Learning Perceptual Kernels for Visualization Design

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Visualizations
Leverage
Perception
Engineering Perception Into Visualization Design?
A Measure of Perceptual Reality

Perceptual Kernel  2D Projection
What are Perceptual Kernels Useful For?
Automating Visualizations
Palette Design
Palette Design

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Palette Design

2D Projection

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Palette Design

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Palette Design

Palettes re-ordered to maximize perceptual discriminability
Visual Embedding:
A Model for Visualization
Visualizations as Functions

$X \xrightarrow{f} Y$

Data Points

Visual Primitives

quantitative
ordinal
nominal
...

color
size
shape
orientation
texture
...

$X$

$Y$
Visual Embedding

$$\text{Data Points: } x \rightarrow y$$

$$d_X$$

$$d_Y$$

$$f : X \rightarrow Y$$

$$X$$

quantitative

ordinal

nominal

... 

$$Y$$

color

size

shape

orientation

texture

...
Visual Embedding

\[ f : X \rightarrow Y \]

**X**
- quantitative
- ordinal
- nominal
- ...

**Y**
- color
- size
- shape
- orientation
- texture
- ...

\[ d_X \]

\[ d_Y \]
Visual Embedding

\[ d_X : X \rightarrow Y \]

\[ d_Y : Y \rightarrow Y \]

\( f : X \rightarrow Y \)

**Data Points**

- \( x_1 \)
- \( x_2 \)
- \( x_3 \)
- \( x_4 \)

**Visual Primitives**

- \( y_1 \)
- \( y_2 \)
- \( y_3 \)
- \( y_4 \)

**Features**

- Quantitative
- Ordinal
- Nominal
- Color
- Size
- Shape
- Orientation
- Texture

**NOT NEED TO BE METRIC**
Rank Correlations

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<thead>
<tr>
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<th>A</th>
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who failed in 40% or more of these judgments. They were also expected to match or filter identical pairs as 0. They were also instructed to rate the similarity of the pairwise and triplet cases to filter "spam" responses. To safeguard data quality, we use errant ratings of identical pairs as 0.

For triplet judgments, we derive per-user kernels from a set of ranked answers. The kernel was obtained using the triplet matching (Tm) task, which linearly increases in area, maps to non-linear perceptual proximity. As shown in Figure 10, of the three visual variables we consider, size is the most robust across judgment task types. The MDS projection on Figure 11 clearly demonstrates a one-dimensional structure, with a high correlation with the crowd-estimated kernel. 

We construct rank correlations in Figure 9 comparing the triplet matching (Tm) kernel with kernels obtained using CIELAB, CIEDE2000, color names, and perceptual distances in Figure 10. The kernel correlates most highly with the crowd-estimated kernel. We use the Hellinger distance between multinomial color name probability distributions.

### Table: Rank Correlations

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Cluster Connectivity

Encode community clusters in a character co-occurrence graph.
CONTRIBUTIONS
CONTRIBUTIONS

1) Estimate perceptual kernels

shape
size
color

shape-size
shape-color
size-color
CONTRIBUTIONS

2) Compare alternative judgment types

- pairwise-5
- pairwise-9
- triplet matching
- triplet discrimination
- manual
CONTRIBUTIONS

3) Assess using existing models

Stevens’ Power Law

I \sim M^\beta

CIELAB
CIEDE2000
Color Names

Garner’s Integrality

28
CONTRIBUTIONS

4) Demonstrate in visualization automation

- Designing palettes
- Visual embedding

Future research might also extend our approach to more situations.
Crowd-sourcing
Perceptual Kernels
Study Overview

Variables

- **shape**:
  - ○
  - □
  - ♦
  - ×
  - △
  - ◆
  - ▽
  - ▼

- **size**:
  - ○
  - □
  - ◆
  - ▾
  - ▿
  - △
  - ▼
  - ▽

- **color**:
  - Red
  - Green
  - Blue
  - Orange
  - Yellow
  - Pink
  - Purple
  - Gray
  - Black
  - White

- **shape-size**:
  - ○
  - □
  - ♦
  - ×
  - △
  - ◆
  - ▽
  - ▼

- **shape-color**:
  - ○
  - □
  - ♦
  - ×
  - △
  - ◆
  - ▽
  - ▼

- **size-color**:
  - ○
  - □
  - ◆
  - ▾
  - ▿

Tasks

- **pairwise-5**
  - L5

- **pairwise-9**
  - L9

- **triplet matching**
  - Tm

- **triplet discrimination**
  - Td

- **manual spatial arrangement**
  - SA

Subjects

- 600 Turkers based in the US
- 95% approval rate
- minimum 100 approved HITs

Platform

- Amazon Mechanical Turk
Univariate Perceptual Kernels

(shape, color, size)
Bivariate Perceptual Kernels

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<th></th>
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<th>SA</th>
<th>Tm</th>
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Judgment Tasks

1. Pairwise rating on 5-point scale (L5)
2. Pairwise rating on 9-point scale (L9)
3. Triplet ranking with matching (Tm)
4. Triplet ranking with discrimination (Td)
5. Spatial arrangement (SA)
Judgment Tasks

1. Pairwise rating on 5-point scale (L5)

- Symbol pair to be rated
- Advances to next symbol pair
- Matrix is filled as ratings are entered
- A rating can be selected by clicking on it or by typing the number directly on the keyboard
Judgment Tasks

1. Pairwise rating on 5-point scale (L5)
2. Pairwise rating on 9-point scale (L9)

- symbol pair to be rated
- advances to next symbol pair
- matrix is filled as ratings are entered
- a rating can be selected by clicking on it or by typing the number directly on the keyboard
Judgment Tasks

3. Triplet ranking with matching (Tm)

Which is more similar to reference, a or b?
Your task is to select the symbol that looks more similar to the reference. You can make your selection by clicking on the symbol or by using the keyboard key. Complete each task as accurately and quickly as possible.

Shortcut Keys:
a - select the symbol a
b - select the symbol b
enter or space bar - advance to next task

reference symbol

instructions

reference

next

shows next symbol triplet

candidate symbols; user can select the symbol that looks more similar to the reference by clicking on it or by using the keyboard key

progress bar
3. Triplet ranking with matching (Tm)

Which symbol looks more similar to the reference?

In a series of tasks, we are going to show you a reference symbol and two other symbols. Your job is to decide which one of the two symbols looks more similar to the reference (see the task interface below).

Which is more similar to reference, a or b?
Your task is to select the symbol that looks more similar to the reference. You can make your selection by clicking on the symbol or by using the keyboard key.
Complete each task as accurately and quickly as possible.

Complete each task as accurately and quickly as possible.
We will start with a short training session to get you familiarized with the task interface. Click the button below to continue with the training session.

start training
Judgment Tasks

4. Triplet ranking with discrimination (Td)

Which one looks the most different, a or b or c?
Your task is to select the symbol that looks the most different from the other two. You can make your selection by clicking on the symbol or by using the keyboard key. Complete each task as accurately and quickly as possible.

Shortcut Keys:
a - select symbol a
b - select symbol b
c - select symbol c
enter or space bar - advance to next task

symbol triplet

user can select the symbol that is visually the most different from the rest by clicking on the symbol or by using the keyboard key

instructions

next

shows next symbol triplet

progress bar
Judgment Tasks

5. Spatial arrangement (SA)

- Arrange the shapes on the right so that similar symbols are nearer each other and dissimilar symbols are farther away from each other.
- The final layout should accurately reflect your sense of the visual similarities and differences among the shapes.
- Drag and drop the shapes to change their position.
- Please perform the task as accurately and quickly as possible. When you are done, click the next button.
- Consider the example below. Here, we have placed each color such that similar colors are near each other and dissimilar colors are farther apart. Your task is to construct a similar layout for shapes.

Example: layout area, where shapes can be arranged with drag and drop.
Judgment Tasks

5. Spatial arrangement (SA)

- Arrange the shapes on the right so that similar symbols are nearer each other and dissimilar symbols are farther away from each other.
- The final layout should accurately reflect your sense of the visual similarities and differences among the shapes.
- Drag and drop the shapes to change their position.
- Please perform the task as accurately and quickly as possible. When you are done, click the next button.
- Consider the example below. Here, we have placed each color such that similar colors are near each other and dissimilar colors are farther apart. Your task is to construct a similar layout for shapes.

example:
Perceptual Kernels & Models of Perception
Size (Tm)

Consistent with Stevens’ Power Law!
Stevens’ Power Law

\[ I \sim M^\beta \]

Perceived Intensity \((I)\)

True Magnitude \((M)\)

- Electric shock \((\beta = 3.5)\)
- Length \((\beta = 1.1)\)
- Brightness \((\beta = 0.5)\)

Stimulus dependent exponent
Stevens’ Power Law Fit
Stevens’ Power Law Fit
Stevens’ Power Law Fit
3) Assess using existing models

- Stevens’ Power Law: $I \sim M^\beta$
- CIELAB
- CIEDE2000
- Color Names
- Garner’s Integrality

Details are in the paper.
Which Judgment Task to Use?
Pairwise Likert ratings (L5 & L9)
- faster & cheaper than triplet comparisons

Manual spatial arrangement (SA)
- fastest, cheapest
- high variance, high sensitivity

Triplet matching (Tm)
- lowest variance, most robust, shortest unit

Triplet comparisons (Tm & Td)
- longest experiment time, highest cost
Pairwise Likert ratings (L5 & L9)  
faster & cheaper than triplet comparisons

Manual spatial arrangement (SA)  
fastest, cheapest  
high variance, high sensitivity

Triplet matching (Tm)  
lowest variance, most robust, shortest unit

Triplet comparisons (Tm & Td)  
longest experiment time, highest cost
Pairwise Likert ratings (L5 & L9)
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Triplet comparisons (Tm & Td)
longest experiment time, highest cost

Manual spatial arrangement (SA)
fastest, cheapest
high variance, high sensitivity
CONCLUSIONS

Perceptual Kernels
operational model

Use ordinal triplet matching
unless prohibited by time & cost

Avoid manual spatial arrangement

Read the paper
Acknowledgments

IDL Group Members

data & source code
https://github.com/uwdata/perceptual-kernels
https://github.com/uwdata/visual-embedding
Data Processing

Pairwise judgments
- Produce a distance matrix directly
- Identical pairs to detect spammers

Triplet judgments
- Generalized non-metric multidimensional scaling
- Use triplets with two identical elements to detect spammers

Spatial arrangements
- Align to a reference and filter-out the outliers
- Planar Euclidean distances produce a distance matrix
Palette Design
What About Context?
What About Context?

What about it?
What About Context?

Which is more similar to reference, a or b?
Your task is to select the symbol that looks more similar to the reference. You can make your selection by clicking on the symbol or by using the keyboard key. Complete each task as accurately and quickly as possible.

Shortcut Keys:
- a - select symbol a
- b - select symbol b
- enter or space bar - advance to next task

Instructions:
- reference shape
- candidate shapes; user can select the shape that looks more similar to the reference by clicking on it or by directly typing its label (a or b) on the keyboard

Reference:
- shows next shape set
- progress bar

Training session
What About Context?

early results suggest no significant effect
Why Tableau?
Why Tableau?

I have Tableau stocks
Why Tableau?

I have Tableau stocks?
Why Tableau?

I have Tableau stocks?
Why Tableau?

Manually designed with perceptual considerations in mind
discriminability, saliency and naming of colors, robustness to spatial overlap of shapes

Provides ecological validity and good baseline
What About Individual Differences?
The layout with gray background is the medoid of the layouts in affine space.
Sensitivity

shape

corr

color

size

shape-color

corr

shape-size

size-color
Why SA Performs Poorly?
Why SA Performs Poorly?

Unstructured nature, leading to higher variance across subjects

Expressivity limited to two dimensions expression of perceptual structures.
Why Tm Outperforms Td?
Why Tm Outperforms Td?

It involves a binary decision (vs. trinary)
Detects more fine-grained similarities
Why Tm Outperforms Td?

It involves a binary decision (vs. trinary)
Detects more fine-grained similarities
Why Tm Outperforms Td?

It involves a binary decision (vs. trinary)
Detects more fine-grained similarities

d(A,B)<d(A,C)
d(A,B)<d(B,C)

Task type = Td
Why Tm Outperforms Td?

It involves a binary decision (vs. trinary)
Detects more fine-grained similarities

task type=Tm
Why Tm Outperforms Td?

It involves a binary decision (vs. trinary)
Detects more fine-grained similarities

\[ d(A, B) < d(A, C) \]

task type = Tm

A

B

3

8

6

C
Why Tm Outperforms Td?

It involves a binary decision (vs. trinary)
Detects more fine-grained similarities

\[ d(A, B) < d(A, C) \]

Task type = Tm
Why Tm Outperforms Td?

It involves a binary decision (vs. trinary)
Detects more fine-grained similarities

d(A,B)<d(A,C)
d(B,C)<d(A,C)

task type=Tm
Why Tm Outperforms Td?

It involves a binary decision (vs. trinary)
Detects more fine-grained similarities

d(A,B) < d(A,C)
d(B,C) < d(A,C)

task type = Tm

Td cannot elicit
Univariate Perceptual Kernels with MDS Projections*

*For each visual variable, projections are aligned to the projection of the L5 kernel.
Bivariate Perceptual Kernels with 3D MDS Projections
Comparison of Perceptual Kernels with Color Models: Rank Correlation Matrices

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Comparison of Perceptual Kernels with Color Models: Rank Correlation Matrices
Comparison of Perceptual Kernels with Color Models

Rank correlation matrices displayed as gray-scale images (brighter entries indicate higher correlations)
Comparison of Perceptual Color Kernels with Color Models

The palette shapes representing the models are chosen automatically with visual embedding (using the triplet matching kernel). They reflect the correlations between the variables. For example, the correlation between the CIELAB and CIEDE2000 is higher than the correlation between the perceptual kernels and color names and the assigned shapes reflect this relationship perceptually.

All projections are aligned to the CIELAB projection in the plane using similarity transformations.
Per-subject SAs: size

The layout with gray background is the medoid of the layouts in affine space.
Per-subject SAs: shape
Per-subject SAs: color
Per-subject SAs: shape-color
Per-subject SAs: shape-size
Per-subject SAs: size-color