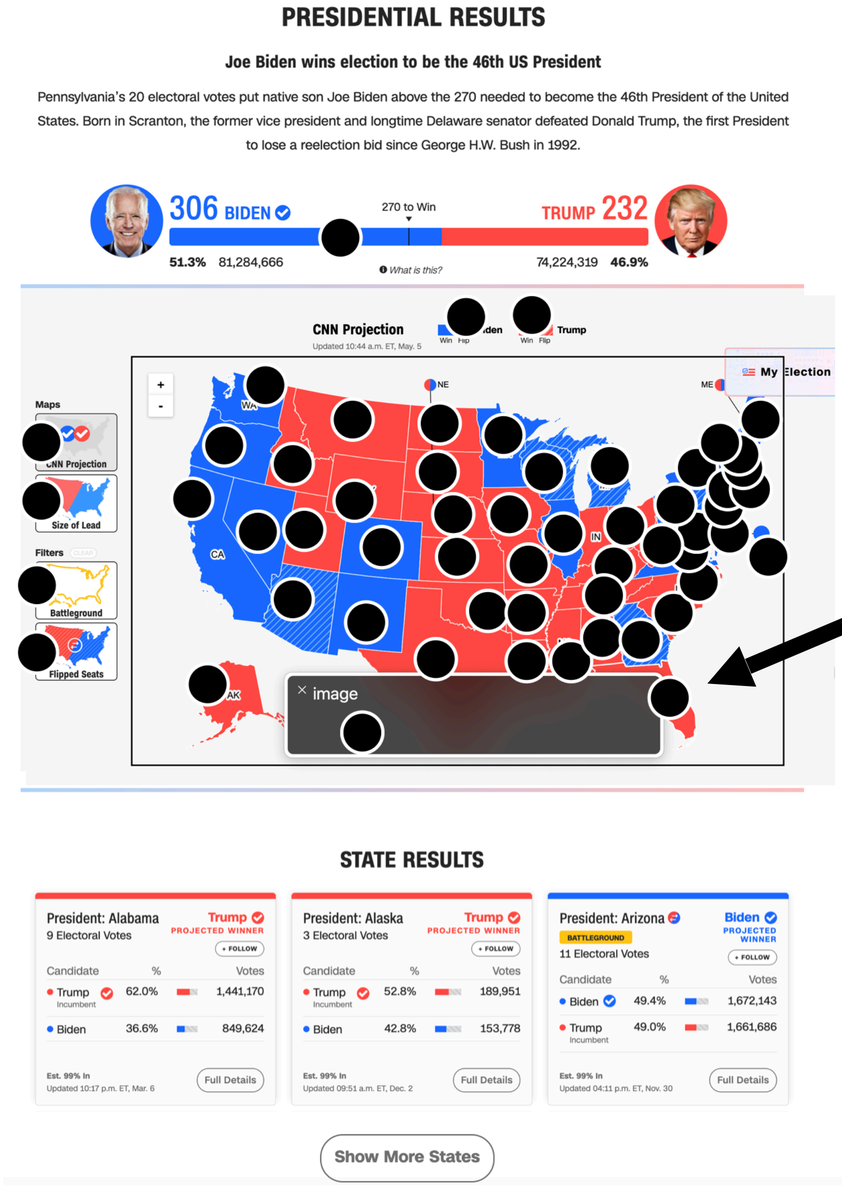
Guidance: https://medium.com/nightingale/writing-alt-text-for-data-visualization-2a218ef43f81

alt= “**Chart type** of **type of data** where **reason for including chart**”

Include a **link to data source** somewhere in the text



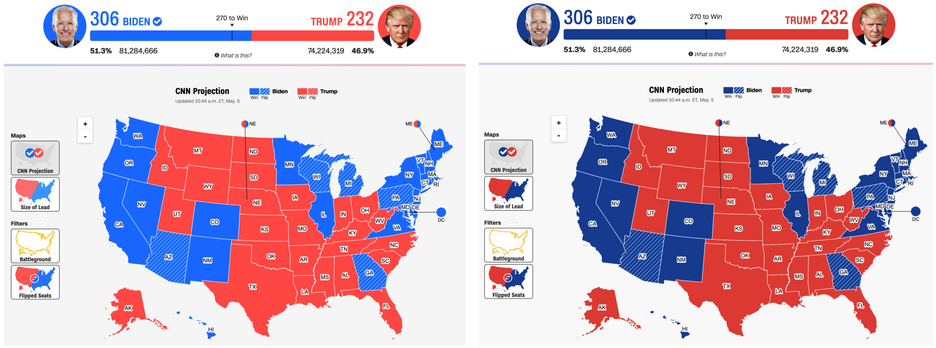
57 instances of “Content is only visual”



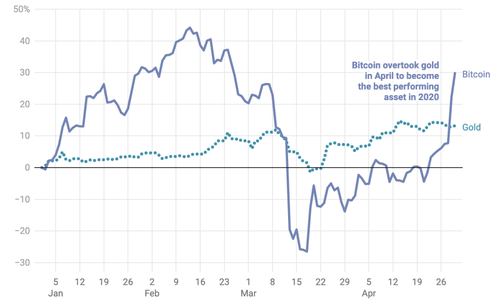
Each state should announce to screen readers what state it is and who won it, not "image!"

Recap: Perceivability

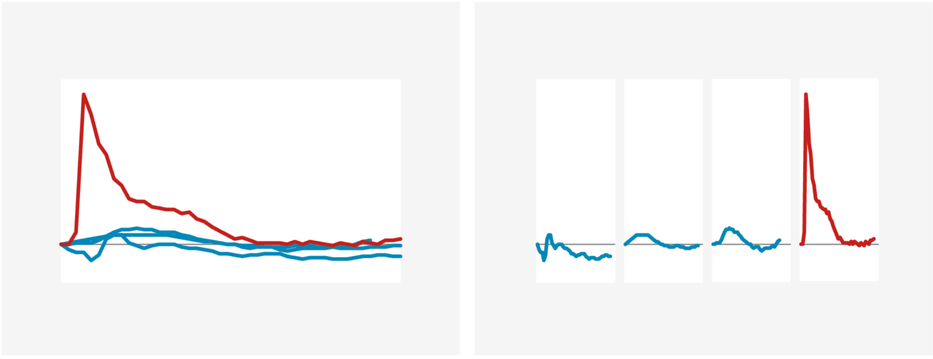
Use high contrast



Use redundant encoding



Reduce colors and crowding

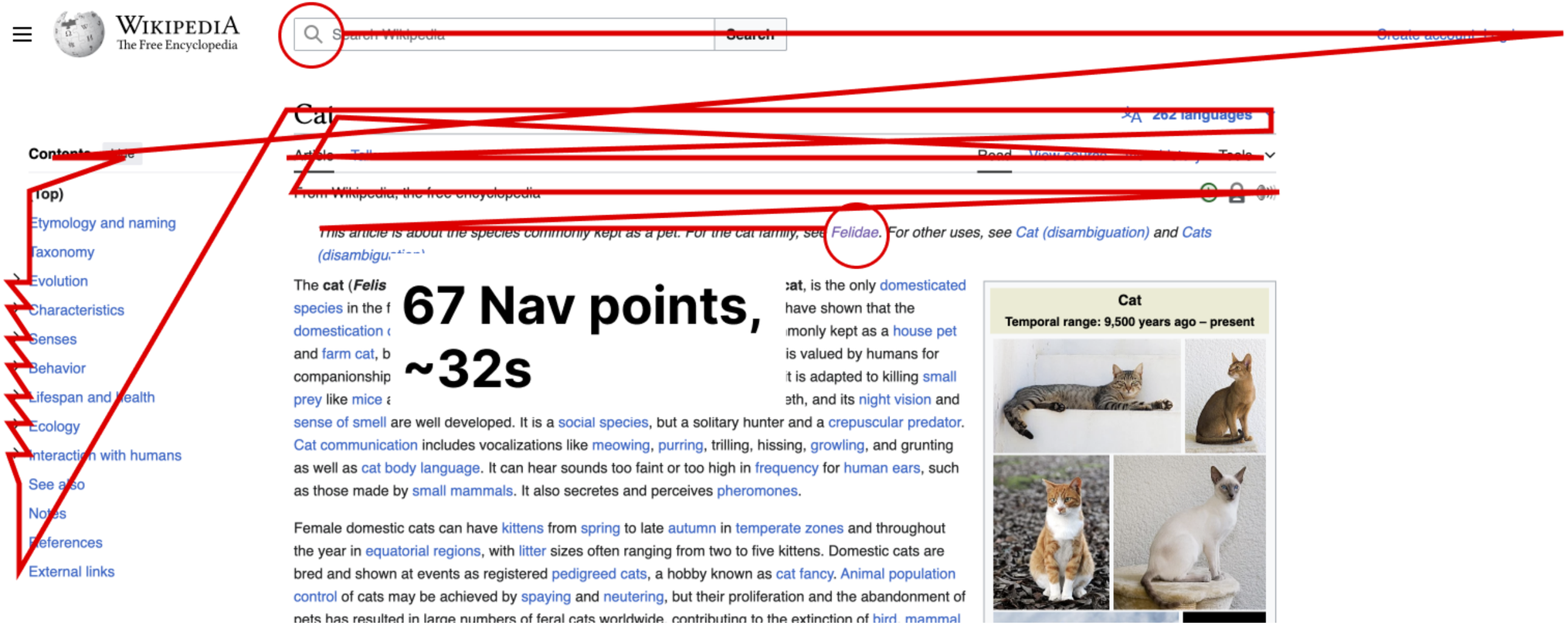


Add alt text

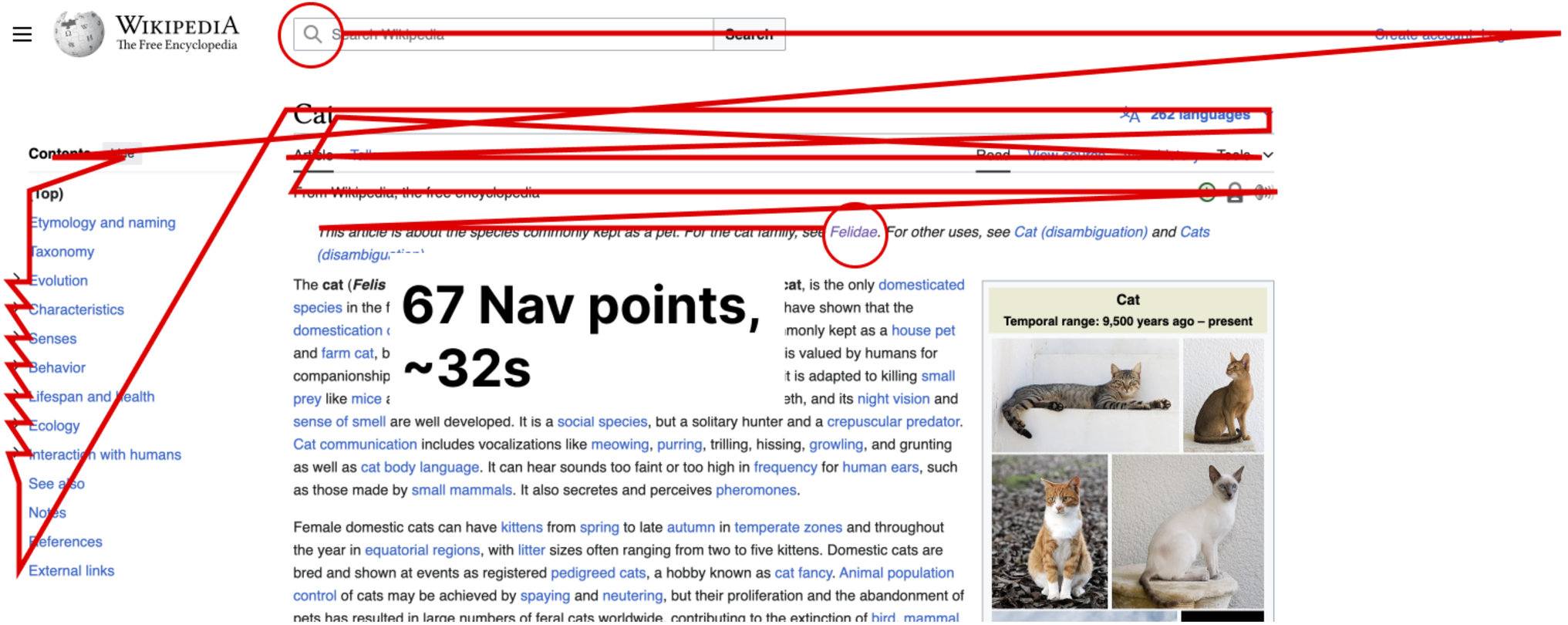
alt= “**Chart type** of **type of data** where **reason for including chart**”

Include a **link to data source** somewhere in the text

Screen readers processes 1 input at a time



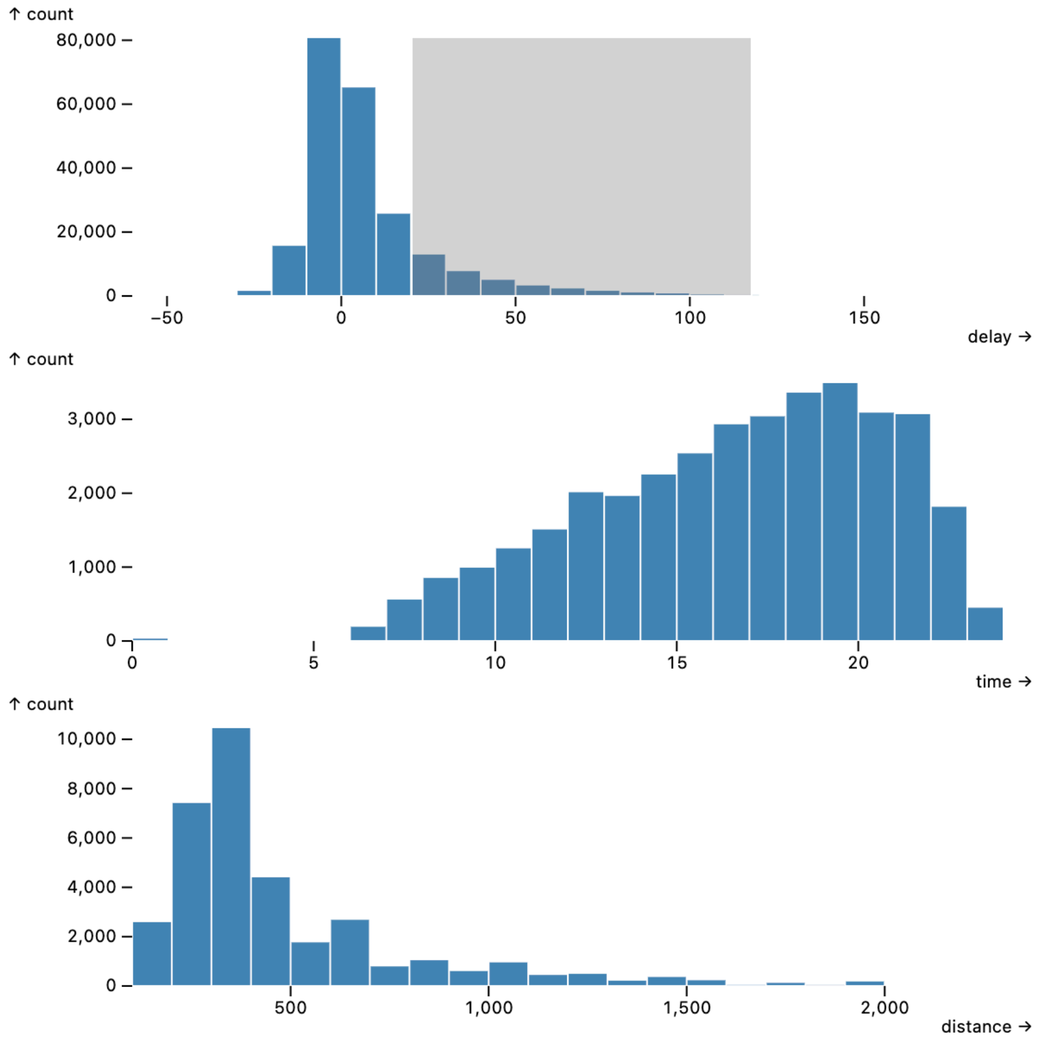
Movement between tasks becomes cognitively expensive



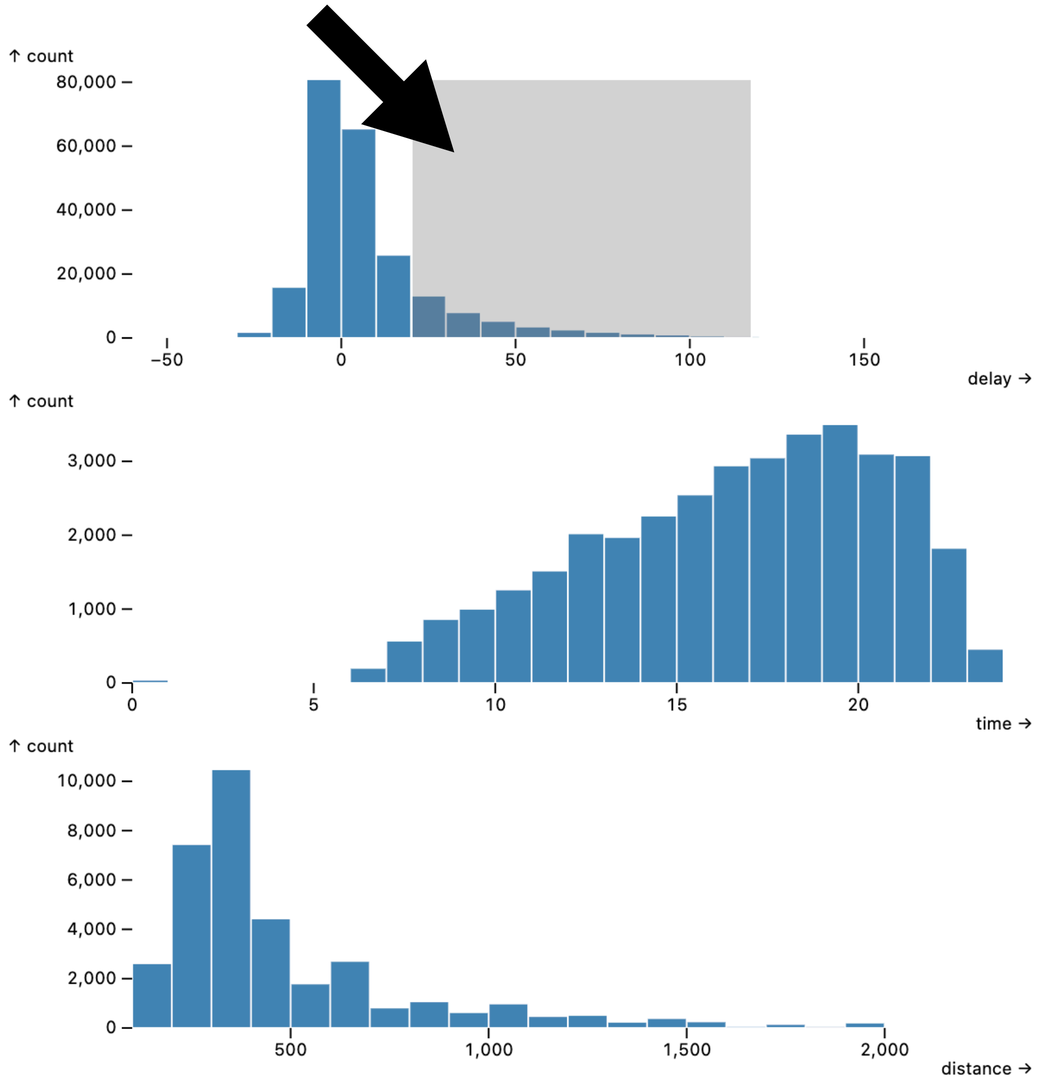
Auditory processing struggles with dual-task paradigms*

*Gherri (2011), Hamlyn (2018)

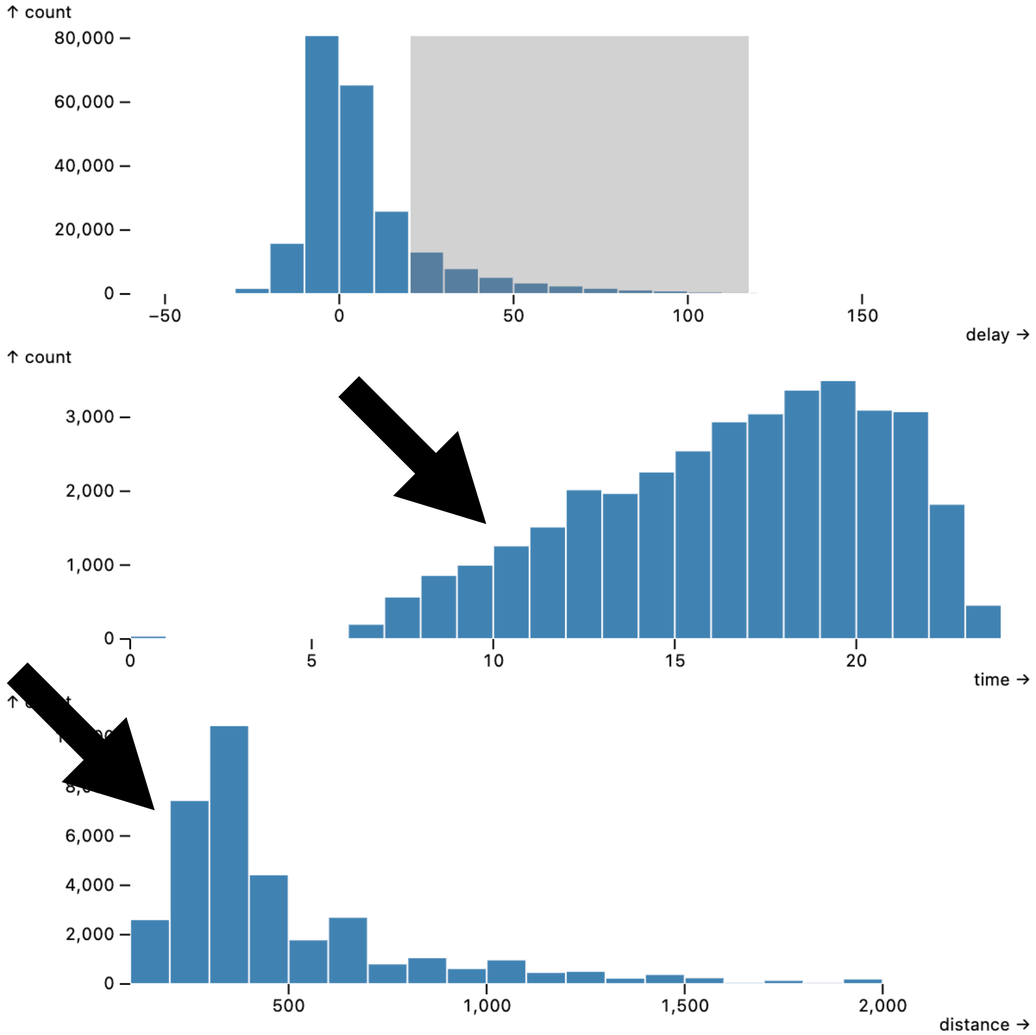
So what about cross-filtering?



Interaction in one space…



Produces simultaneous, coordinated change in another.



For blind users, descriptions, structural navigation, and sonifications will likely not solve this challenge.

Observing: Embossed braille in a research context

Image source

Observation 1: Spatial memory storage

My friend didn’t remember the details of a math equation exactly, but he knew where that equation was located in his stack of braille pages and *where* on the page the equation was.

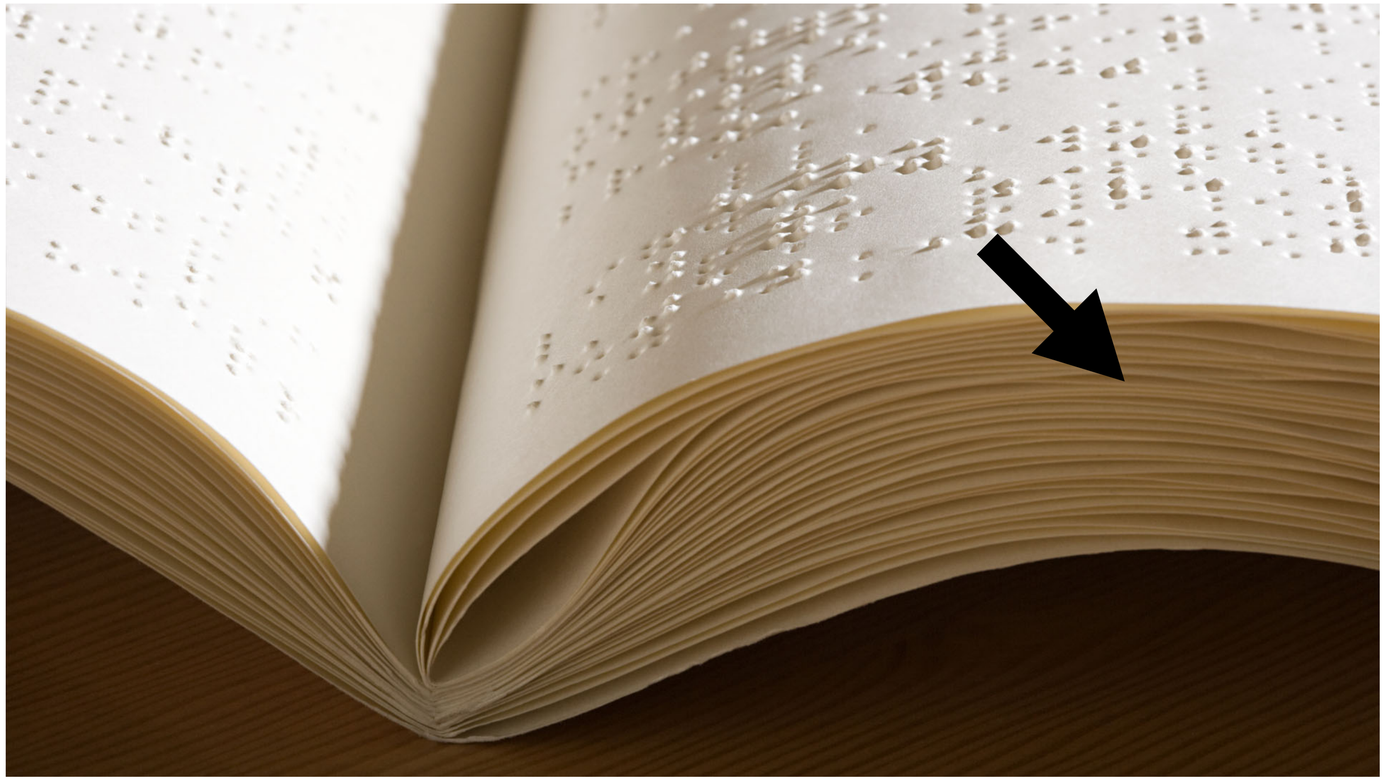
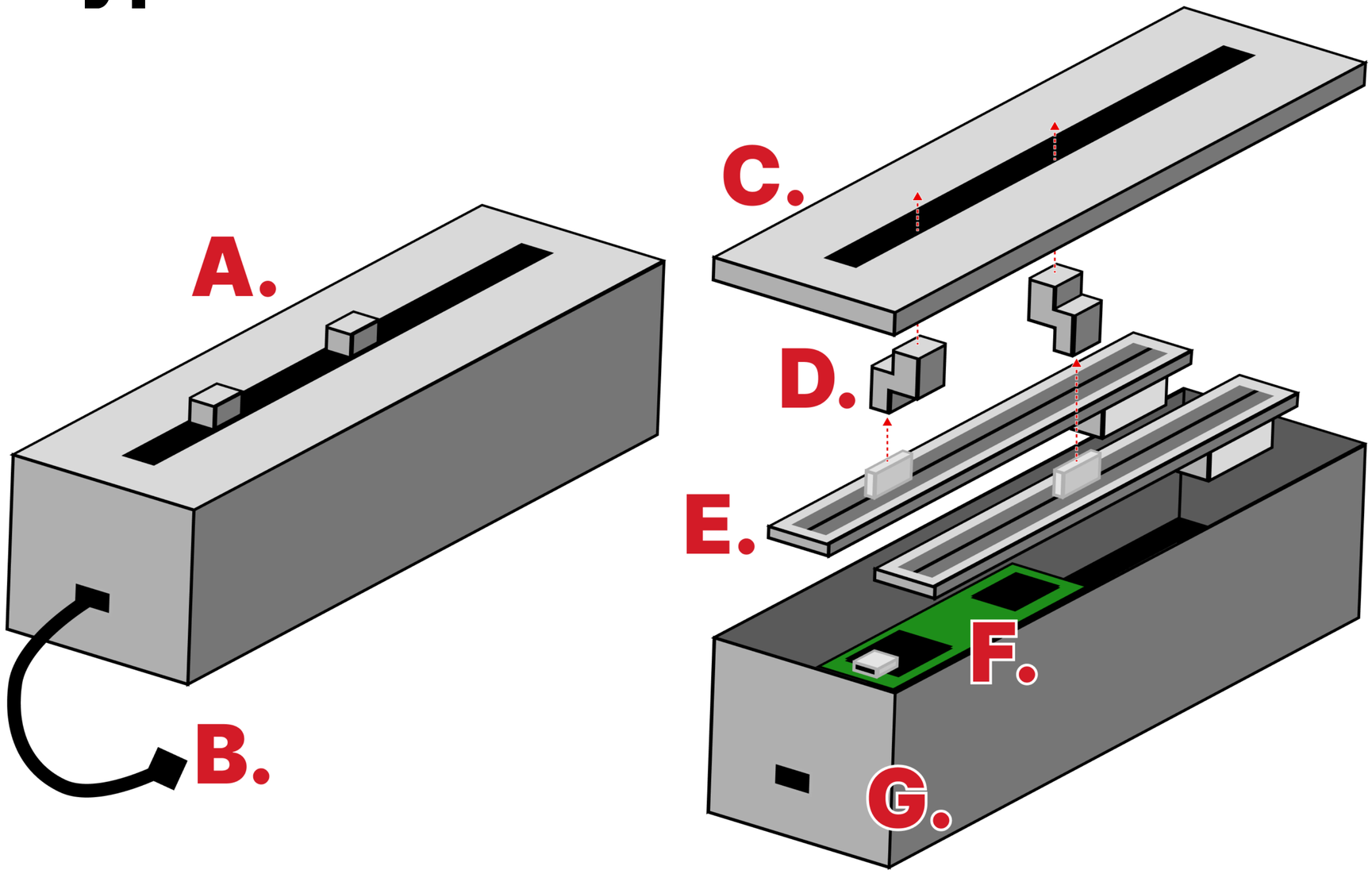


Image source

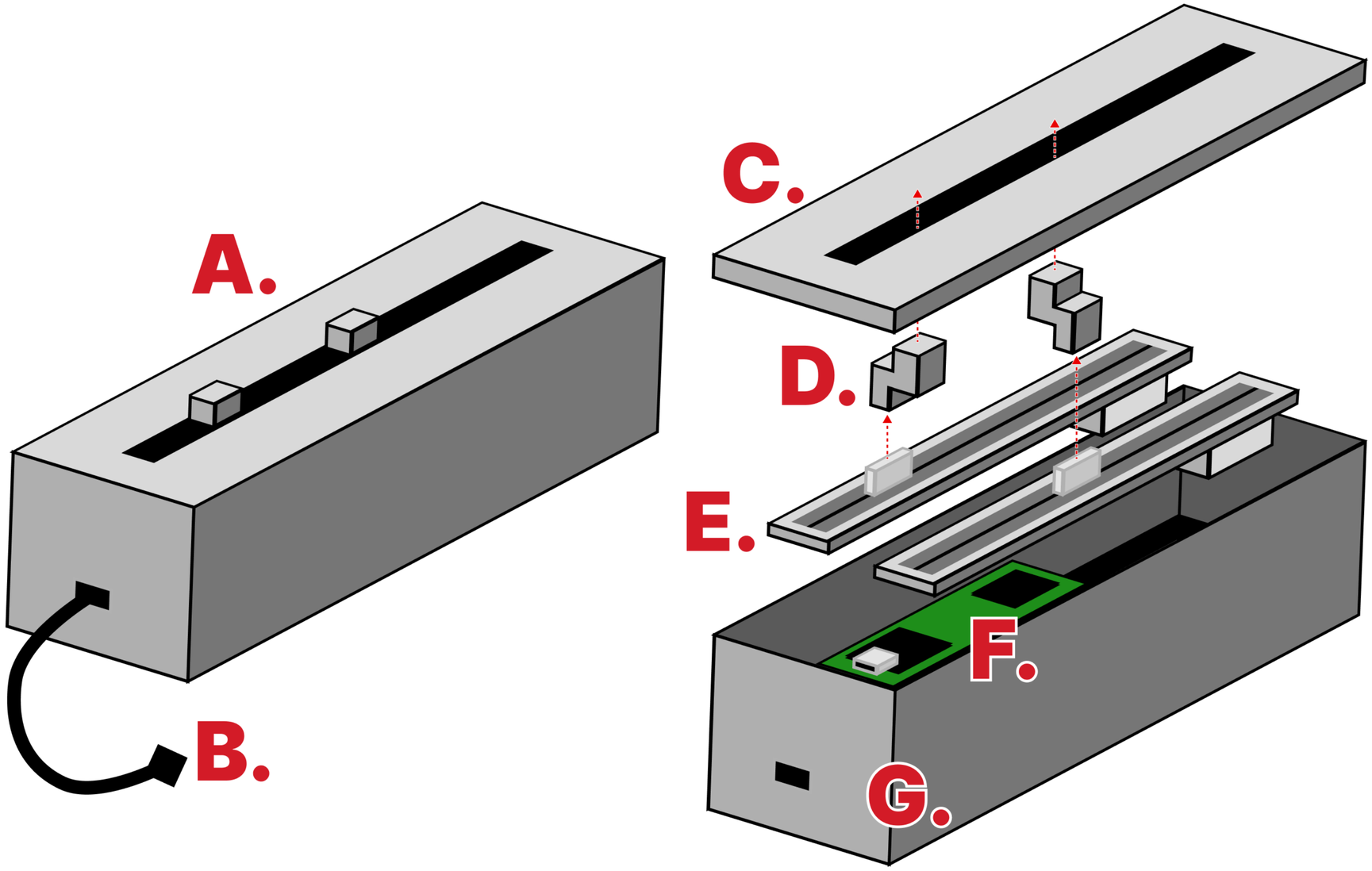
Observation 2: Coordinating perception and comparison

He then compared 2 equations at once. The details of each weren’t important. He was feeling for differences simultaneously.

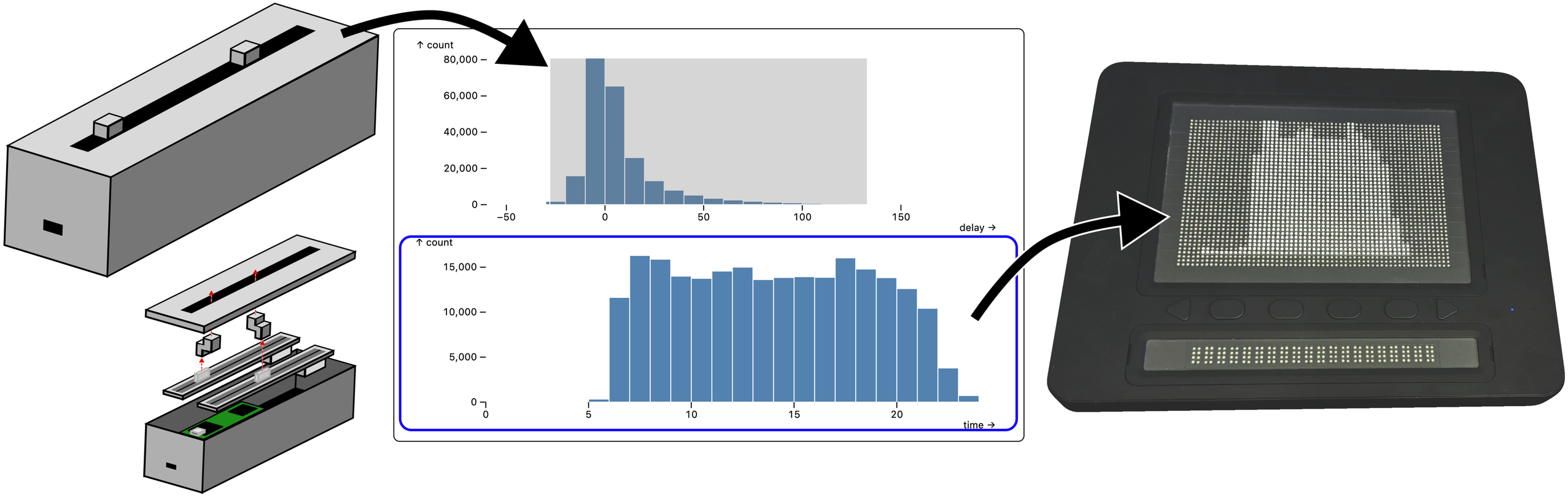
Prototype: *cross-feelter*



Special knobs (D.) enable single-track usage



Cross-*perception*! A tactile, dual-task paradigm.



What you learned today

- Why Perception is important for Visualization
  - How to show relationships
  - How to draw attention
  - How to minimize risk of overlooking
  - Different ways that people perceive