Lectures 5&6: *Perception & Color, Rules of Thumb*

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DSCI 532, Data Visualization 2
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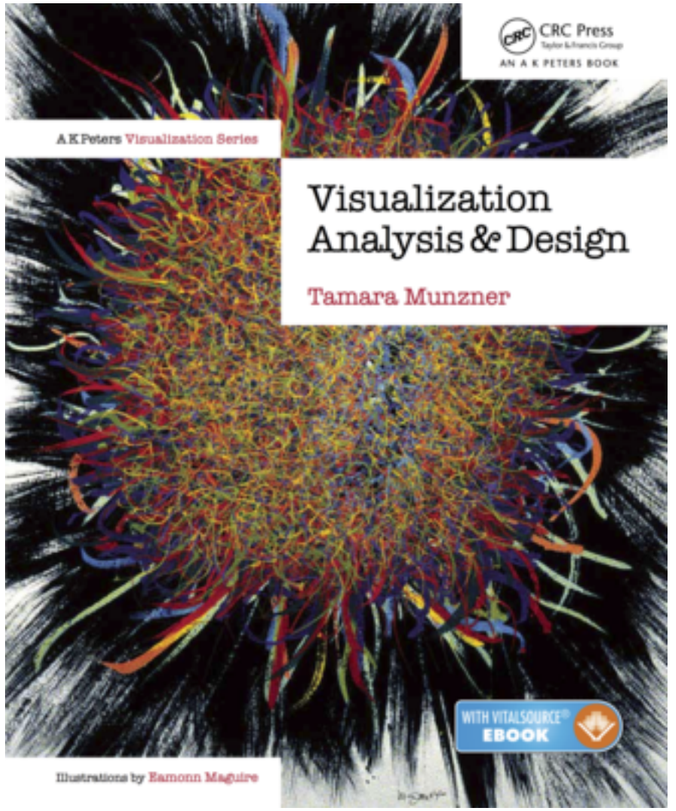


www.cs.ubc.ca/~tmm/courses/mds-viz2-17

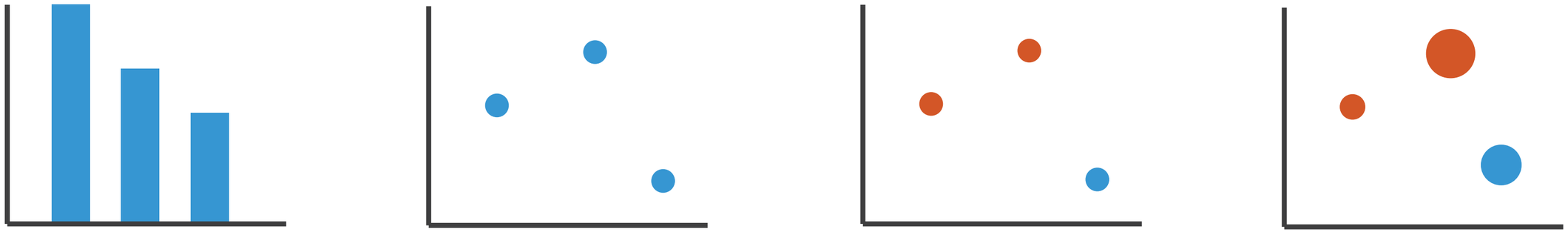
@tamaramunzner

Marks and Channels (Geoms and Aesthetics)

Perceptual Principles

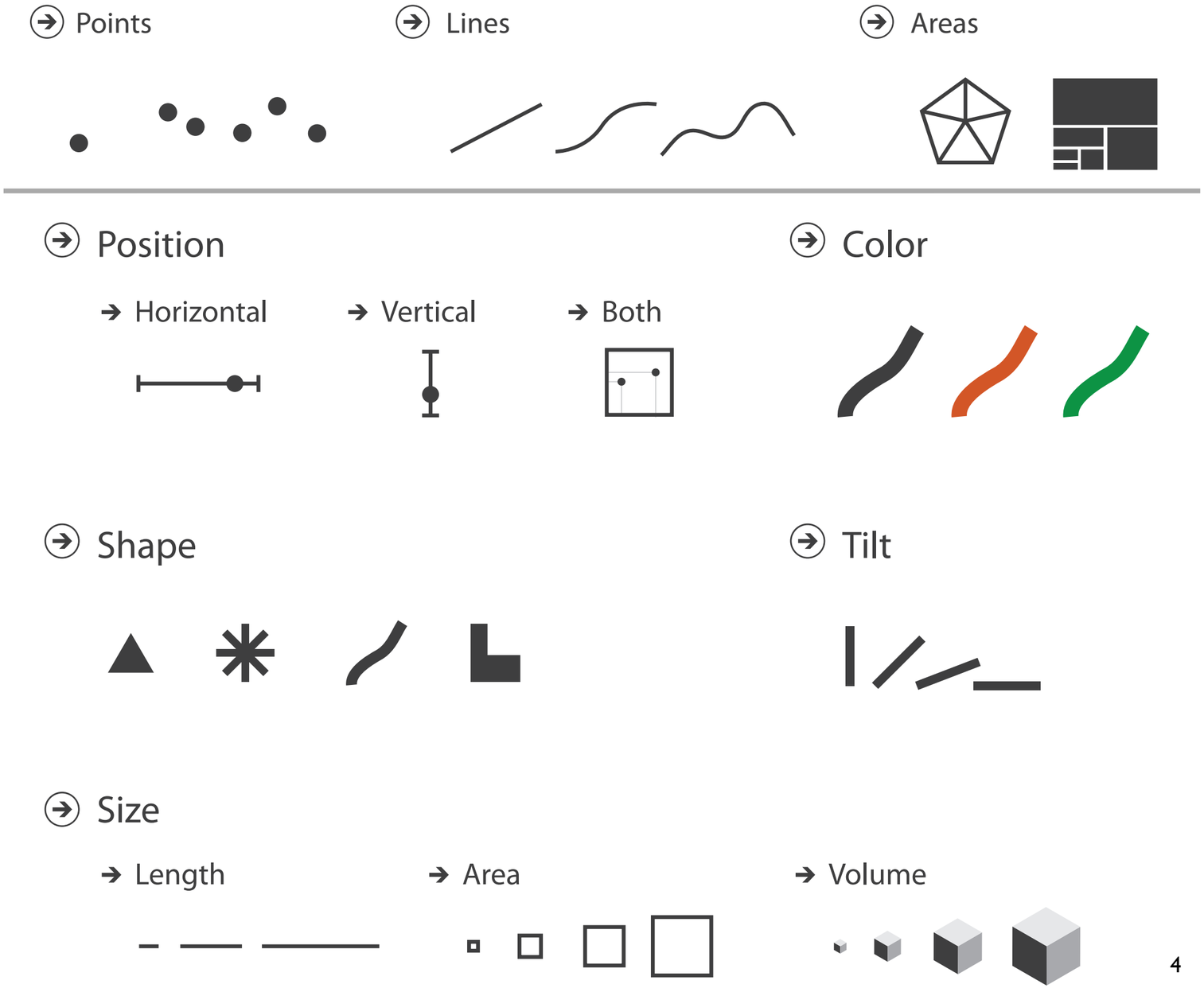
Visual encoding

- analyze idiom structure



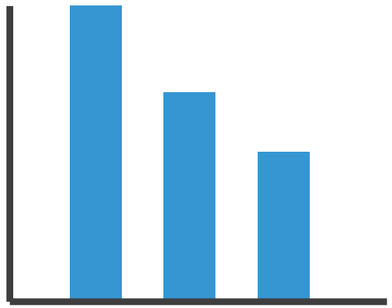
Definitions: Marks and channels

- marks (geoms)
  - geometric primitives
- channels (aesthetics)
  - control appearance of marks
  - can redundantly code with multiple channels



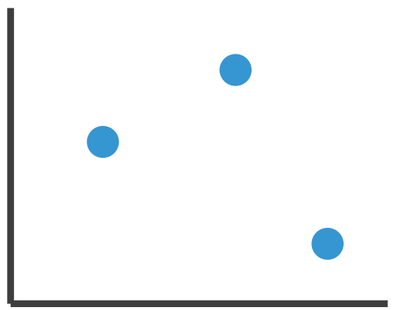
Visual encoding

- analyze idiom structure
  - as combination of marks/geoms and channels/aesthetics



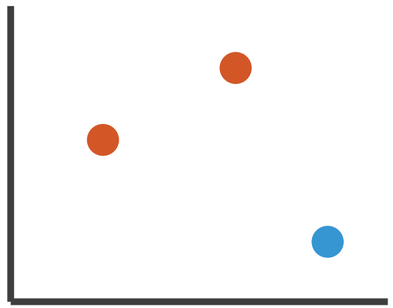
1:
vertical position

mark: line



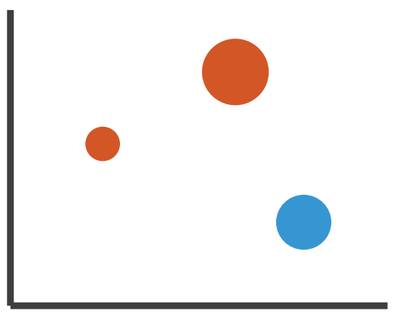
2:
vertical position
horizontal position

mark: point



3:
vertical position
horizontal position
color hue

mark: point



4:
vertical position
horizontal position
color hue
size (area)

mark: point

Channels

Position on common scale

Position on unaligned scale

Length (1D size)

Tilt/angle

Area (2D size)

Depth (3D position)

Color luminance

Color saturation

Curvature

Volume (3D size)

Same

Same

Spatial region

Color hue

Motion

Shape

Channels/Aesthetics: Matching Types

Magnitude Channels: Ordered Attributes

Position on common scale

Position on unaligned scale

Length (1D size)

Tilt/angle

Area (2D size)

Depth (3D position)

Color luminance

Color saturation

Curvature

Volume (3D size)

Same

Same

Identity Channels: Categorical Attributes

Spatial region

Color hue

Motion

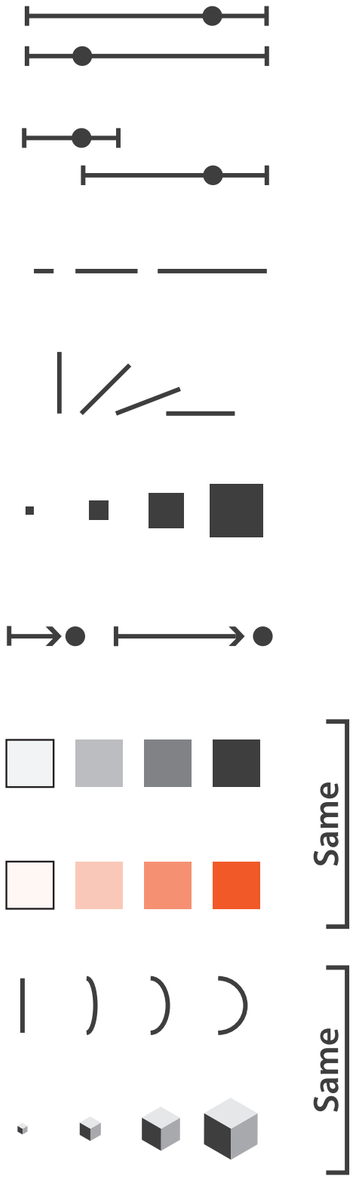
Shape

- expressiveness principle
  - match channel/aesthetics & data characteristics

Channels/Aesthetics: Rankings

Magnitude Channels: Ordered Attributes

- Position on common scale
- Position on unaligned scale
- Length (1D size)
- Tilt/angle
- Area (2D size)
- Depth (3D position)
- Color luminance
- Color saturation
- Curvature
- Volume (3D size)



Identity Channels: Categorical Attributes

- Spatial region
- Color hue
- Motion
- Shape

- expressiveness principle
  - match channel/aesthetics & data characteristics
- effectiveness principle
  - encode most important attributes with highest ranked channels

Channels/Aesthetics: Spatial position

Magnitude Channels: Ordered Attributes

Position on common scale

Position on unaligned scale

Length (1D size)

Tilt/angle

Area (2D size)

Depth (3D position)

Color luminance

Color saturation

Curvature

Volume (3D size)

Same

Same

Best

Effectiveness

Least

Identity Channels: Categorical Attributes

Spatial region

Color hue

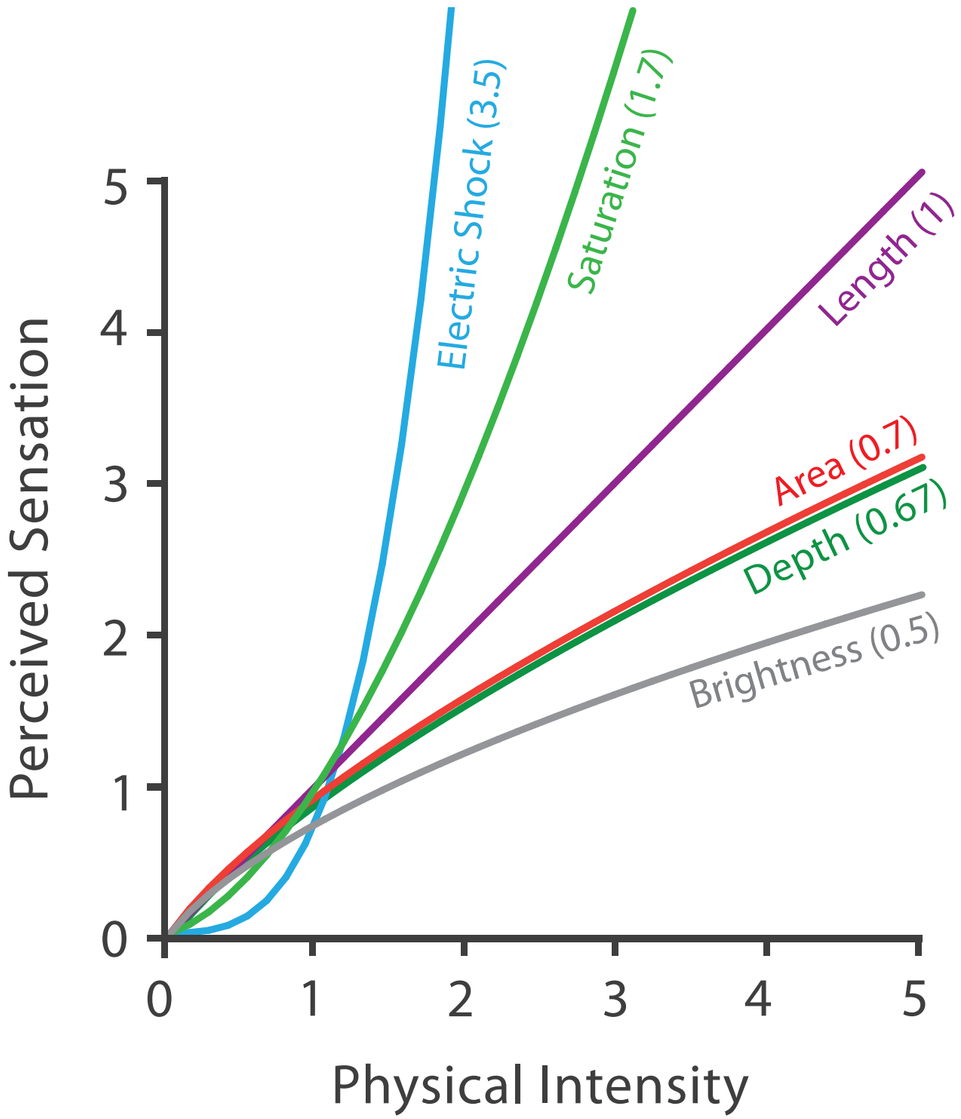
Motion

Shape

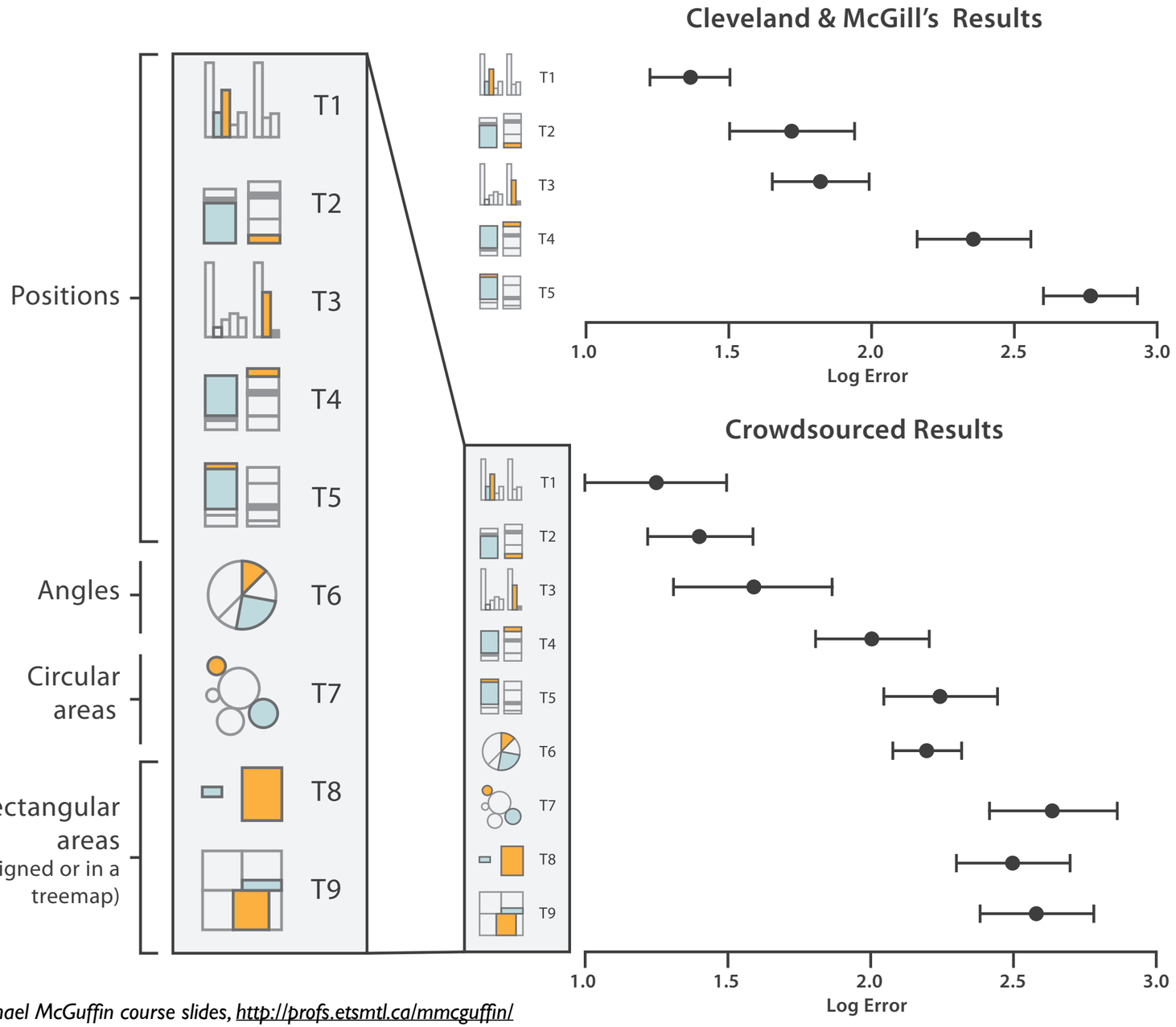
- expressiveness principle
  - match channel and data characteristics
- effectiveness principle
  - encode most important attributes with highest ranked channels
  - spatial position ranks high for both

Accuracy: Fundamental Theory

Steven's Psychophysical Power Law: $S = I^N$



Accuracy: Vis experiments

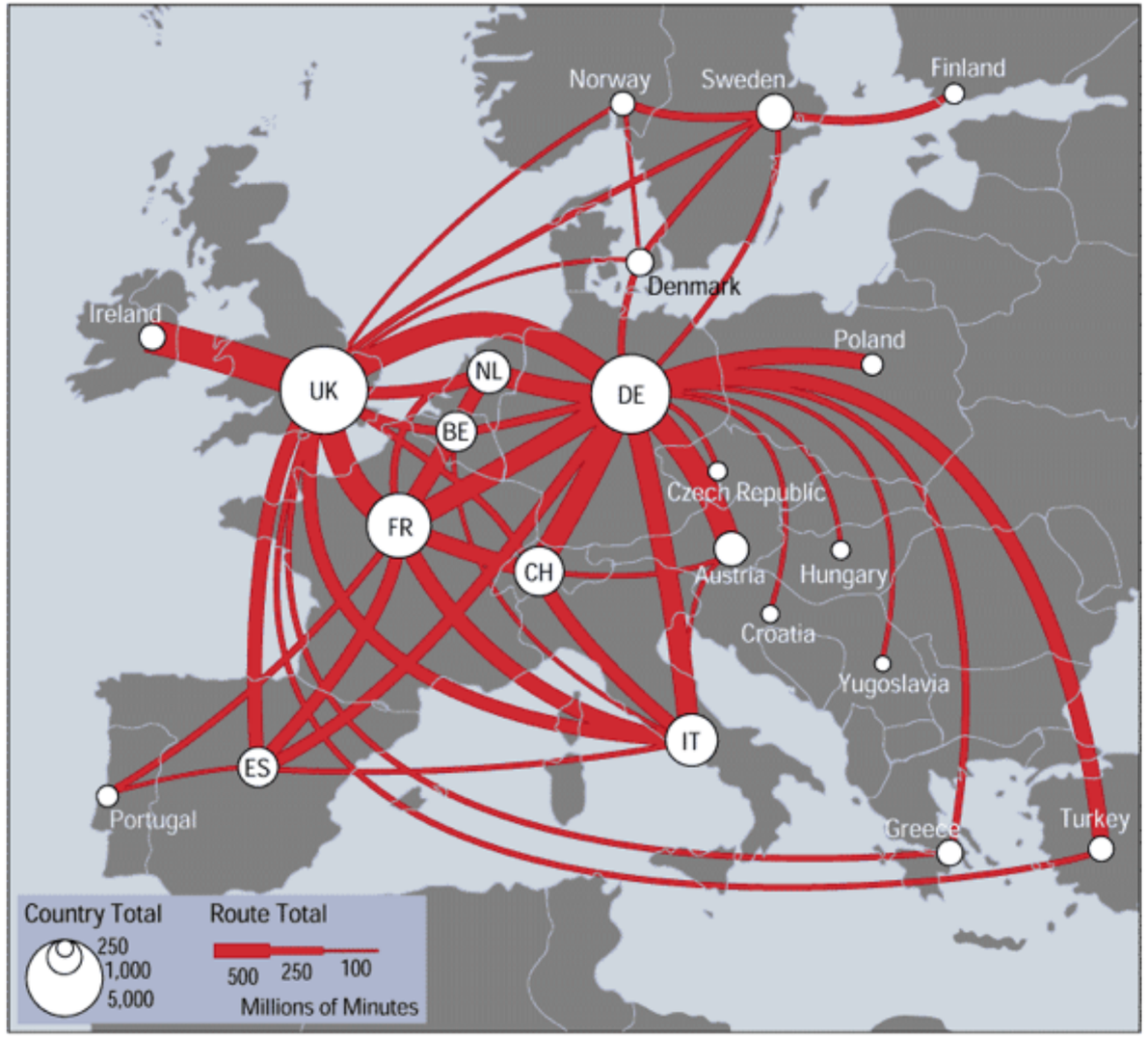


[Crowdsourcing Graphical Perception: Using Mechanical Turk to Assess Visualization Design. Heer and Bostock. Proc ACM Conf. Human Factors in Computing Systems (CHI) 2010, p. 203–212.]

after Michael McGuffin course slides, http://profs.etsmtl.ca/mmcguffin/

Discriminability: How many usable steps?

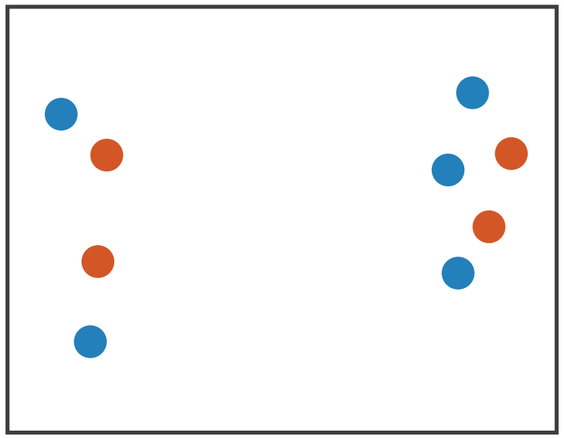
- must be sufficient for number of attribute levels to show
  - linewidth: few bins but salient



[mappa.mundi.net/maps/maps 014/telegeography.html]

Separability vs. Integrality

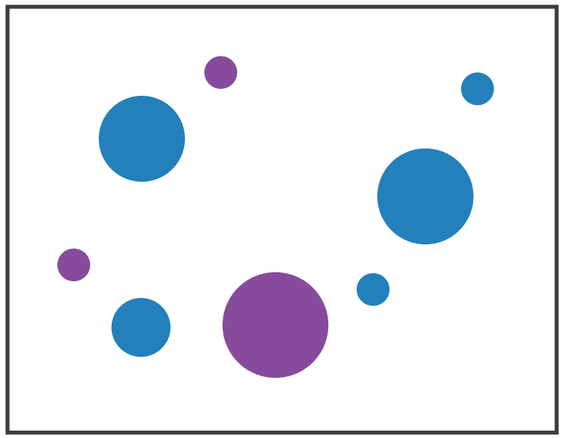
Position
+ Hue (Color)



Fully separable

2 groups each

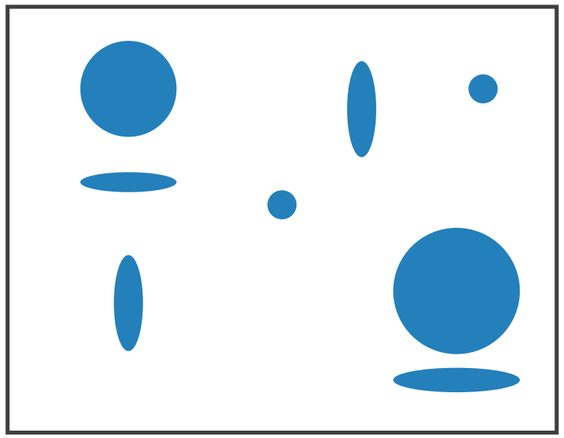
Size
+ Hue (Color)



Some interference

2 groups each

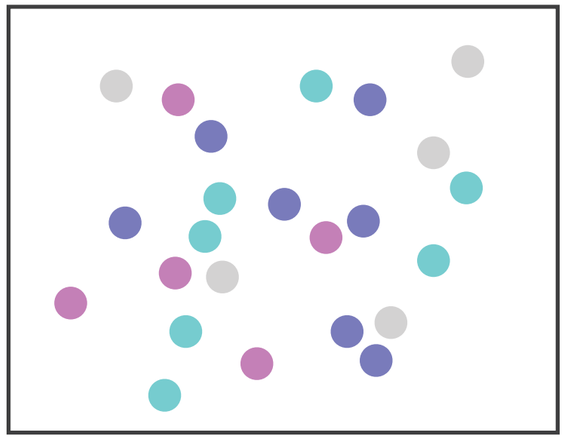
Width
+ Height



Some/significant interference

3 groups total: integral area

Red
+ Green

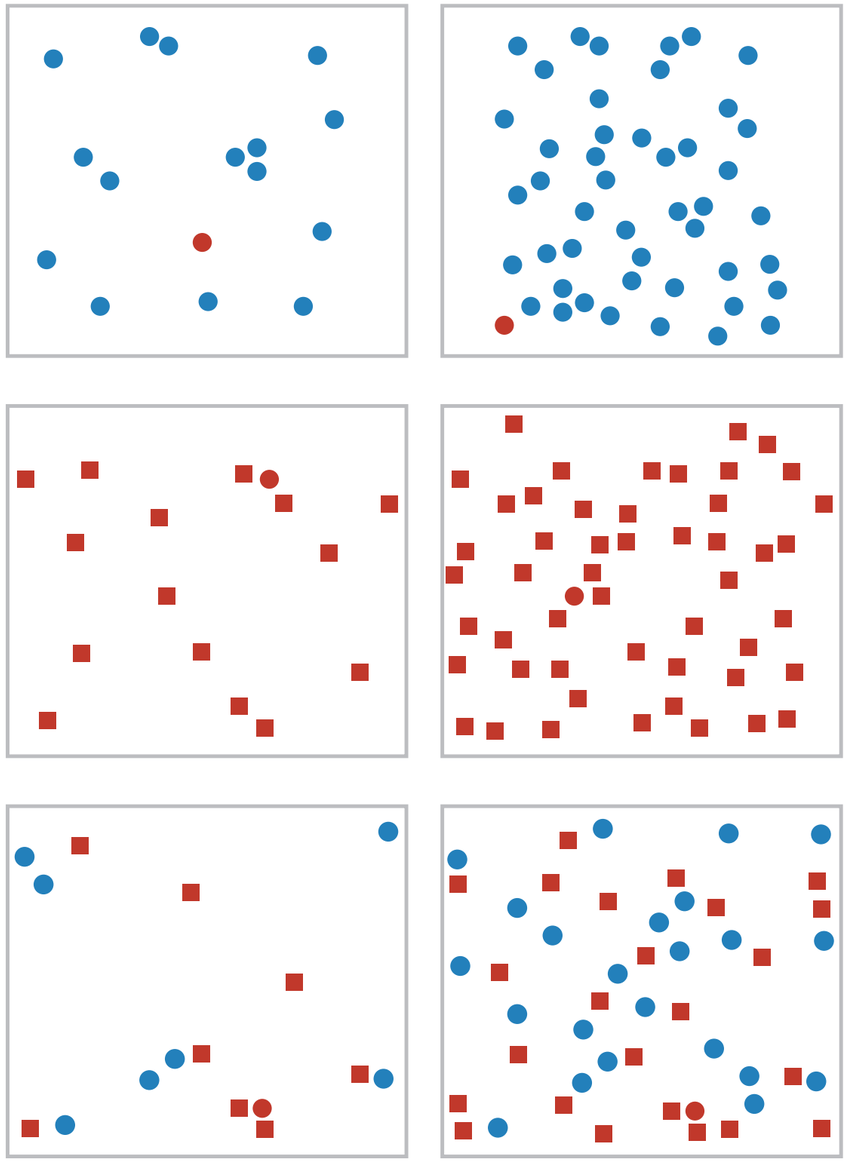


Major interference

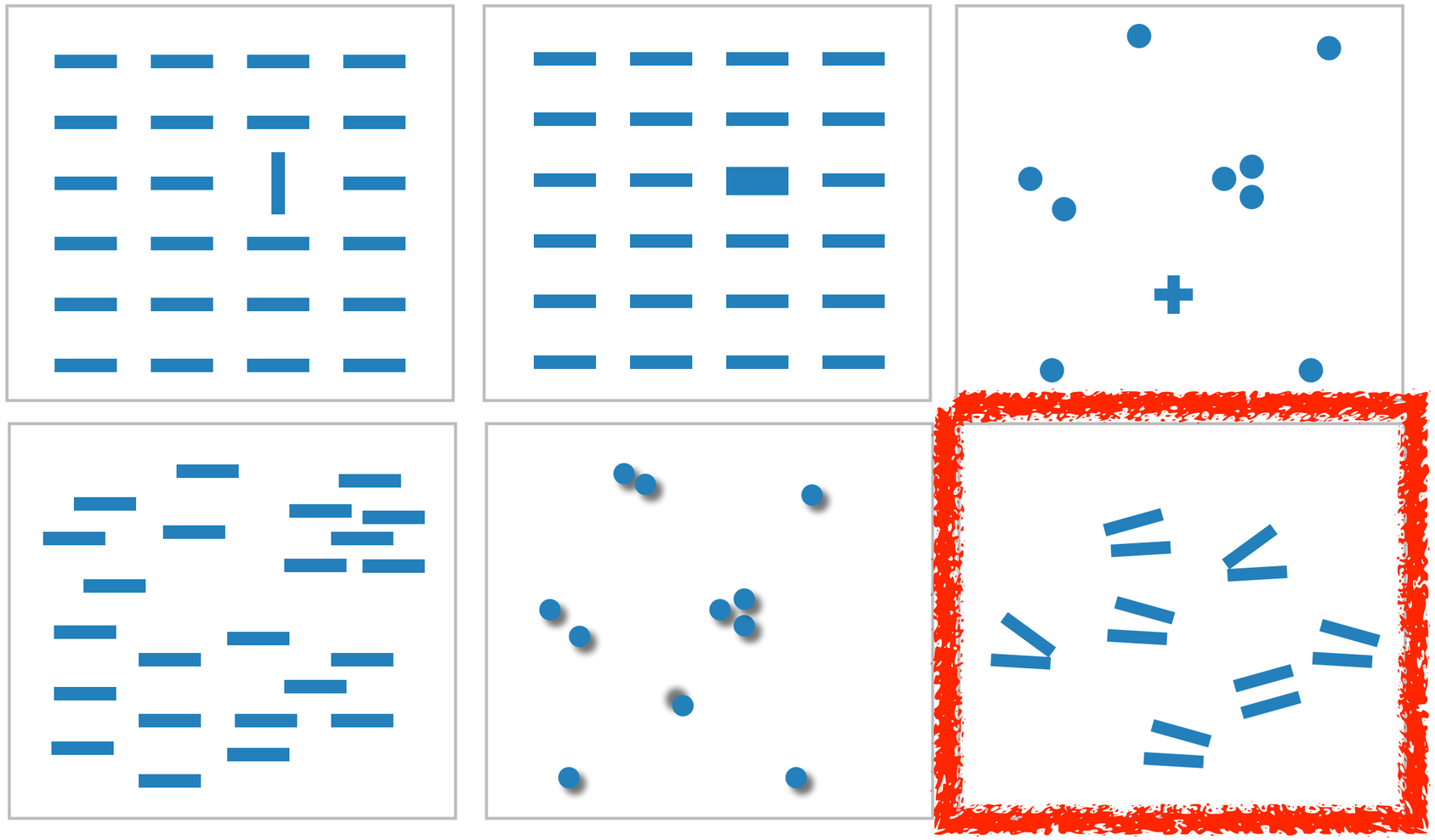
4 groups total: integral hue

Popout

- find the red dot
  - how long does it take?
- parallel processing on many individual channels
  - speed independent of distractor count
  - speed depends on channel and amount of difference from distractors
- serial search for (almost all) combinations
  - speed depends on number of distractors



Popout



- many channels: tilt, size, shape, proximity, shadow direction, ...
- but not all! parallel line pairs do not pop out from tilted pairs

Grouping

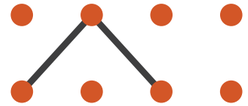
- containment
- connection

- proximity
  - same spatial region
- similarity
  - same values as other categorical channels

Marks as Links

Containment

Connection

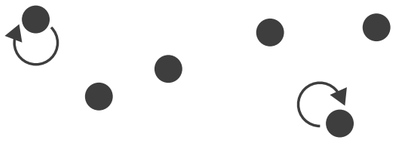


Identity Channels: Categorical Attributes

Spatial region

Color hue

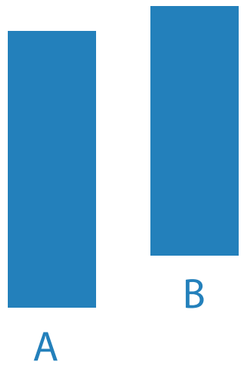
Motion



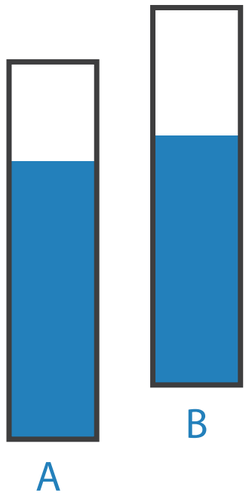
Shape

Relative vs. absolute judgements

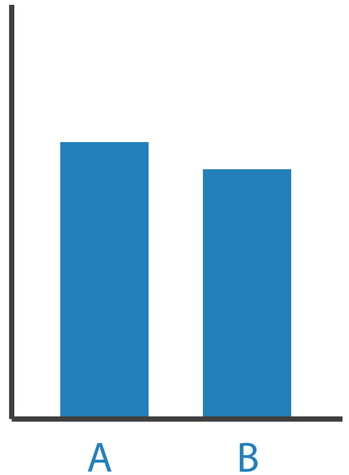
- perceptual system mostly operates with relative judgements, not absolute
  - that's why accuracy increases with common frame/scale and alignment
  - Weber's Law: ratio of increment to background is constant
    - filled rectangles differ in length by 1:9, difficult judgement
    - white rectangles differ in length by 1:2, easy judgement



length



position along unaligned common scale

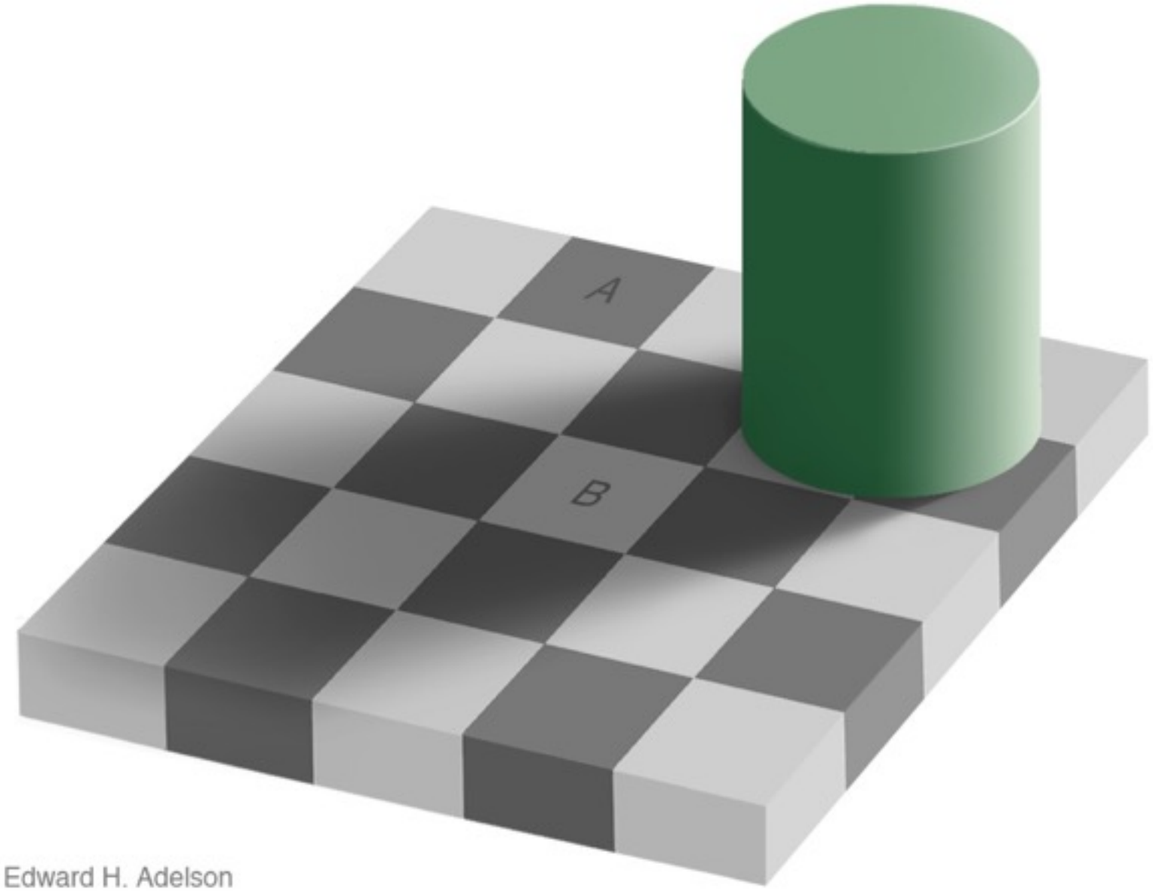


position along aligned scale

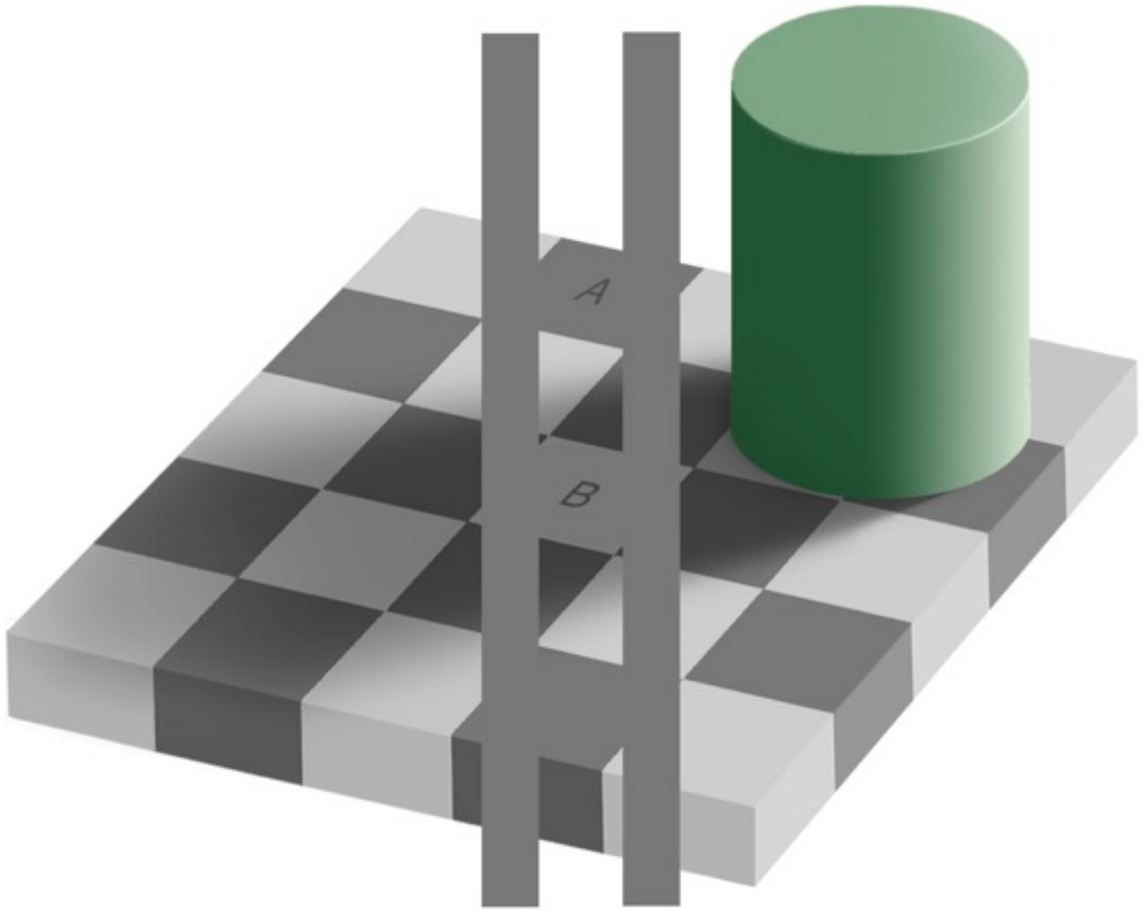
after [Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods. Cleveland and McGill. Journ. American Statistical Association 79:387 (1984), 531–554.]

Relative luminance judgements

- perception of luminance is contextual based on contrast with surroundings



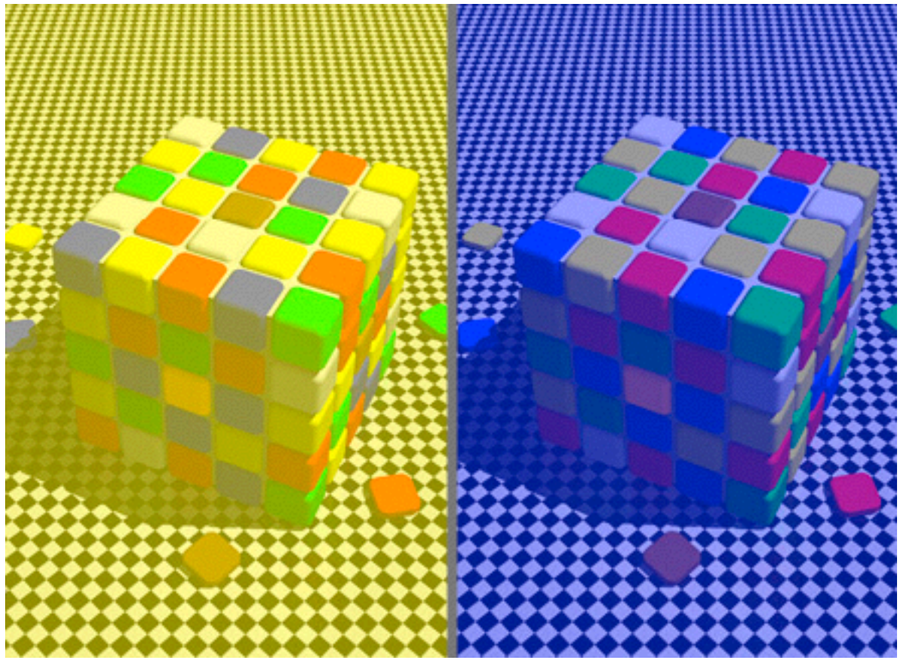
Edward H. Adelson

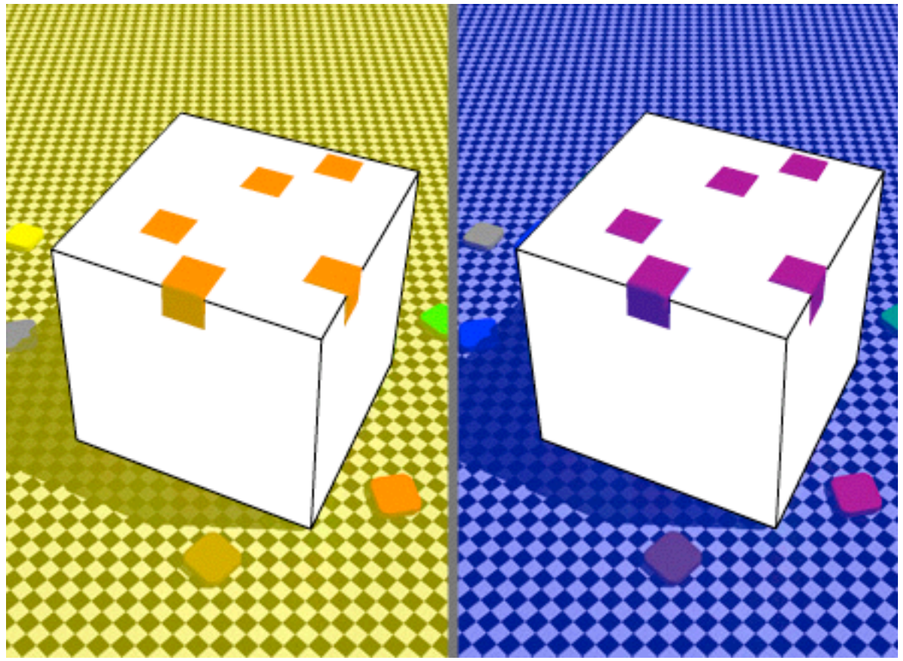


http://persci.mit.edu/gallery/checkershadow

Relative color judgements

- color constancy across broad range of illumination conditions





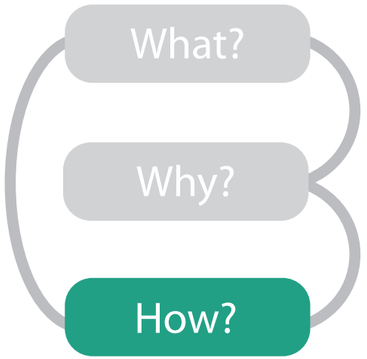
http://www.purveslab.net/seeforyourself/

Further reading

- Visualization Analysis and Design. Munzner. AK Peters Visualization Series, CRC Press, 2014.
  - *Chap 5: Marks and Channels*
- *On the Theory of Scales of Measurement*. Stevens. Science 103:2684 (1946), 677–680.
- Psychophysics: Introduction to its Perceptual, Neural, and Social Prospects. Stevens. Wiley, 1975.
- *Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods*. Cleveland and McGill. Journ. American Statistical Association 79:387 (1984), 531–554.
- *Perception in Vision*. Healey. http://www.csc.ncsu.edu/faculty/healey/PP
- Visual Thinking for Design. Ware. Morgan Kaufmann, 2008.
- Information Visualization: Perception for Design, 3rd edition. Ware. Morgan Kaufmann /Academic Press, 2004.

Color Theory

Idiom design choices: Encode

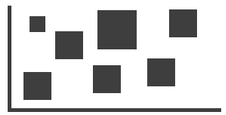


Encode

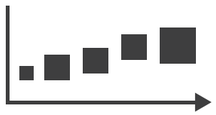
Arrange

- Express

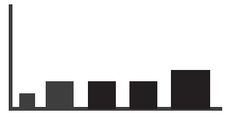
- Separate



- Order



- Align



- Use

Map

from categorical and ordered attributes

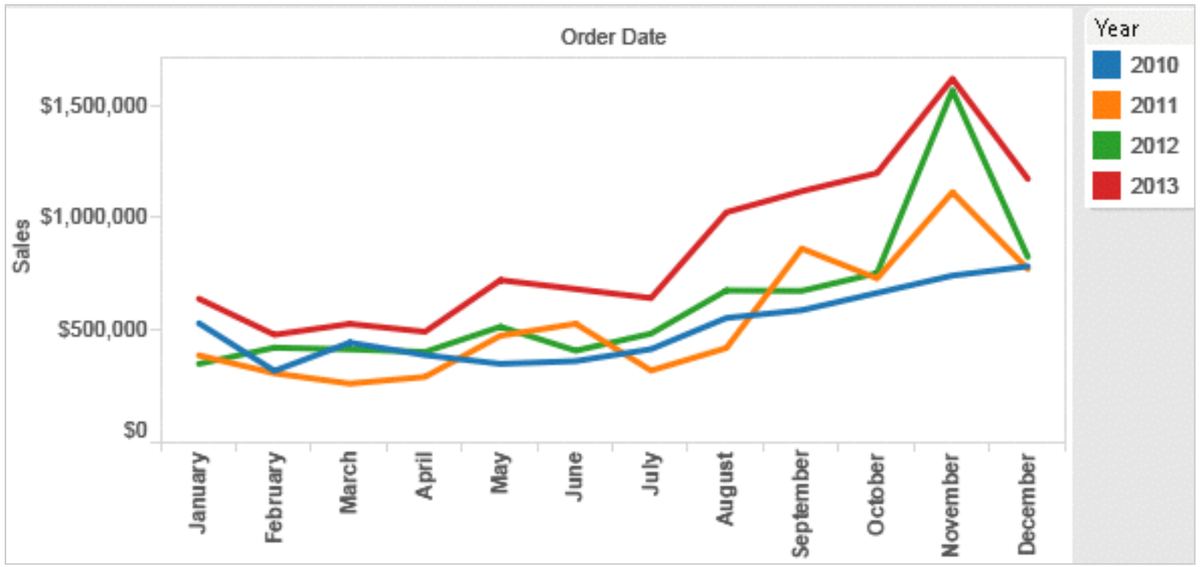
- Color
  - *Hue*
  - *Saturation*
  - *Luminance*

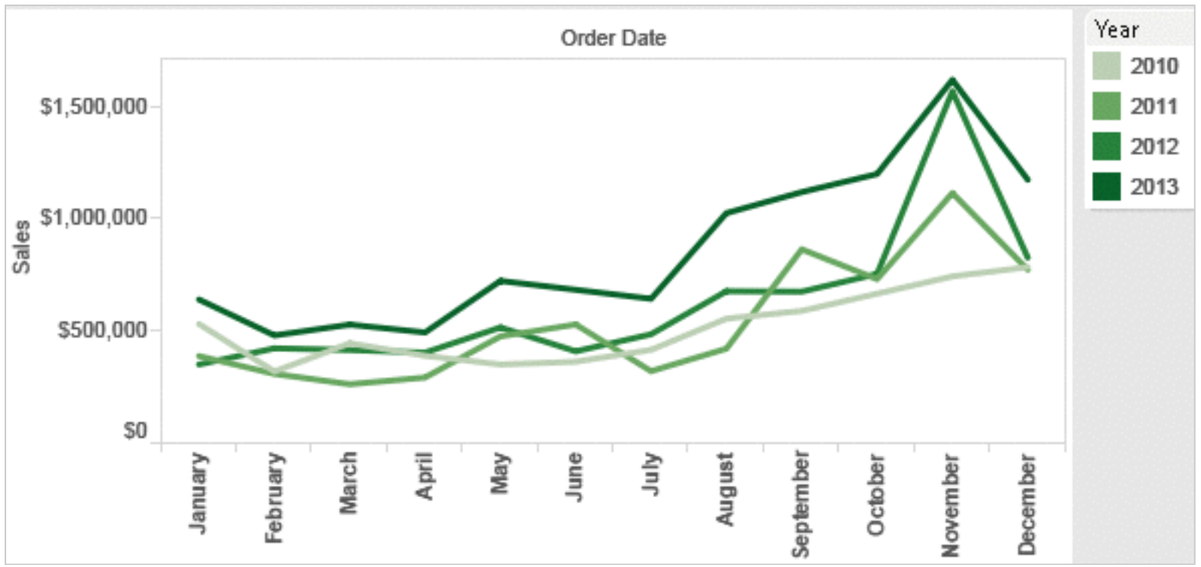
- Size, Angle, Curvature, ...

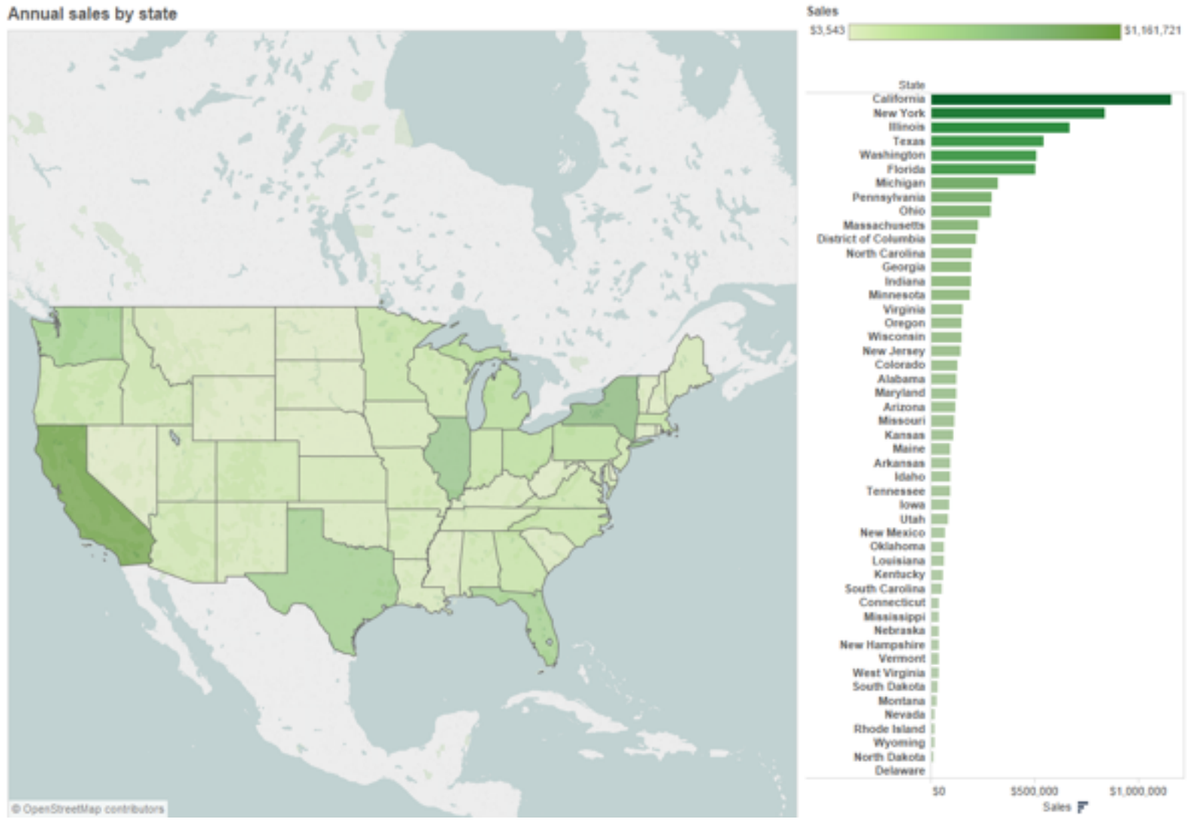
- Shape

- Motion
  Direction, Rate, Frequency, ...

Categorical vs ordered color





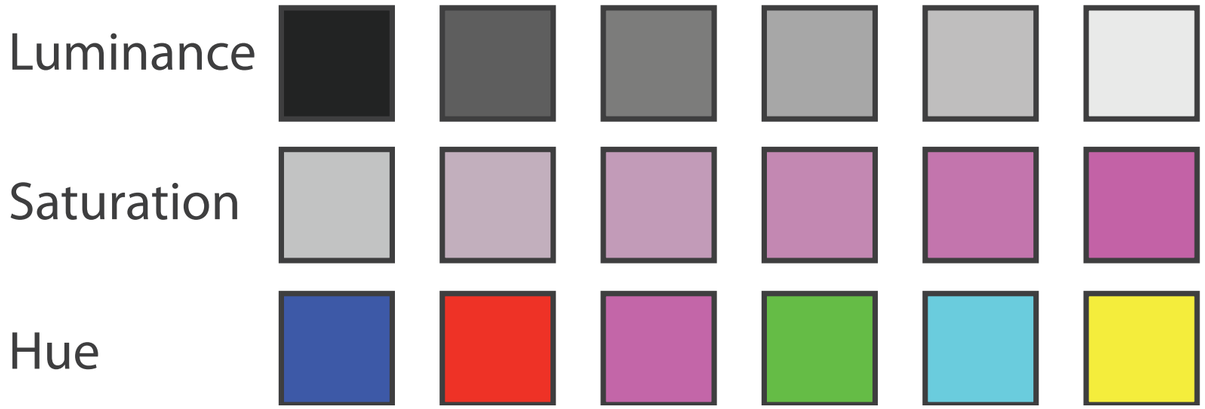


[Seriously Colorful: Advanced Color Principles & Practices. Stone. Tableau Customer Conference 2014.]

Decomposing color

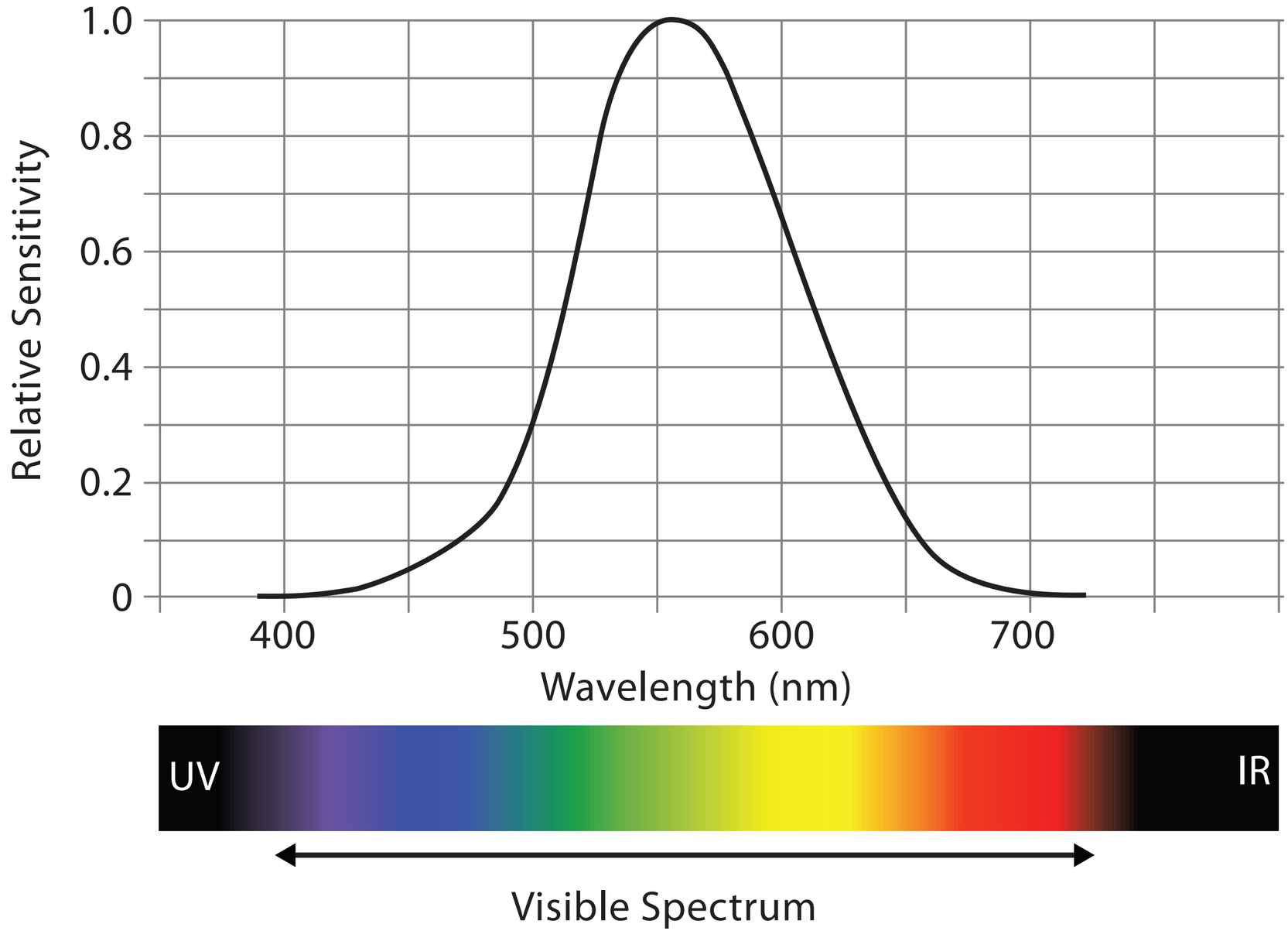
- first rule of color: do not talk about color!
  - color is confusing if treated as monolithic

- decompose into three channels
  - ordered can show magnitude
    - luminance: how bright
    - saturation: how colorful
  - categorical can show identity
    - hue: what color



- channels have different properties
  - what they convey directly to perceptual system
  - how much they can convey: how many discriminable bins can we use?

Spectral sensitivity



Luminance

- need luminance for edge detection
  - fine-grained detail only visible through luminance contrast
  - legible text requires luminance contrast!

- intrinsic perceptual ordering

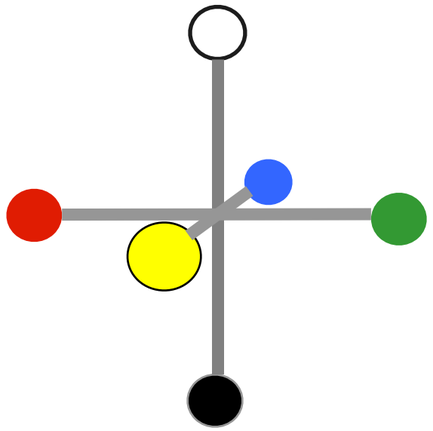
Luminance information

Chroma information

[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Opponent color and color deficiency

- perceptual processing before optic nerve
  - one achromatic luminance channel (L*)
    - edge detection through luminance contrast
  - 2 chroma channels
    - red-green (a*) & yellow-blue axis (b*)
- "color blind": one axis has degraded acuity
  - 8% of men are red/green color deficient
  - blue/yellow is rare



Luminance information

Chroma information

[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Color spaces

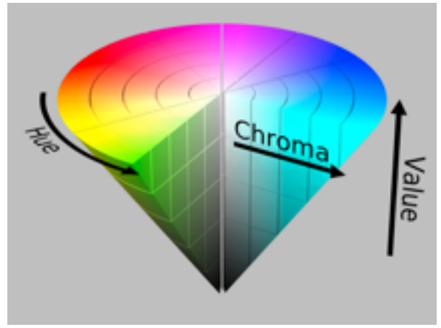
- CIE L*a*b*: good for computation
  - L* intuitive: perceptually linear luminance
  - a*b* axes: perceptually linear but nonintuitive
- RGB: good for display hardware
  - poor for encoding
- HSL/HSV: somewhat better for encoding
  - hue/saturation wheel intuitive
  - beware: only pseudo-perceptual!
  - lightness (L) or value (V) ≠ luminance or L*
- Luminance, hue, saturation
  - good for encoding
  - but not standard graphics/tools colorspace

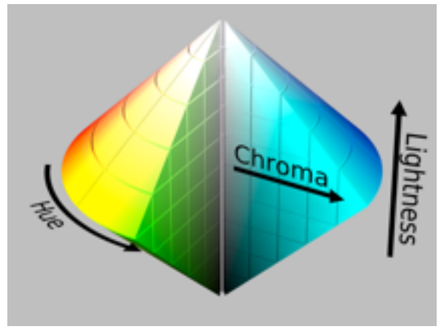
Corners of the RGB color cube

L from HLS
All the same

Luminance values

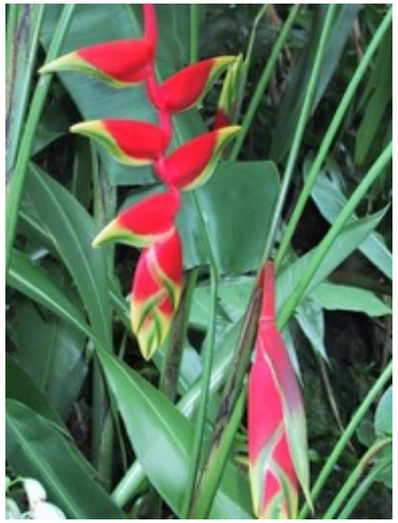
L* values



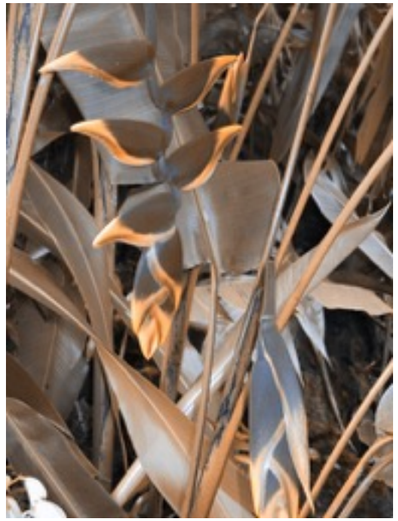


[https://en.wikipedia.org/wiki/HSL_and_HSV]

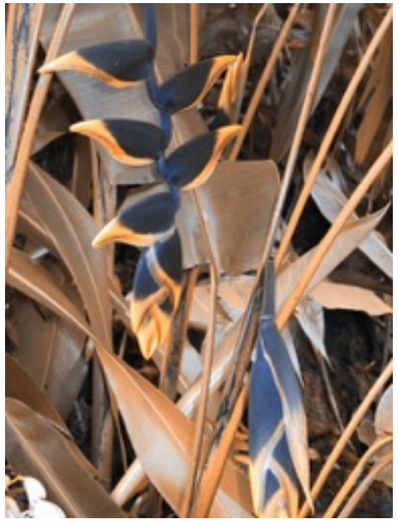
Designing for color deficiency: Check with simulator



Normal vision



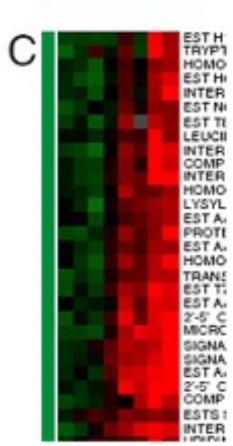
Deuteranope



Protanope

Tritanope

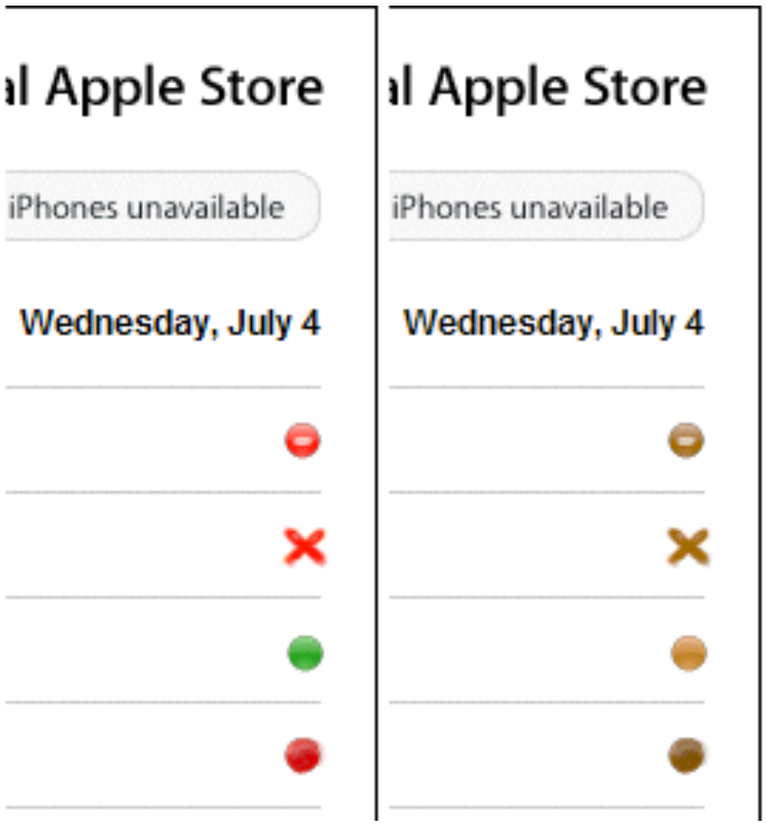
http://rehue.net

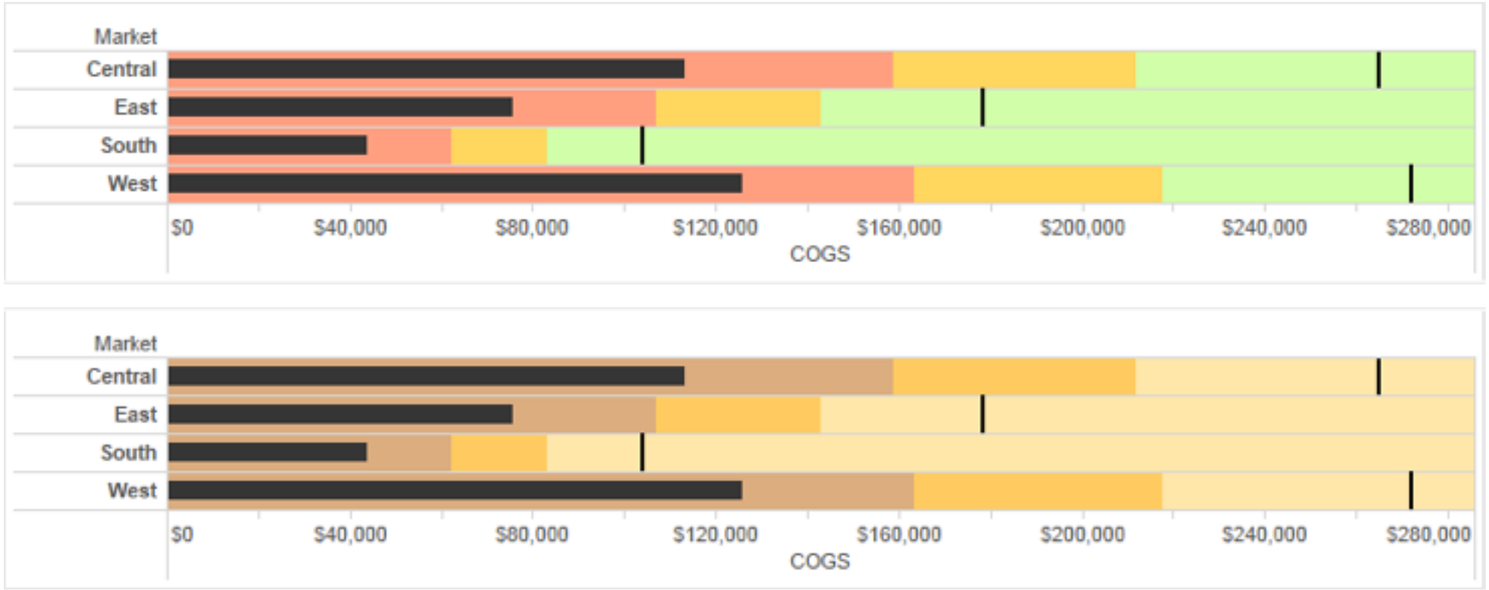


[Seriously Colorful: Advanced Color Principles & Practices. Stone. Tableau Customer Conference 2014.]

Designing for color deficiency: Avoid encoding by hue alone

- redundantly encode
  - vary luminance
  - change shape





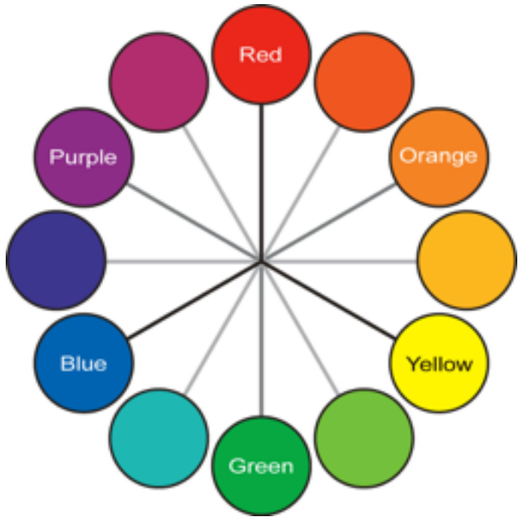
Deuteranope simulation

Change the shape

Vary luminance

[Seriously Colorful: Advanced Color Principles & Practices. Stone. Tableau Customer Conference 2014.]

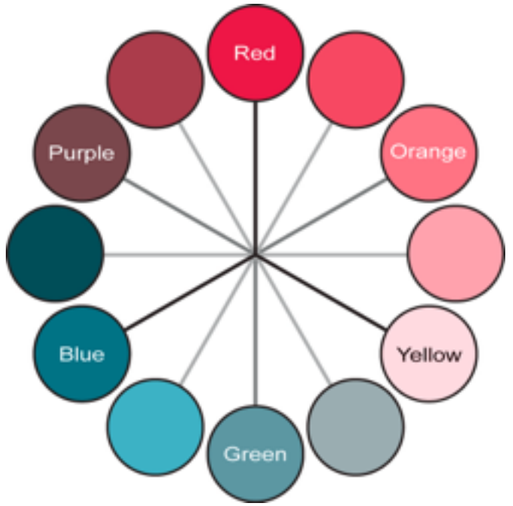
Color deficiency: Reduces color to 2 dimensions



Normal

Protanope

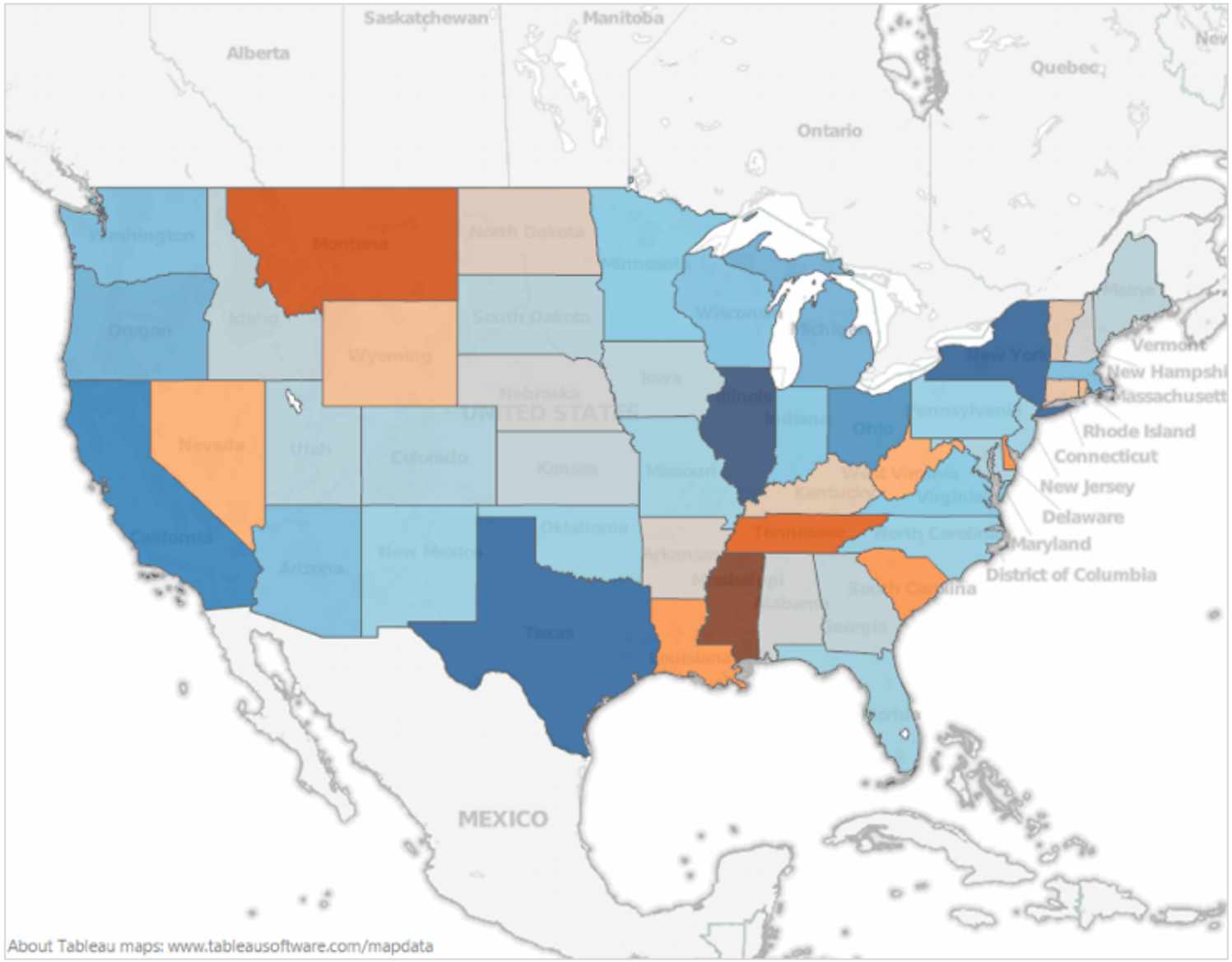
Deuteranope



Tritanope

[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

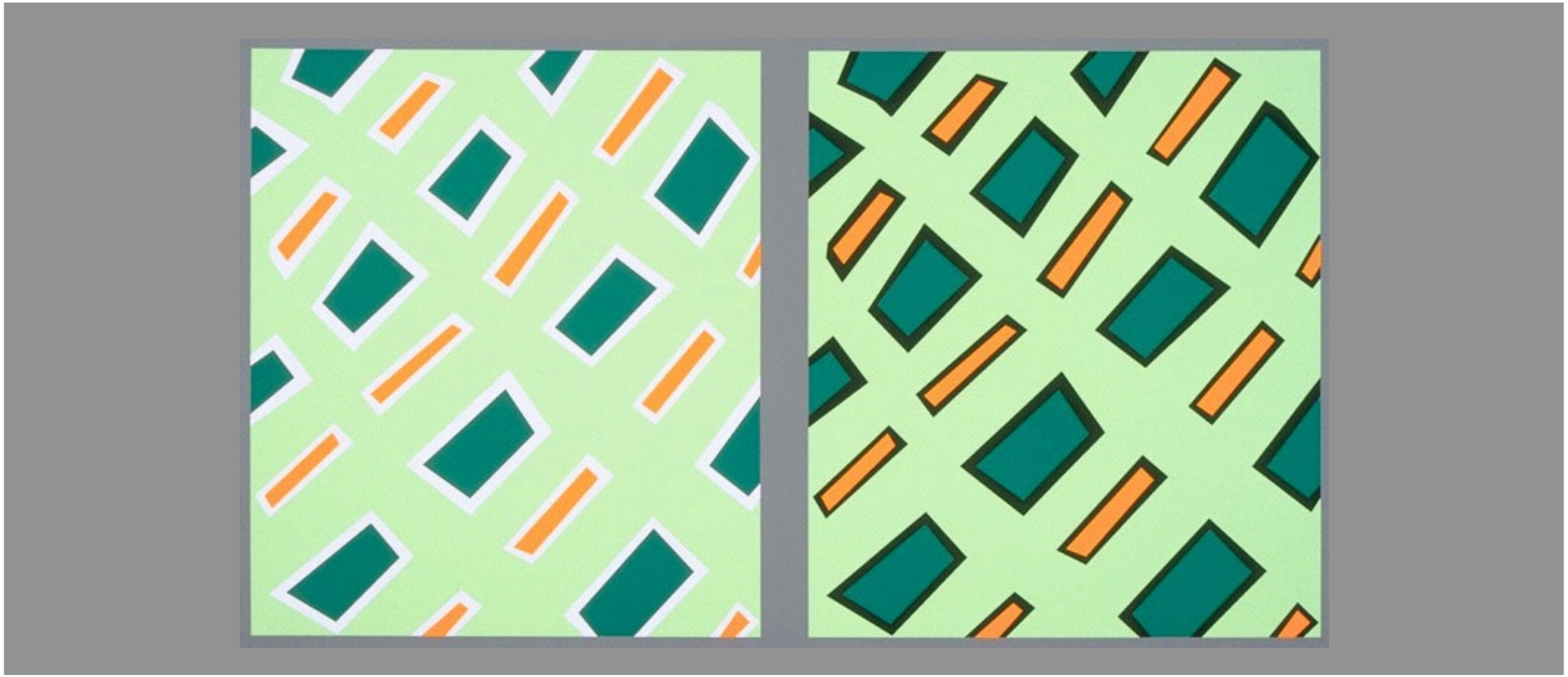
Designing for color deficiency: Blue-Orange is safe



[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Bezold Effect: Outlines matter

- color constancy: simultaneous contrast effect



[Seriously Colorful: Advanced Color Principles & Practices. Stone.Tableau Customer Conference 2014.]

Relative judgements: Color & illumination

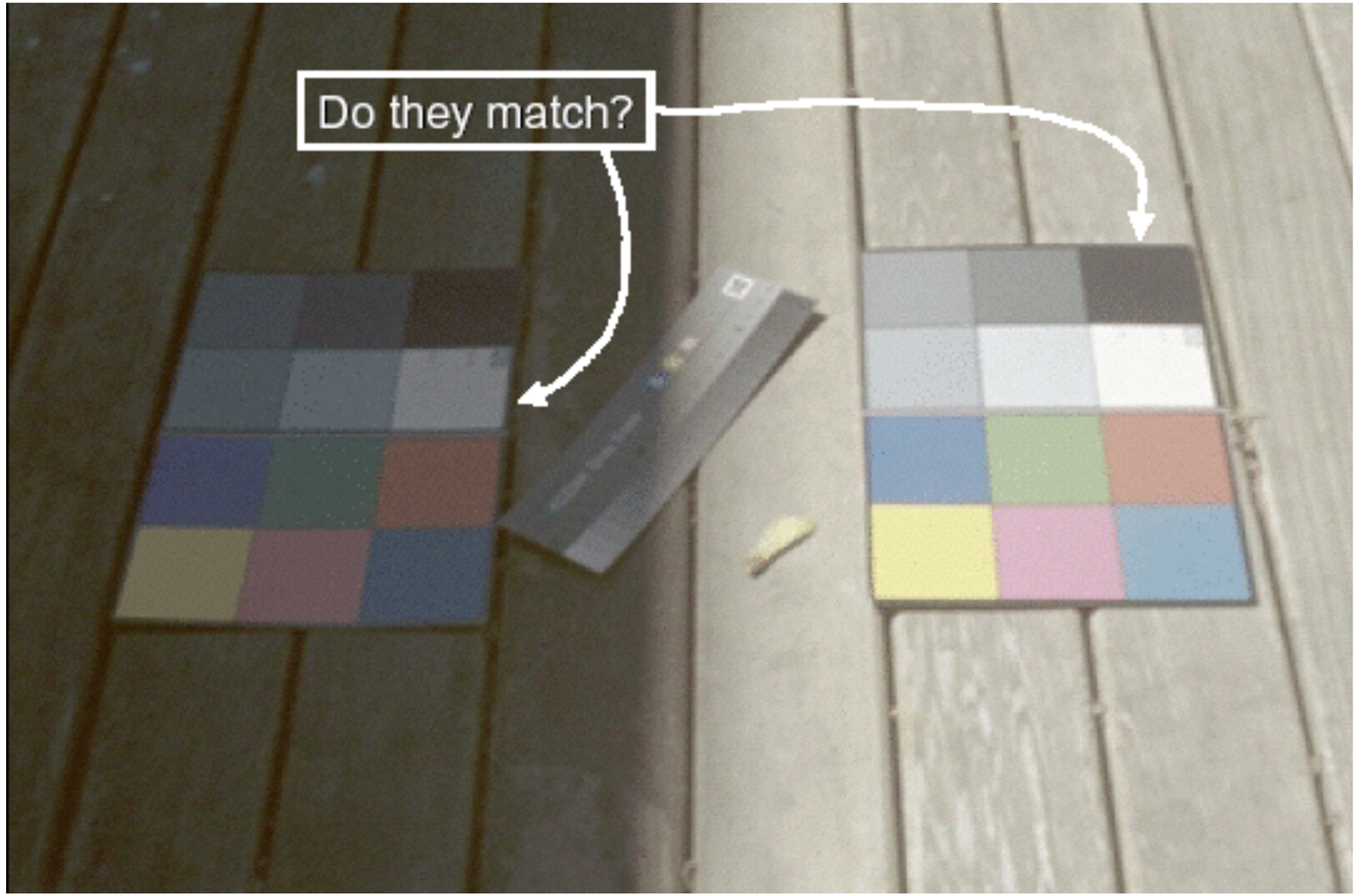


Image courtesy of John McCann

Relative judgements: Color & illumination

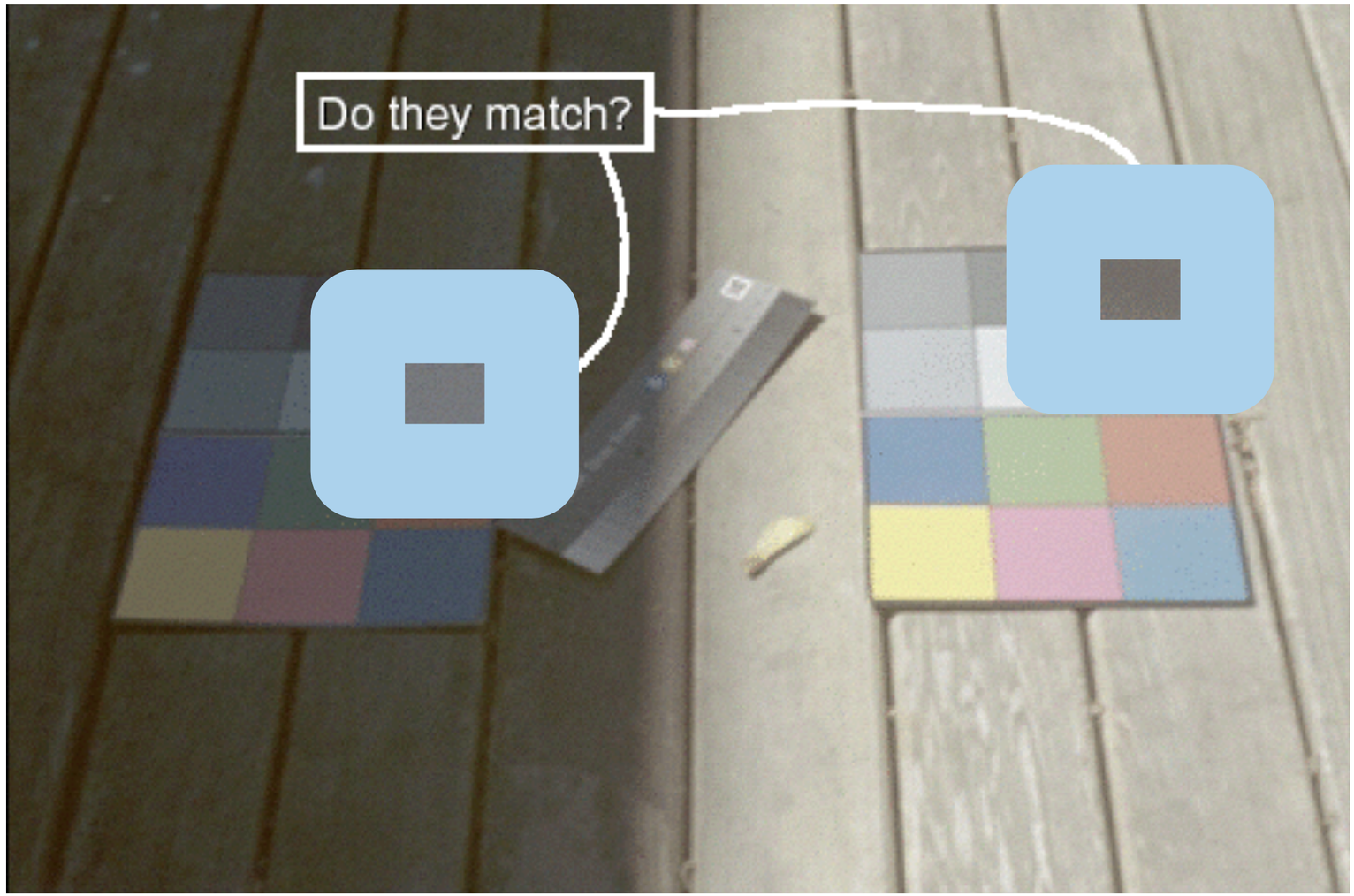
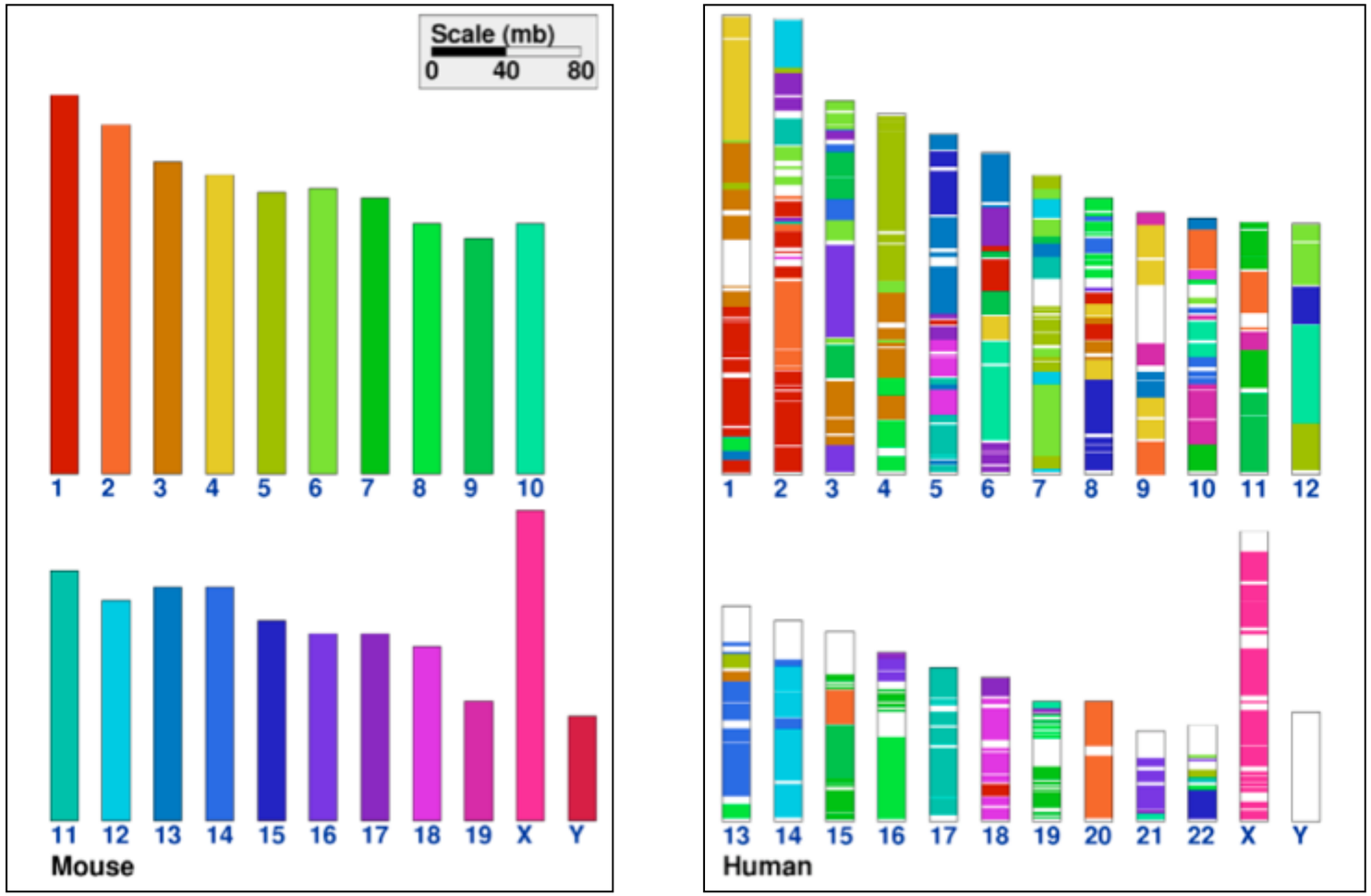


Image courtesy of John McCann

Categorical color: limited number of discriminable bins

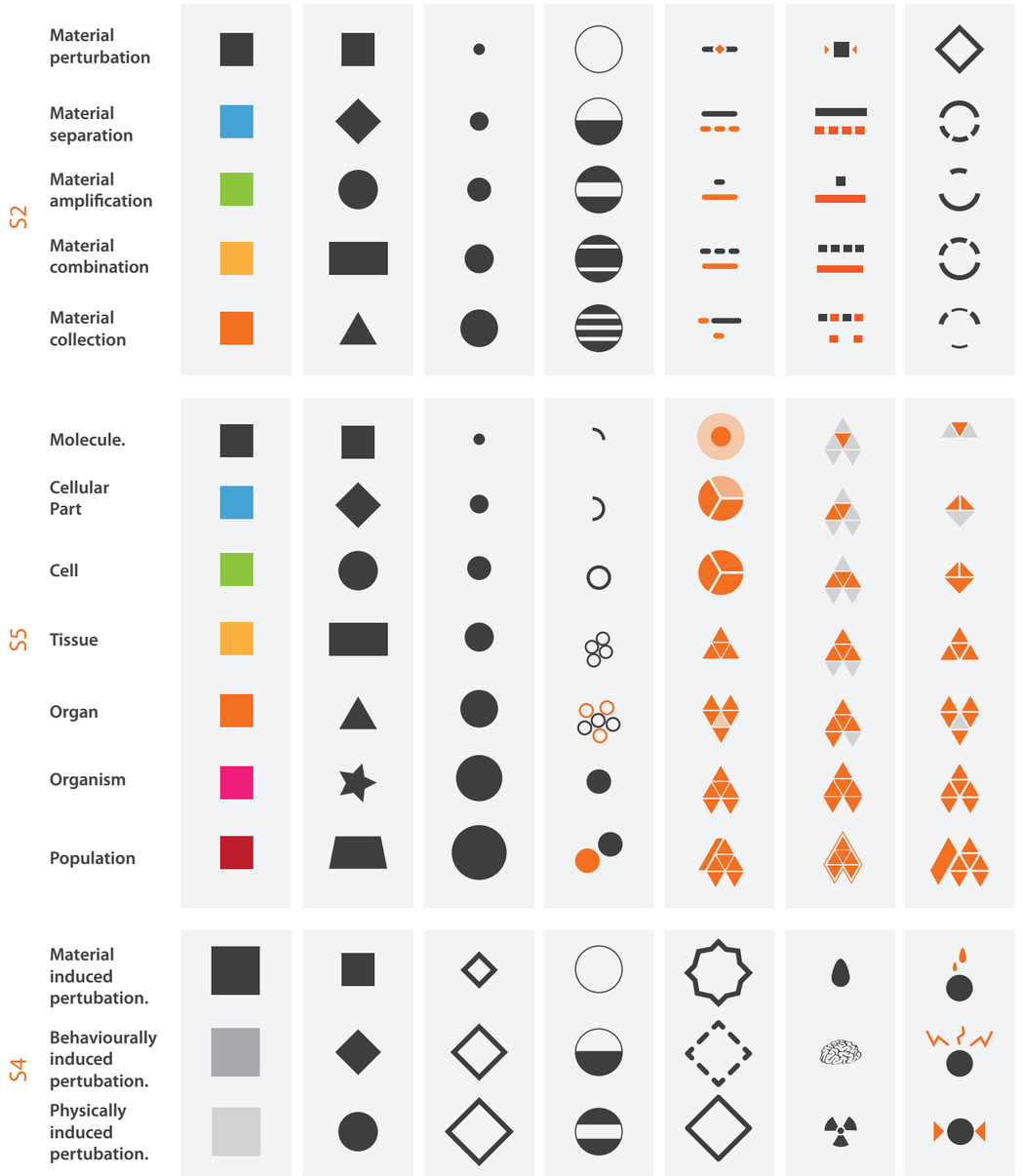
- human perception built on relative comparisons
  - great if color contiguous
  - surprisingly bad for absolute comparisons
- noncontiguous small regions of color
  - fewer bins than you want
  - rule of thumb: 6-12 bins, including background and highlights



[Cinteny: flexible analysis and visualization of synteny and genome rearrangements in multiple organisms. Sinha and Meller. BMC Bioinformatics, 8:82, 2007.]

Glyphs

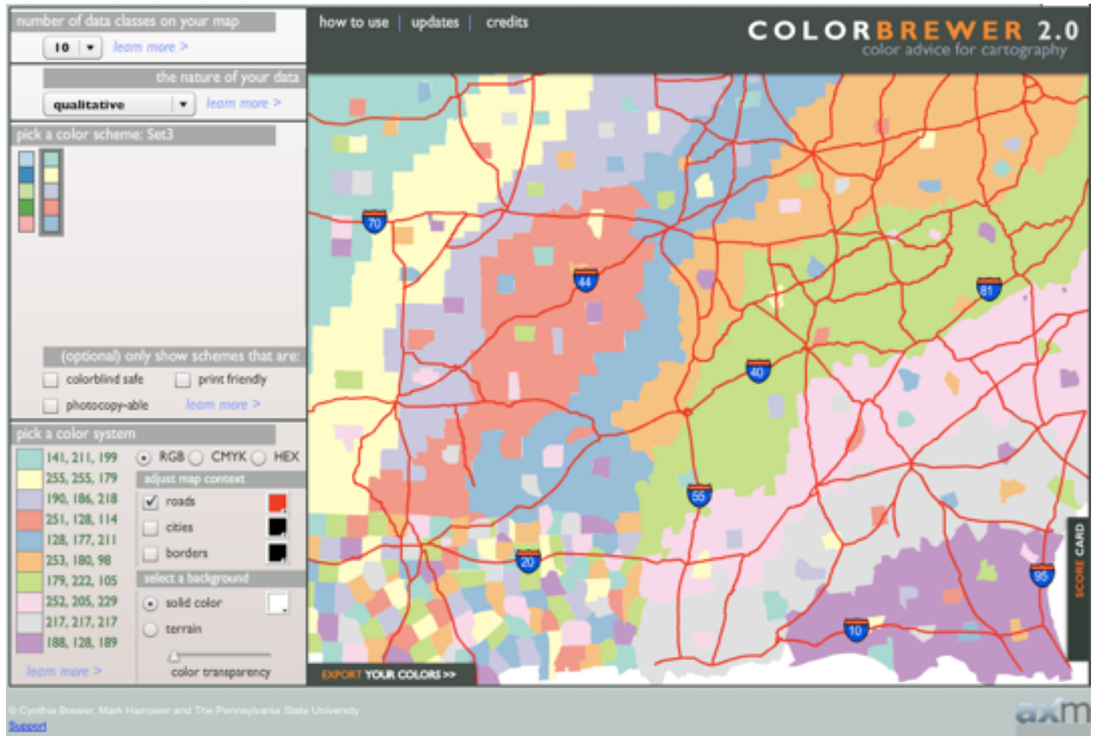
- glyphs: composite objects
  - internal structure with multiple marks
- alternative to color coding
  - or coding with any single channel

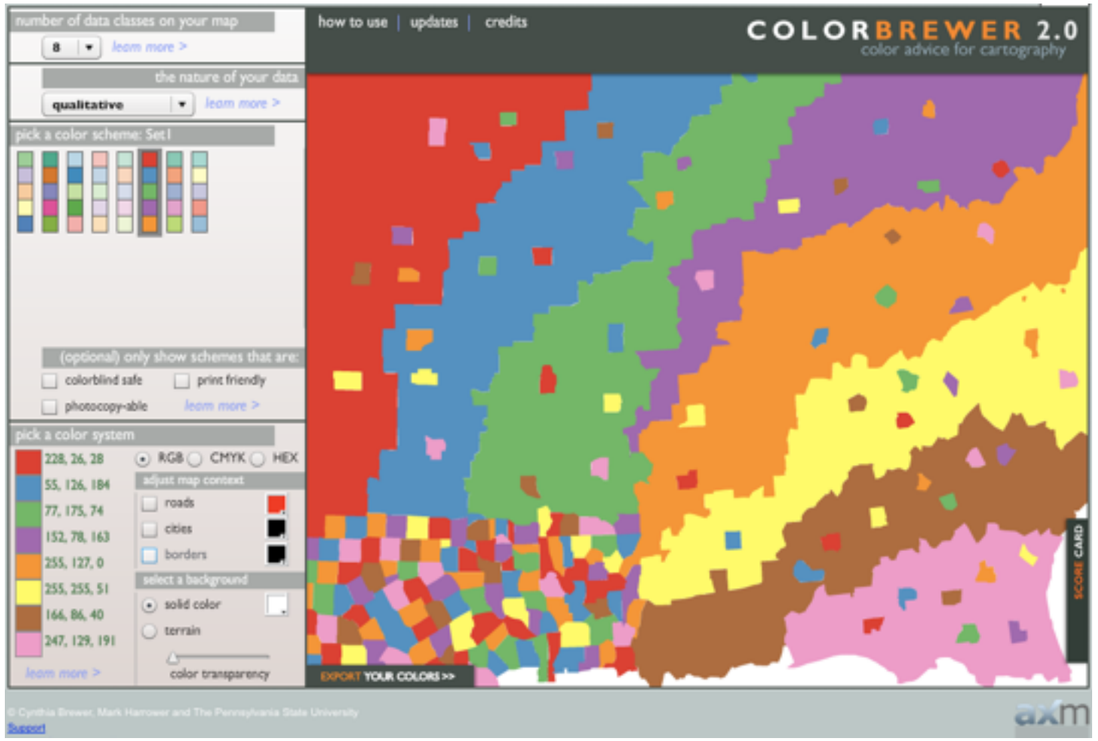


[Fig 5. Taxonomy-Based Glyph Design - with a Case Study on Visualizing Workflows of Biological Experiments. Maguire, Rocca-Serra, Sansone, Davies, and Chen. IEEE Trans. Visualization and Computer Graphics 18:12:2603-2612 (Proc. InfoVis 12).]

ColorBrewer

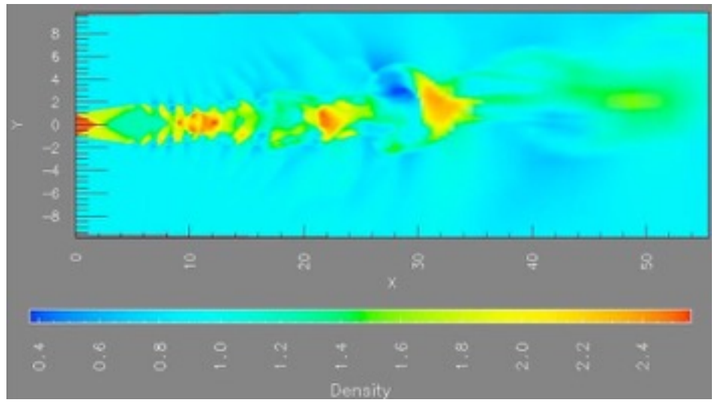
- http://www.colorbrewer2.org
- saturation and area example: size affects salience!



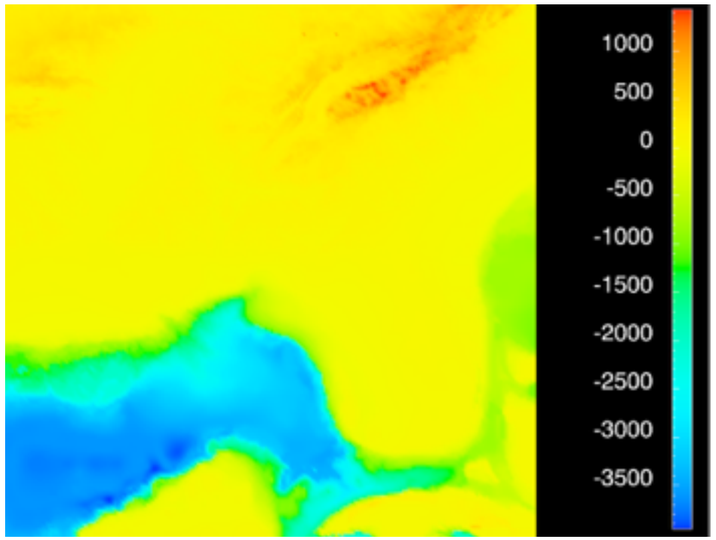


Ordered color: Rainbow is poor default

- problems
  - perceptually unordered
  - perceptually nonlinear
- benefits
  - fine-grained structure visible and nameable



[A Rule-based Tool for Assisting Colormap Selection. Bergman,. Rogowitz, and. Treinish. Proc. IEEE Visualization (Vis), pp. 118–125, 1995.]



[Why Should Engineers Be Worried About Color? Treinish and Rogowitz 1998. http://www.research.ibm.com/people/l/lloydt/color/color.HTM]

[Transfer Functions in Direct Volume Rendering: Design, Interface, Interaction. Kindlmann. SIGGRAPH 2002 Course Notes]

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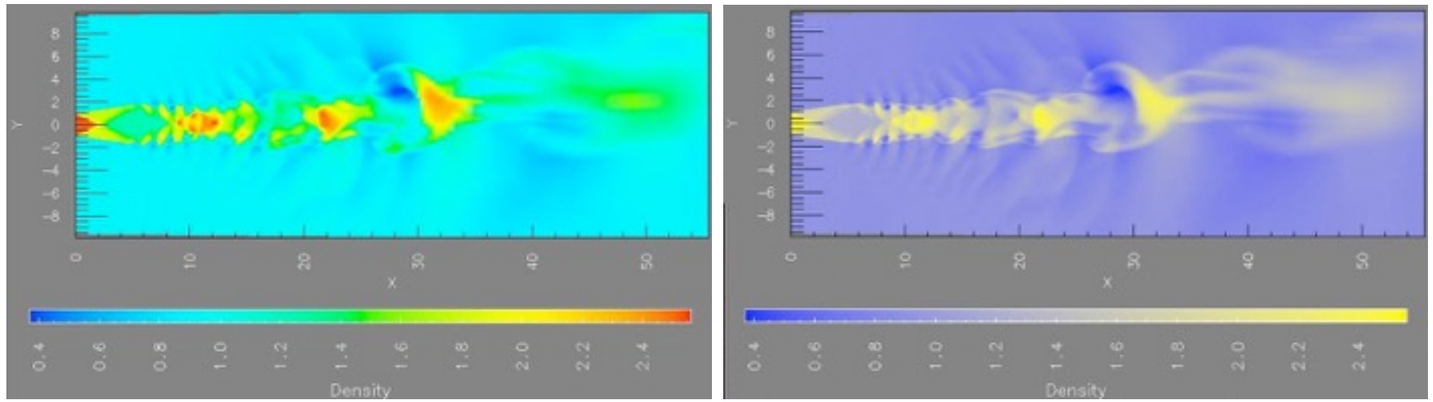
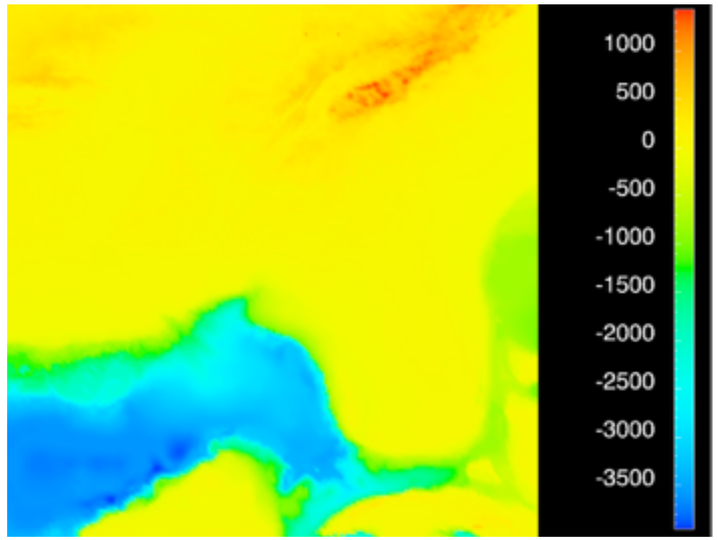
  - fine-grained structure visible and nameable
- alternatives
  - large-scale structure: fewer hues



[A Rule-based Tool for Assisting Colormap Selection. Bergman,. Rogowitz, and. Treinish. Proc. IEEE Visualization (Vis), pp. 118–125, 1995.]



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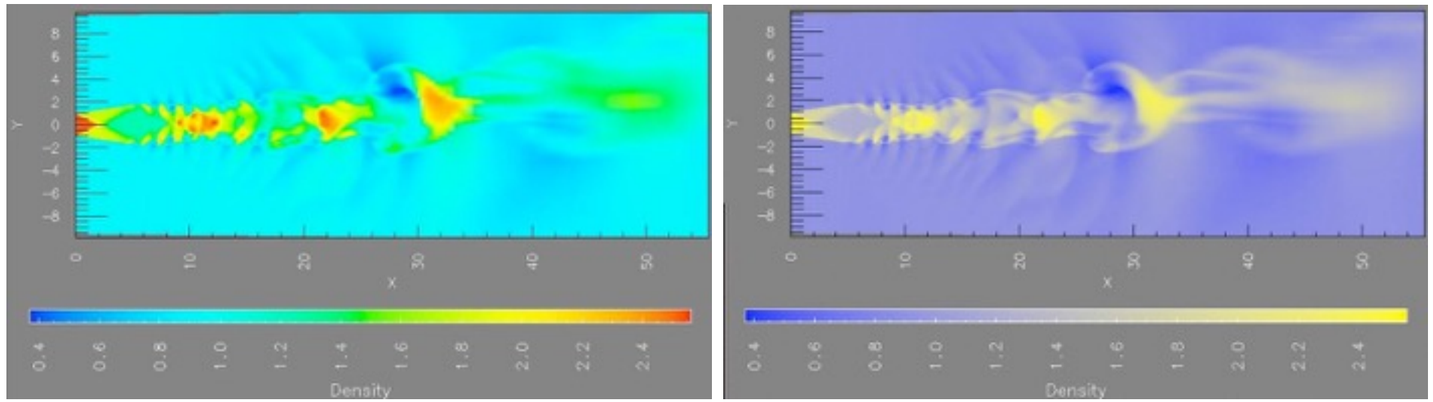
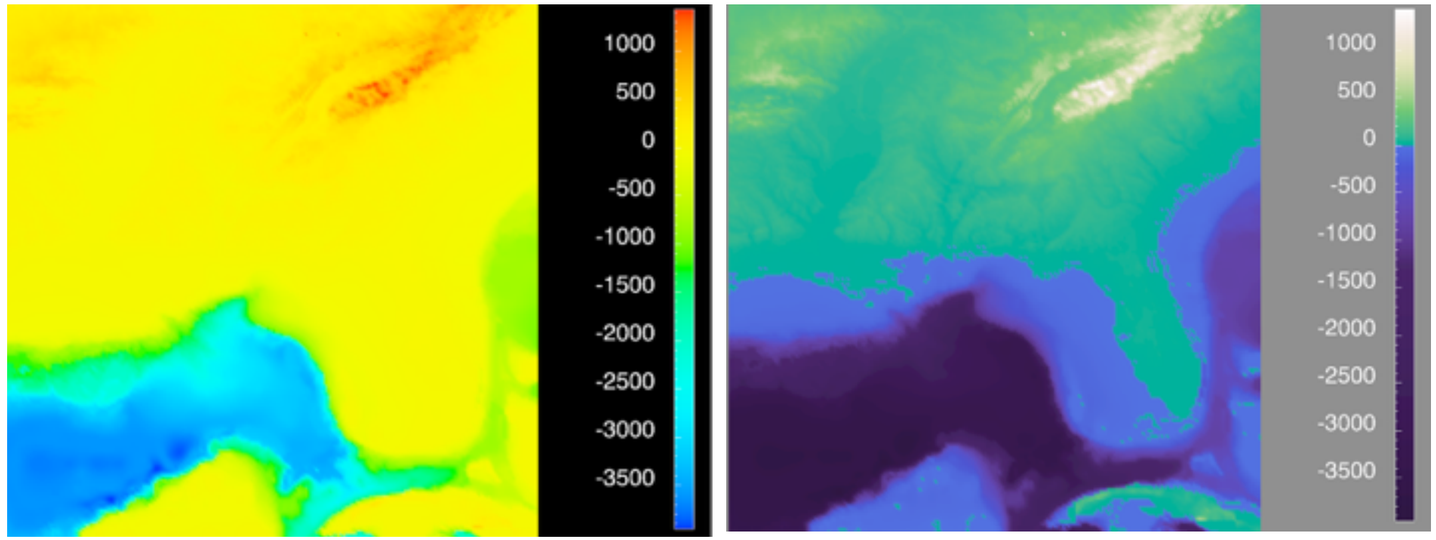
- alternatives
  - large-scale structure: fewer hues
  - fine structure: multiple hues with monotonically increasing luminance [eg viridis R/python]



[A Rule-based Tool for Assisting Colormap Selection. Bergman,. Rogowitz, and. Treinish. Proc. IEEE Visualization (Vis), pp. 118–125, 1995.]

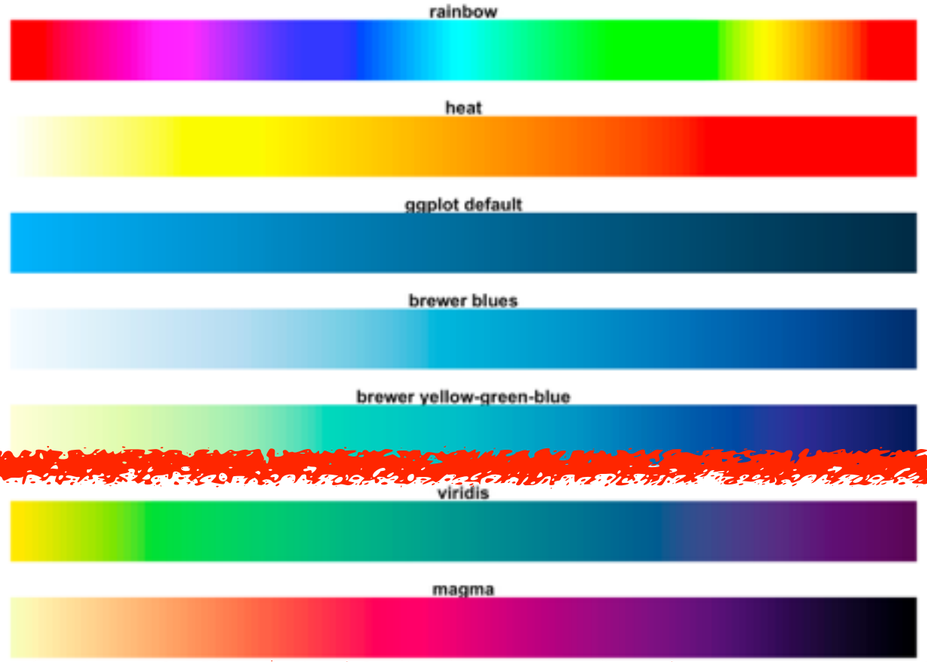


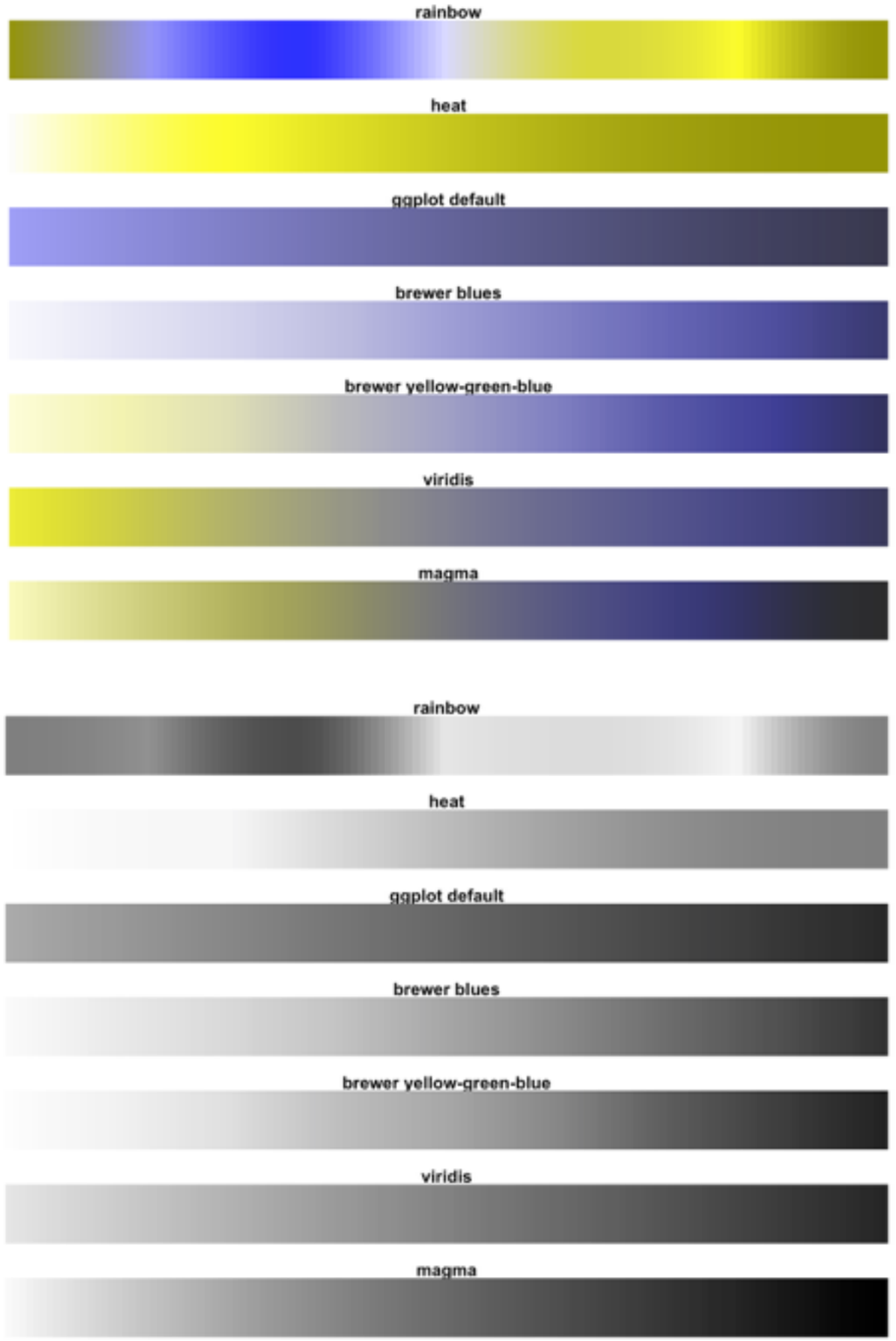
[Why Should Engineers Be Worried About Color? Treinish and Rogowitz 1998. http://www.research.ibm.com/people/l/lloydt/color/color.HTM]

[Transfer Functions in Direct Volume Rendering: Design, Interface, Interaction. Kindlmann. SIGGRAPH 2002 Course Notes]

Viridis

- colorful, perceptually uniform, colorblind-safe, monotonically increasing luminance





https://cran.r-project.org/web/packages/viridis/vignettes/intro-to-viridis.html

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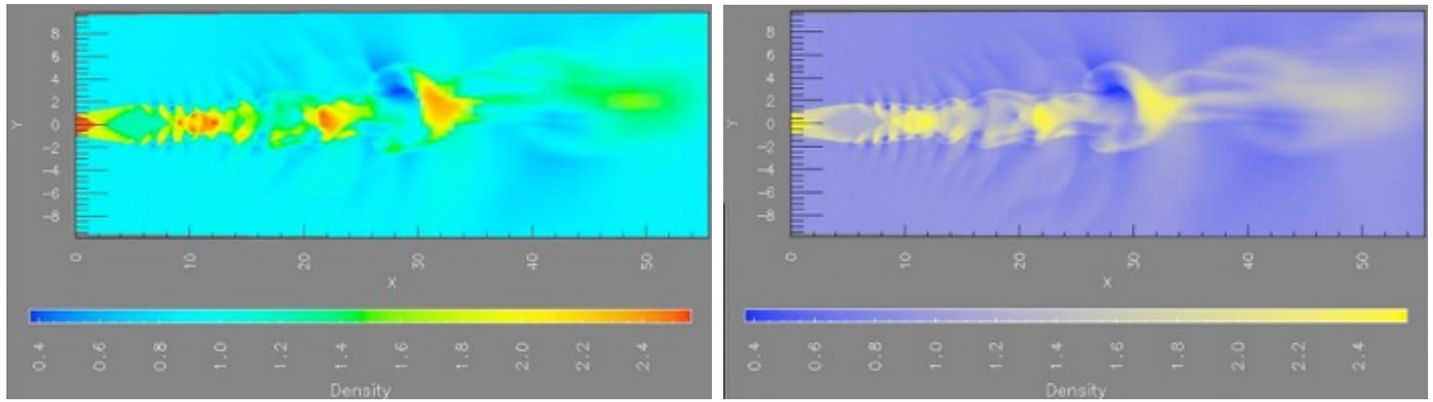
- alternatives
  - large-scale structure: fewer hues
  - fine structure: multiple hues with monotonically increasing luminance [eg viridis R/python]
  - segmented rainbows for binned or categorical



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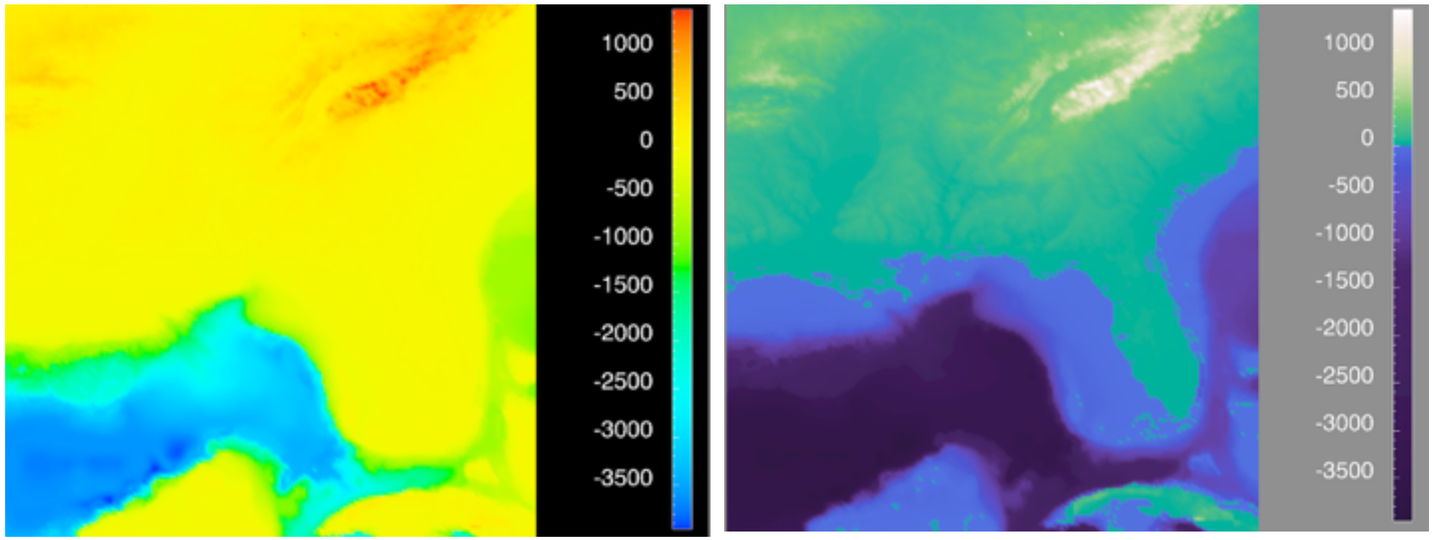

[Why Should Engineers Be Worried About Color? Treinish and Rogowitz 1998. http://www.research.ibm.com/people/l/lloydt/color/color.HTM]

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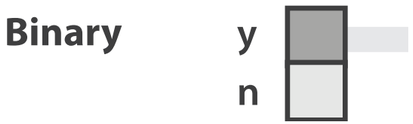
Colormaps

- Categorical

- Ordered
  - *Sequential*
  - *Diverging*



after [Color Use Guidelines for Mapping and Visualization. Brewer, 1994. http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html]

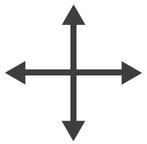
Colormaps

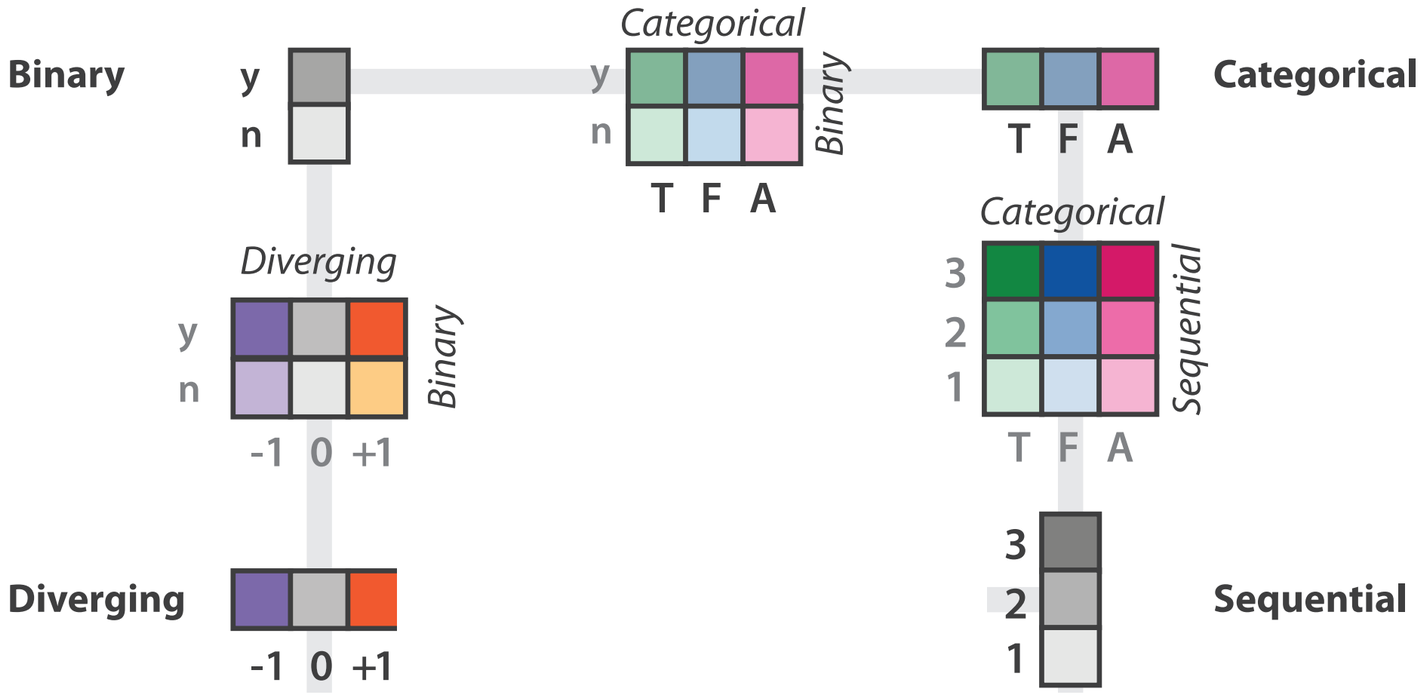
- Categorical

- Ordered
  - *Sequential*

  - *Diverging*

- Bivariate





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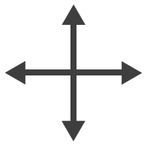
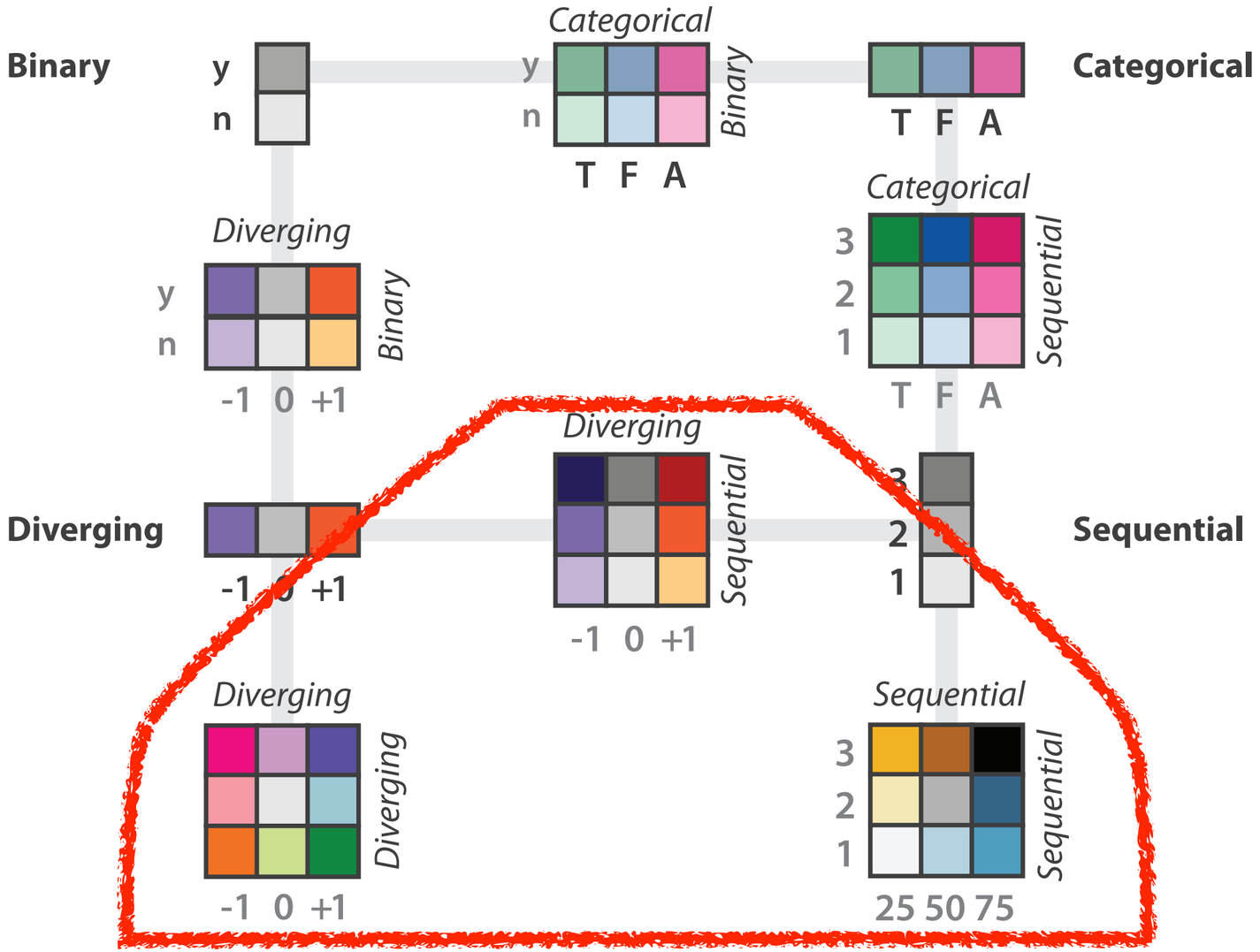


use with care!



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Colormaps

- Categorical
- Ordered
  - *Sequential*
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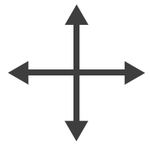
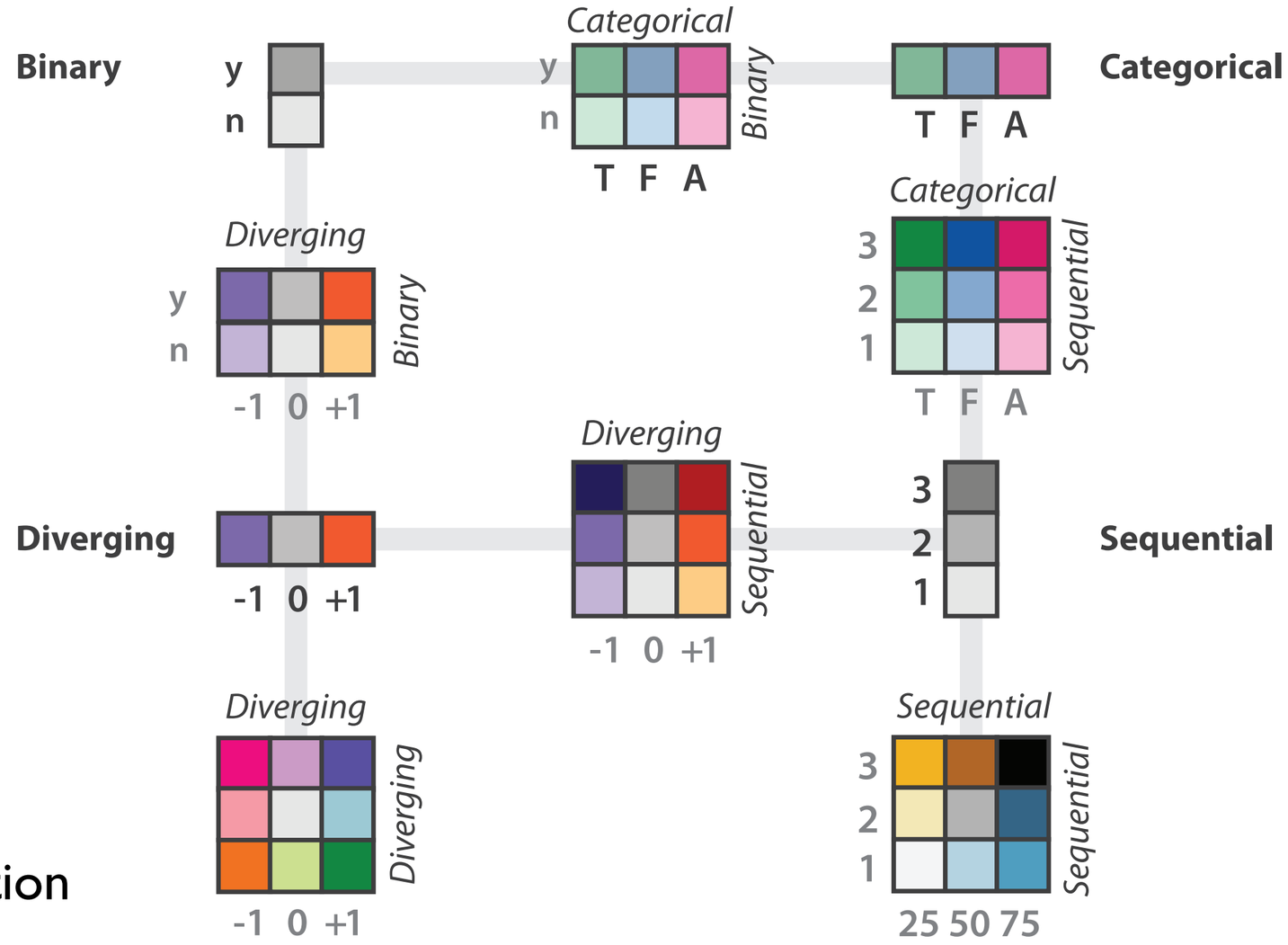


- color channel interactions
  - size heavily affects salience
    - small regions need high saturation
    - large need low saturation
  - saturation & luminance: 3-4 bins max
    - also not separable from transparency



after [Color Use Guidelines for Mapping and Visualization. Brewer, 1994. http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html]

Map other channels

- size
  - length accurate, 2D area ok, 3D volume poor
- angle
  - nonlinear accuracy
    - horizontal, vertical, exact diagonal
- shape
  - complex combination of lower-level primitives
  - many bins
- motion
  - highly separable against static
    - binary: great for highlighting
  - use with care to avoid irritation

➔ **Size, Angle, Curvature, ...**

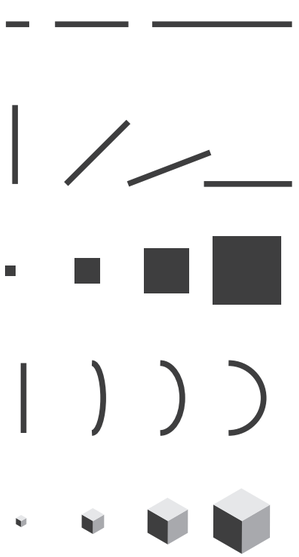
➔ Length

➔ Angle

➔ Area

➔ Curvature

➔ Volume



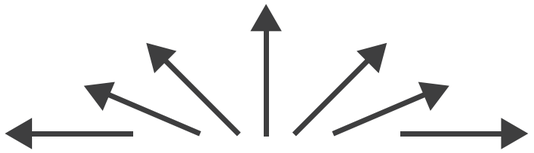
➔ **Shape**

➔ **Motion**

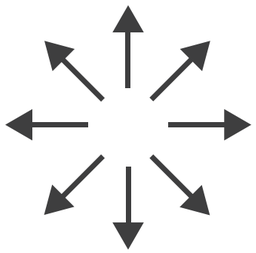
➔ Motion
Direction, Rate, Frequency, ...

Angle

Sequential ordered
line mark or arrow glyph



Diverging ordered
arrow glyph



Cyclic ordered
arrow glyph

Further reading

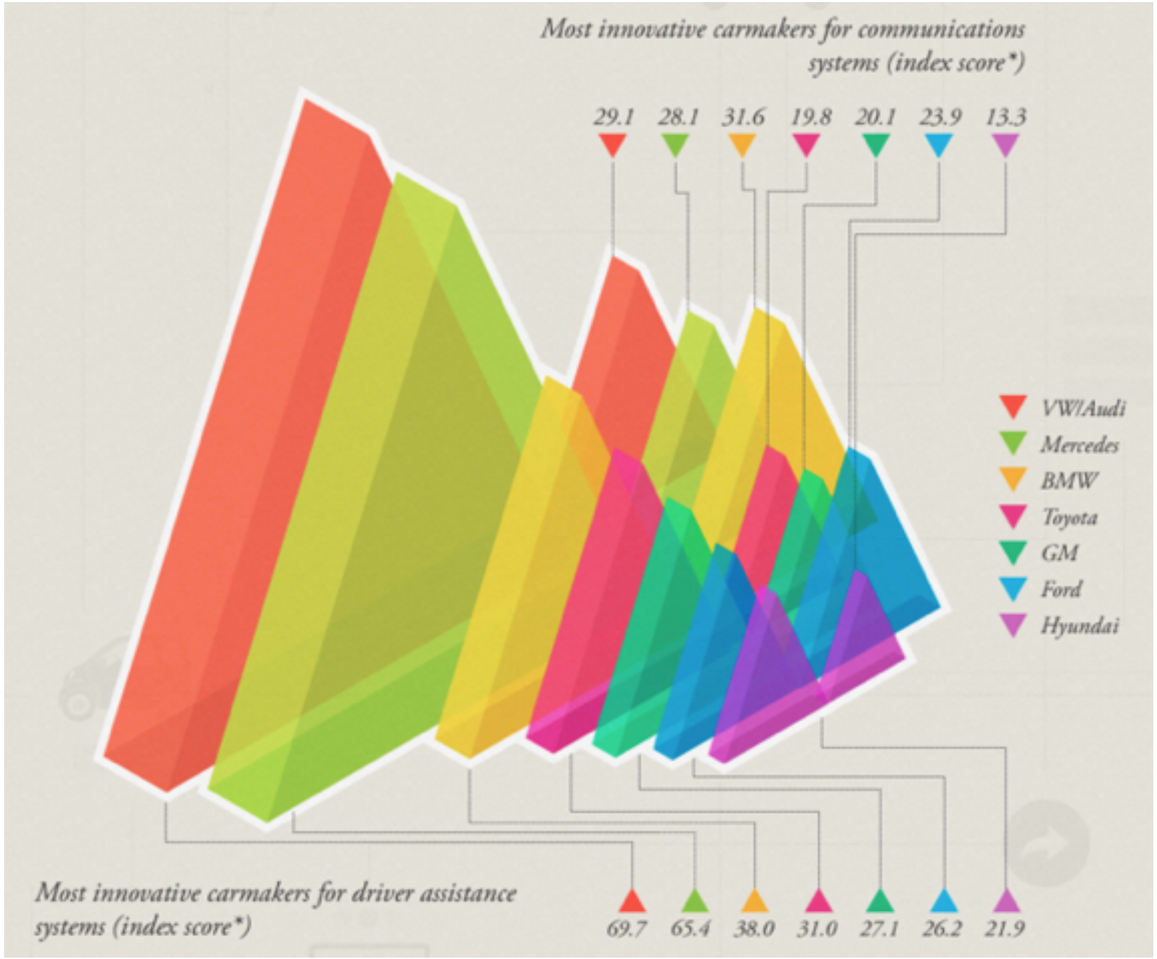
- Visualization Analysis and Design. Munzner. AK Peters Visualization Series, CRC Press, 2014
  - *Chap 10: Map Color and Other Channels*
- ColorBrewer, Brewer.
  - http://www.colorbrewer2.org
- *Color In Information Display*. Stone. IEEE Vis Course Notes, 2006.
  - http://www.stonesc.com/Vis06
- A Field Guide to Digital Color. Stone. AK Peters, 2003.
- *Rainbow Color Map (Still) Considered Harmful.* Borland and Taylor. IEEE Computer Graphics and Applications 27:2 (2007), 14–17.
- Visual Thinking for Design. Ware. Morgan Kaufmann, 2008.
- Information Visualization: Perception for Design, 3rd edition. Ware. Morgan Kaufmann / Academic Press, 2004.
- https://cran.r-project.org/web/packages/viridis/vignettes/intro-to-viridis.html

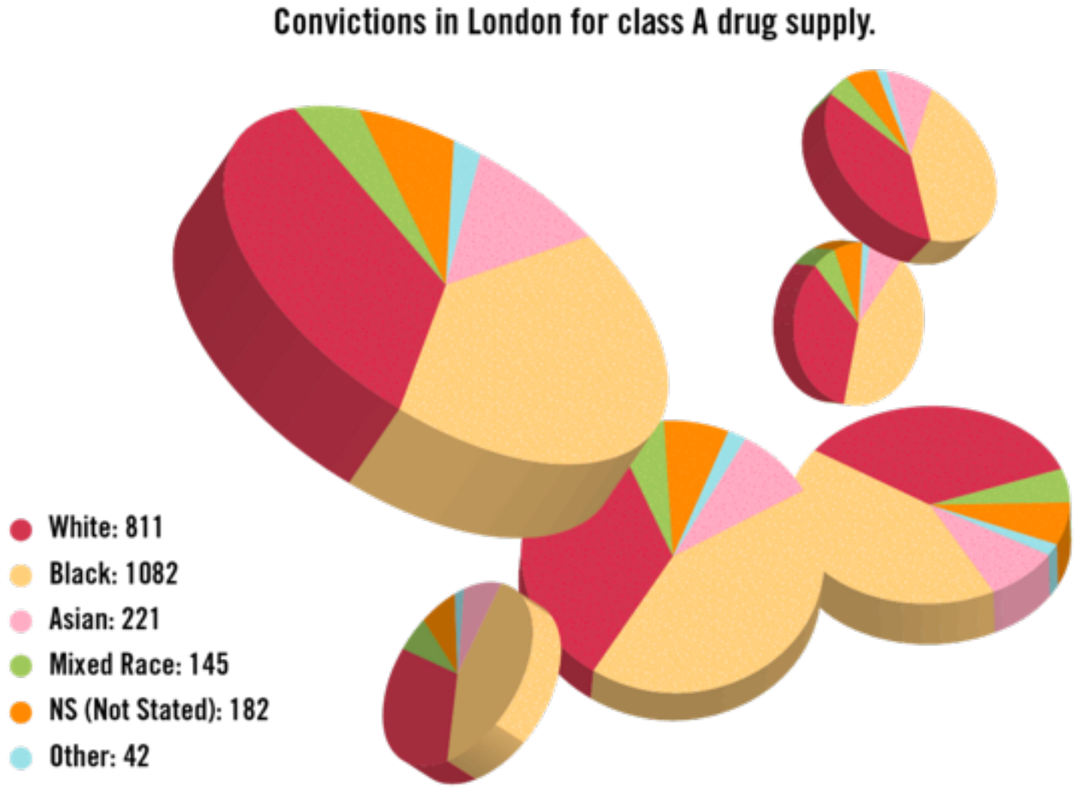
Rules of Thumb

Rules of Thumb

- No unjustified 3D
  - Power of the plane
  - Disparity of depth
  - Occlusion hides information
  - Perspective distortion dangers
  - Tilted text isn't legible
- No unjustified 2D
- Eyes beat memory
- Resolution over immersion
- Overview first, zoom and filter, details on demand
- Responsiveness is required
- Function first, form next

Unjustified 3D all too common, in the news and elsewhere





http://viz.wtf/post/137826497077/eye-popping-3d-triangles

http://viz.wtf/post/139002022202/designer-drugs-ht-ducqn

Depth vs power of the plane

- high-ranked spatial position channels: **planar** spatial position
  - not depth!

Magnitude Channels: Ordered Attributes

Position on common scale

Position on unaligned scale

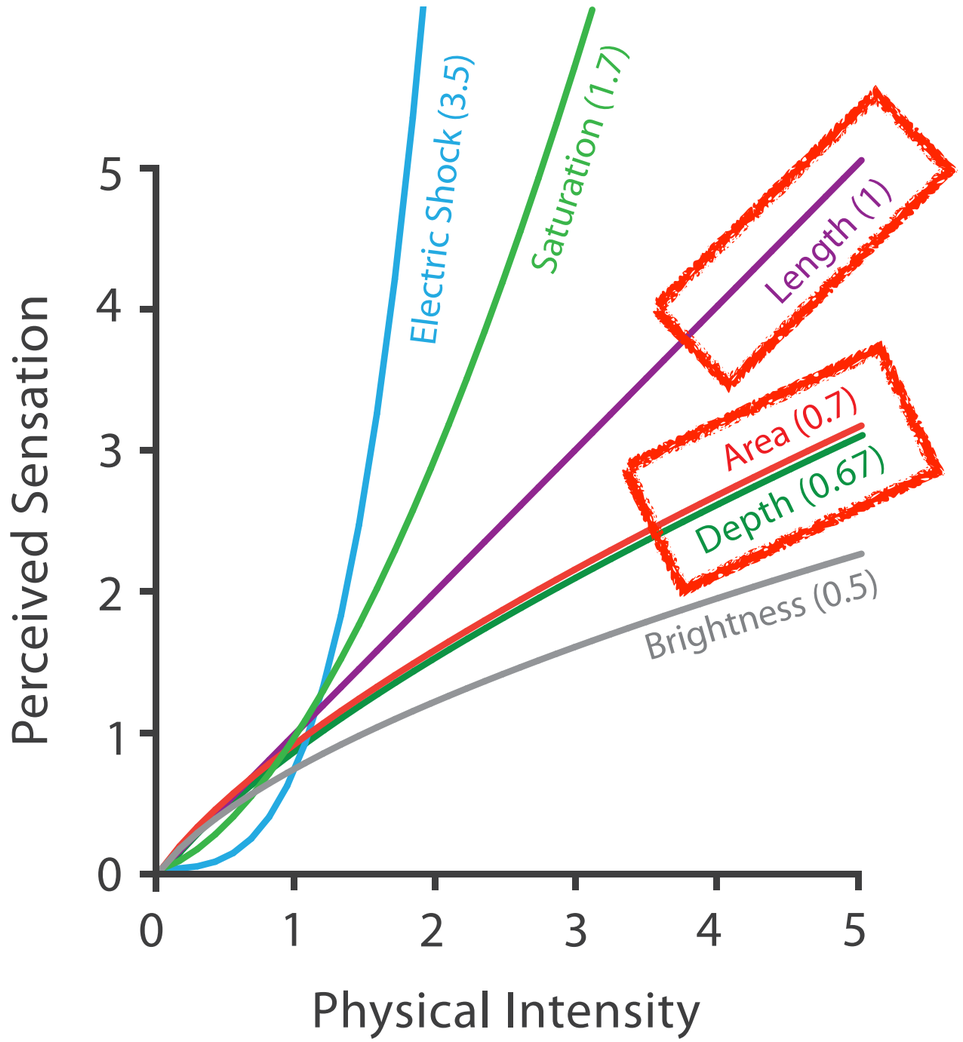
Length (1D size)

Tilt/angle

Area (2D size)

Depth (3D position)

Steven's Psychophysical Power Law: $S = I^N$



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Tilt/angle

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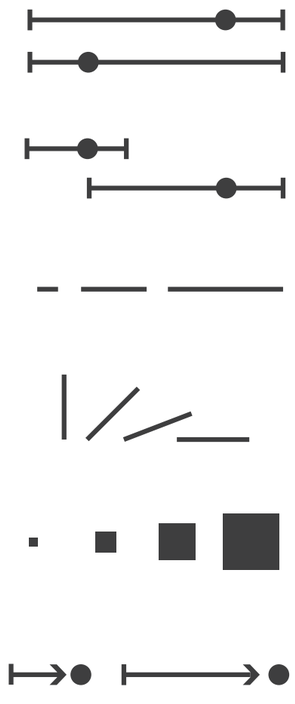

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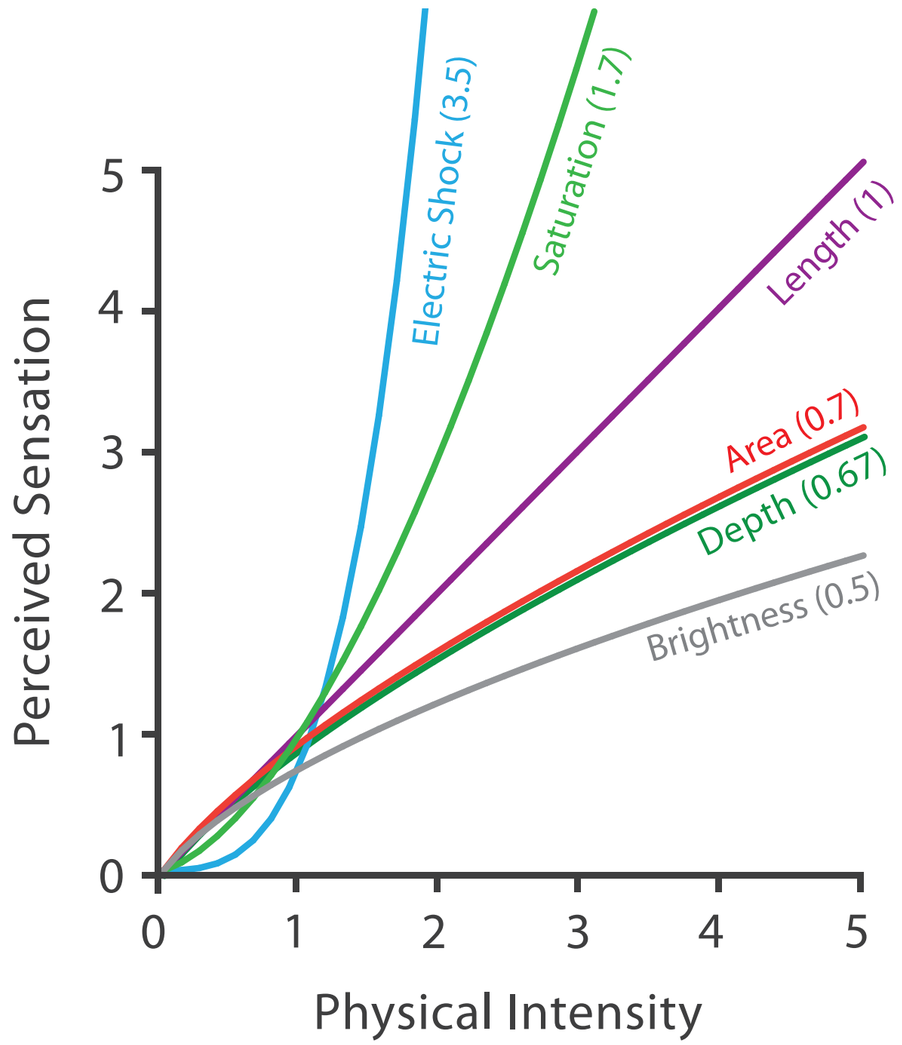
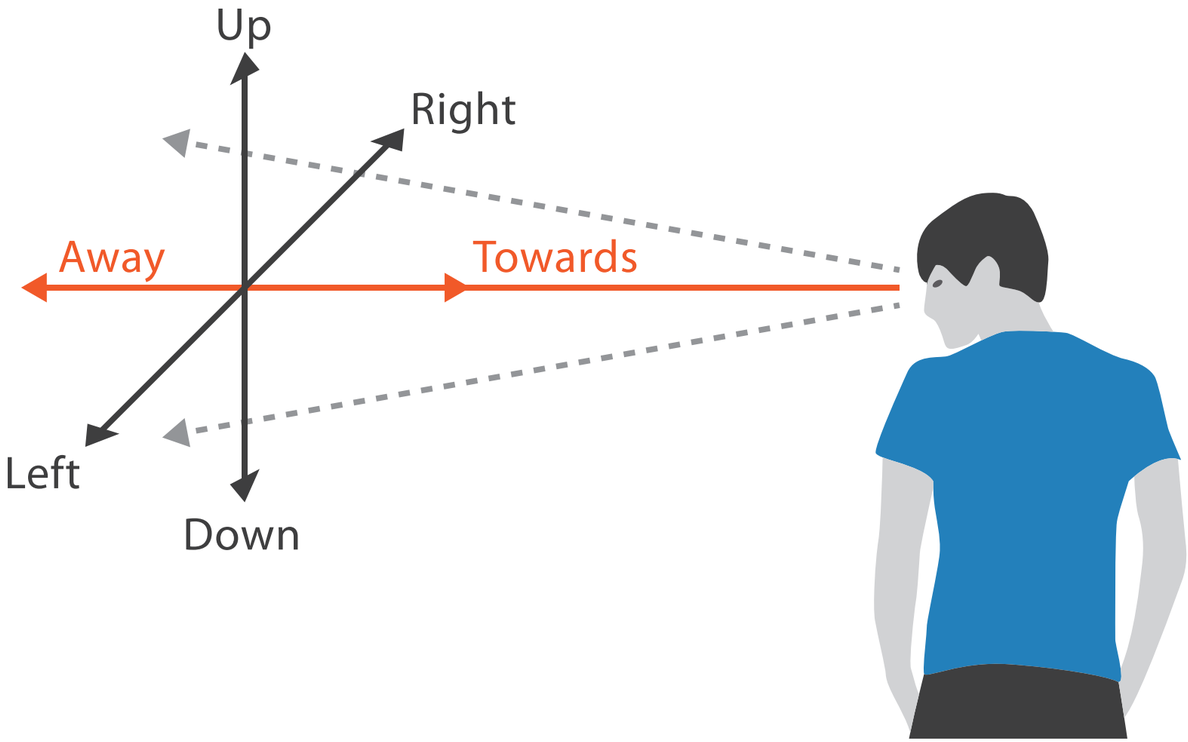
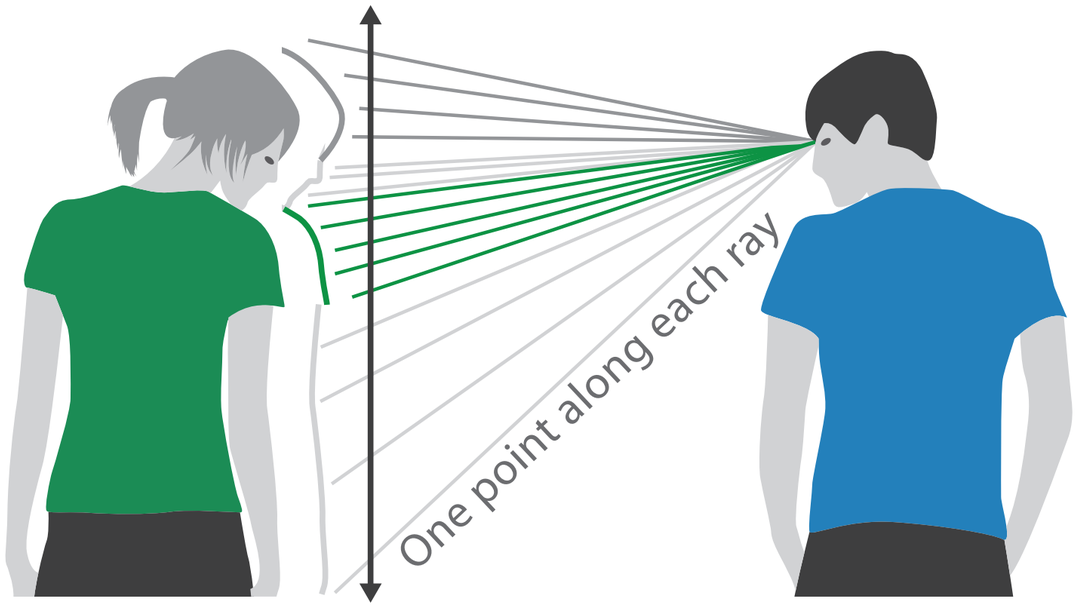


No unjustified 3D: Danger of depth

- we don't really live in 3D: we ***see*** in 2.05D
  - acquire more info on image plane quickly from eye movements
  - acquire more info for depth slower, from head/body motion



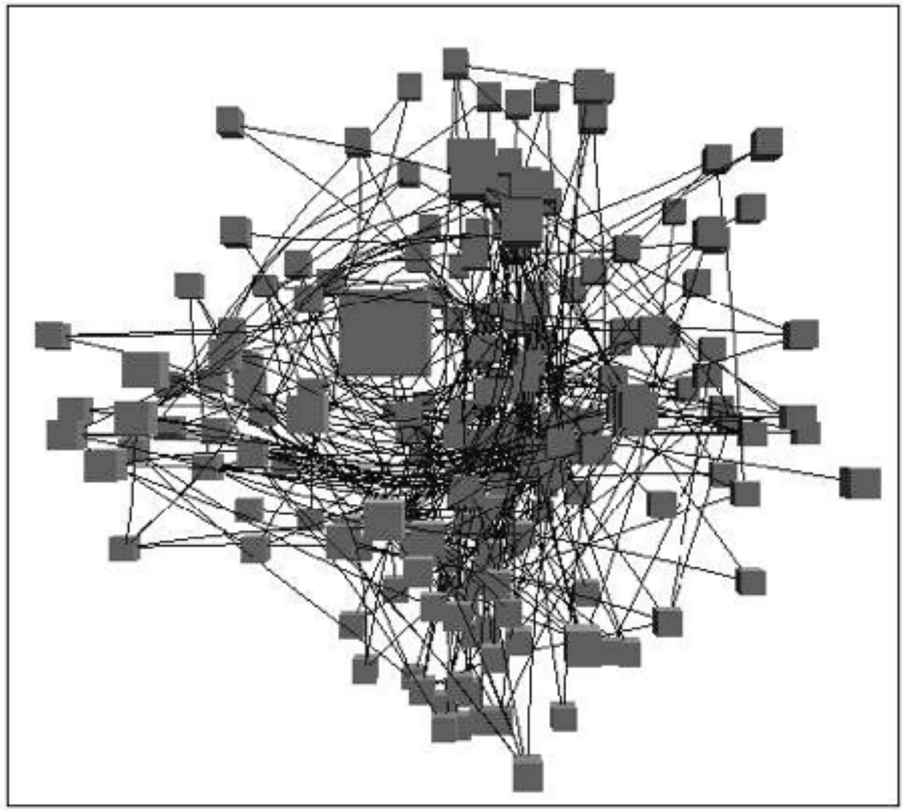
Thousands of points up/down and left/right



We can only see the outside shell of the world

Occlusion hides information

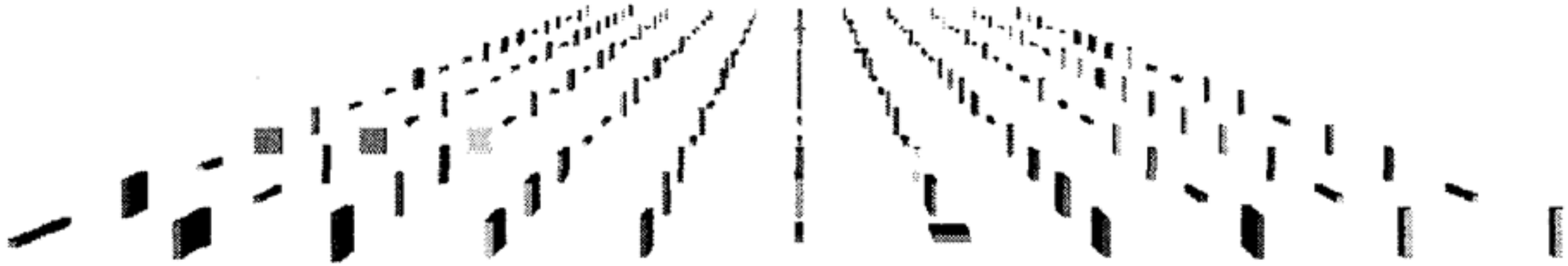
- occlusion
- interaction can resolve, but at cost of time and cognitive load



[Distortion Viewing Techniques for 3D Data. Carpendale et al. InfoVis1996.]

Perspective distortion loses information

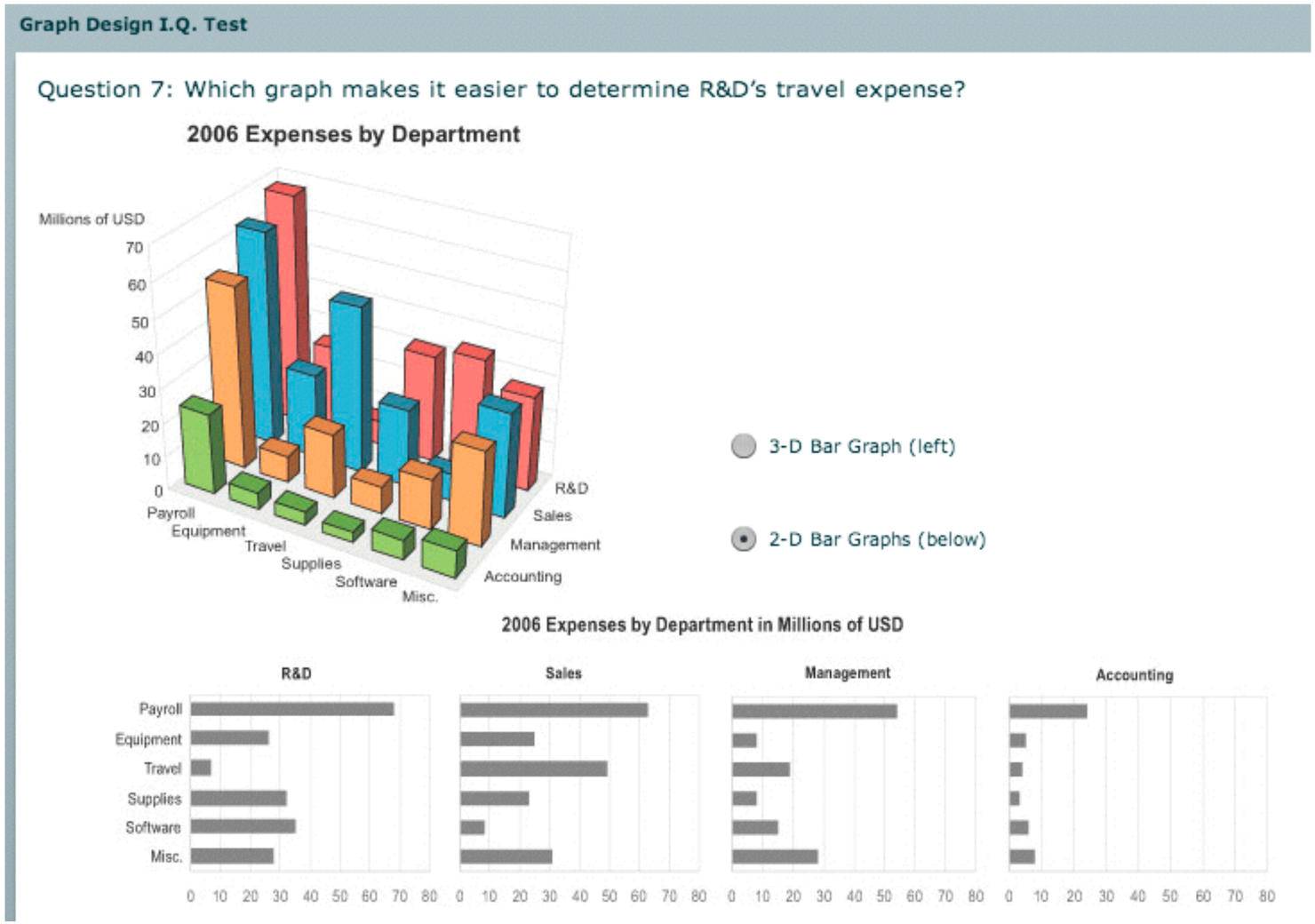
- perspective distortion
  - interferes with all size channel encodings
  - power of the plane is lost!



[Visualizing the Results of Multimedia Web Search Engines. Mukherjea, Hirata, and Hara. InfoVis 96]

3D vs 2D bar charts

- 3D bars very difficult to justify!
  - perspective distortion
  - occlusion
- faceting into 2D almost always better choice



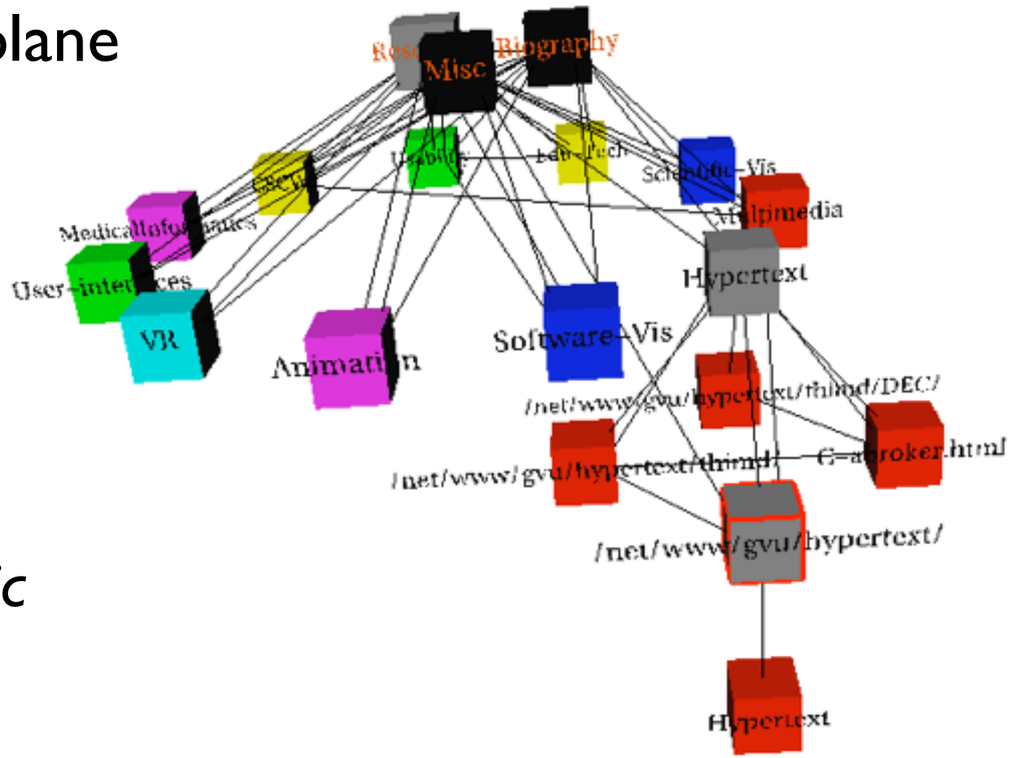
[http://perceptualedge.com/files/GraphDesignIQ.html]

Tilted text isn't legible

- text legibility
  - –far worse when tilted from image plane

- further reading

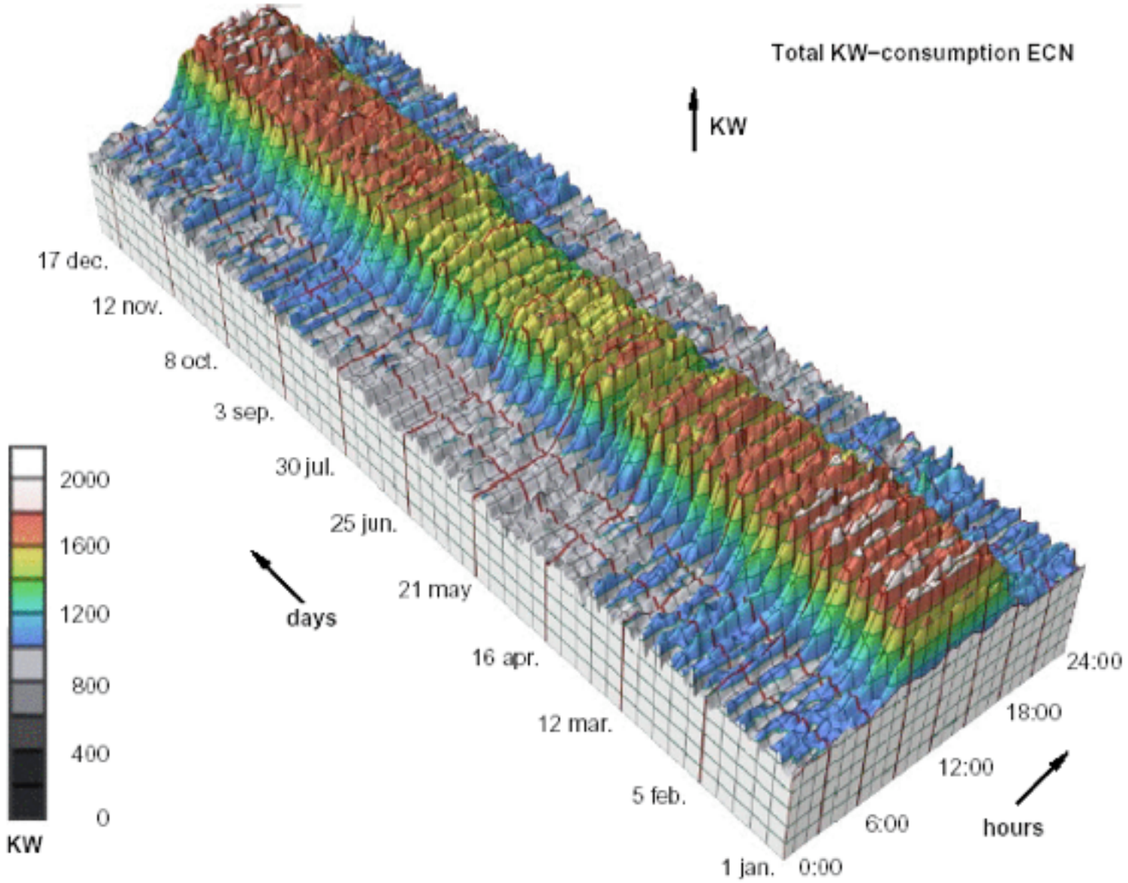
  [Exploring and Reducing the Effects of Orientation on Text Readability in Volumetric Displays.
  Grossman et al. CHI 2007]



[*Visualizing the World-Wide Web with the Navigational View Builder. Mukherjea and Foley. Computer Networks and ISDN Systems, 1995.]*

No unjustified 3D example: Time-series data

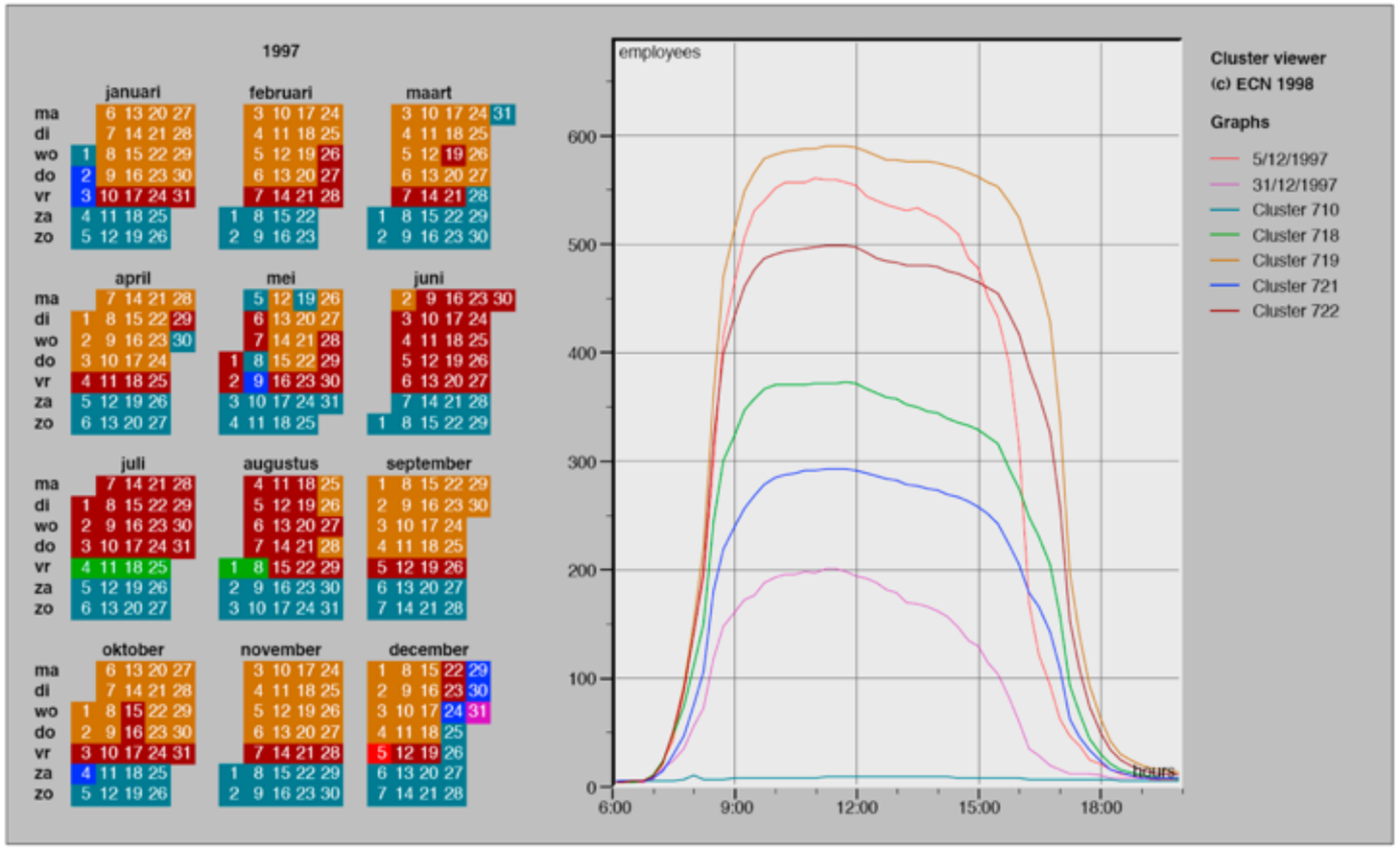
- extruded curves: detailed comparisons impossible



[Cluster and Calendar based Visualization of Time Series Data. van Wijk and van Selow, Proc. InfoVis 99.]

No unjustified 3D example: Transform for new data abstraction

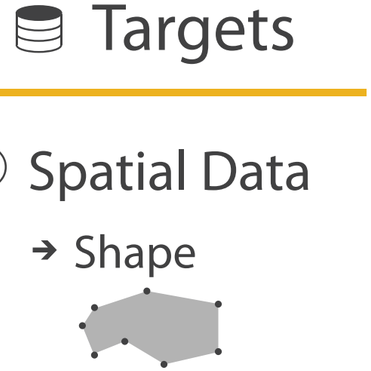
- derived data: cluster hierarchy
- juxtapose multiple views: calendar, superimposed 2D curves

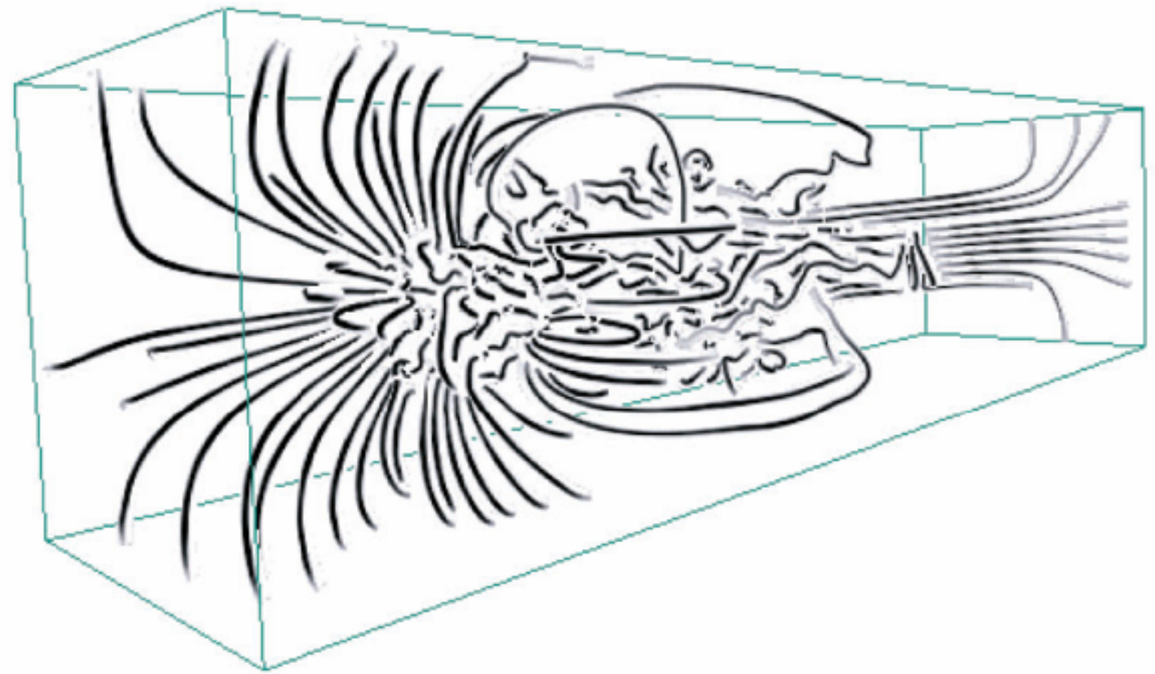


[Cluster and Calendar based Visualization of Time Series Data. van Wijk and van Selow, Proc. InfoVis 99.]

Justified 3D: shape perception

- benefits outweigh costs when task is shape perception for 3D spatial data
  - interactive navigation supports synthesis across many viewpoints

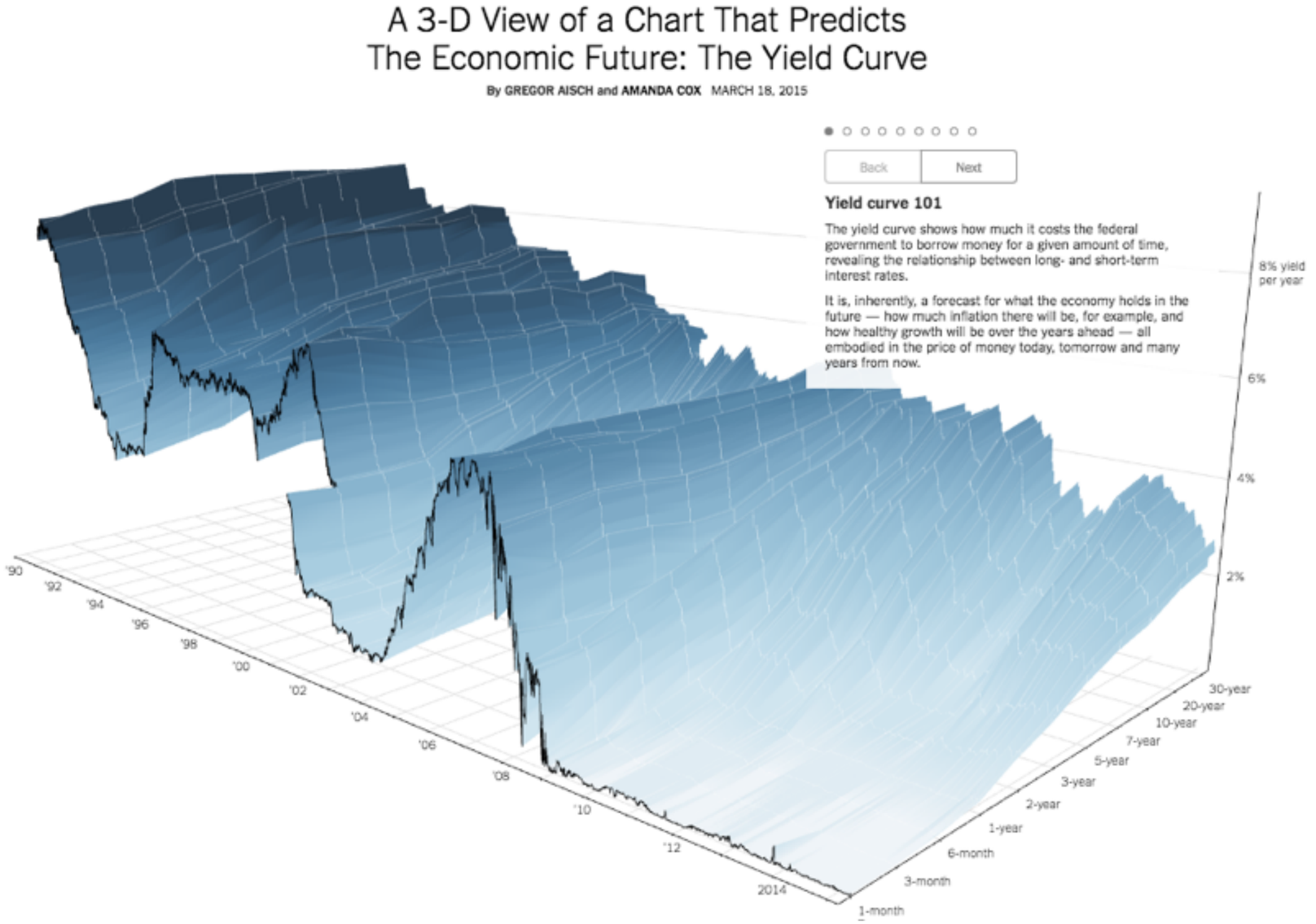




[Image-Based Streamline Generation and Rendering. Li and Shen. IEEE Trans. Visualization and Computer Graphics (TVCG) 13:3 (2007), 630–640.]

Justified 3D: Economic growth curve

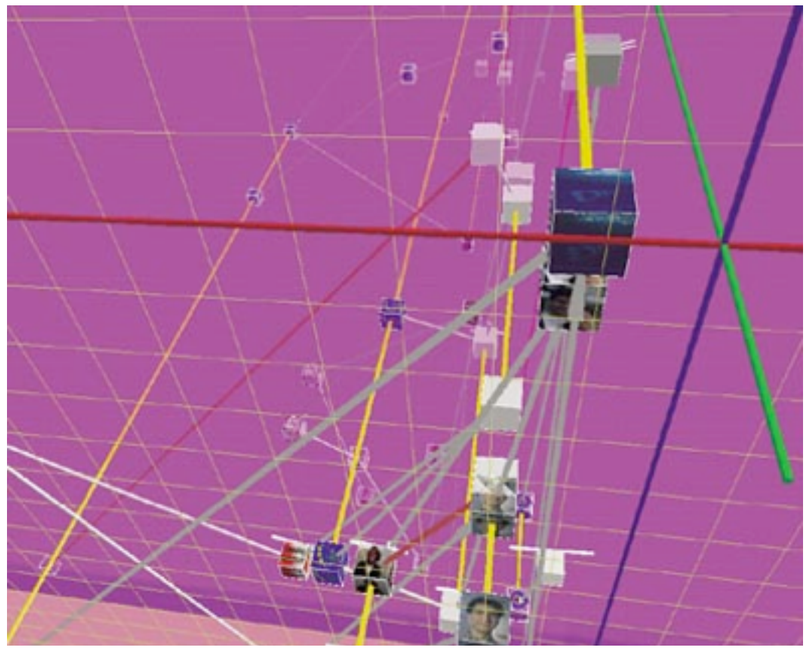
- constrained navigation steps through carefully designed viewpoints



http://www.nytimes.com/interactive/2015/03/19/upshot/3d-yield-curve-economic-growth.html

No unjustified 3D

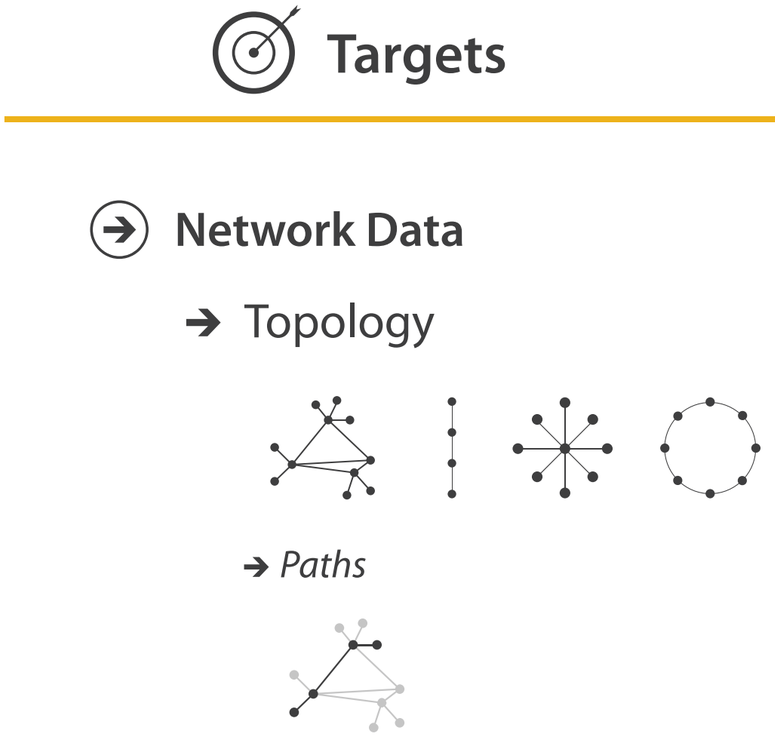
- 3D legitimate for true 3D spatial data
- 3D needs very careful justification for abstract data
  - enthusiasm in 1990s, but now skepticism
  - be especially careful with 3D for point clouds or networks



[WEBPATH-a three dimensional Web history. Frecon and Smith. Proc. InfoVis 1999]

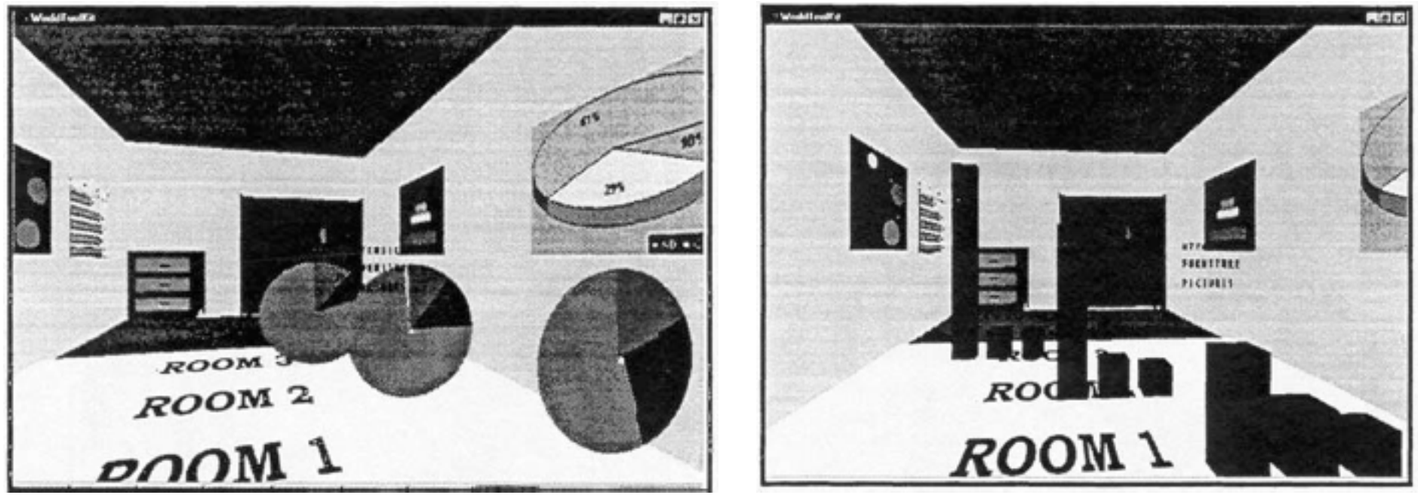
No unjustified 2D

- consider whether network data requires 2D spatial layout
  - especially if reading text is central to task!
  - arranging as network means lower information density and harder label lookup compared to text lists
- benefits outweigh costs when topological structure/context important for task
  - be especially careful for search results, document collections, ontologies



Resolution beats immersion

- immersion typically not helpful for abstract data
  - do not need sense of presence or stereoscopic 3D
  - desktop also better for workflow integration
- resolution much more important: pixels are the scarcest resource
- virtual reality for abstract data difficult to justify thus far
  - but stay tuned with second wave



[Development of an information visualization tool using virtual reality. Kirner and Martins. Proc. Symp. Applied Computing 2000]

Function first, form next

- start with focus on functionality
  - possible to improve aesthetics later on, as refinement
  - if no expertise in-house, find good graphic designer to work with
  - aesthetics do matter: another level of function
    - visual hierarchy, alignment, flow
    - Gestalt principles in action

- dangerous to start with aesthetics
  - usually impossible to add function retroactively

[The Non-Designer's Design Book. Robin Williams. 3rd edition. Peachpit Press, 2008.]

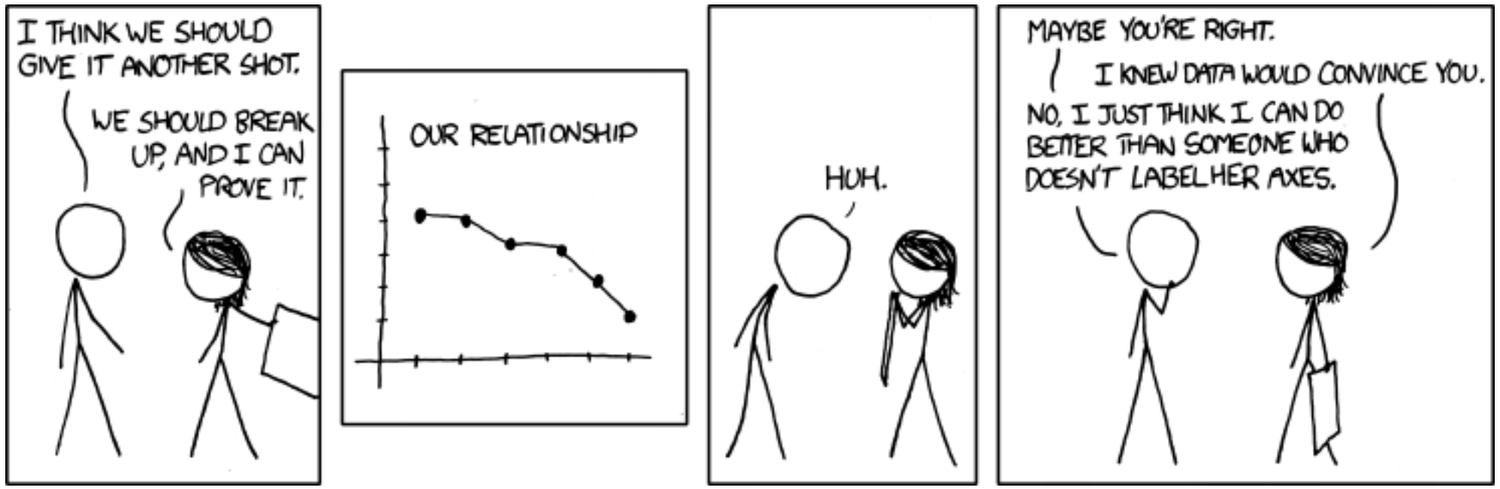
Form: Basic graphic design principles

- proximity
  - do group related items together
  - avoid equal whitespace between unrelated
- alignment
  - do find/make strong line, stick to it
  - avoid automatic centering
- repetition
  - do unify by pushing existing consistencies
- contrast
  - if not identical, then very different
  - avoid similar

- buy now and read cover to cover - very practical, worth your time, fast read!
  The Non-Designer's Design Book, 4th ed. Robin Williams, Peachpit Press, 2015.

Best practices: Labelling

- make visualizations as self-documenting as possible
  - meaningful & useful title, labels, legends
    - axes and panes/subwindows should have labels
      - and axes should have good mix/max boundary tick marks
    - everything that's plotted should have a legend
      - and own header/labels if not redundant with main title
    - use reasonable numerical format
      - avoid scientific notation in most cases



[https://xkcd.com/833/]

Further reading

- Visualization Analysis and Design. Tamara Munzner. CRC Press, 2014.
  - *Chap 6: Rules of Thumb*

- Designing with the Mind in Mind: Simple Guide to Understanding User Interface Design Rules. Jeff Johnson. Morgan Kaufmann, 2010.
  - *Chap 12: We Have Time Requirements*

- The Non-Designer's Design Book. 3rd edition. Robin Williams. Peachpit Press, 2008.

Usability Testing

Guerilla/Discount Usability

- grab a few people and watch them use your interface
  - even 3-5 gives substantial coverage of major usability problems
  - agile/lean qualitative, vs formal quantitative user studies
    - goal is not statistical significance!
- think-aloud protocol
  - contextual inquiry (conversations back and forth) vs fly on the wall (you're silent)
- normally: generate tasks, scenarios
  - shortcut in next week's lab

Further reading

- 7 Step Guide to Guerrilla Usability Testing, Markus Piper
  - https://userbrain.net/blog/7-step-guide-guerrilla-usability-testing-diy-usability-testing-method
- The Art of Guerrilla Usability Testing, David Peter Simon
  - http://www.uxbooth.com/articles/the-art-of-guerrilla-usability-testing/
- Discount Usability: 20 Years, Jakob Nielsen
  - https://www.nngroup.com/articles/discount-usability-20-years/
- Interaction Design: Beyond Human-Computer Interaction
  - Preece, Sharp, Rogers. Wiley, 4th edition, 2015.
- About Face: The Essentials of Interaction Design
  - Cooper, Reimann, Cronin, Noessel. Wiley, 4th edition, 2014.
- Task-Centered User Interface Design. Lewis & Rieman, 1994
  - http://hcibib.org/tcuid/
- Designing with the Mind in Mind. Jeff Johnson. Morgan Kaufmann, 2nd, 2014.