CSE 442 - Data Visualization

Graphical Perception

Jeffrey Heer  University of Washington
Design Principles  [Mackinlay 86]

Expressiveness
A set of facts is expressible in a visual language if the sentences (i.e. the visualizations) in the language express all the facts in the set of data, and only the facts in the data.

Effectiveness
A visualization is more effective than another visualization if the information conveyed by one visualization is more readily perceived than the information in the other visualization.
Design Principles *Translated*

Tell the truth and nothing but the truth
(don’t lie, and don’t lie by omission)

Use encodings that people decode better
(where better = faster and/or more accurate)
## Effectiveness Rankings

[Mackinlay 86]

<table>
<thead>
<tr>
<th>QUANTITATIVE</th>
<th>ORDINAL</th>
<th>NOMINAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>Position</td>
<td>Position</td>
</tr>
<tr>
<td>Length</td>
<td>Density (Value)</td>
<td>Color Hue</td>
</tr>
<tr>
<td>Angle</td>
<td>Color Sat</td>
<td>Texture</td>
</tr>
<tr>
<td>Slope</td>
<td>Color Hue</td>
<td>Connection</td>
</tr>
<tr>
<td>Area (Size)</td>
<td>Texture</td>
<td>Containment</td>
</tr>
<tr>
<td>Volume</td>
<td>Connection</td>
<td>Density (Value)</td>
</tr>
<tr>
<td>Density (Value)</td>
<td>Containment</td>
<td>Color Sat</td>
</tr>
<tr>
<td>Color Sat</td>
<td>Length</td>
<td>Shape</td>
</tr>
<tr>
<td>Color Hue</td>
<td>Angle</td>
<td>Length</td>
</tr>
<tr>
<td>Texture</td>
<td>Slope</td>
<td>Angle</td>
</tr>
<tr>
<td>Connection</td>
<td>Area (Size)</td>
<td>Slope</td>
</tr>
<tr>
<td>Containment</td>
<td>Volume</td>
<td>Area</td>
</tr>
<tr>
<td>Shape</td>
<td>Shape</td>
<td>Volume</td>
</tr>
</tbody>
</table>
Graphical Perception
The ability of viewers to interpret visual (graphical) encodings of information and thereby decode information in graphs.
Topics

Signal Detection
Magnitude Estimation
Using Multiple Visual Encodings
Pre-Attentive Processing
Gestalt Grouping
Change Blindness
Signal Detection
Detecting Brightness

Which is brighter?

L

R

Which is brighter?
Detecting Brightness

(128, 128, 128)  (144, 144, 144)

Which is brighter?
Detecting Brightness

Which is brighter?

L

R

Which is brighter?
Detecting Brightness

Which is brighter?

(134, 134, 134)  (128, 128, 128)
Just Noticeable Difference (JND)

JND (Weber’s Law)

Perceived Change → $\Delta S = k \frac{\Delta I}{I}$

Ratios more important than magnitude

Most continuous variation in stimuli are perceived in discrete steps
Encoding Data with Color

Value is perceived as ordered
- Encode ordinal variables (O)

- Encode continuous variables (Q) [not as well]

Hue is normally perceived as unordered
- Encode nominal variables (N) using color
Steps in Font Size

Sizes standardized in 16th century

6 7 8 9 10 11 12 14 16 18 21 24 36 48 60 72
Magnitude Estimation
A Quick Experiment...
Compare area of circles
Compare length of bars
Compare area of circles
Compare length of bars
Steven’s Power Law

$$S = I^p$$

Perceived Sensation

Physical Intensity

Exponent (Empirically Determined)

Predicts bias, not necessarily accuracy!

[Graph from Wilkinson ‘99, based on Stevens ‘61]
## Exponents of Power Law

<table>
<thead>
<tr>
<th>Sensation</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loudness</td>
<td>0.6</td>
</tr>
<tr>
<td>Brightness</td>
<td>0.33</td>
</tr>
<tr>
<td>Smell</td>
<td>0.55 (Coffee) - 0.6 (Heptane)</td>
</tr>
<tr>
<td>Taste</td>
<td>0.6 (Saccharine) - 1.3 (Salt)</td>
</tr>
<tr>
<td>Temperature</td>
<td>1.0 (Cold) – 1.6 (Warm)</td>
</tr>
<tr>
<td>Vibration</td>
<td>0.6 (250 Hz) – 0.95 (60 Hz)</td>
</tr>
<tr>
<td>Duration</td>
<td>1.1</td>
</tr>
<tr>
<td>Pressure</td>
<td>1.1</td>
</tr>
<tr>
<td>Heaviness</td>
<td>1.45</td>
</tr>
<tr>
<td>Electric Shock</td>
<td>3.5</td>
</tr>
</tbody>
</table>

[Psychophysics of Sensory Function, Stevens ’61]
Apparent Magnitude Scaling

\[ S = 0.98A^{0.87} \]  [from Flannery '71]
Graphical Perception  [Cleveland & McGill 84]
Figure 3. Graphs from position–angle experiment.
Figure 16. Log absolute error means and 95% confidence intervals for judgment types in position—length experiment (top) and position—angle experiment (bottom).
Graphical Perception Experiments
Empirical estimates of encoding effectiveness

Heer & Bostock ‘10
Relative Magnitude Comparison

Most accurate:
- Position (common) scale
- Position (non-aligned) scale

Least accurate:
- Length
- Slope
- Angle
- Area
- Volume
- Color hue-saturation-density
## Effectiveness Rankings

[Mackinlay 86]

<table>
<thead>
<tr>
<th>QUANTITATIVE</th>
<th>ORDINAL</th>
<th>NOMINAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>Position</td>
<td>Position</td>
</tr>
<tr>
<td>Length</td>
<td>Density (Value)</td>
<td>Color Hue</td>
</tr>
<tr>
<td>Angle</td>
<td>Color Sat</td>
<td>Texture</td>
</tr>
<tr>
<td>Slope</td>
<td>Color Hue</td>
<td>Connection</td>
</tr>
<tr>
<td>Area (Size)</td>
<td>Texture</td>
<td>Containment</td>
</tr>
<tr>
<td>Volume</td>
<td>Connection</td>
<td>Density (Value)</td>
</tr>
<tr>
<td>Density (Value)</td>
<td>Containment</td>
<td>Color Sat</td>
</tr>
<tr>
<td>Color Sat</td>
<td>Length</td>
<td>Shape</td>
</tr>
<tr>
<td>Color Hue</td>
<td>Angle</td>
<td>Length</td>
</tr>
<tr>
<td>Texture</td>
<td>Slope</td>
<td>Angle</td>
</tr>
<tr>
<td>Connection</td>
<td>Area (Size)</td>
<td>Slope</td>
</tr>
<tr>
<td>Containment</td>
<td>Volume</td>
<td>Area</td>
</tr>
<tr>
<td>Shape</td>
<td>Shape</td>
<td>Volume</td>
</tr>
</tbody>
</table>
Multiple Attributes
One-Dimensional: Lightness

- White
- Black
- White
- Black
- White
- Black
- White
One-Dimensional: Shape

Square
Circle
Circle
Square
Circle

Circle
Circle
Square
Circle
Circle
Redundant: Shape & Lightness

Circle
Square
Square
Circle
Square
Circle
Orthogonal: Shape & Lightness

- Circle
- Square
- Circle
- Square
- Circle
- Square
Speeded Classification

Redundancy Gain
Facilitation in reading one dimension when the other provides redundant information

Filtering Interference
Difficulty in ignoring one dimension while attending to the other
Speeded Classification

Response Time

Interference

Gain

Dimension Classified

Lightness  Shape

R 1 O  R 1 O
Types of Perceptual Dimensions

Integral
Filtering interference and redundancy gain

Separable
No interference or gain

Asymmetric
One dim separable from other, not vice versa

Example: The Stroop effect – color naming is influenced by word identity, but word naming is not influenced by color
Stroop Effect: What word?

blue
yellow
red
orange
green
purple
Stroop Effect: What color?

blue
yellow
red
orange
green
purple
Size and Brightness

W. S. Dobson, Visual information processing and cartographic communication: The role of redundant stimulus dimensions, 1983 (reprinted in MacEachren, 1995)
Orientation & Size

How well can you see temperature or precipitation? Is there a correlation between the two?

[MacEachren 95]
Length & Length

FIGURE 3.38. An example of the use of an ellipse as a map symbol in which the horizontal and vertical axes represent different (but presumably related) variables.

[MacEachren 95]
Angle & Angle

FIGURE 3.39. Bivariate map of NO$_3$ and SO$_4$ trends. The original Carr et al. version of this map used a wheel with eight spokes, rather than a simple dot, as the center of each glyph. When large enough, this added feature facilitates judgment of specific values. After Carr et al. (1992, Fig. 7a, p. 234). Adapted by permission of the American Congress on Surveying and Mapping.

[MacEachren 95]
Summary of Integral & Separable

[Figure 5.25, Color Plate 10, Ware 2000]
Set

Each card has **4 features**:
- Color
- Symbol
- Number
- Shading/Texture

A set consists of 3 cards in which each feature is the SAME or DIFFERENT on each card.
Pre-Attentive Processing
How Many 3’s?

1281768756138976546984506985604982826762
9809858458224509856458945098450980943585
9091030209905959595772564675050678904567
8845789809821677654876364908560912949686

[based on a slide from J. Stasko]
How Many 3’s?

[based on a slide from J. Stasko]
Visual Pop-Out: Color

http://www.csc.ncsu.edu/faculty/healey/PP/index.html
Visual Pop-Out: Shape

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

http://www.csc.ncsu.edu/faculty/healey/PP/index.html
Pre-Attentive Features

[Information Visualization. Figure 5. 5 Ware 04]
# More Pre-Attentive Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line (blob) orientation</td>
<td>Julesz &amp; Bergen [1983]; Wolfe et al. [1992]</td>
</tr>
<tr>
<td>Length</td>
<td>Triesman &amp; Gormican [1988]</td>
</tr>
<tr>
<td>Width</td>
<td>Julesz [1985]</td>
</tr>
<tr>
<td>Size</td>
<td>Triesman &amp; Gelade [1980]</td>
</tr>
<tr>
<td>Curvature</td>
<td>Triesman &amp; Gormican [1988]</td>
</tr>
<tr>
<td>Number</td>
<td>Julesz [1985]; Trick &amp; Pylyshyn [1994]</td>
</tr>
<tr>
<td>Terminators</td>
<td>Julesz &amp; Bergen [1983]</td>
</tr>
<tr>
<td>Intersection</td>
<td>Julesz &amp; Bergen [1983]</td>
</tr>
<tr>
<td>Closure</td>
<td>Enns [1986]; Triesman &amp; Souther [1985]</td>
</tr>
<tr>
<td>Intensity</td>
<td>Beck et al. [1983]; Triesman &amp; Gormican [1988]</td>
</tr>
<tr>
<td>Flicker</td>
<td>Julesz [1971]</td>
</tr>
<tr>
<td>Direction of motion</td>
<td>Nakayama &amp; Silverman [1986]; Driver &amp; McLeod [1992]</td>
</tr>
<tr>
<td>Binocular lustre</td>
<td>Wolfe &amp; Franzel [1988]</td>
</tr>
<tr>
<td>Stereoscopic depth</td>
<td>Nakayama &amp; Silverman [1986]</td>
</tr>
<tr>
<td>3-D depth cues</td>
<td>Enns [1990]</td>
</tr>
<tr>
<td>Lighting direction</td>
<td>Enns [1990]</td>
</tr>
</tbody>
</table>
Pre-Attentive Conjunctions

Spatial conjunctions are often pre-attentive
Motion and 3D disparity
Motion and color
Motion and shape
3D disparity and color
3D disparity and shape

But most conjunctions are NOT pre-attentive
Feature Integration Theory

Treisman’s feature integration model [Healey 04]
Final Project
Final Project

Produce interactive web-based visualizations

Initial prototype and design review

Final deliverables and video presentation

Submit and publish on GitHub

Projects from previous classes have been:

• Published as research papers
• Shared widely (some in the New York Times!)
• Released as successful open source projects
Final Project Theme

Data Visualization for Social Good

Goal: find data of social or scientific import, design visualizations to explore or communicate it effectively.

The specific data domain is open-ended. Possibilities include transportation, housing, public health, education, climate, campaign finance, scientific research, and so on...

You must identify a target audience. May be general (residents, voters) or specialized (scientists, policy makers).
Final Project Schedule

Proposal          Fri Nov 13
Milestone         Tue Dec 1
Demo Video        Wed Dec 9
Video Showcase    Thur Dec 10 (in class)
Deliverables      Mon Dec 14

Logistics
Final project description posted online
Work in groups of up to 5 people
Start determining your project topic!
Tips for a Successful Project

Focus on a compelling real-world problem. How will you gauge success?

Consider multiple design alternatives. Prototype quickly (use Tableau, R, etc…).

Seek feedback (representative users, peers, …). Even informal usage can provide insights.

Choose appropriate team roles.

Start early (and read the suggested paper!)
Gestalt Grouping
Gestalt Principles

Figure/Ground
Proximity
Similarity
Symmetry
Connectedness
Continuity
Closure
Common Fate
Transparency
Figure/Ground

Ambiguous

Principle of surroundedness

Principle of relative size

http://www.aber.ac.uk/media/Modules/MC10220/visper07.html
Figure/Ground

Ambiguous

Unambiguous (?)

http://www.aber.ac.uk/media/Modules/MC10220/visper07.html
Proximity

[Ware '00]
Similarity

Rows dominate due to similarity [from Ware ’04]
Symmetry

Bilateral symmetry gives strong sense of figure [from Ware ’04]
Connectedness

Connectedness overrules proximity, size, color shape [from Ware ‘04]
Continuity

We prefer smooth not abrupt changes [from Ware ’04]

Connections are clearer with smooth contours [from Ware ’04]
Continuity: Vector Fields

Prefer field that shows smooth continuous contours [from Ware 04]
Continuity: Vector Fields

Prefer field that shows smooth continuous contours [from Ware ’04]
Closure

We see a circle behind a rectangle, not a broken circle [from Ware ‘04]

Illusory contours [from Durand ‘02]
Common Fate

Dots moving together are grouped
Transparency

Requires continuity and proper color correspondence [from Ware ‘04]
Change Blindness
Change Blindness
Change Blindness
Change Blindness
Change Blindness
Change Blindness

[Example from Palmer 99, originally due to Rock]
Demonstrations

http://www.psych.ubc.ca/~rensink/flicker/download/

http://www.youtube.com/watch?v=Ahg6qcgoay4
Summary

Choosing effective visual encodings requires knowledge of visual perception.

Visual features/attributes
Individual attributes often pre-attentive
Multiple attributes may be separable or integral

Gestalt principles provide high-level guidelines

We don’t always see everything that is there!