CSCI 1377

Tools for Thought

Visualization I
Princples of Perception

"Little effort is expended in seeing the structure once the right visualization method is used, so we are mislead into thinking nothing exciting has occurred."

— William Cleveland, *Visualizing Data* (1993)

Let's play a game!

Game: Take turn picking numbers for your team.

Goal: pick numbers such that any subset of three adds up to 15.

1 2 3 4 5 6 7 8 9

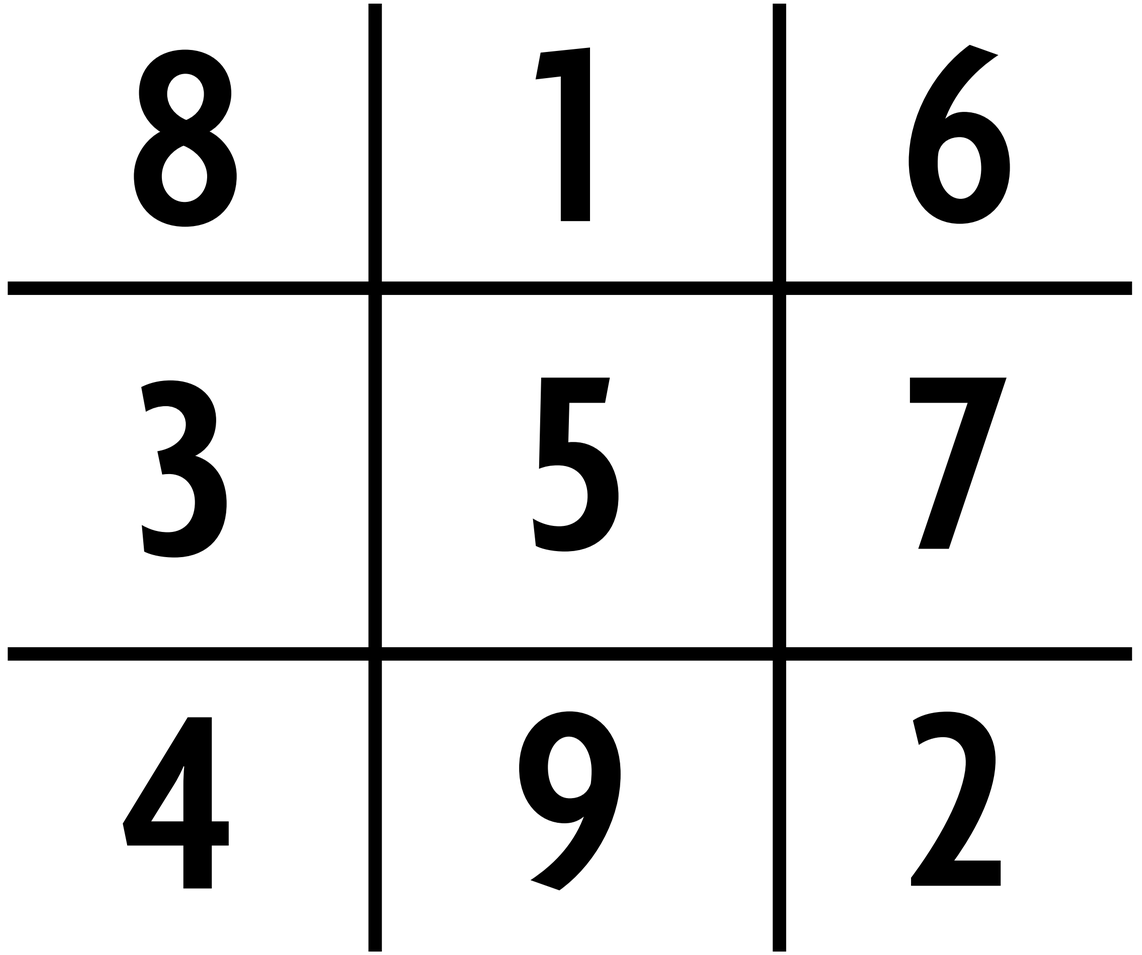
Team Red

Team Blue

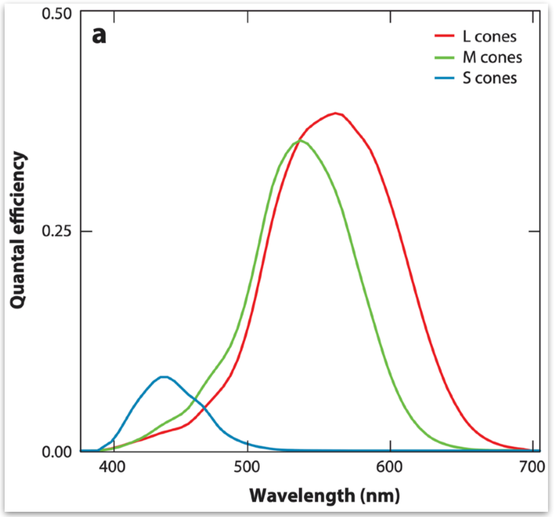
Let’s play again!

Team X

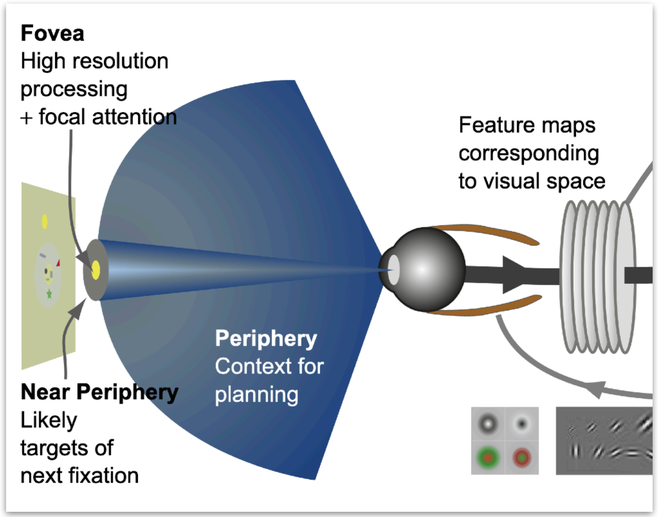
Team O



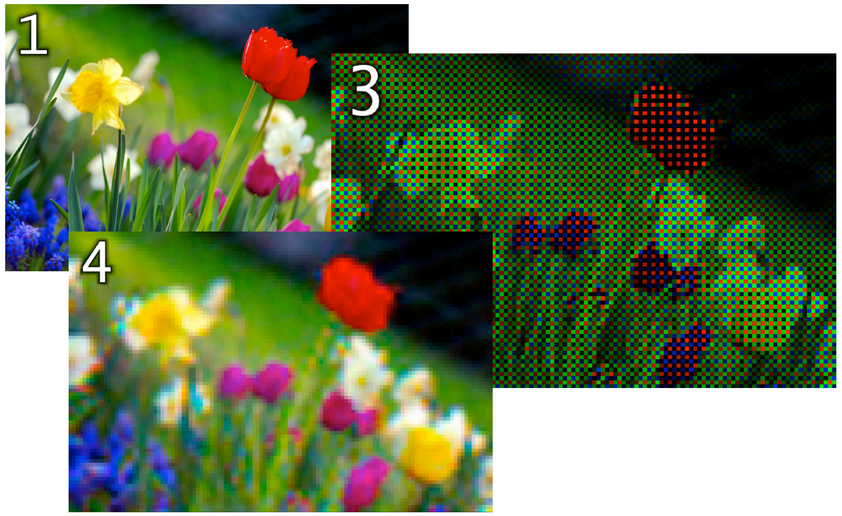
Charts



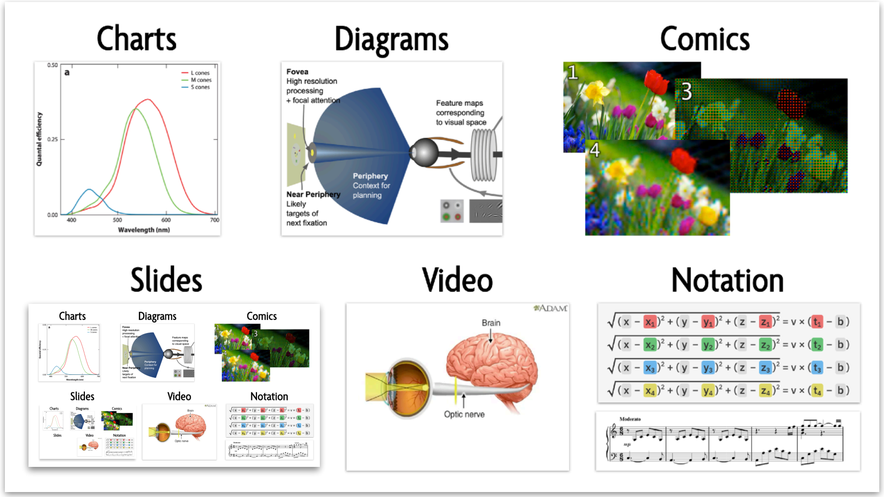
Diagrams



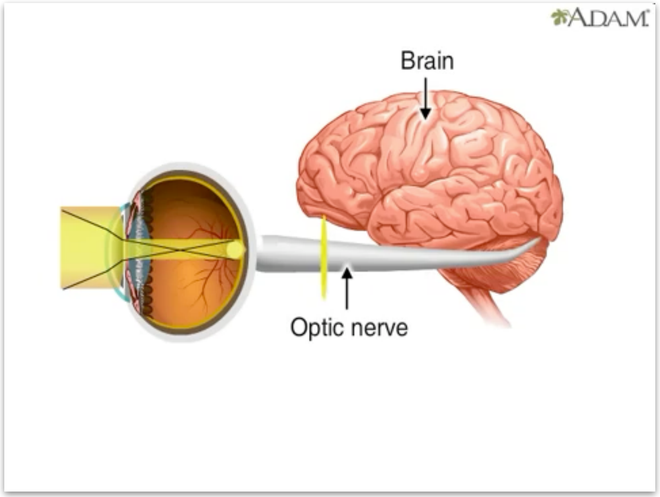
Comics



Slides



Video



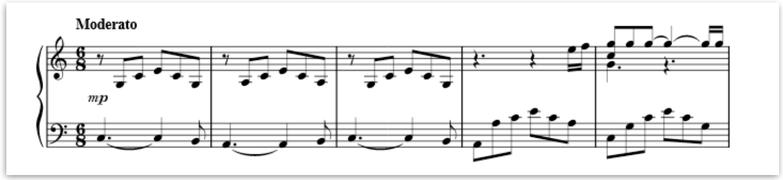
Notation

$$\sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} = v \times (t_1 - b)$$

$$\sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} = v \times (t_2 - b)$$

$$\sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} = v \times (t_3 - b)$$

$$\sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} = v \times (t_4 - b)$$



Visualization can* improve cognitive efficiency

- **Externalization**: visualizations take information out of your head into the world
  - A check list exists as a durable bag of symbols rather than a fragile mnemonic entity
- **Parallelism**: brain performs limited processing of visual field
  - c.f. serial processing: you can't easily overlay multiple sounds and pick just one out
  - But you still can't read an entire paragraph at once!
- **Permanence**: static visualizations persist in time, allowing one to revisit, scan, annotate, rehearse
  - c.f. sound and video: information is gone as soon as it's made

Visualization can* improve cognitive efficiency

- **Spatiality**: visualizations exist in 2 (sometimes 3) dimensions, enabling sequential processing of non-linear information
  - e.g. spotting the trend in data you can see vs. is spoken aloud to you
  - e.g. reading through a diagram along multiple pathways

- * only if the visualization is carefully designed!
  - Visualizations can be cognitively inefficient or actively misleading
  - Much of visualization design is knowing what not to do

Consider how our games compare on each axis

1 2 3 4 5 6 7 8 9

- **Externalization**
- **Parallelism**
- **Permanence**
- **Spatiality**

8	1	6
3	5	7
4	9	2

Mental imagery is important for thought, but its connection to visualization is a WIP

"The words or the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be "voluntarily" reproduced and combined. [...] this combinatory play seems to be the essential feature in productive thought before there is any connection with logical construction in words or other kinds of signs which can be communicated to others."

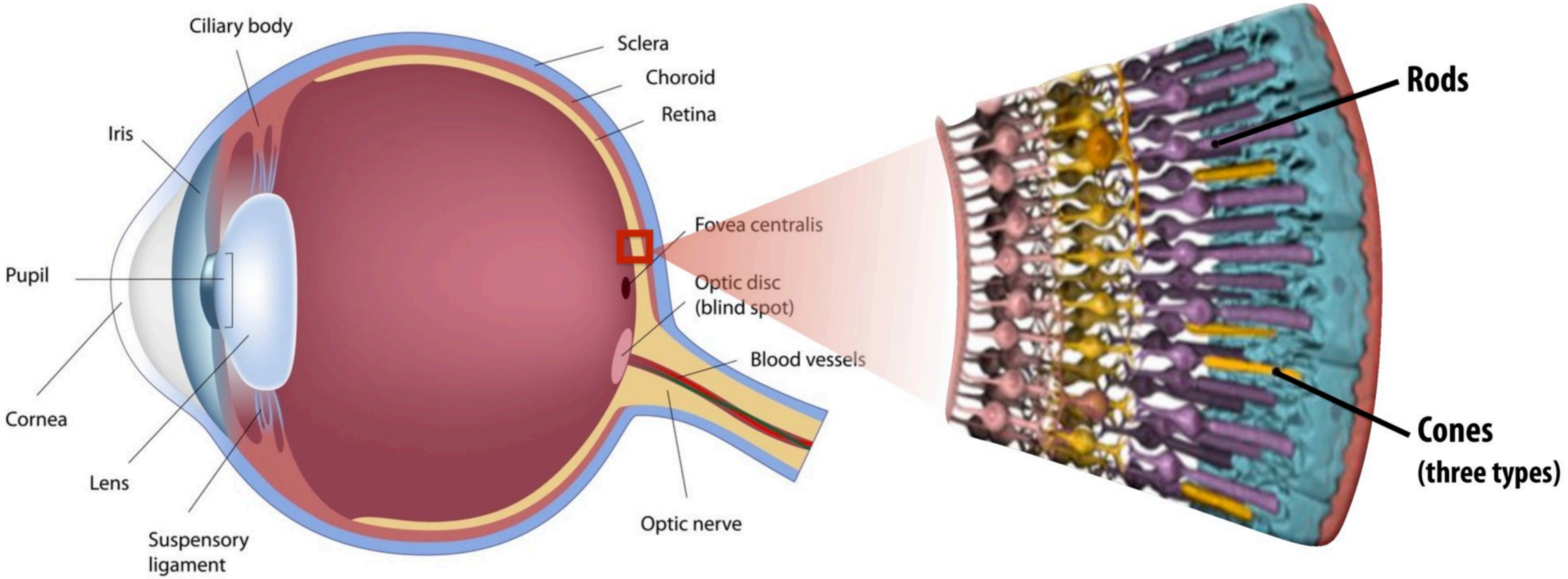
— Albert Einstein, in correspondence to Jacques Hadamard, 1945

"Although it seems clear that perceptual processes are involved in visual imagery to some degree, the degree to which the mechanisms of visual imagery are the same as the mechanisms of visual perception remains an open question."

— John Anderson, *Cognitive Psychology*, 2020

This lecture: introduction to the science of perception

Eye contains rods and cones concentrated in fovea



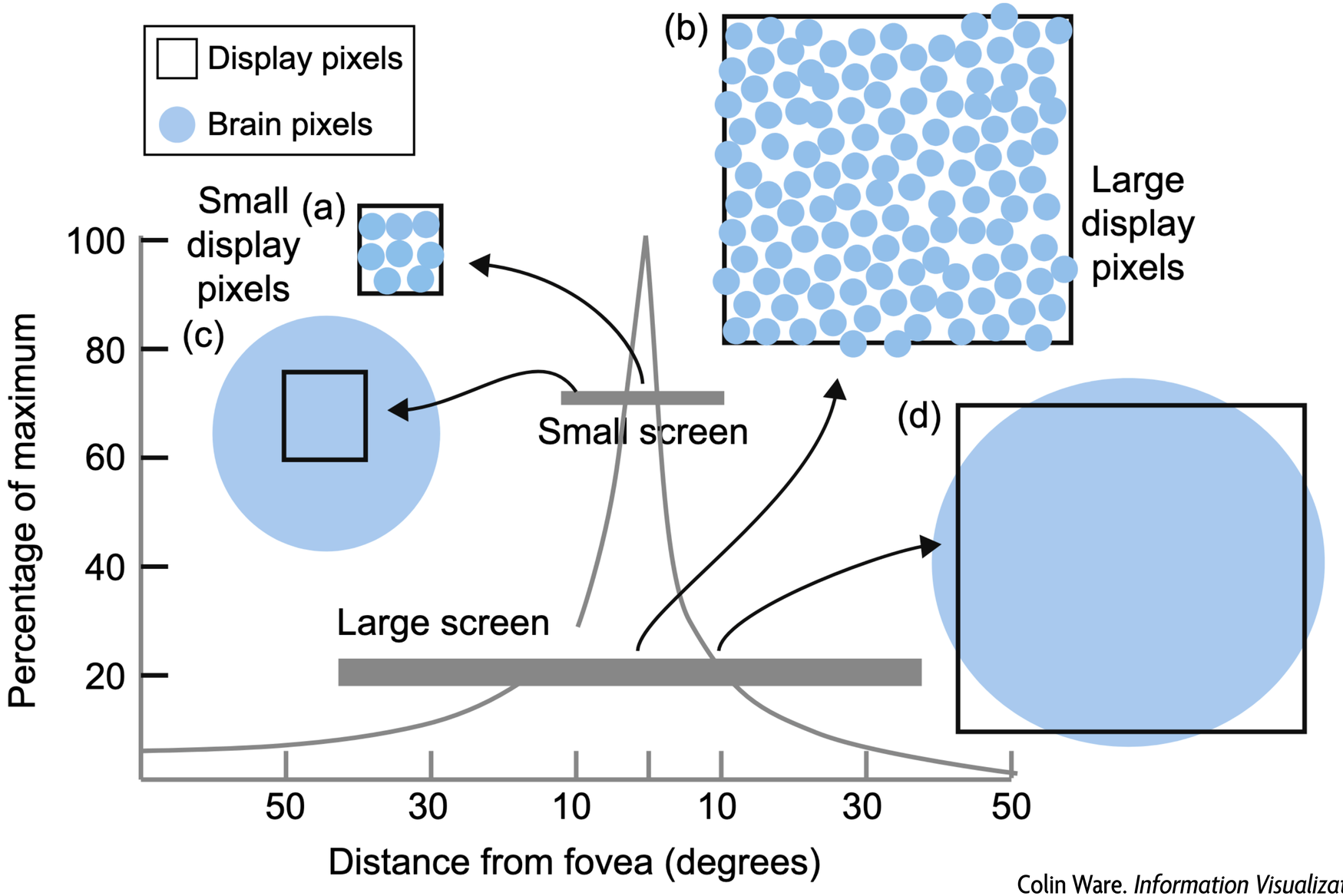
Rods (~100 mil): light intensity receptors for night vision

Cones (~6 mil): color receptors for day vision

Image via Stanford CS 248A

Colin Ware. *Information Visualization: Perception for Design*. 2021

Visual acuity outside fovea drops quickly

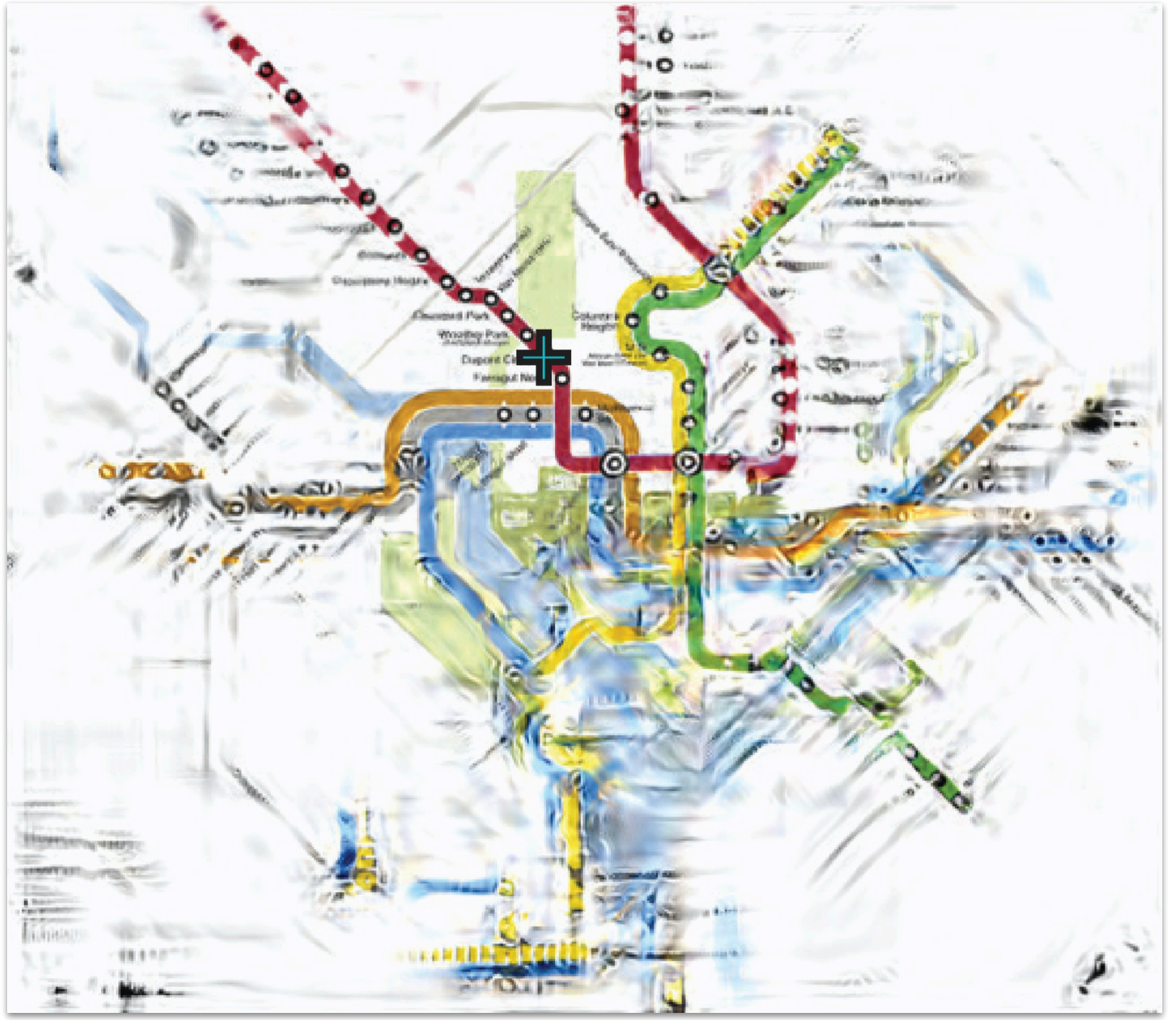


Colin Ware. *Information Visualization: Perception for Design.* 2021

Periphery contains a coarse view of the world

True image

Model of perceived image

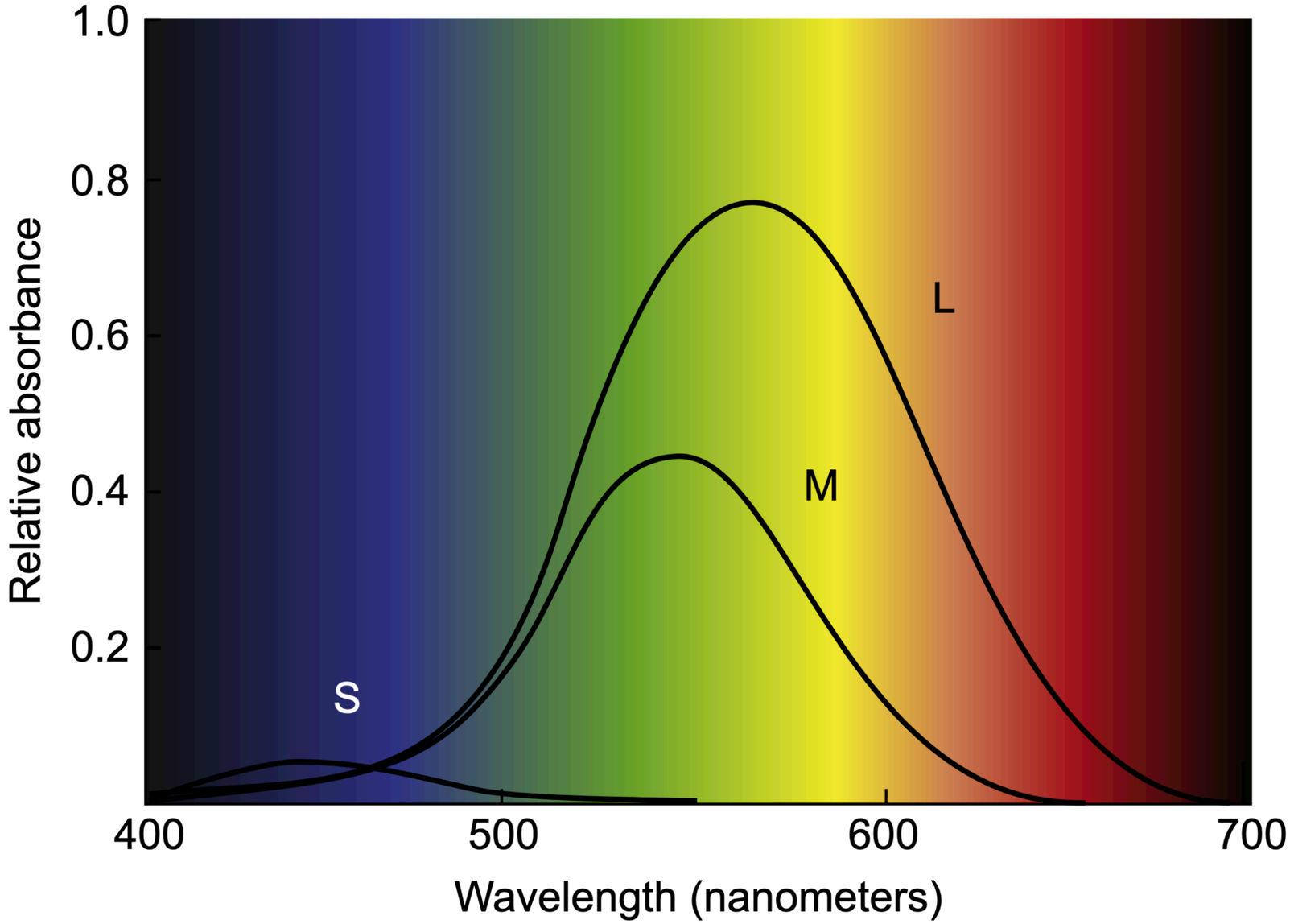


Ruth Rosenholtz. “Capabilities and Limitations of Peripheral Vision” 2016

Foveated rendering reduces render time by rendering at lower quality outside foveal region

https://youtu.be/OUjhJqpJjEo

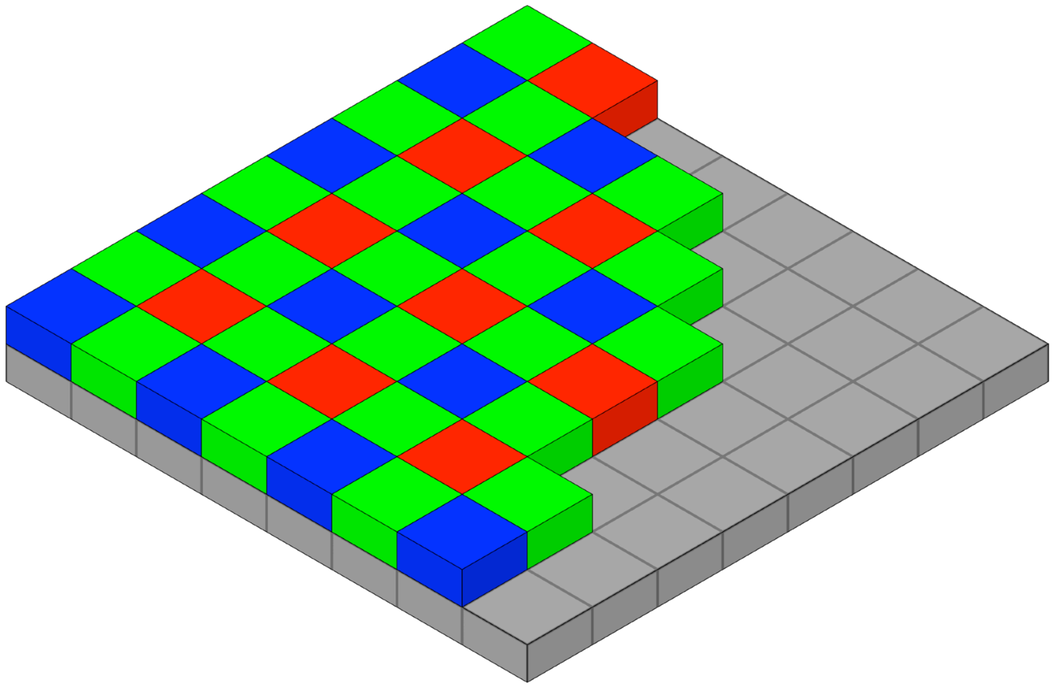
Different cones types detect different wavelengths



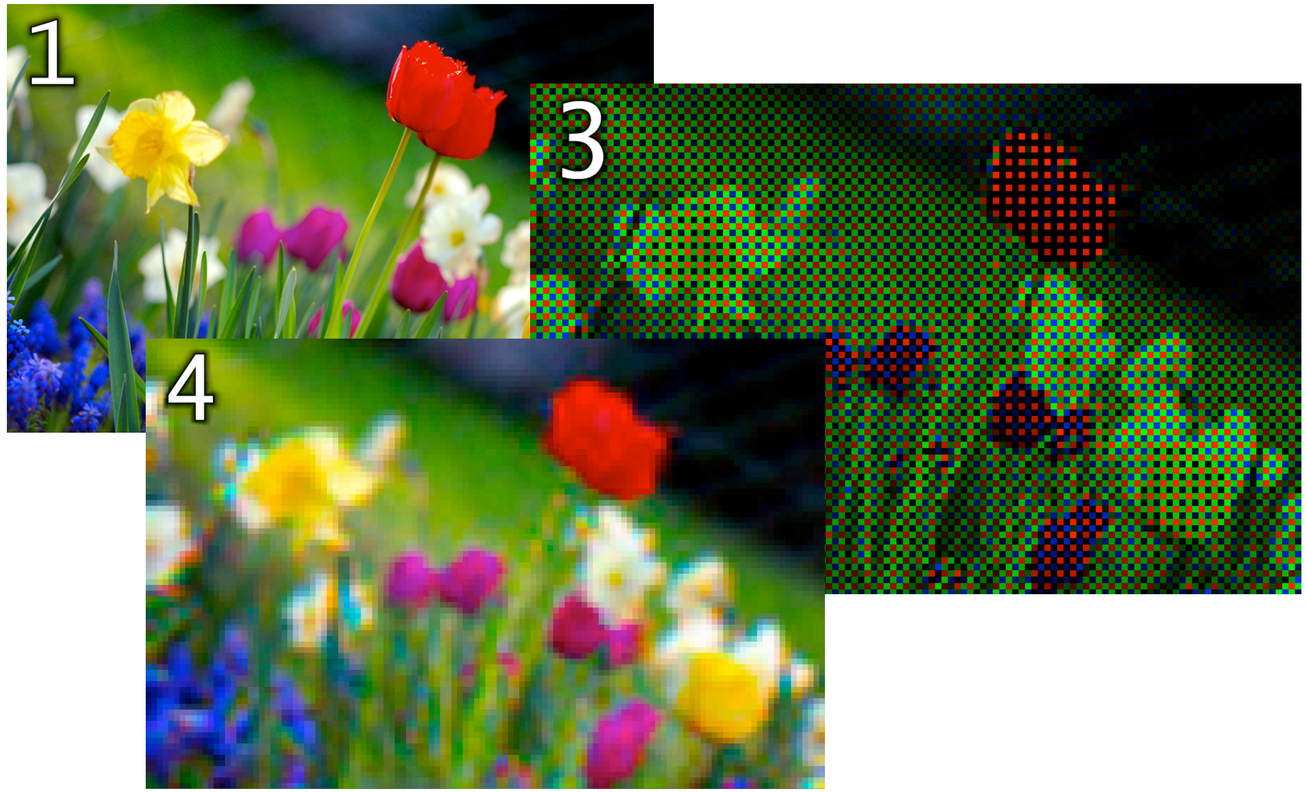
Colin Ware. *Information Visualization: Perception for Design.* 2021

Cones disproportionately detect green, so cameras are designed to pick up more green

Bayer mosaic

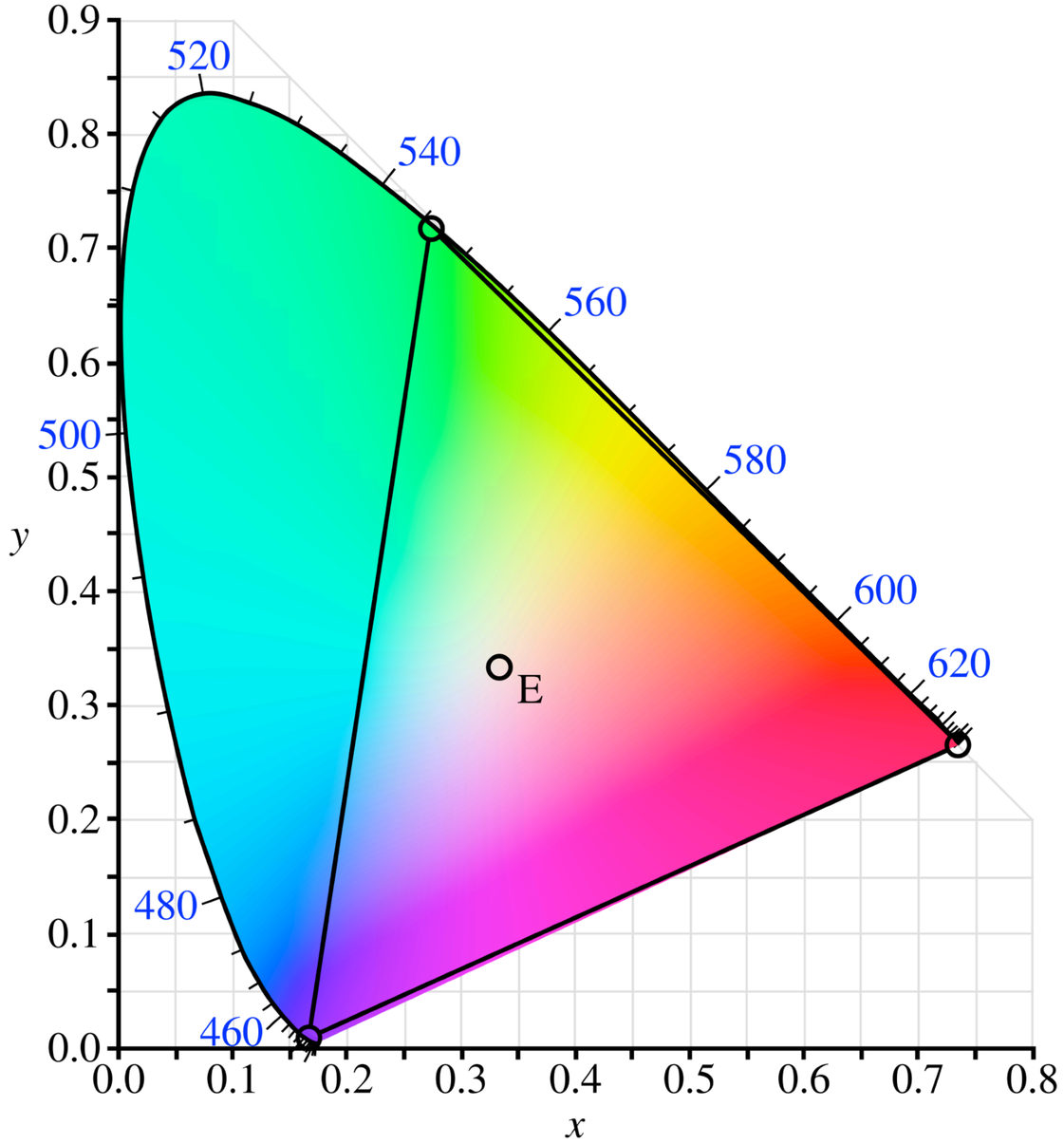


Demosaicking



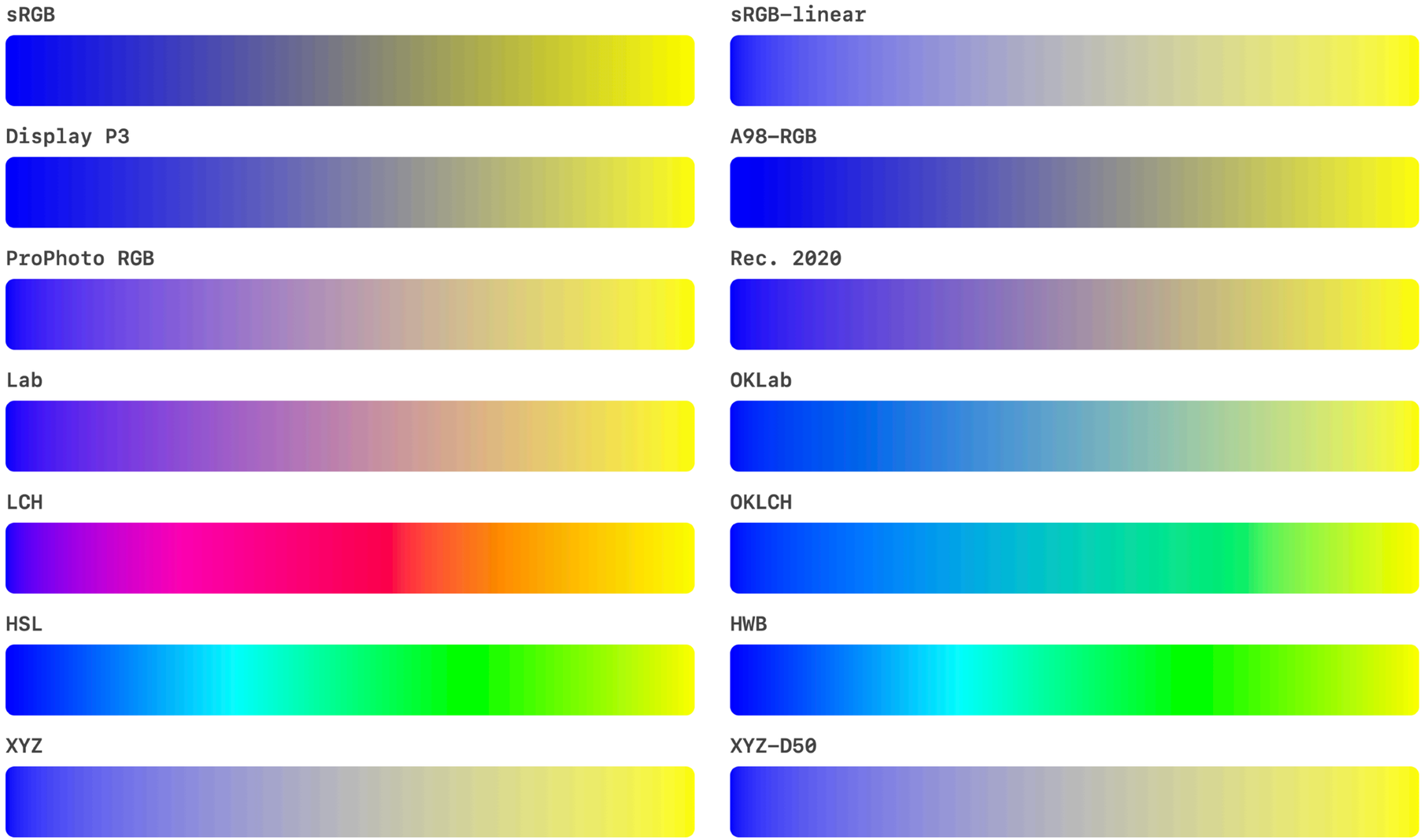
All images via Wikimedia Commons

Color spaces represent color as vectors



CIE XYZ color space

There's many color spaces to pick from!




```
background: linear-gradient(in <color space> to right, blue, yellow)
```

Model of visual processing

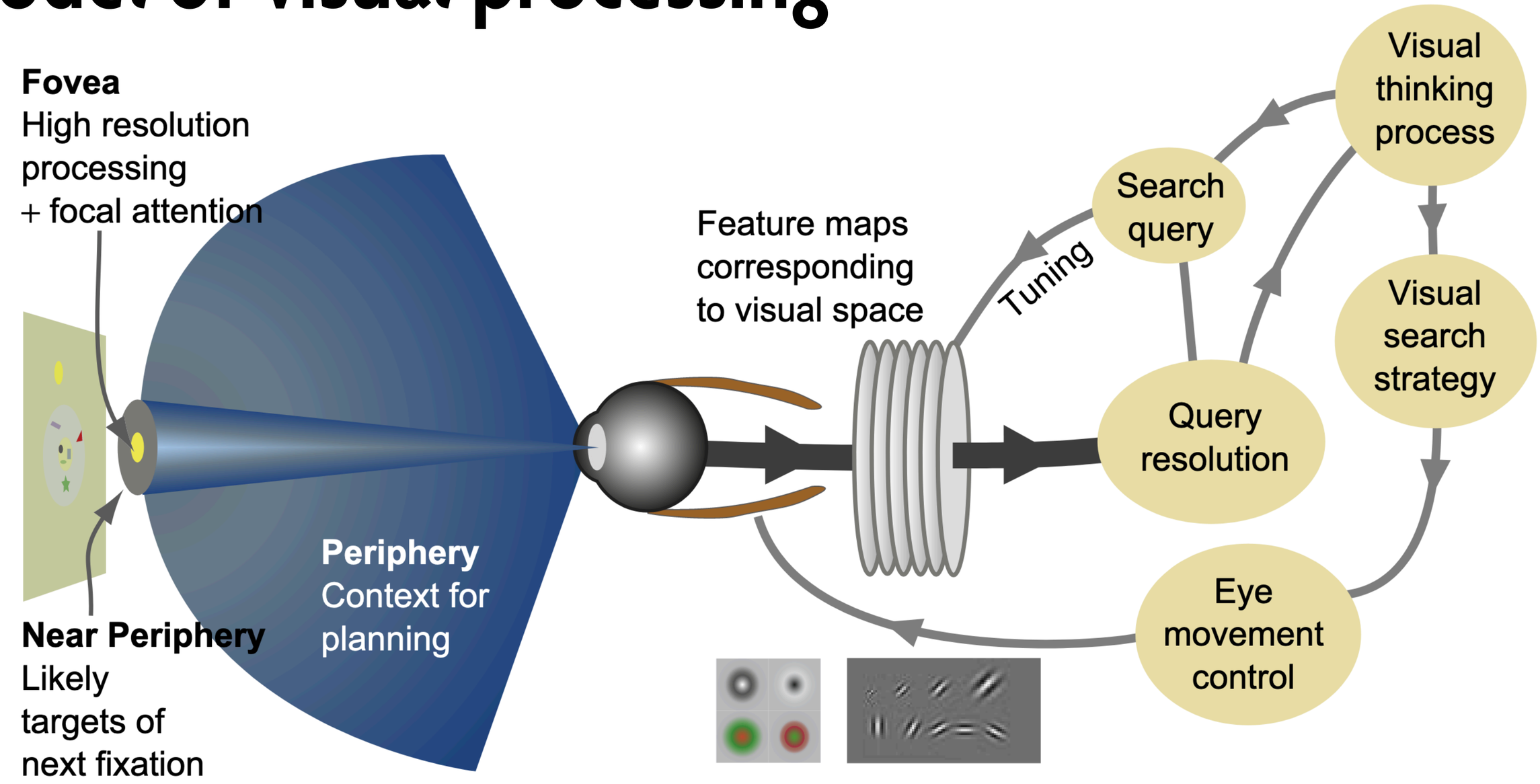


Image via Ware

Colin Ware. *Information Visualization: Perception for Design.* 2021

Signal Detection

Discriminability: how easy is it to tell two things apart?

Magnitude Estimation

Accuracy: how correctly can we read off values?

Preattentive Processing

Pop out: how easy is it to spot some values from the rest?

Selective Attention

Separability: how much interaction occurs between attributes

This and all following slides borrow heavily from Arvind Satyanarayan's Vis & Society course at MIT. Thanks Arvind!

Signal Detection	Discriminability: how easy is it to tell two things apart?
Magnitude Estimation	Accuracy: how correctly can we read off values?
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Selective Attention	Separability: how much interaction occurs between attributes

This and all following slides borrow heavily from Arvind Satyanarayan's Vis & Society course at MIT. Thanks Arvind!

Which is brighter?

`rgb(128, 128, 128)`

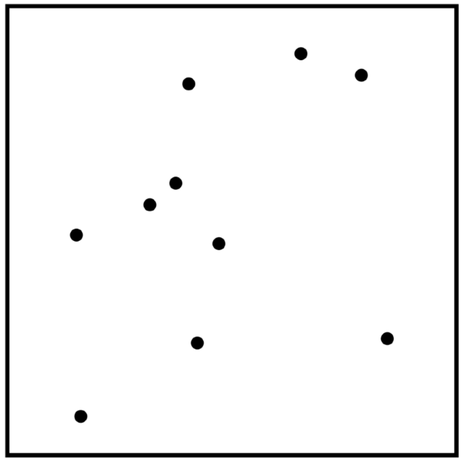
`rgb(144, 144, 144)`

Which is brighter?

`rgb(134, 134, 134)`

`rgb(128, 128, 128)`

Increases are less perceptible with larger stimuli



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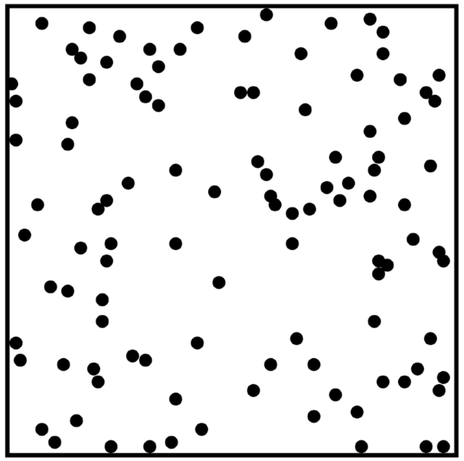

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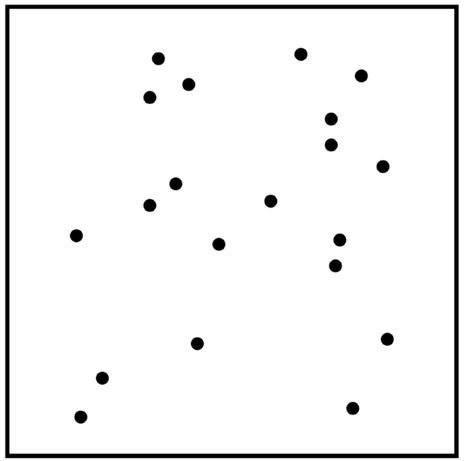

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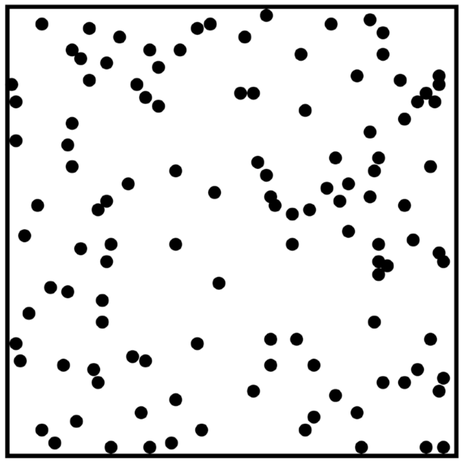

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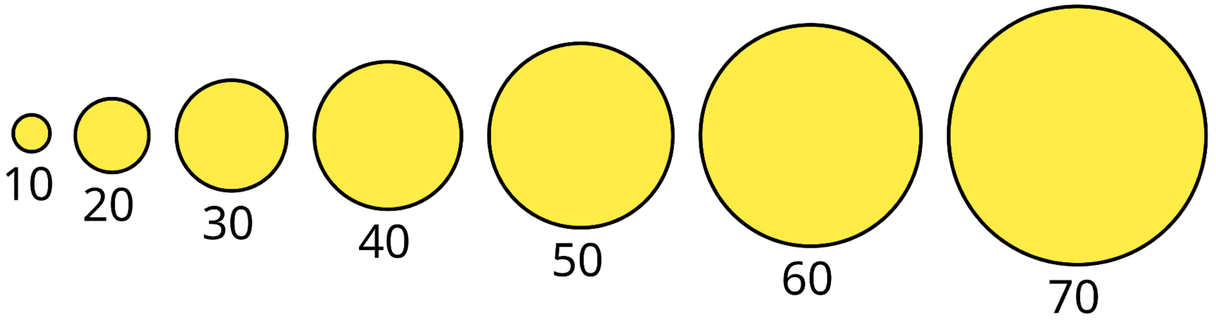

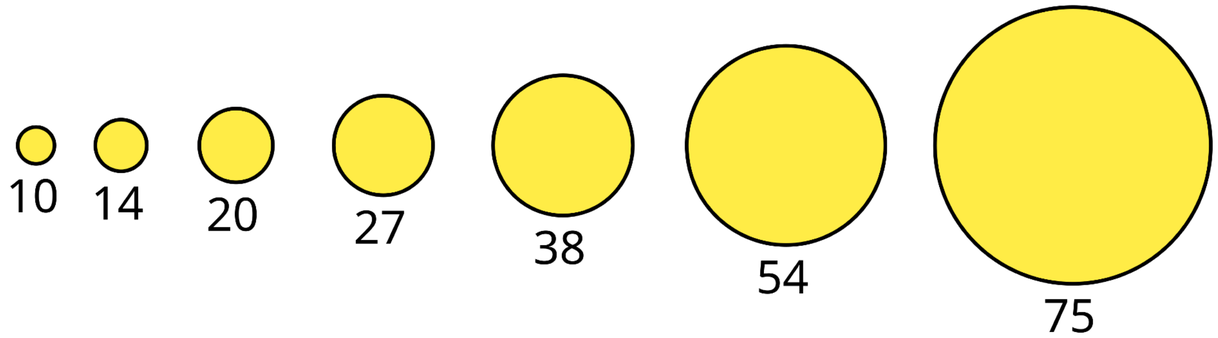

Images via Wikimedia Commons

Weber's law: "just noticeable difference" depends on the magnitude of previous intensity

Scale factor

Change of intensity

$$\Delta S = k \frac{\Delta I}{I}$$

Perceived change

Absolute intensity

Signal Detection

Discriminability: how easy is it to tell two things apart?

Magnitude Estimation

Accuracy: how correctly can we read off values?

Preattentive Processing

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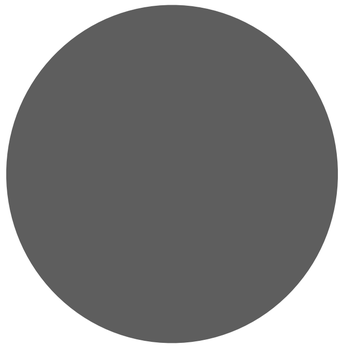
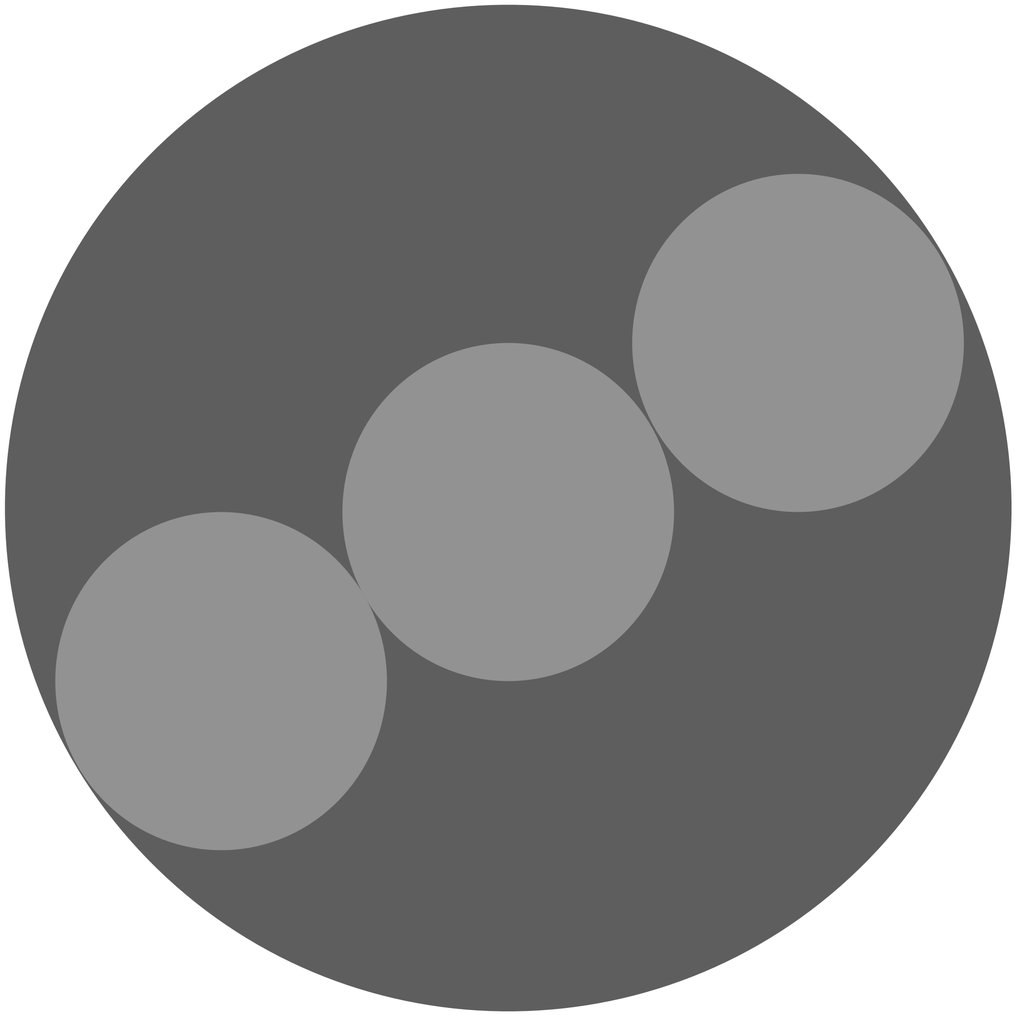
Selective Attention

Separability: how much interaction occurs between attributes

How much larger is the area of the big circle?





How much longer is the big bar?

Two competing theories of absolute perceptual magnitude

Perceived intensity Scale factor Intensity

Fechner's law (1860): $S = k \log(I)$

Perception is a **logarithmic** function of intensity

Sensory-specific exponent

Steven's law (1957): $S = k\, I^{\alpha}$

Perception is a **power** function of intensity

Decibel puts units on a logarithmic scale

dB
= decibel
= 1/10 bel

$$X \text{ bel } Y = 10^{X} \times Y$$

$$X \text{ decibel } Y = 10^{\frac{X}{10}} \times Y$$

10 dB = 10 × [something]
20 dB = 100 × [something]
30 dB = 1000 × [something]

SPL = sound pressure level = 20 μPa

20 dBSPL = 100 × 20 μPa

Decibels are used for image compression quality

PSNR = 40 dB

PSNR = 30 dB

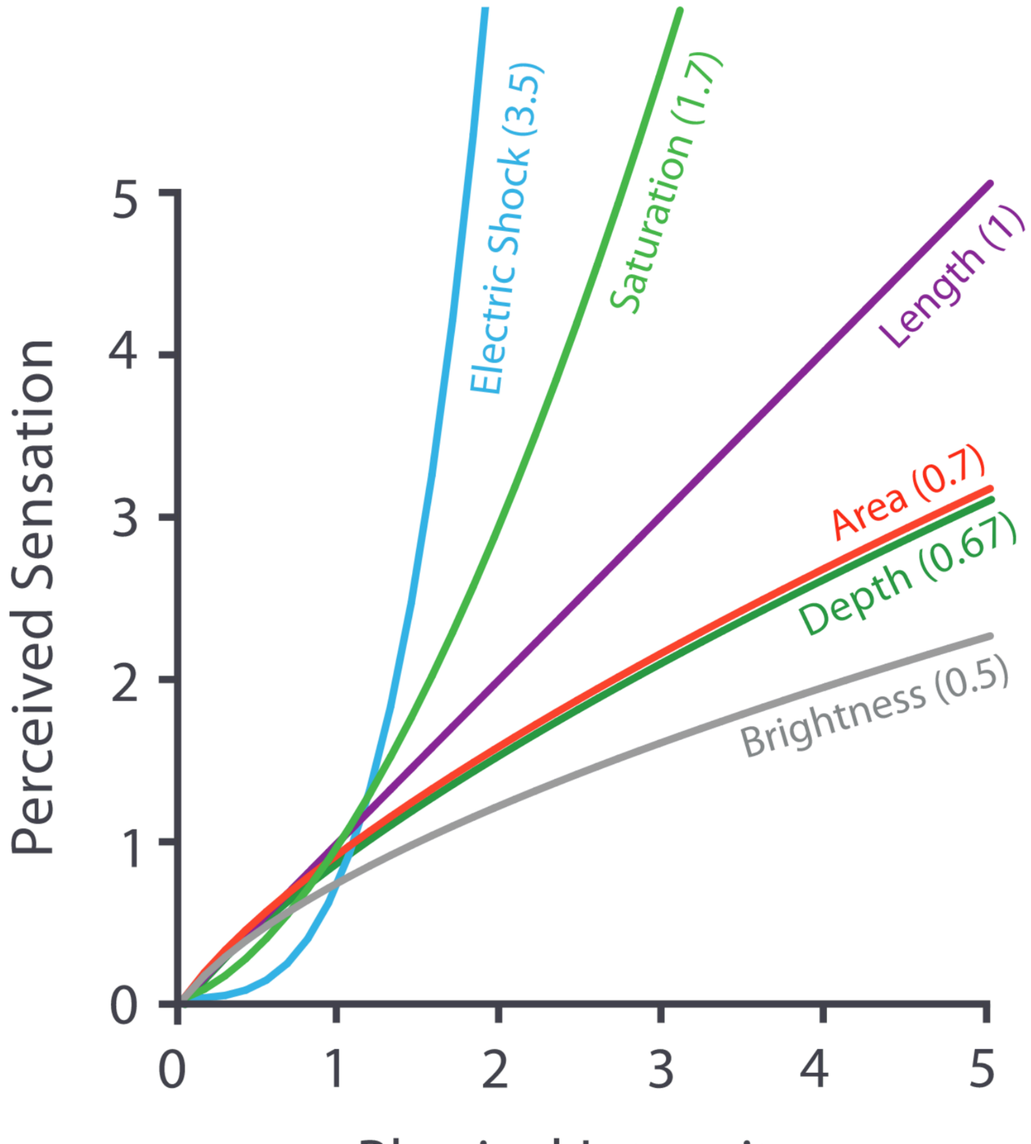
PSNR = 20 dB

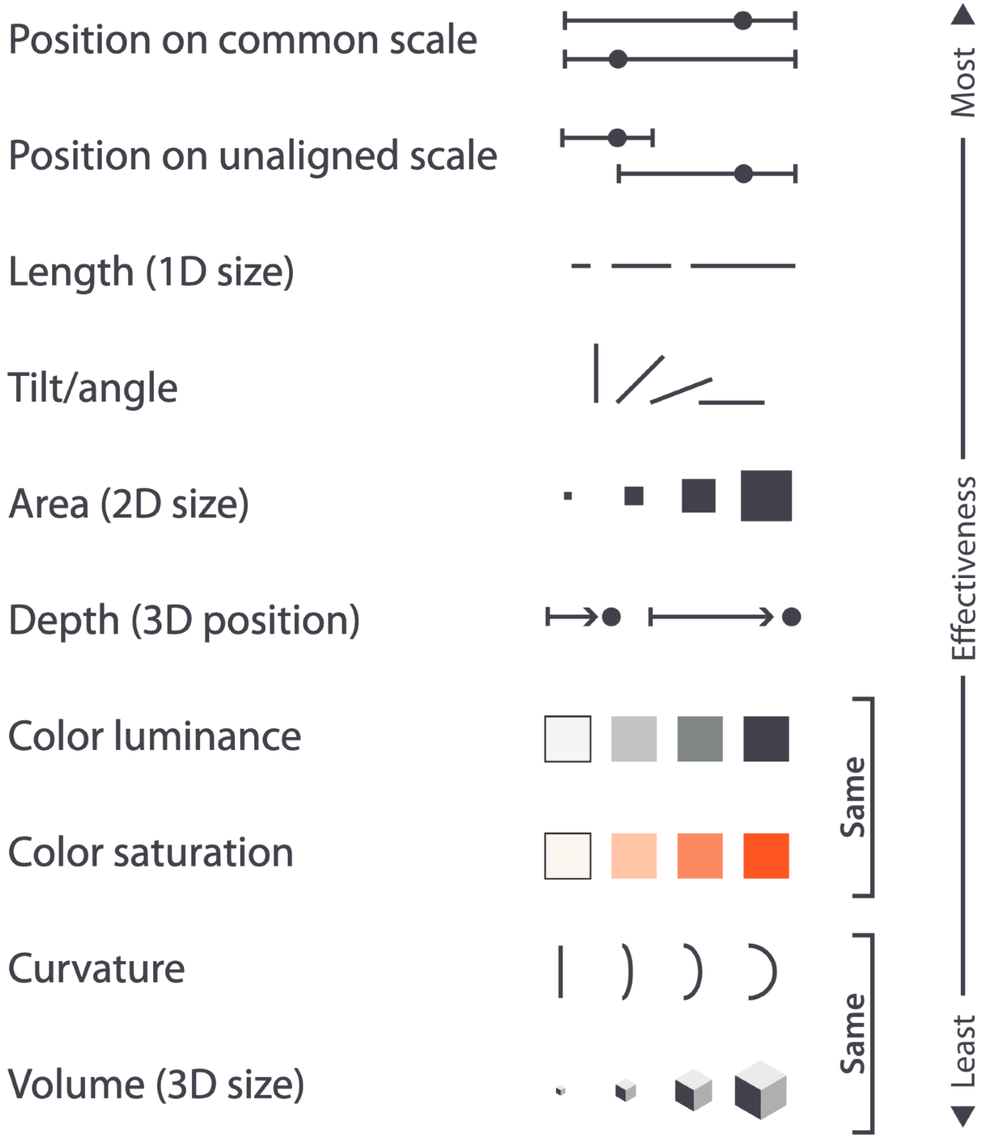
PSNR = 10 dB

PSNR = 0 dB

https://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/VELDHUIZEN/node18.html

Stevens' law suggests encodings of quantity





Images via Munzner 2014

Stevens. *Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects.* 1975

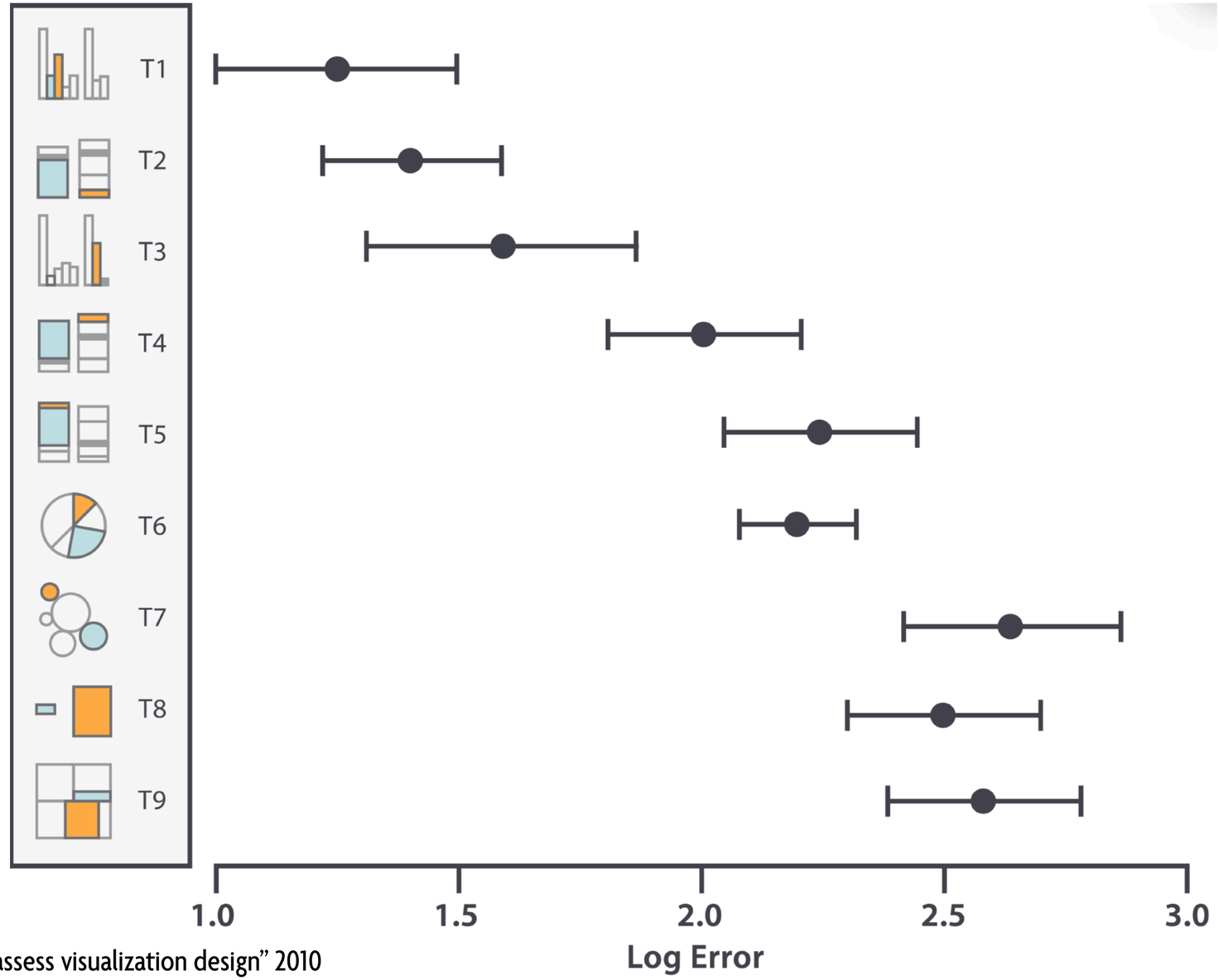
Stevens' law predictions hold up experimentally

Materials

Nine visual encodings of quantity × 10 charts per encoding

Procedure

Ask participants snap judgment about relative size of areas



Heer and Bostock. "Crowdsourcing graphical perception: using mechanical turk to assess visualization design" 2010

Signal Detection — Discriminability: how easy is it to tell two things apart?

Magnitude Estimation — Accuracy: how correctly can we read off values?

Preattentive Processing — Pop out: how easy is it to spot some values from the rest?

Selective Attention — Separability: how much interaction occurs between attributes

How many 3's?

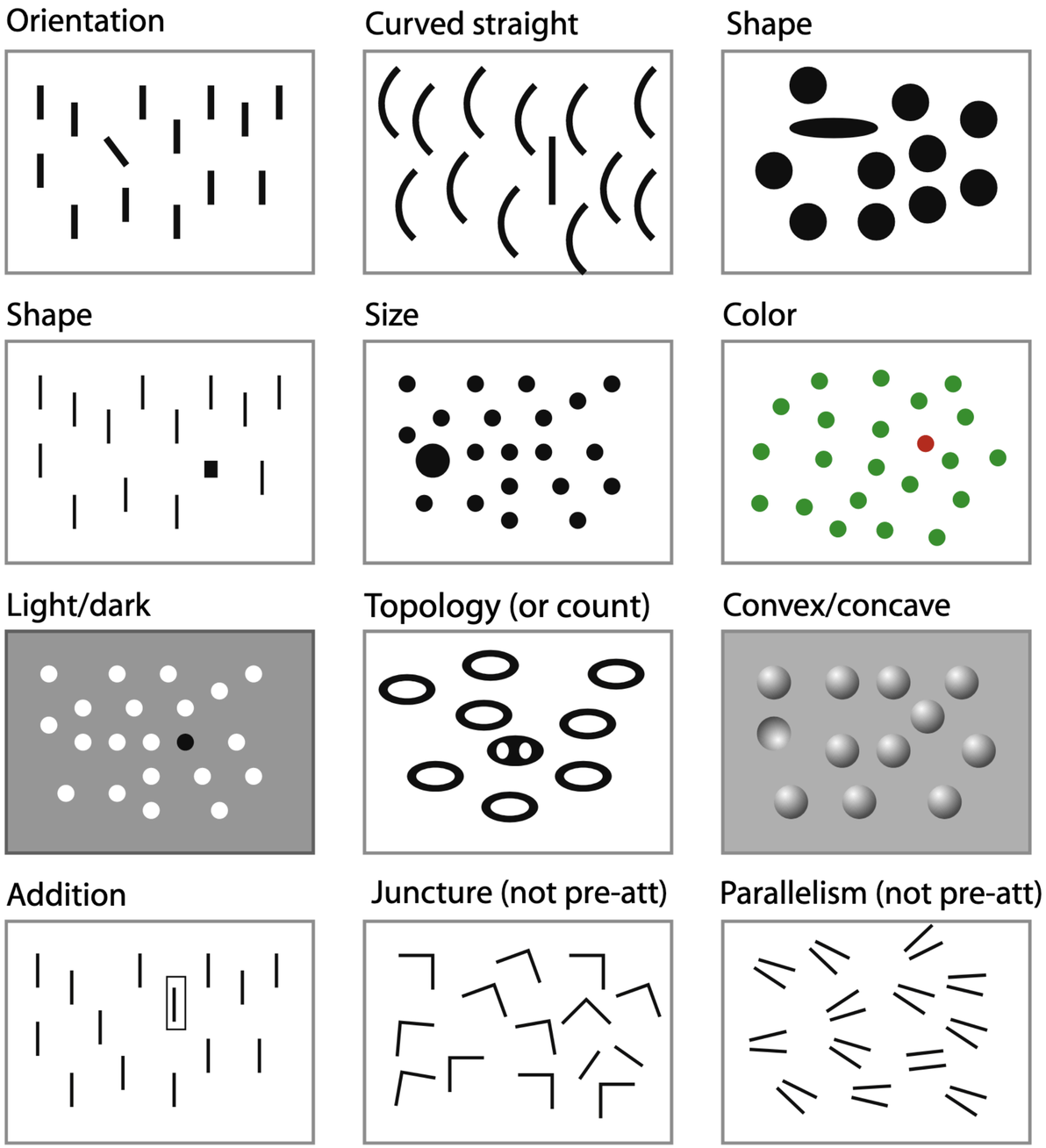
```
45929078059772098775972655665110049836645
27107462144654207079014738109743897010971
43907097349266847858715819048630901889074
25747072354745666142018774072849875310665
```

```
45929078059772098775972655665110049836645
27107462144654207079014738109743897010971
43907097349266847858715819048630901889074
25747072354745666142018774072849875310665
```

Colin Ware. *Information Visualization: Perception for Design.* 2021

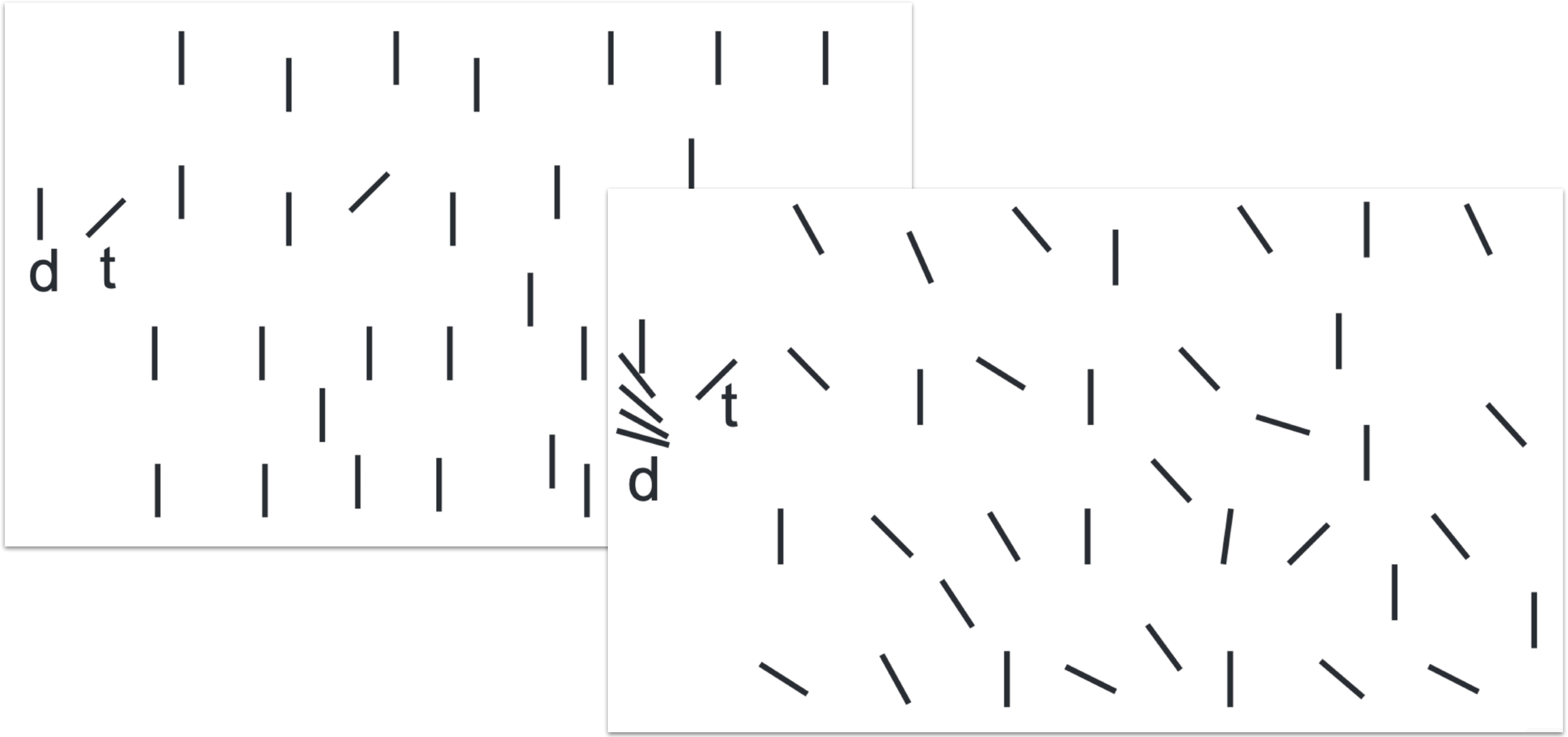
Preattentive processing

is the phenomenon where certain visual features appear to be processed automatically, facilitating effortless visual search against distractors.



Colin Ware. *Information Visualization: Perception for Design.* 2021

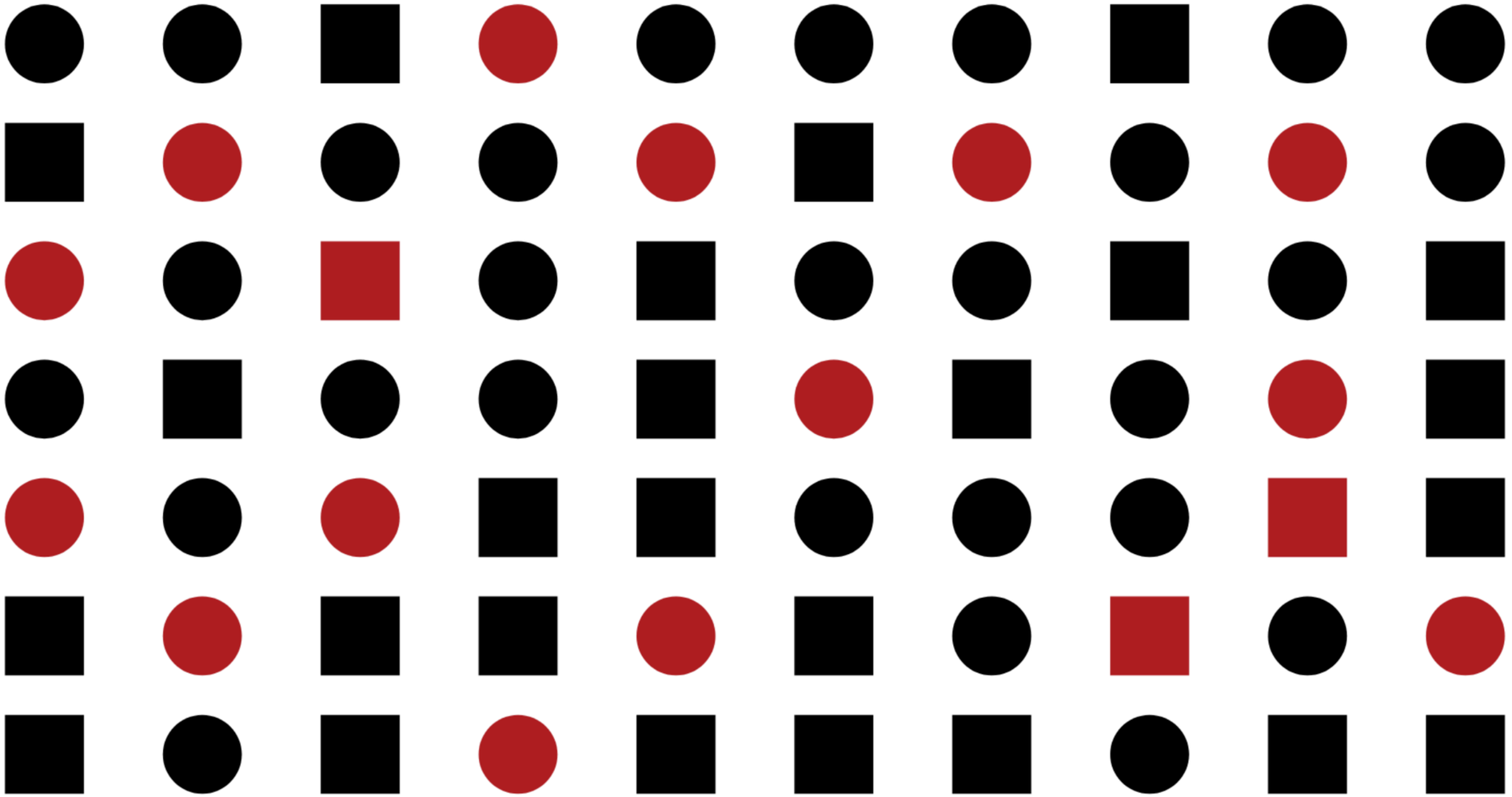
Preattention cues should be asymmetric



Colin Ware. *Information Visualization: Perception for Design.* 2021

Conjunctions are not preattentive

Find the
red circles



Colin Ware. *Information Visualization: Perception for Design.* 2021

Vision scientists are still debating the precise nature of preattention

- Treisman and Gelade 1980: early vision can only access simple feature maps of color, orientation, or motion
- However, could not explain experiments where people quickly perceive the gist of an entire scene at a glance
- Rosenholtz 2025: early vision computes summary statistics on the periphery which guide attention

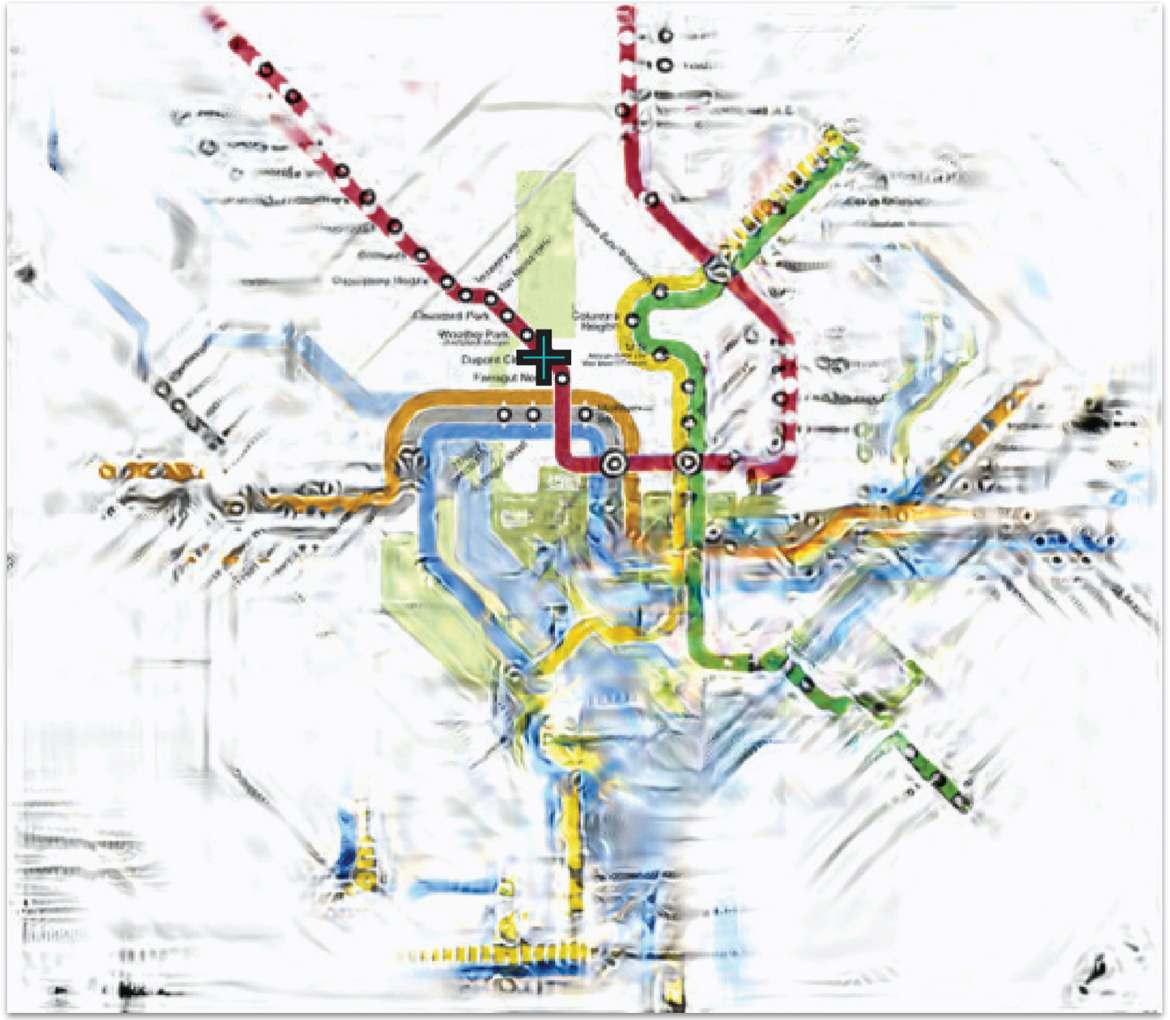
Treisman and Gelade. “A feature-integration theory of attention” 1980

Ruth Rosenholtz. “Visual Attention in Crisis” 2025

Periphery contains a coarse view of the world

True image

Model of perceived image



Ruth Rosenholtz. “Capabilities and Limitations of Peripheral Vision” 2016

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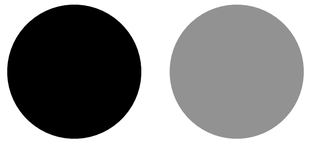
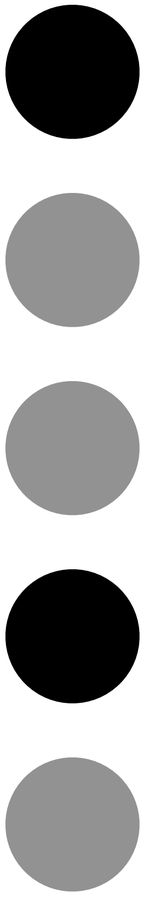
One-dimensional: lightness





Black

Gray

Gray

Black

Gray

Gray

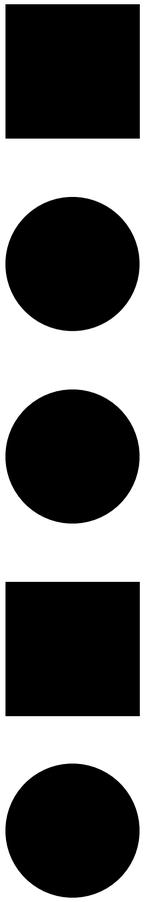
Black

Black

Black

Gray

One-dimensional: shape



Square

Circle

Circle

Square

Circle

Circle

Square

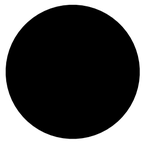
Square

Square

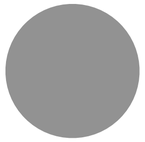
Circle

Redundant: shape & lightness

Black

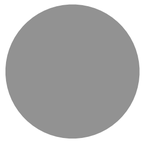


Circle



Gray

Square

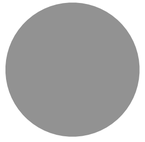


Gray

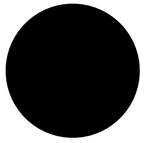
Square

Black

Square



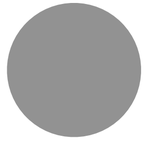
Gray



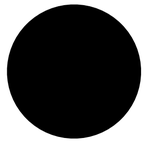
Circle

Orthogonal: shape & lightness

Black + square

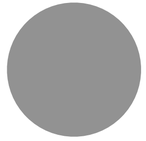


Gray + circle



Black + circle

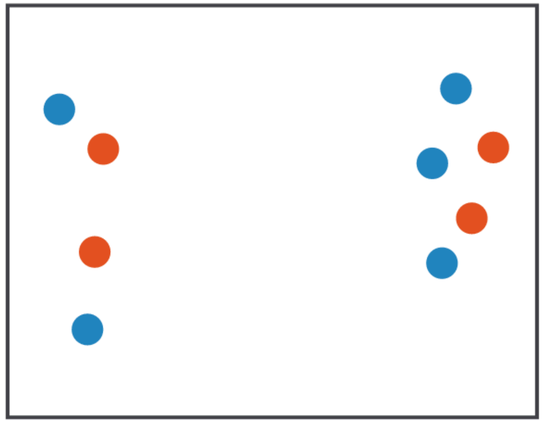
Gray + square



Gray + circle

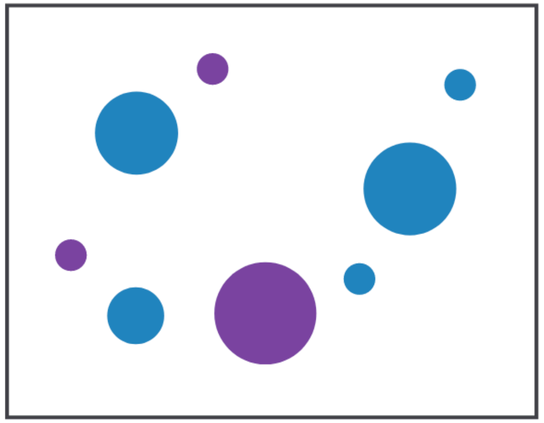
Attribute pairs vary in their separability

Position
+ Hue (Color)



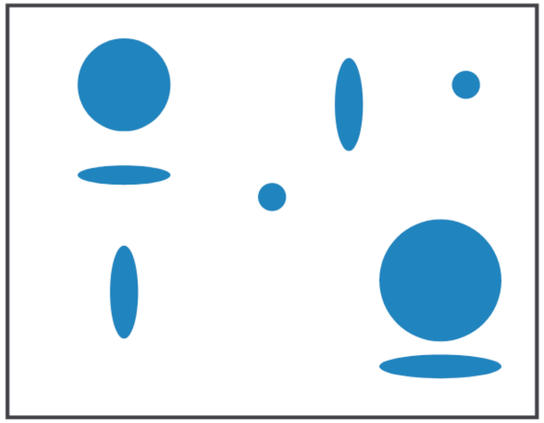
Fully separable

Size
+ Hue (Color)



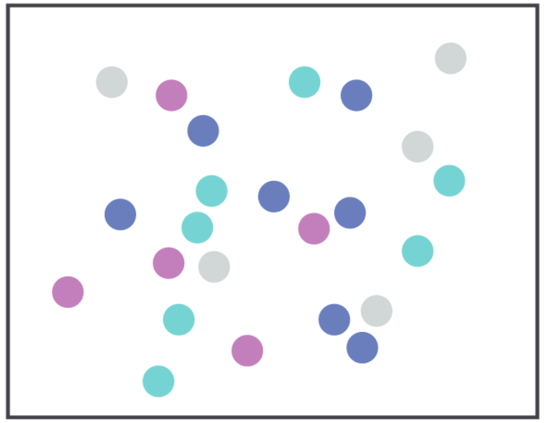
Some interference

Width
+ Height



Some/significant interference

Red
+ Green



Major interference