CSE 512 - 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)
Which best encodes quantities?

Position
Length
Area
Volume
Value (Brightness)
Color Hue
Orientation (Angle)
Shape
Effectiveness Rankings

QUANTITATIVE
Position
Length
Angle
Slope
Area (Size)
Volume
Density (Value)
Color Sat
Color Hue
Texture
Connection
Containment
Shape

ORDINAL
Position
Density (Value)
Color Sat
Color Hue
Texture
Connection
Containment
Length
Angle
Slope
Area (Size)
Volume
Shape

NOMINAL
Position
Color Hue
Texture
Connection
Containment
Density (Value)
Color Sat
Shape
Length
Angle
Slope
Area
Volume
Graphical Perception
The ability of viewers to interpret visual (graphical) encodings of information and thereby decode information in graphs.
Topics

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

Which is brighter?
Detecting Brightness

(128, 128, 128)  

Which is brighter?  

(144, 144, 144)
Detecting Brightness

Which is brighter?
Detecting Brightness

Which is brighter?

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

JND (Weber’s Law)

\[ \Delta S = k \frac{\Delta I}{I} \]

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 16\textsuperscript{th} century

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

\[ S = I^p \]

Exponent (Empirically Determined)
Perceived Sensation
Physical Intensity

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]
Graduated Sphere Map

Steven’s Power Law

\[ S = I^p \]

Exponent (Empirically Determined)

Perceived Sensation

Physical Intensity

Predicts bias, not necessarily accuracy!

[Graph from Wilkinson 99, based on Stevens 61]
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
Relative Magnitude Comparison

Most accurate

Position (common) scale
Position (non-aligned) scale

Length
Slope
Angle
Area
Volume
Color hue-saturation-density

Least accurate
## Effectiveness Rankings

### QUANTITATIVE
- Position
- Length
- Angle
- Slope
- Area (Size)
- Volume
- Density (Value)
- Color Sat
- Color Hue
- Texture
- Connection
- Containment
- Shape

### ORDINAL
- Position
- Density (Value)
- Color Sat
- Color Hue
- Texture
- Connection
- Containment
- Length
- Angle
- Slope
- Area (Size)
- Volume
- Shape

### NOMINAL
- Position
- Color Hue
- Texture
- Connection
- Containment
- Density (Value)
- Color Sat
- Shape
- Length
- Angle
- Slope
- Area
- Volume

[MacKinlay 86]
Administrivia
A2: Exploratory Data Analysis

Use visualization software to form & answer questions

First steps:
Step 1: Pick domain & data
Step 2: Pose questions
Step 3: Profile the data
Iterate as needed

Create visualizations
Interact with data
Refine your questions

Make a notebook
Keep record of your analysis
Prepare a final graphic and caption

Due by 5:00pm Friday, April 17
D3.js Tutorial

Date: Monday, April 20
Time: 4pm to 5:30pm
Location: More Hall, Room 230

D3.js is a popular JavaScript visualization library, valuable for A3 and your Final Project...
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
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

Most conjunctions are not pre-attentive
Feature Integration Theory

Treisman’s feature integration model [Healey 04]

Feature maps for orientation & color [Green]
Multiple Attributes
One-Dimensional: Lightness

White
White
Black
White
Black

White
Black
Black
White
White
One-Dimensional: Shape

Square
Circle
Circle
Square
Circle

Circle
Circle
Square
Circle
Redundant: Shape & Lightness

Circle
Square
Square
Circle
Square
Circle
Orthogonal: Shape & Lightness

Circle

Square

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

C
1
O

C
1
O
Types of 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.
W. S. Dobson, Visual information processing and cartographic communication: The role of redundant stimulus dimensions, 1983 (reprinted in MacEachren, 1995)
Orientation & Size

FIGURE 3.36. A map of temperature and precipitation using symbol size and orientation to represent data values on the two variables.

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

[MacEachren 95]
Shape & Size

Easier to see one shape across multiple sizes than one size of across multiple shapes?

[MacEachren 95]
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]
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.
Gestalt Grouping
Gestalt Principles

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

Ambiguous

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

Principle of surroundedness

Principle of relative size
Figure/Ground

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]
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]
Layering
Layering: Gridlines

Signal and background compete above, as an electrocardiogram trace-line becomes caught up in a thick grid. Below, the screened-down grid stays behind traces from each of 12 monitoring leads:*

Electrocardiogram tracelines [from Tufte 90]
Layering: Gridlines

Stravinsky score [from Tufte 90]
Setting Gridline Contrast

How light can gridlines be and remain visible? How dark can gridlines be and not distract?

Safe setting: 20% Alpha

[Stone & Bartram 2009]
[Heer & Bostock 2010]
Layering: Color & Line Width

IBM Series III Copier [from Tufte 90]
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!