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A Comparative Study of the Perceptual Sensitivity of Topological Visualizations to Feature Variations

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U.S. Department of Energy

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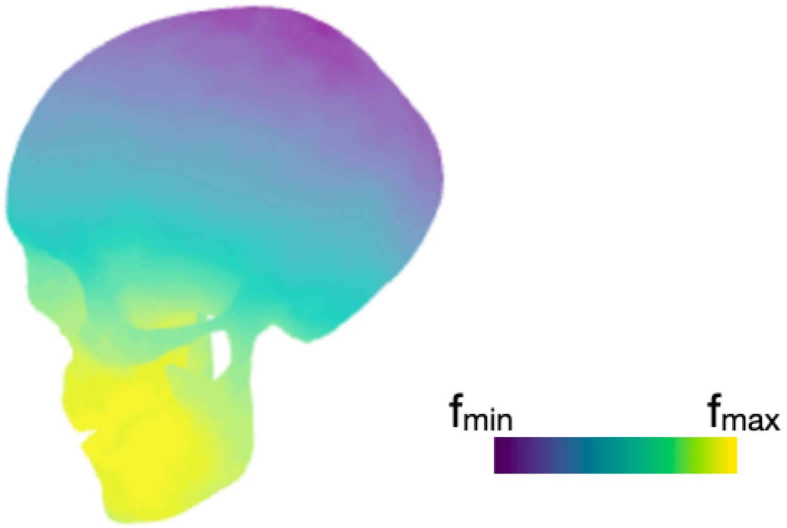
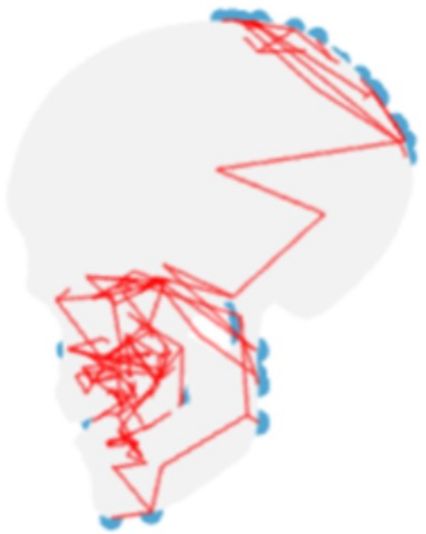
Color Maps Vs. Topological Visualizations

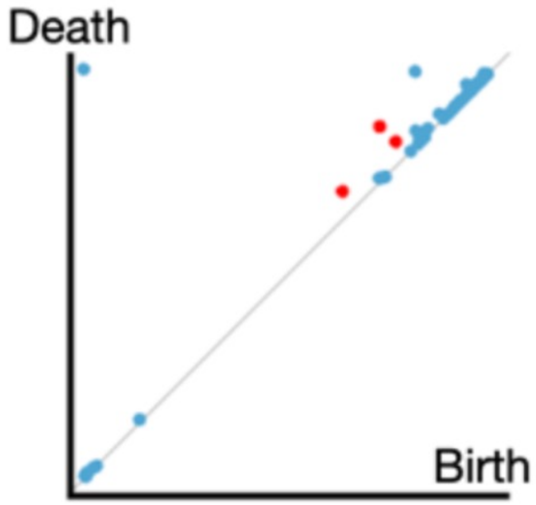


Color map

Isocontours



Reeb graph

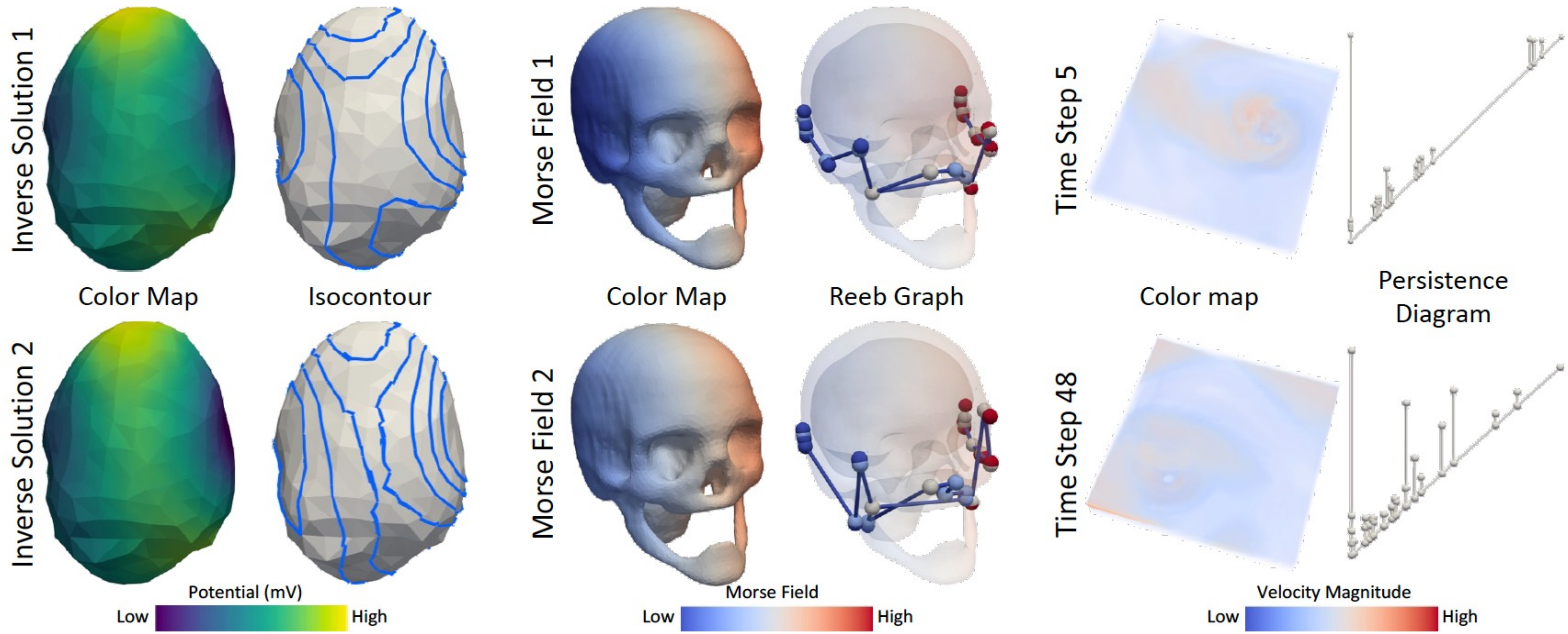


Persistence diagram

Implicit portrayal of data features

Explicit portrayal of data features

Application of Visualization Comparisons



(a) Potentials on heart surface [Njeru et al., 2022]

(b) Patient-specific cephalometric landmarks [Makram and Kamel, 2014]

(c) Time-varying simulations of a hurricane [Vidal et al., 2020]

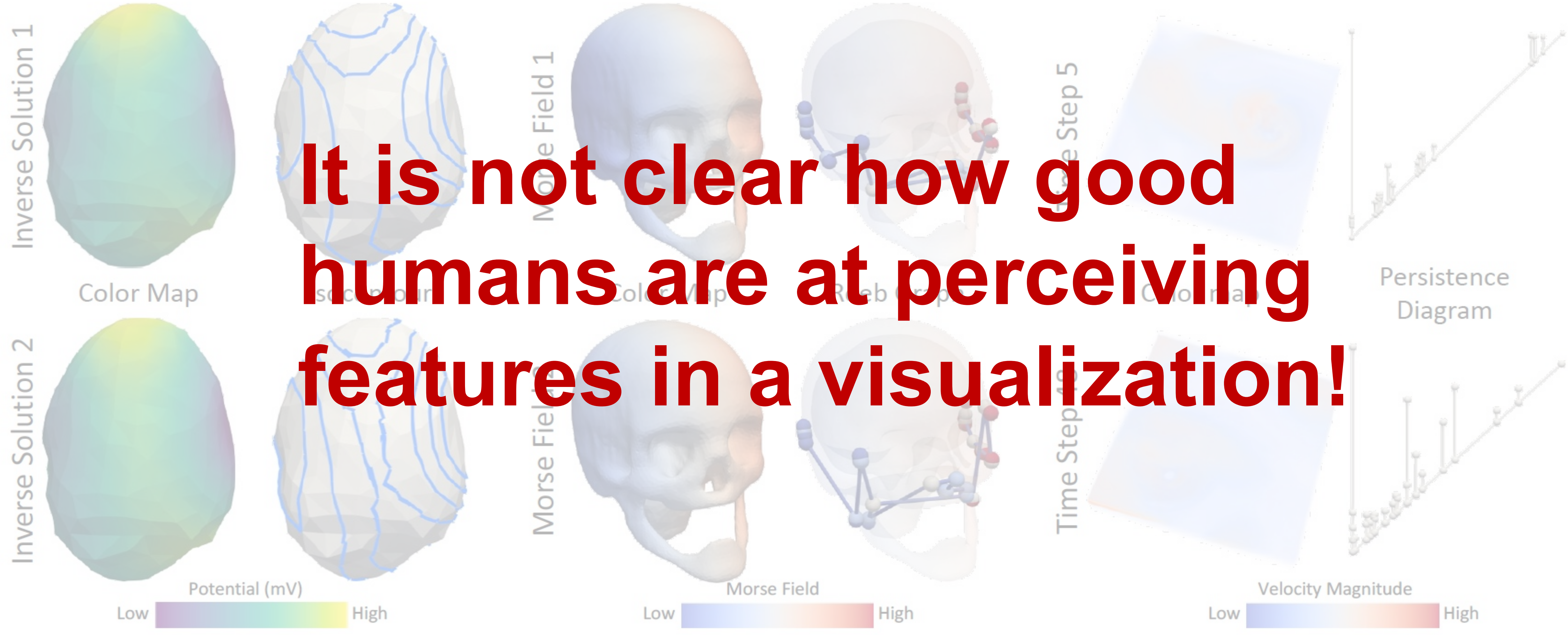
Ensemble simulations

Observational data

Time-varying data

Provocation

It is not clear how good humans are at perceiving features in a visualization!



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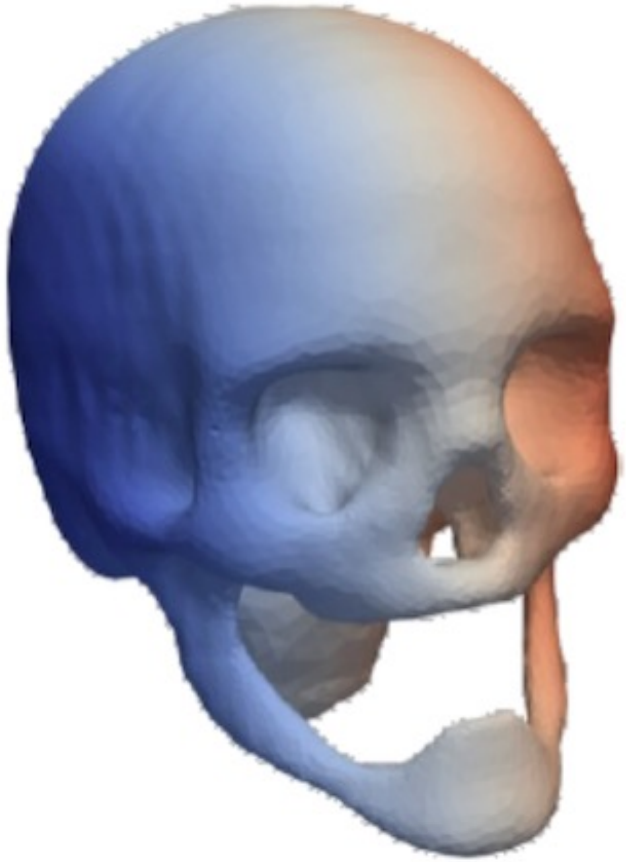
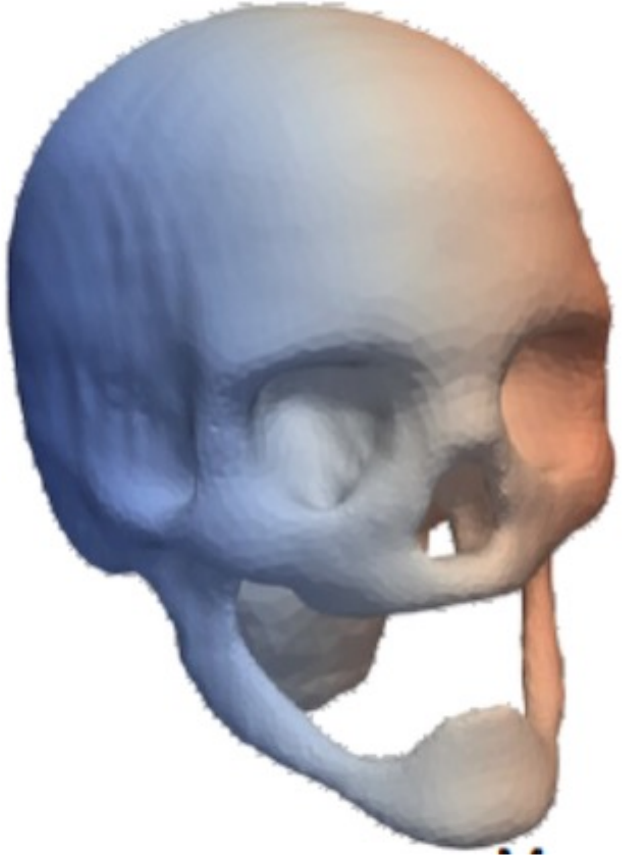
Can You Tell Where and How Much the Following Visualizations are Different?

Dataset 1



Dataset 2



Color Map

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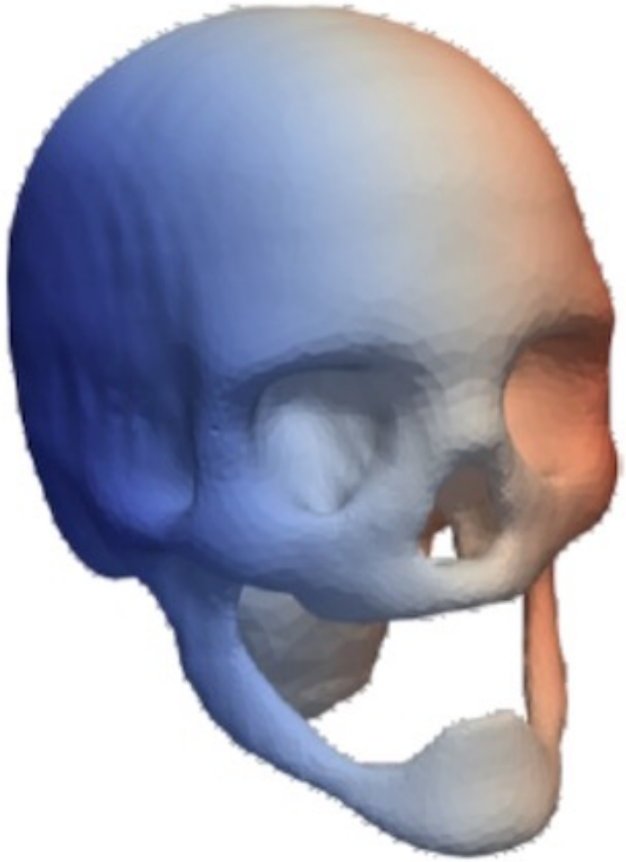
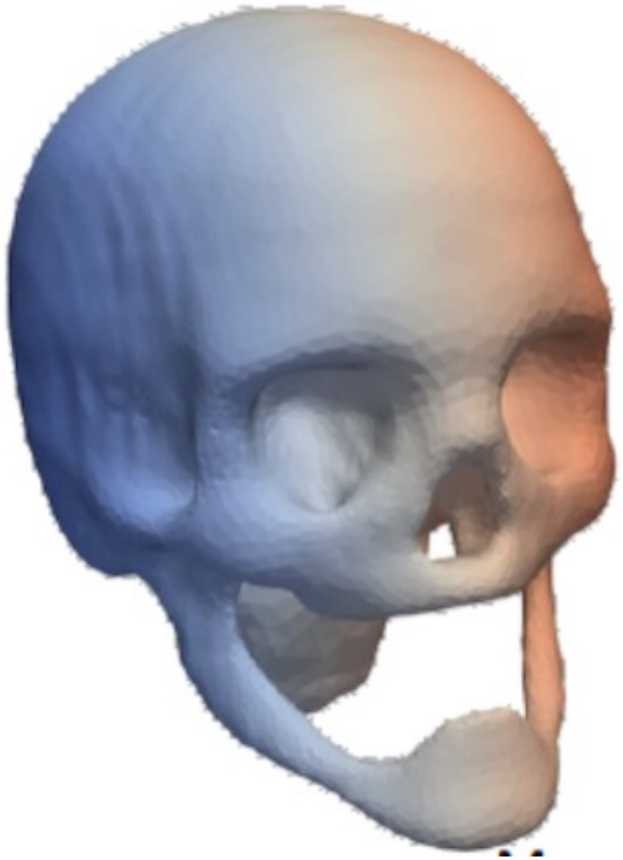


Dataset 2



Color Map

Perhaps it is difficult to notice differences!

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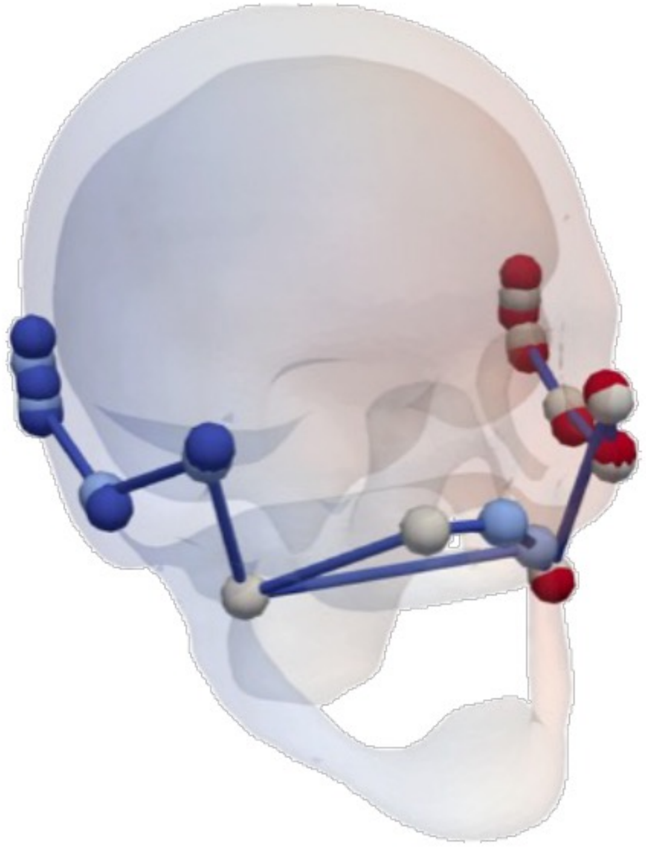
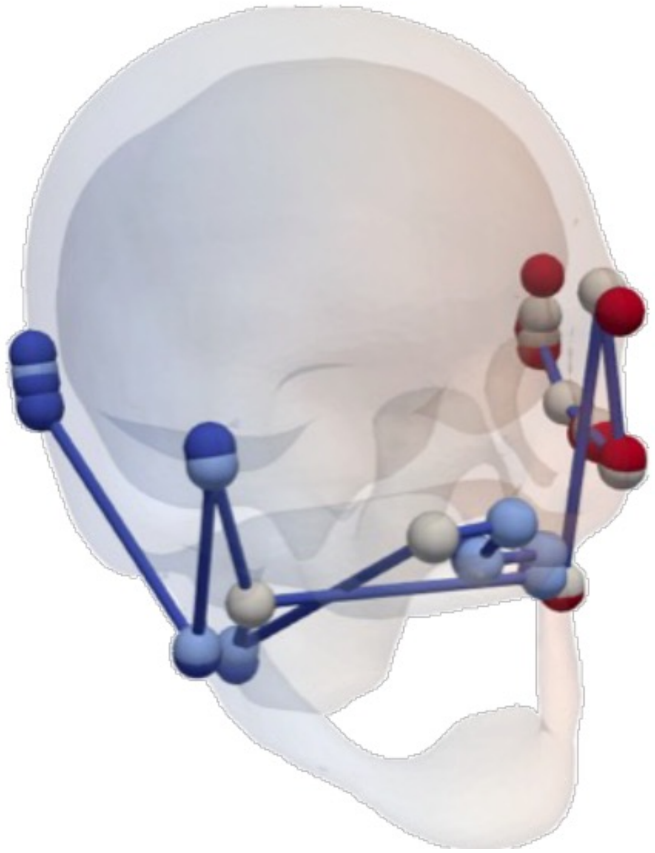
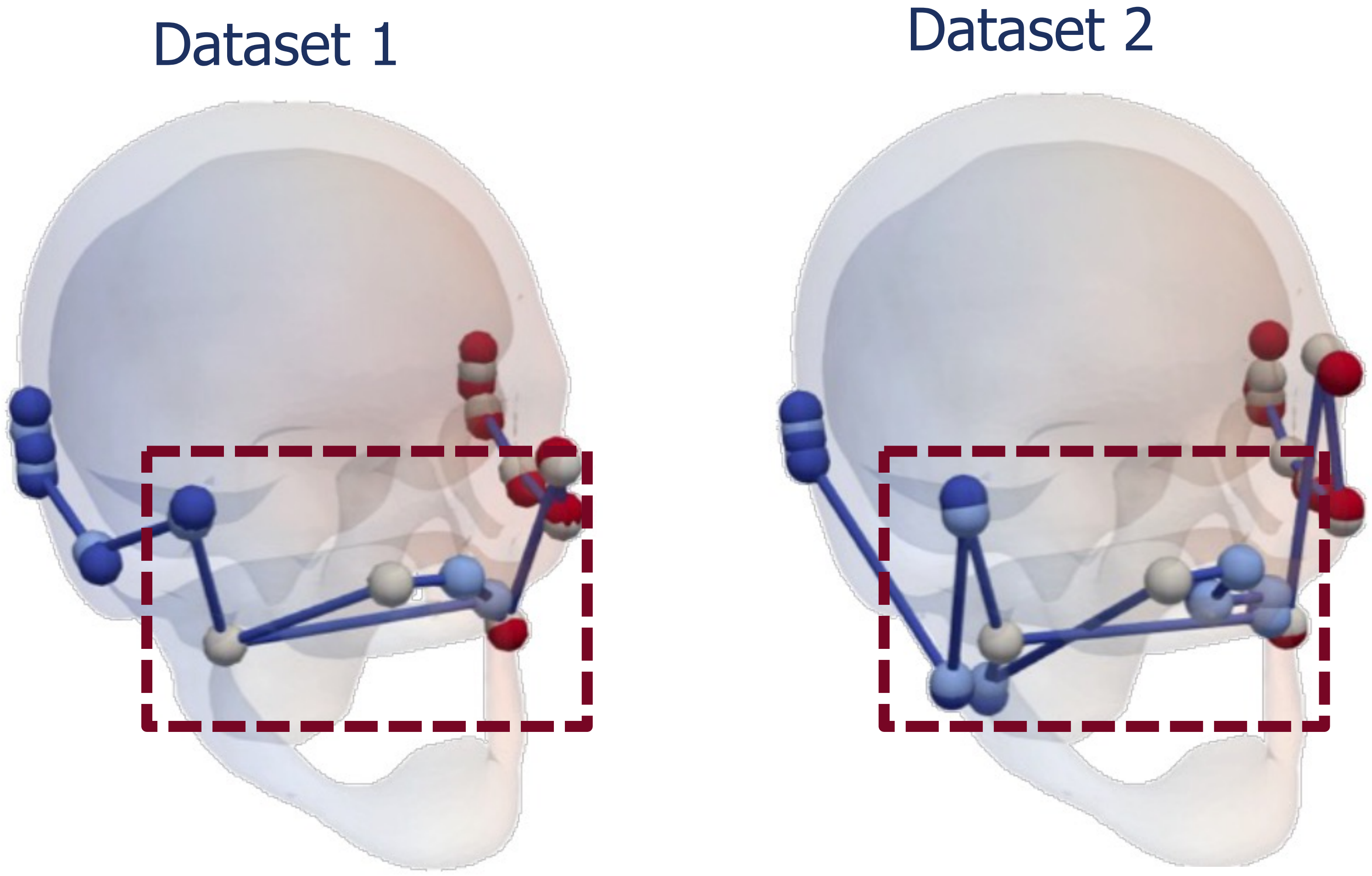


Dataset 2



Reeb graph (topological skeleton of a scalar field)

Can You Tell Where and How Much the Following Visualizations are Different?



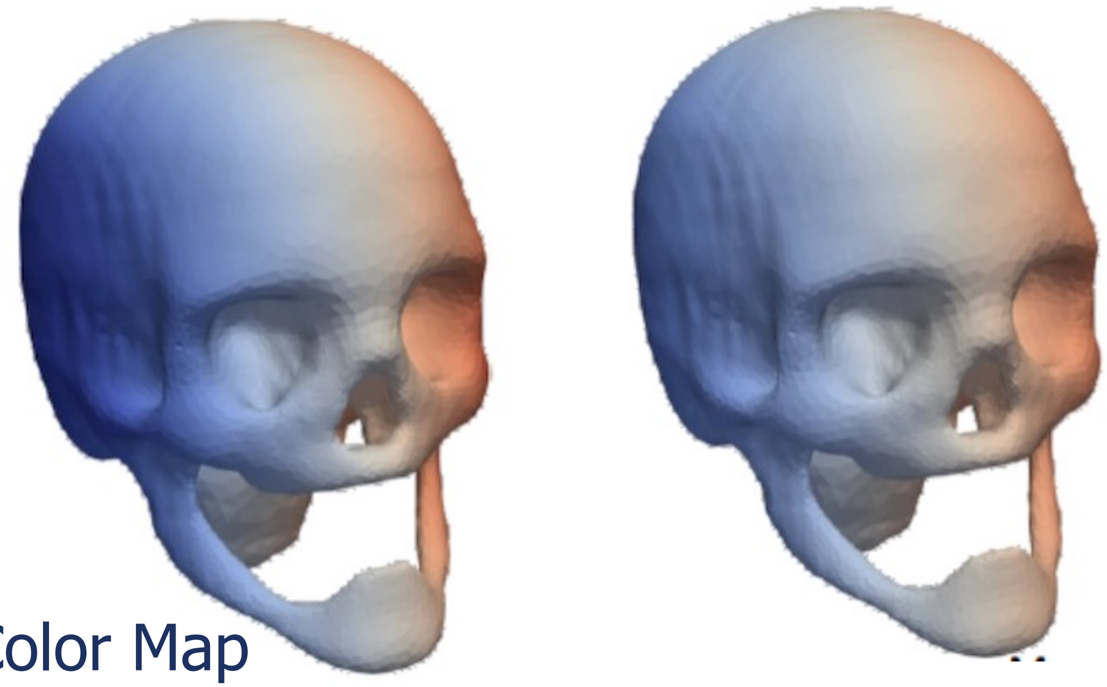
Perhaps it is easier to notice differences!

Reeb graph (topological skeleton of a scalar field)

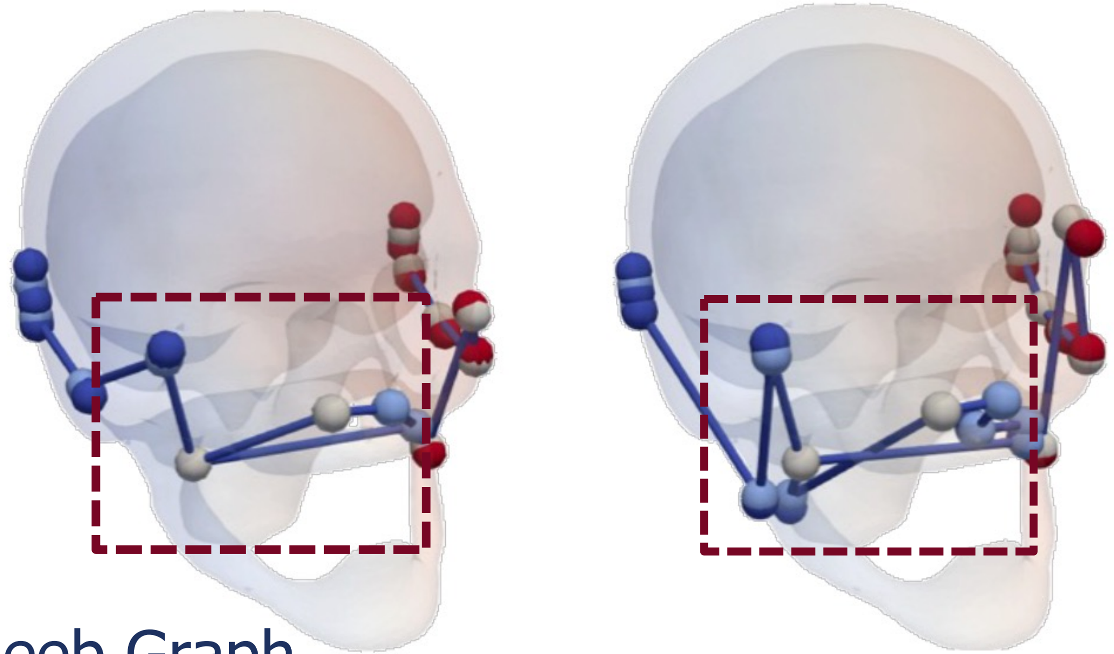
We Investigate What Features Users Perceive When Comparing Visualizations

Studying perceptual sensitivity of visualizations is crucial to:

- gaining insight into limitations of visualization types
- enhancing visualization design
- choosing optimal visualization type



Color Map



Reeb Graph

Related Work

- Factors contributing to effective visualization
  [Kosara et al., 2003], [Wijk, 2005], [North, 2006], [Munzner, 2009], [Quadri and Rosen, 2022]

- Perception
  [Rogowitz et al., 1996], [Liu and Heer, 2009], [Moreland, 2009], [Zhou and Hansen, 2016], [Cooper et al., 2021], [Laidlaw et al., 2005], [Forsberg et al., 2009]

- Quantitative comparison of topological visualizations
  [Cohen-Steiner et al., 2007], [Edelsbrunner and Harer, 2010], [Morozov et al., 2013], [Sridharamurthy et al., 2020], [Pont et al., 2022], [Bollen et al., 2023], [Lan et al., 2023]

- Sensitivity analysis of functions and visualizations
  [Cacuci et al., 2005], [Saltelli et al., 2008], [Liu et al., 2014], [Chan et al., 2010], [Brecheisen et al., 2009]

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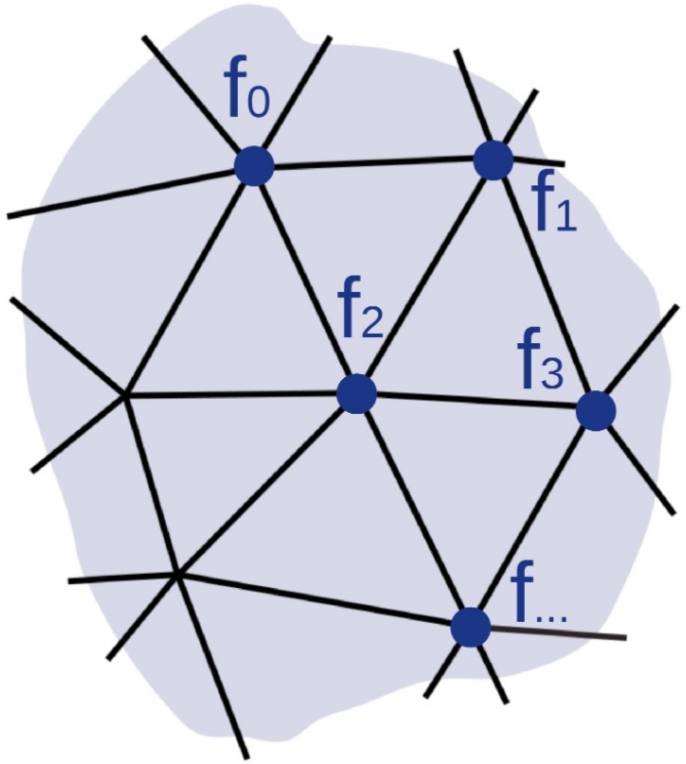
To our understanding, no prior work has evaluated feature perception sensitivity for topological visualizations

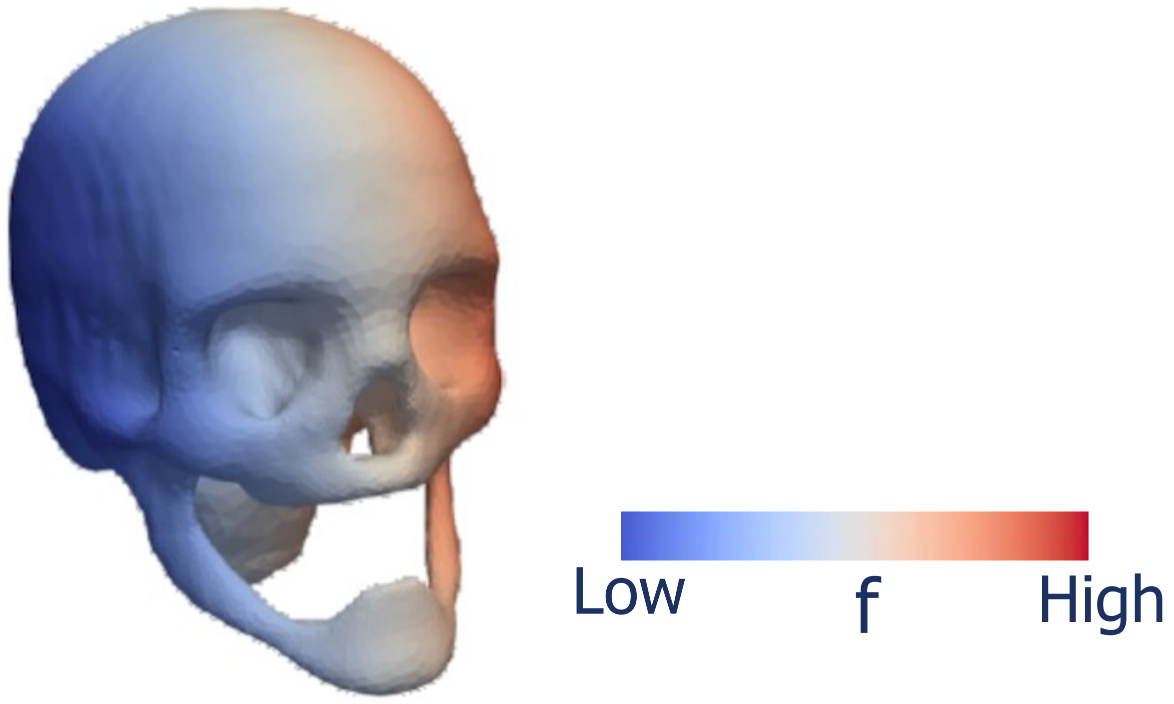
Evaluated Data and Techniques and Hypothesis

Data

Scalar fields sampled on 2D manifolds embedded in 3D

$$f : \mathscr{M} \to \mathbb{R}$$





Data

Scalar field is represented as a mixture of Gaussians

[Vidal et al., 2020] [Yan et al., 2021]

Perlin noise

Gaussian function

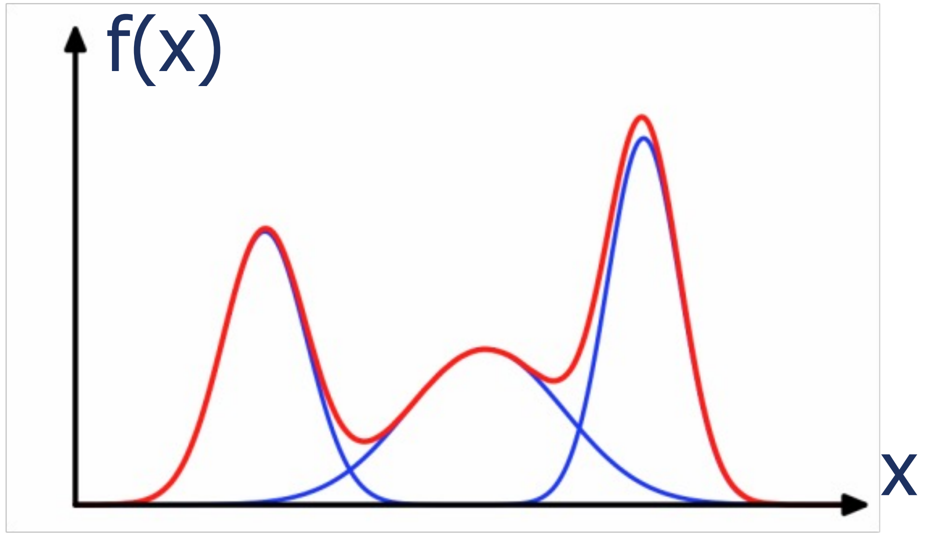
$$f(x,y,z) = \mathcal{N}(x,y,z) + \sum_{i}^{NOF} \mathcal{G}_i(x,y,z),$$

(x_i, y_i, z_i): Mean of a Gaussian

$$\mathcal{G}_i(x,y,z) = a_i \cdot \exp\left(-\left(\frac{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}{2\sigma^2}\right)\right)$$

Amplitude

Standard deviation



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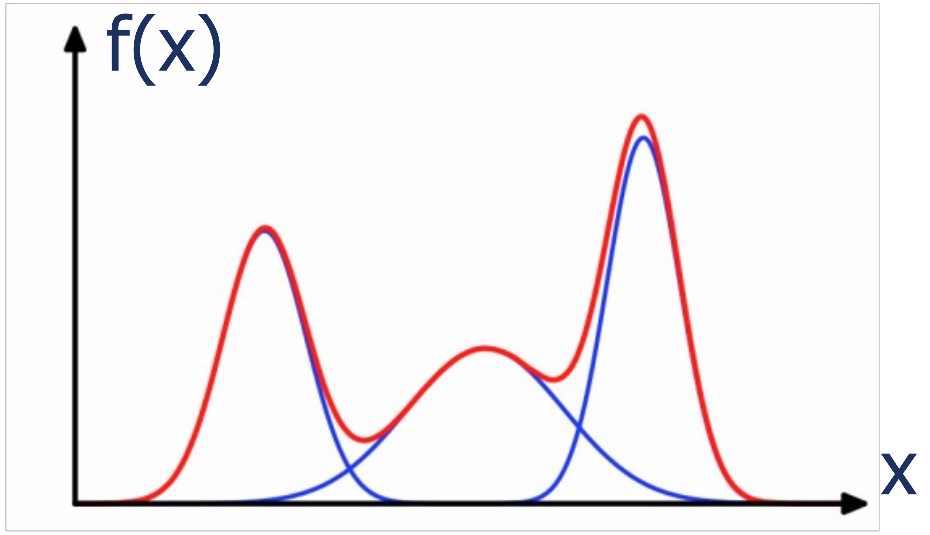
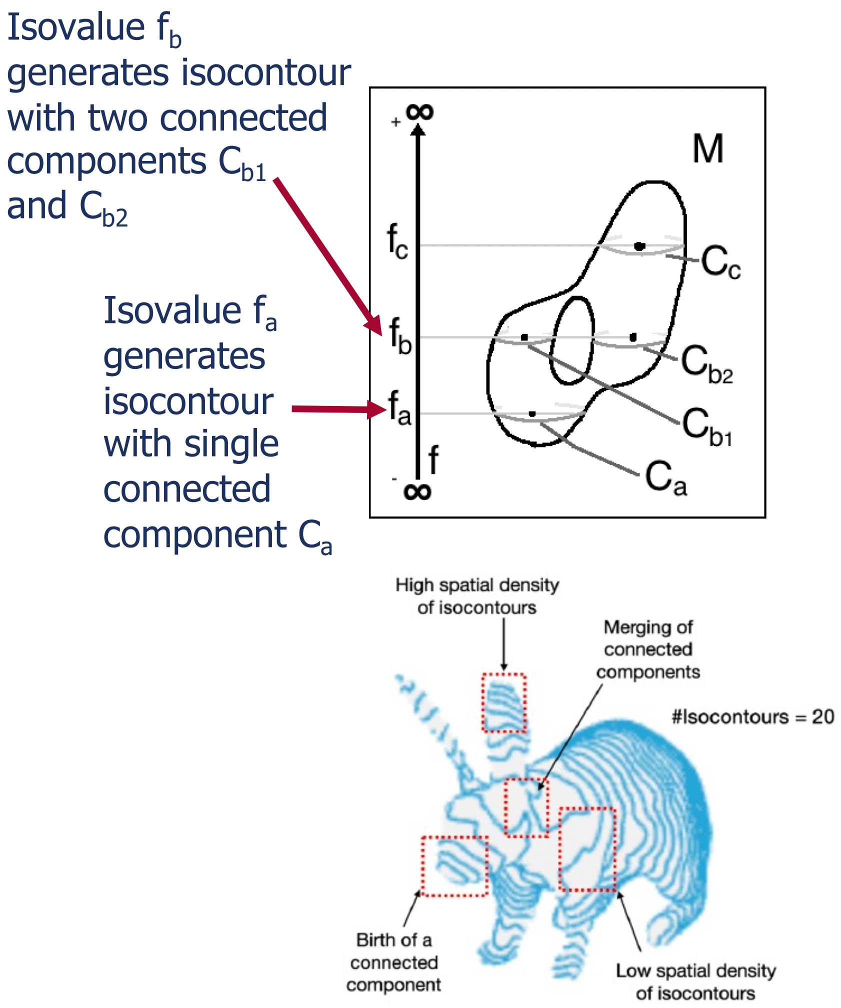
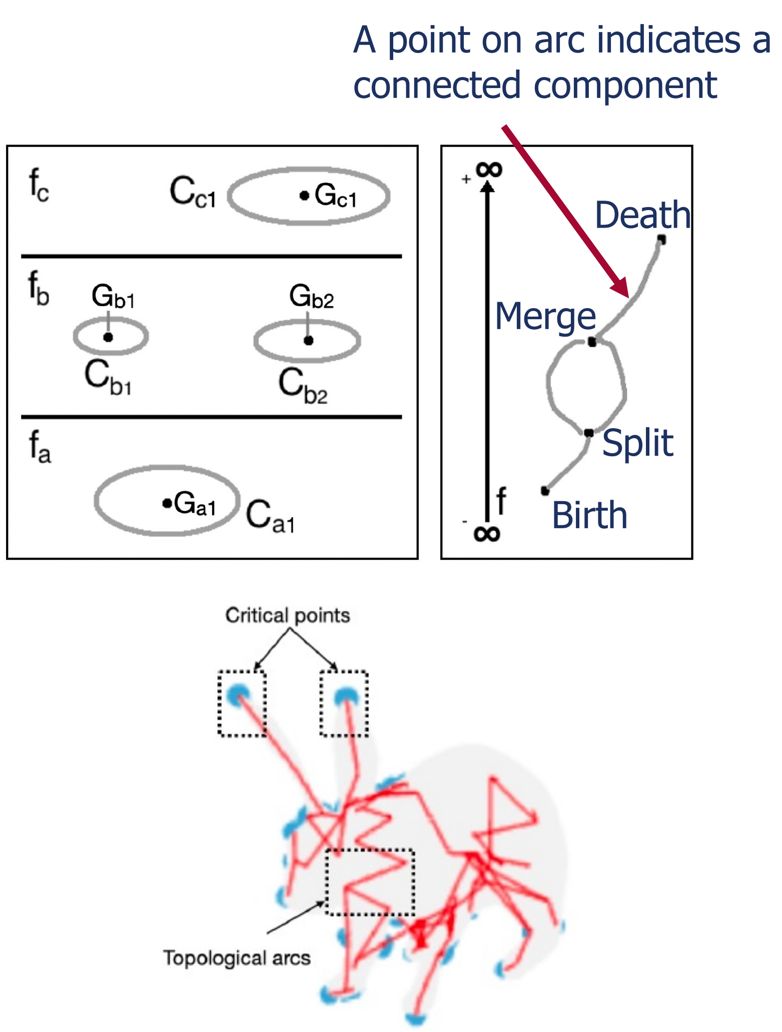


How much visualization is sensitive to changes in amplitude and mean of a Gaussian?

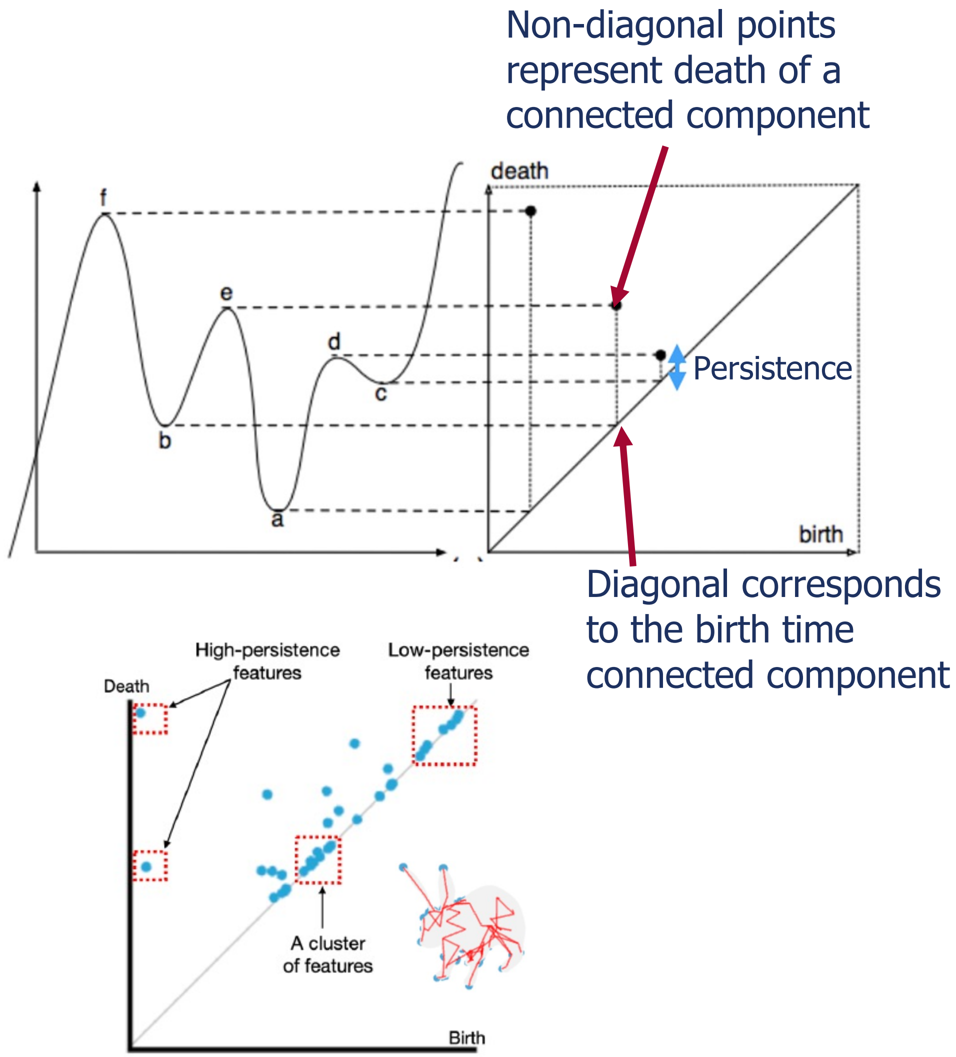
Evaluated Topological Visualizations



(a) Isocontours
[Lorenson and Cline, 1987]



(b) Reeb graphs
[Edelsbrunner and Harer, 2010]

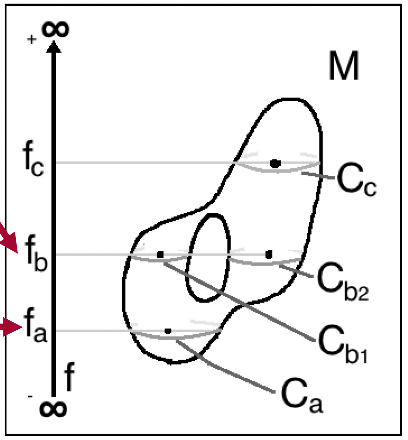


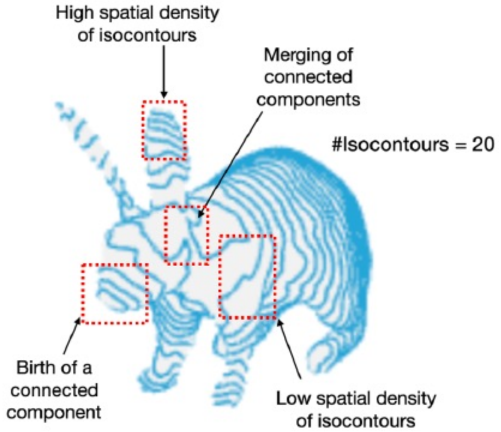
(c) Persistence diagram
[Cohen-Steiner et al., 2005]

Evaluated Topological Visualizations

Isovalue f_b generates isocontour with two connected components C_{b1} and C_{b2}

Isovalue f_a generates isocontour with single connected component C_a





(a) Isocontours
[Lorenson and Cline, 1987]

A point on arc indicates a connected component

(b) Reeb graphs
[Edelsbrunner and Harer, 2010]

Non-diagonal points represent death of a connected component

Diagonal corresponds to the birth time connected component

(c) Persistence diagram
[Cohen-Steiner et al., 2005]

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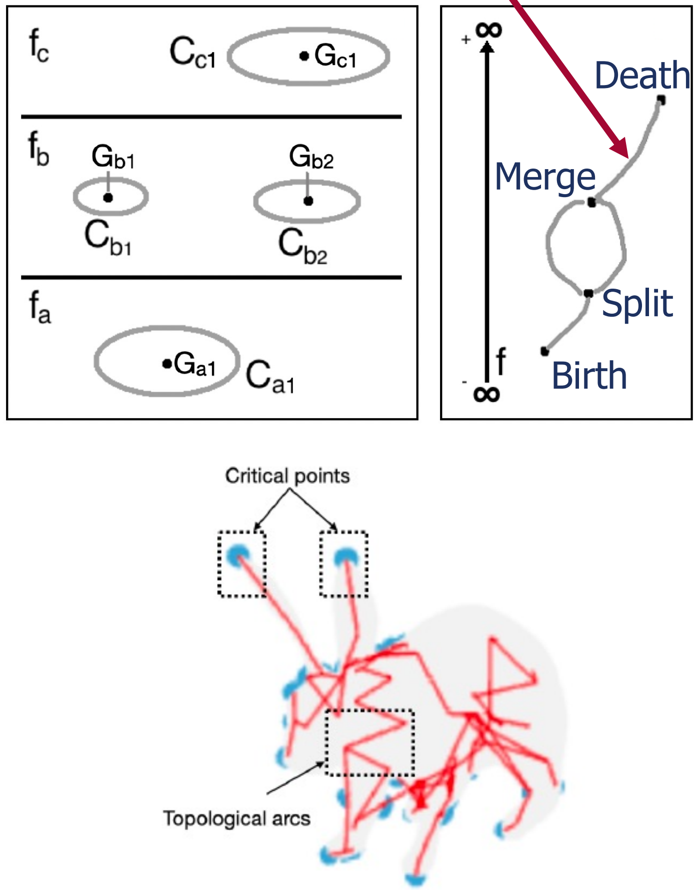

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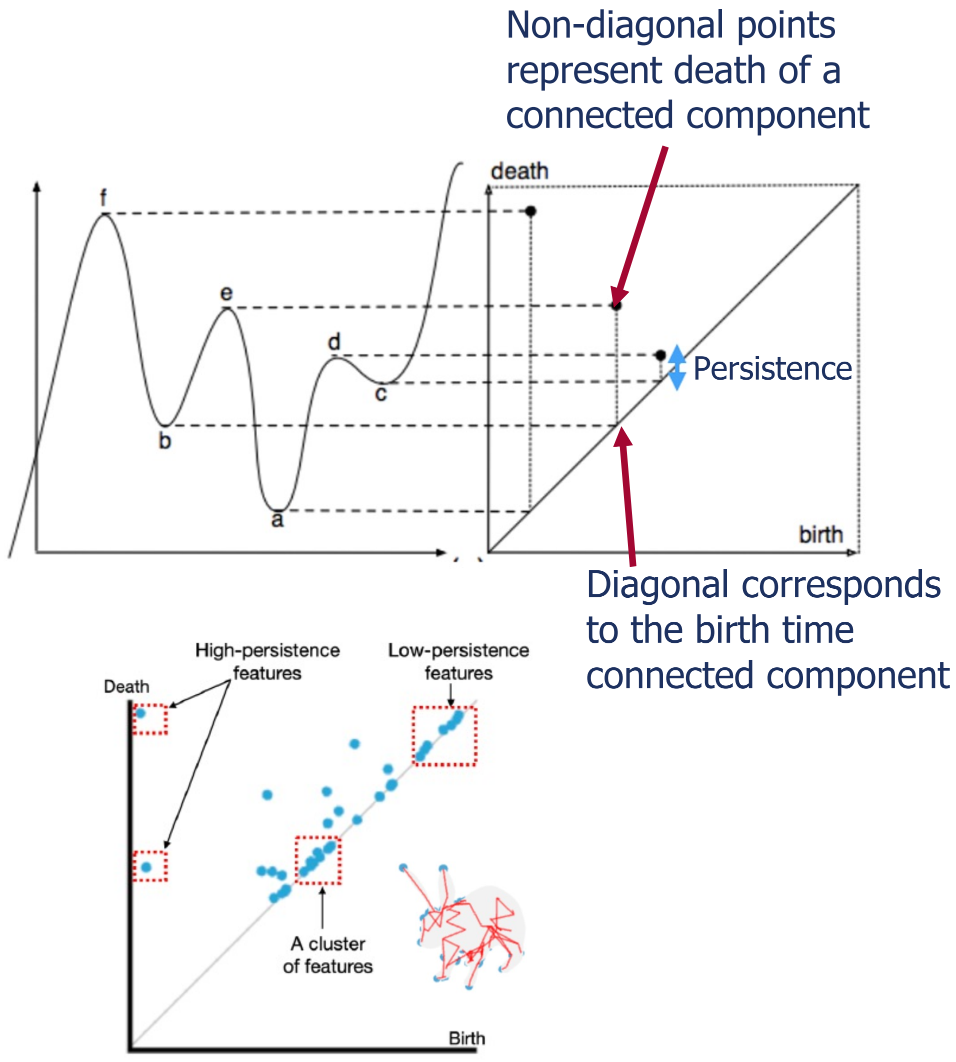
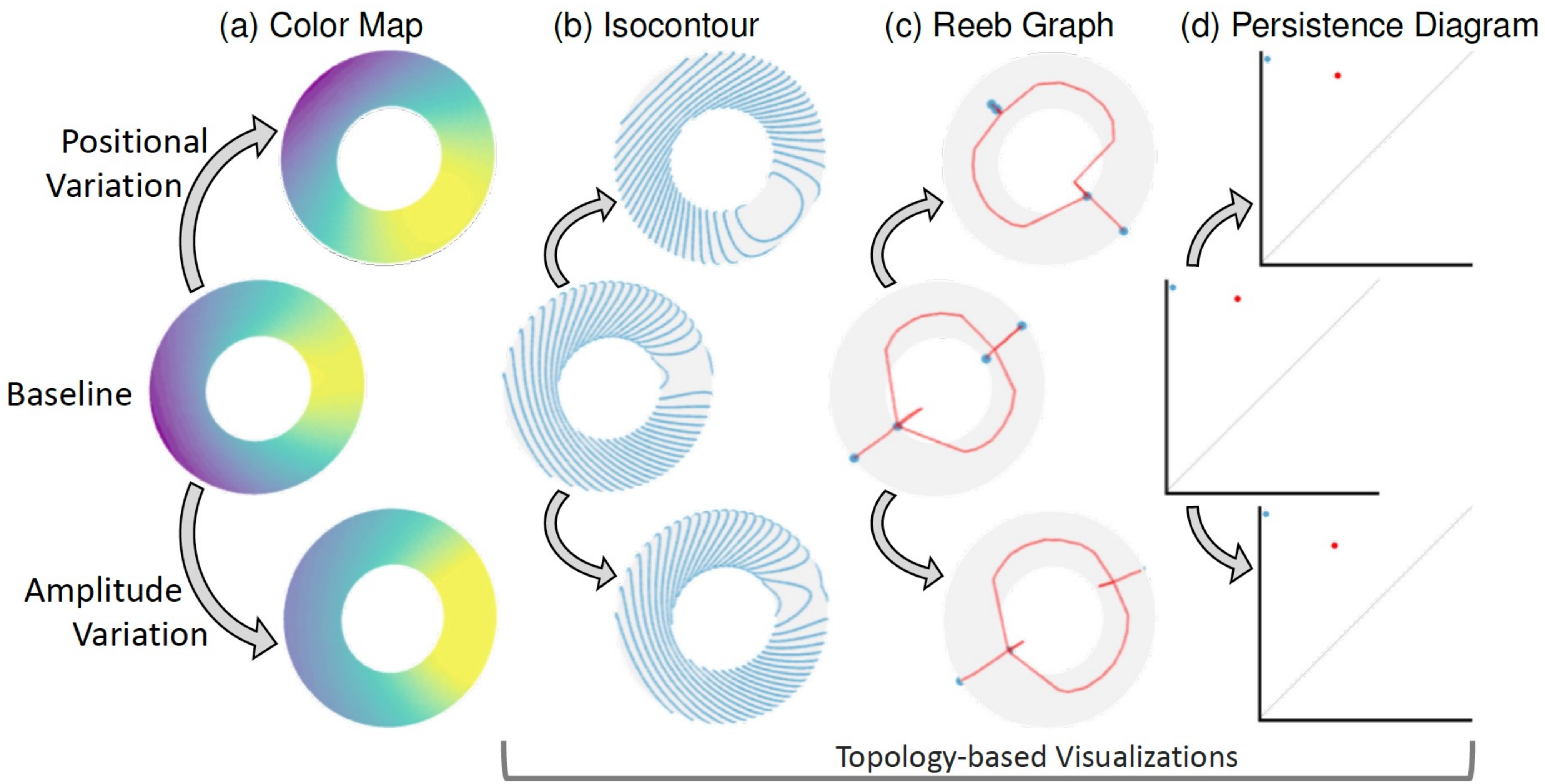
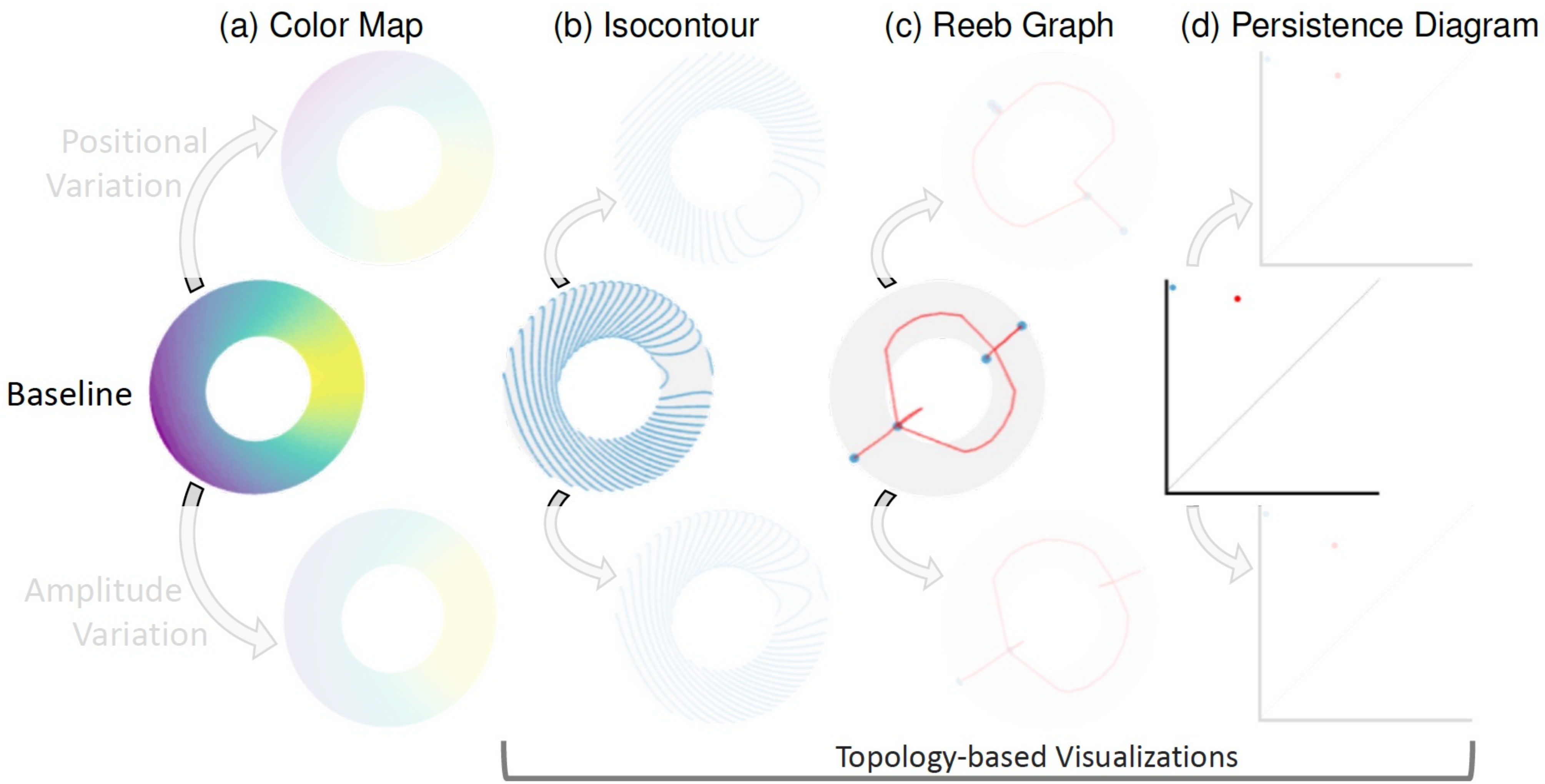


(c) Persistence diagram
[Cohen-Steiner et al., 2005]

Hypothesis


(a) Color Map
(b) Isocontour
(c) Reeb Graph
(d) Persistence Diagram
Positional Variation
Baseline
Amplitude Variation
Topology-based Visualizations

Hypothesis



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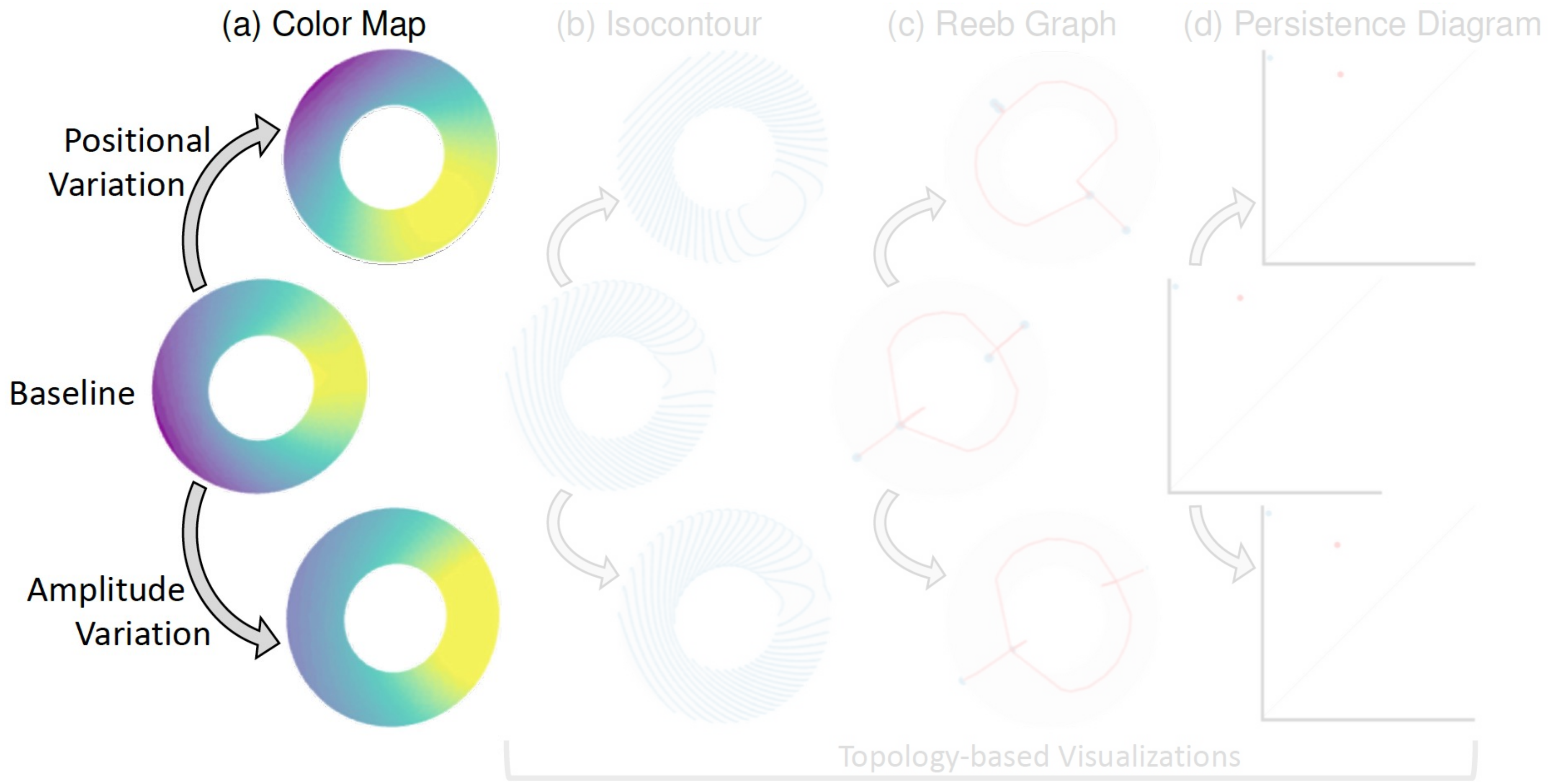
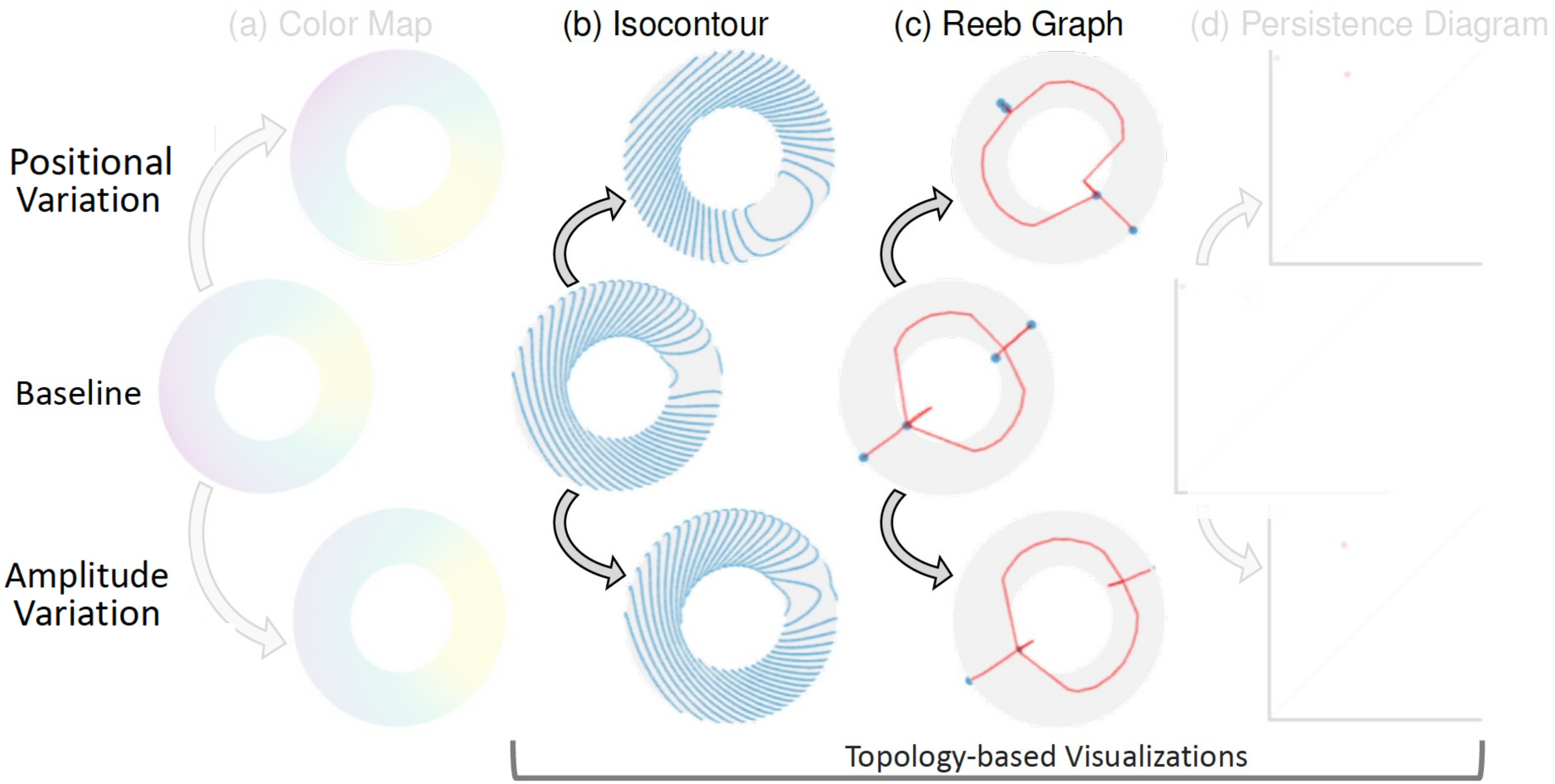


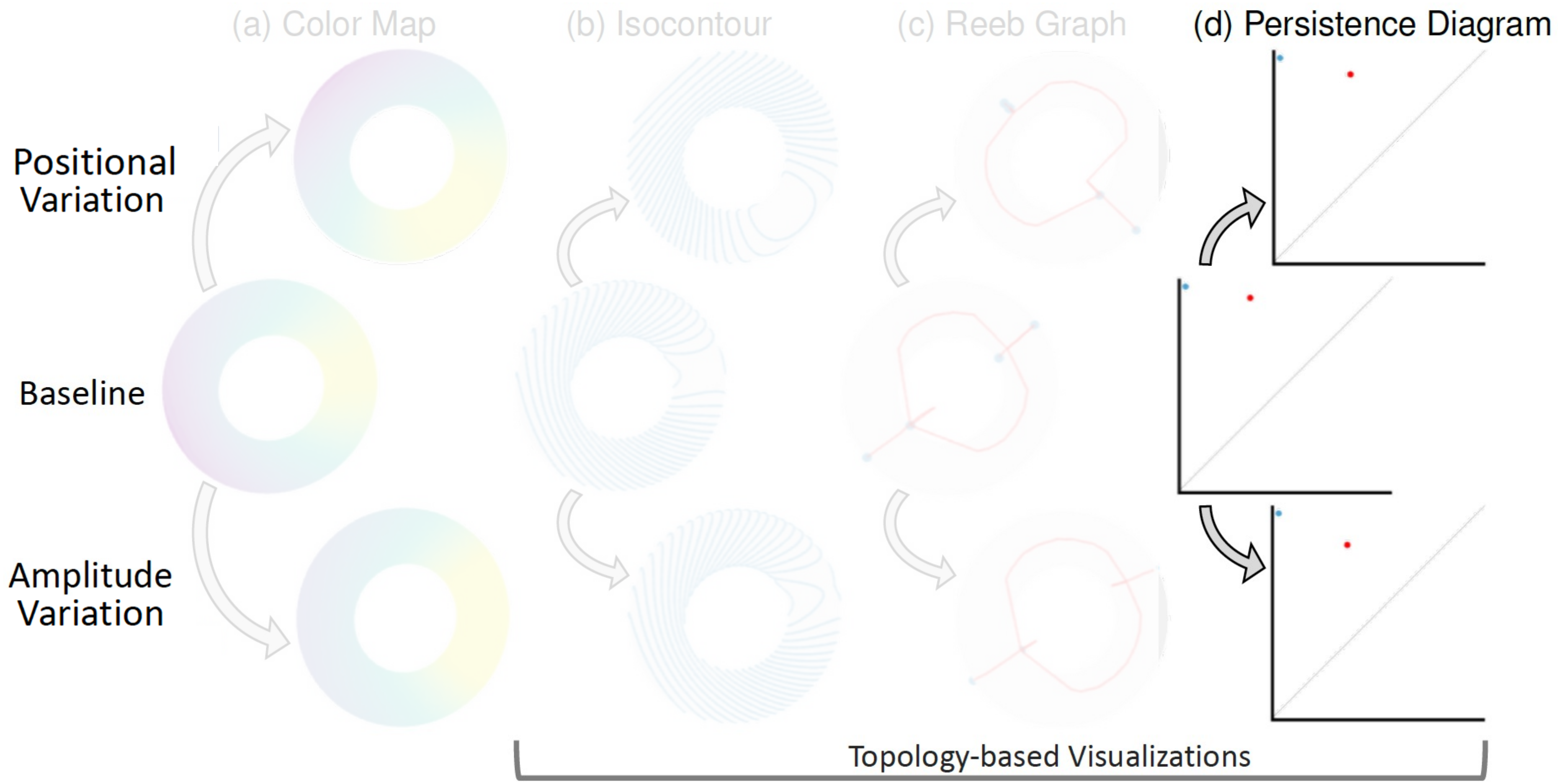
Visualization Method	Position sensitive	Amplitude sensitive
Color map	✓	✓

Hypothesis



Visualization Method	Position sensitive	Amplitude sensitive
Color map	✓	✓
Isocontours	✓	✗
Reeb graph	✓	✗

Hypothesis



Visualization Method	Position sensitive	Amplitude sensitive
Color map	✓	✓
Isocontours	✓	✗
Reeb graph	✓	✗
Persistence diagram	✗	✓

Method: Sensitivity Analysis for Visualizations

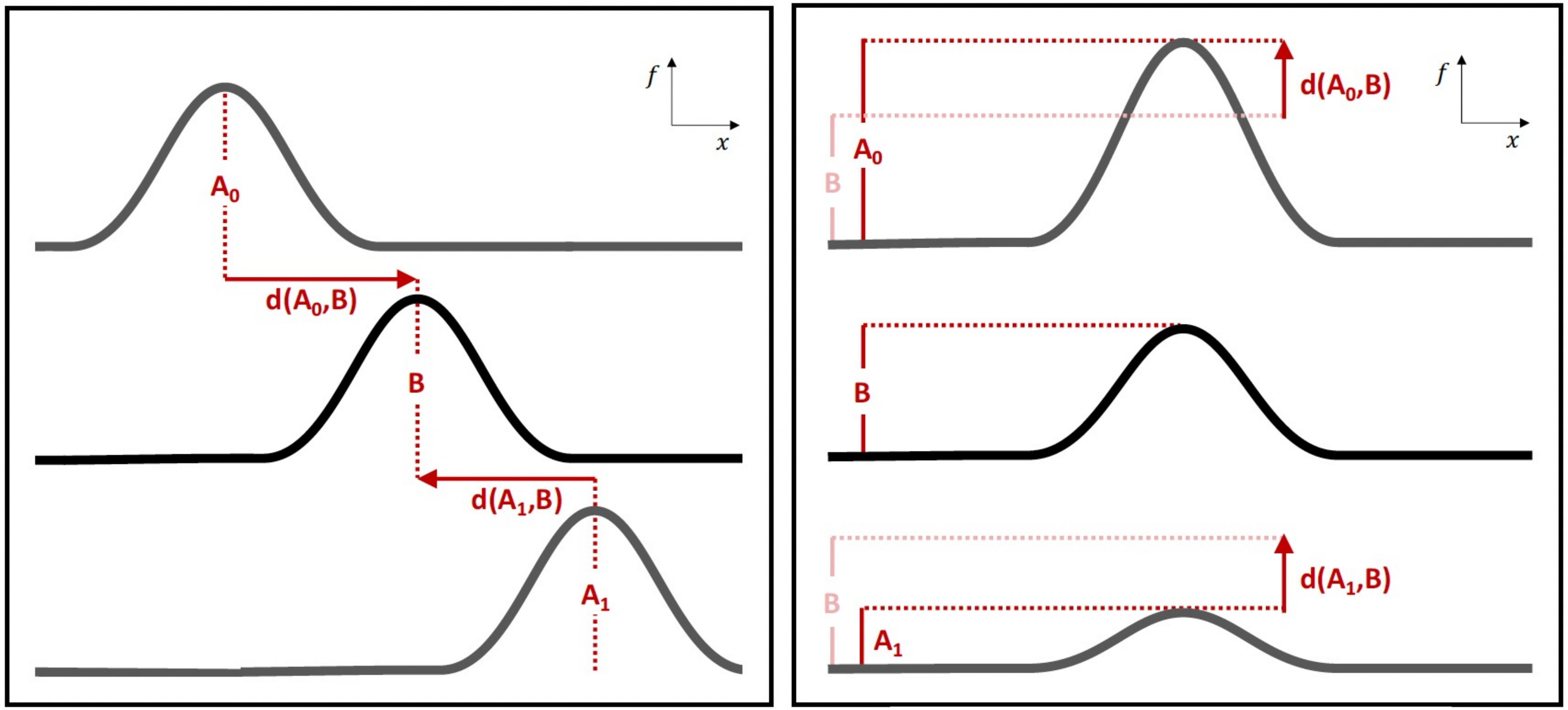
1D Example

Difficult to tell if variation A0 or A1 is closer to the baseline B

$$d(A_0, B) \approx d(A_1, B)$$

OR

$$A' = |d(A0,B) - d(A1,B)| \approx 0$$



Positional Variation

Amplitude Variation

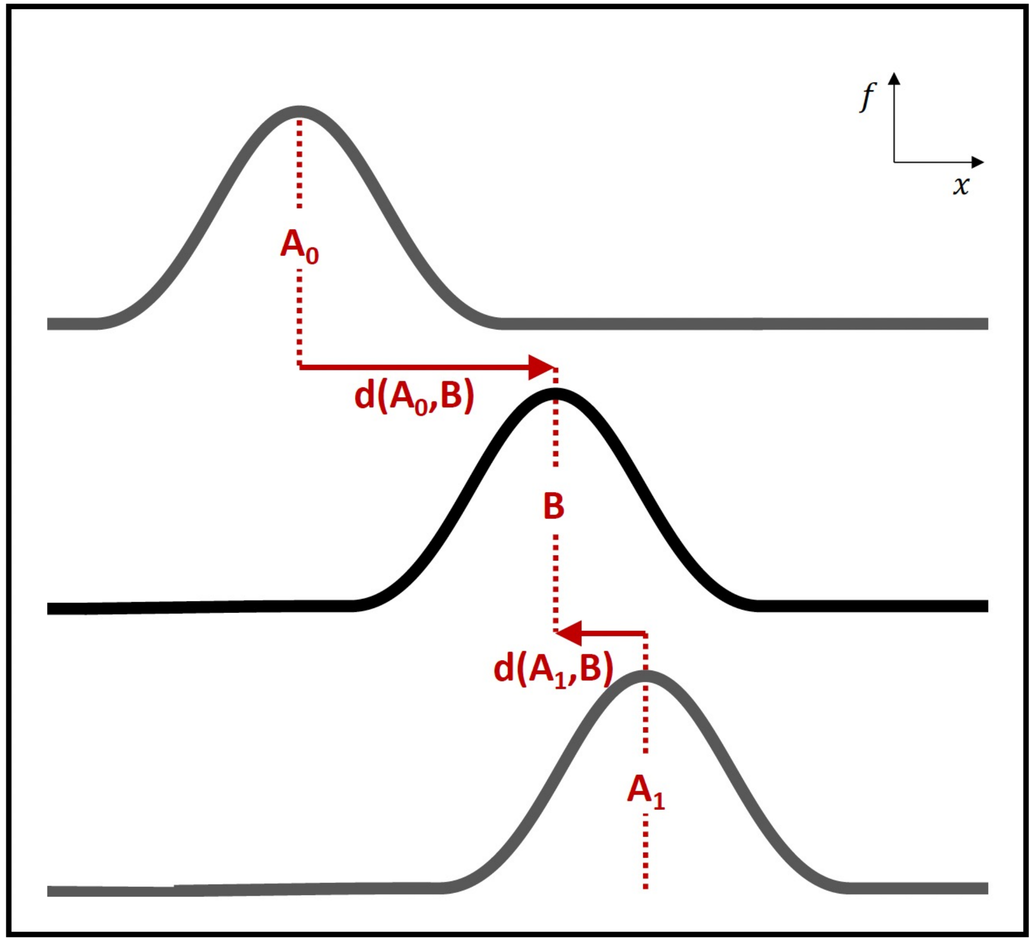
1D Example

Easier to tell if variation A0 or A1 is closer to the baseline B

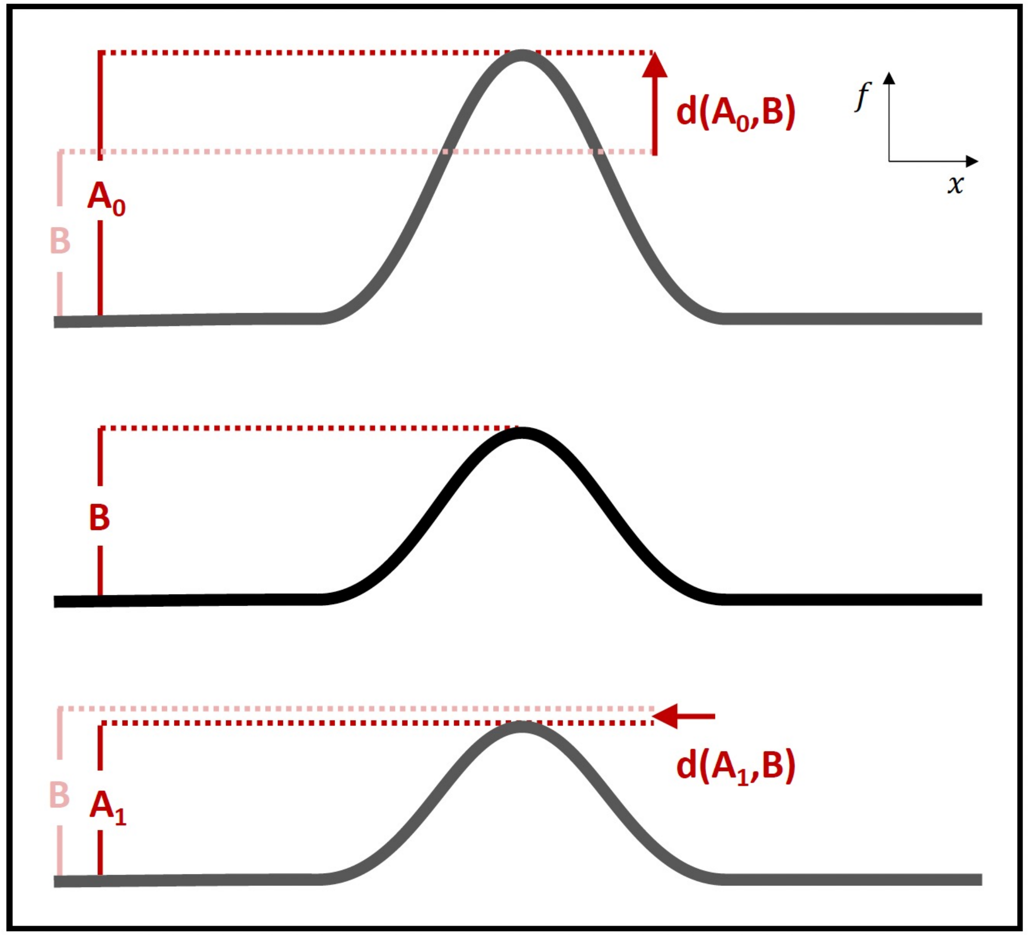
$$d(A_0, B) > d(A_1, B)$$

OR

$$A' = |d(A0,B) - d(A1,B)| > 0$$

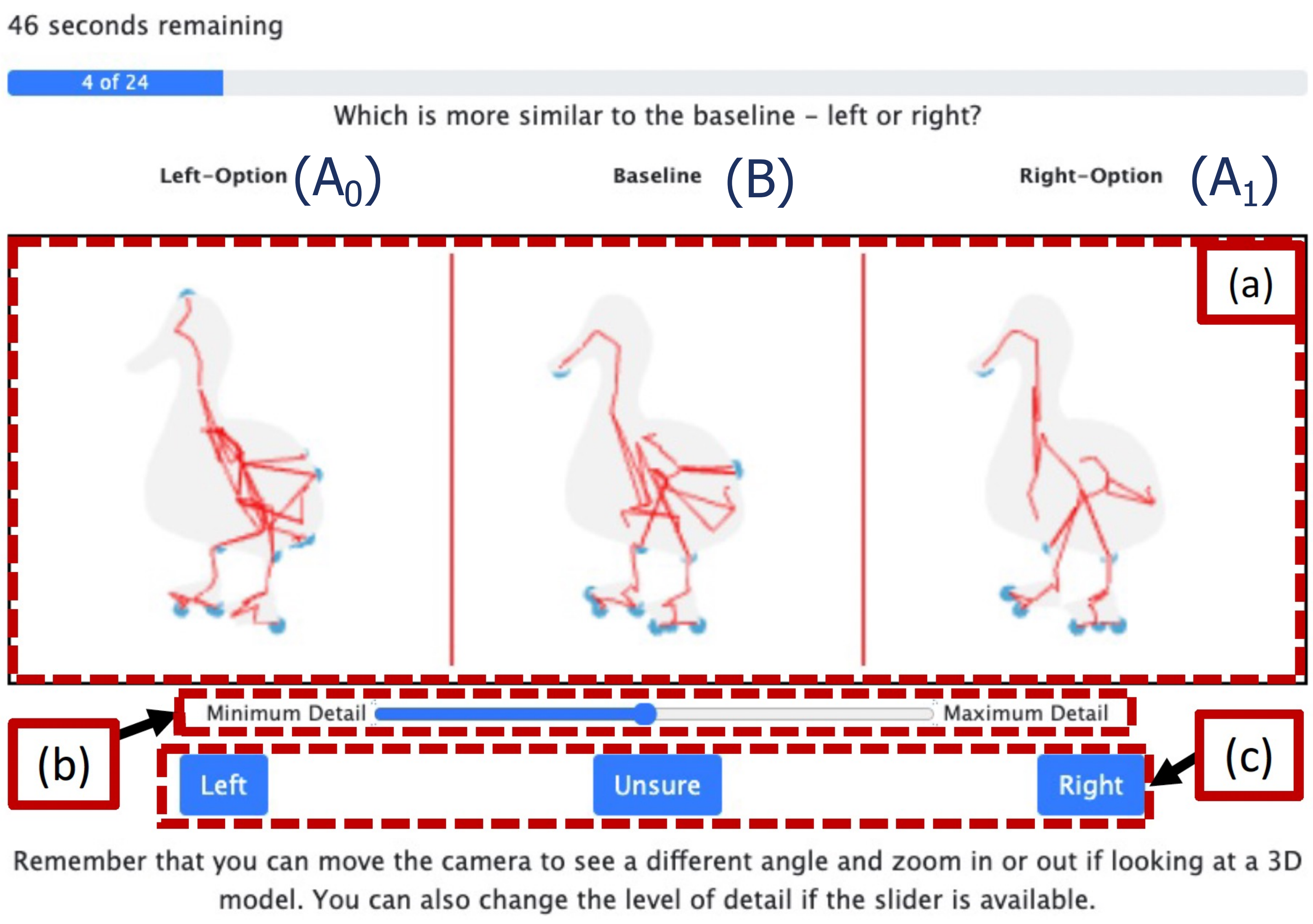


Positional Variation



Amplitude Variation

User Evaluation for 3D Topological Visualizations



(a) Users are presented baseline B in the centre and variations A_0 and A_1 on left and right, respectively.

(b) Users can change the level of detail and rotate view and zoom in or out

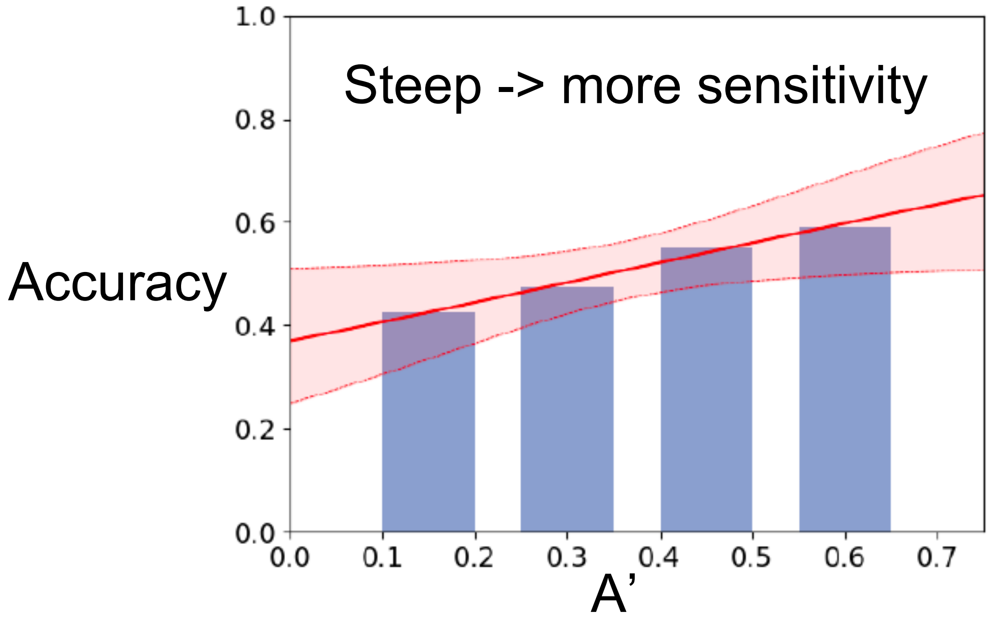
(c) Users need to visually select if visualization for variation A0 or A1 is closer to the visualization for baseline B

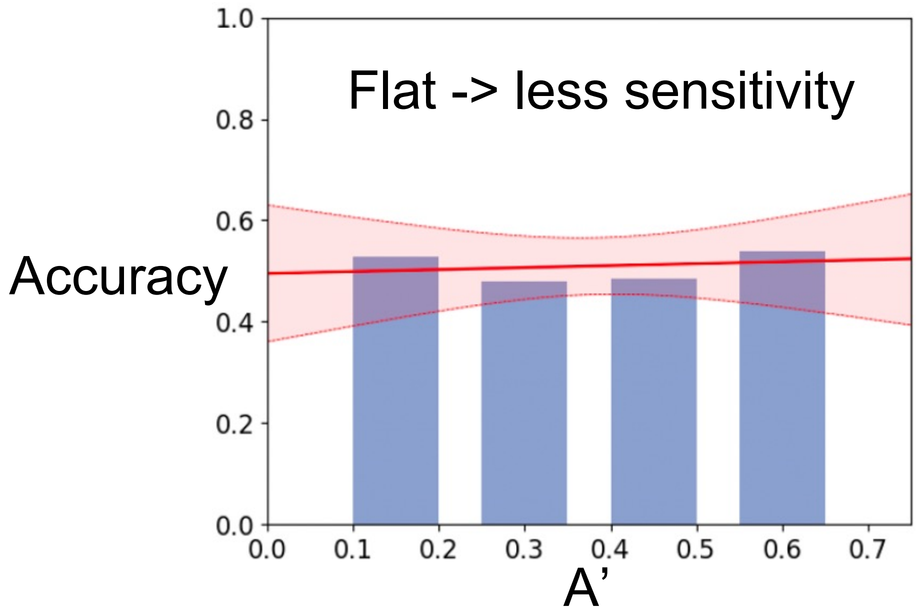
Our Approach for Measuring Sensitivity

- Single experimental trial has an associated measure A′ =|d(A0,B) - d(A1,B)|
  (Hidden from users, but known to the designers of the experiment)

- Small A′ : We expect users to make random guess (close to 50% accuracy)
  Large A′ : We expect users to be more accurate

- Sensitivity: Plot selection accuracy Vs. A′ and estimate the rate of change in accuracy



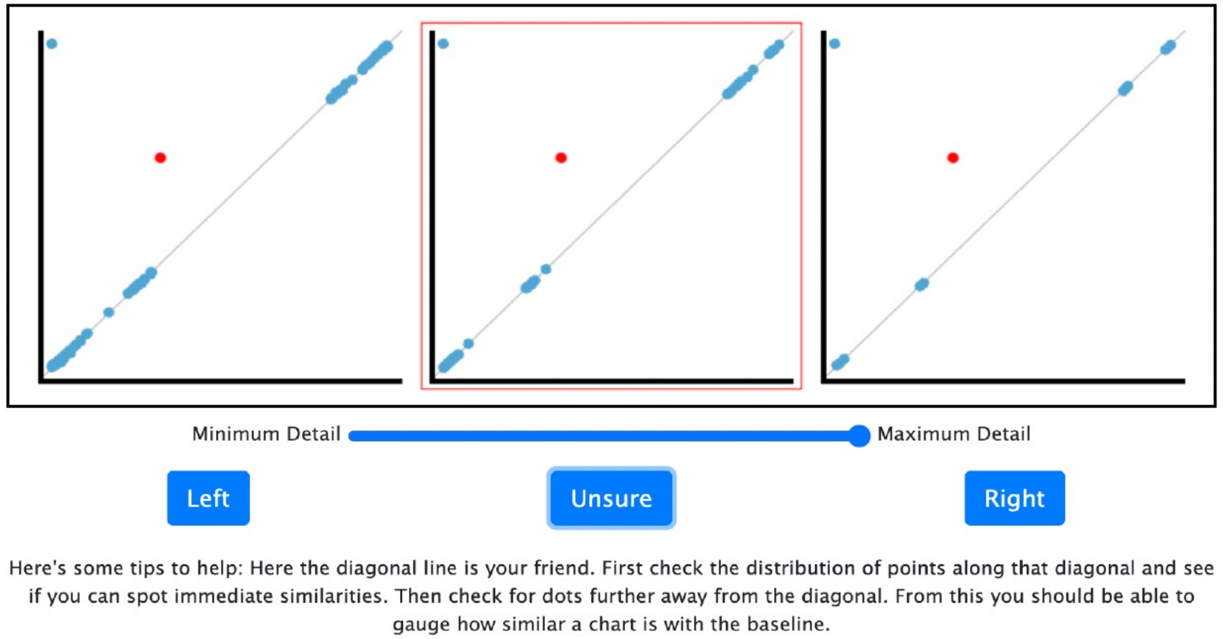


Experimental Setup and Results

Experimental Setup

- 102 non-expert participants, 24 experimental trials per participant, sensitivity analysis based on 102*24=2448 trials
- Each user was presented with tutorial and practice session to get familiar with visualization types and the features to look for
- Between-subject experiment with the following parameters across 24 experimental trials
  - 1 trial per 3D model
  - 6 trials per visualizations type: {color map, isocontour, Reeb graph, persistence diagram}
  - 12 trials per variation type: {position, scale}
  - 6 trials per A': $\{0.15, 0.30, 0.45, 0.60\}$
  - 8 trials per SNR value: $\{80, 90, 100\}$
  - 3 trials per NOF in the range: $[2, 9]$
- Conducted study on Amazon Mechanical Turk (users with HIT approval rate > 95%)

Practice question for persistence diagram



Results: Accuracy

Accuracy = N_{corr}/N_{trials}

Positional variation

Method	Accuracy				
	$A' = .15$	$A' = .30$	$A' = .45$	$A' = .60$	**Overall**
Color maps	62.3%	61.4%	56.6%	67.4%	**64.0%** ($p < .001$)
Isocontours	54.7%	59.3%	56.7%	56.0%	**58.8%** ($p = .002$)
Reeb graph	42.7%	47.4%	55.1%	58.9%	52.5% ($p = .208$)
Persistence diagrams	56.5%	66.2%	55.2%	50.6%	**57.8%** ($p = .002$)

Amplitude variation

Method	Accuracy				
	$A' = .15$	$A' = .30$	$A' = .45$	$A' = .60$	**Overall**
Color maps	48.8%	52.9%	60.3%	67.1%	**59.3%** ($p < .001$)
Isocontours	48.7%	49.4%	54.9%	62.5%	**55.8%** ($p = .022$)
Reeb graph	52.8%	48.1%	48.5%	53.9%	52.2% ($p = .243$)
Persistence diagrams	47.4%	57.5%	65.7%	81.3%	**63.0%** ($p < .001$)

- A' =|d(A0,B) - d(A1,B)|
- **Our hypothesis:**
  Small A': lower expected accuracy
  Large A': higher expected accuracy
- Our hypothesis statistically significant for all visualization types except for Reeb graphs

Results: Accuracy

Accuracy = N_{corr}/N_{trials}

Positional variation

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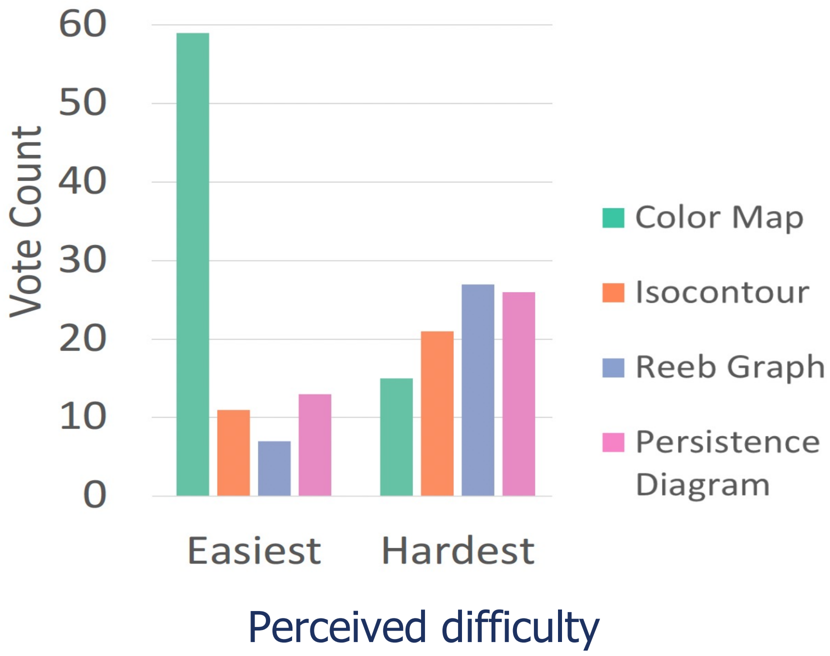
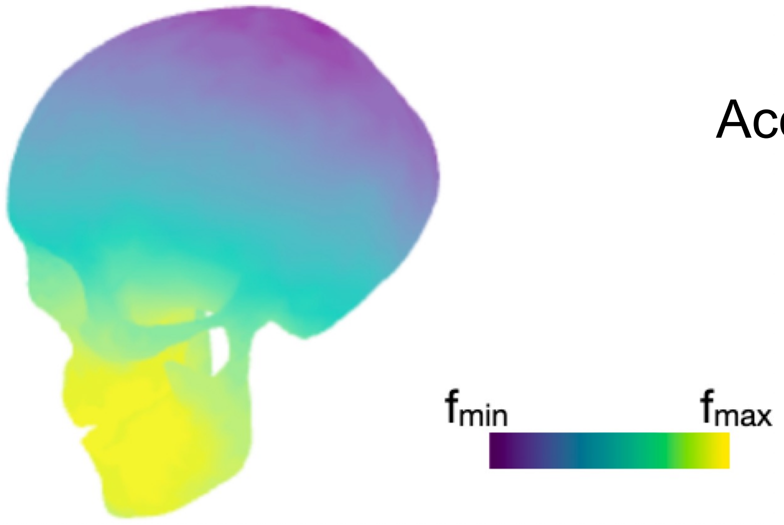
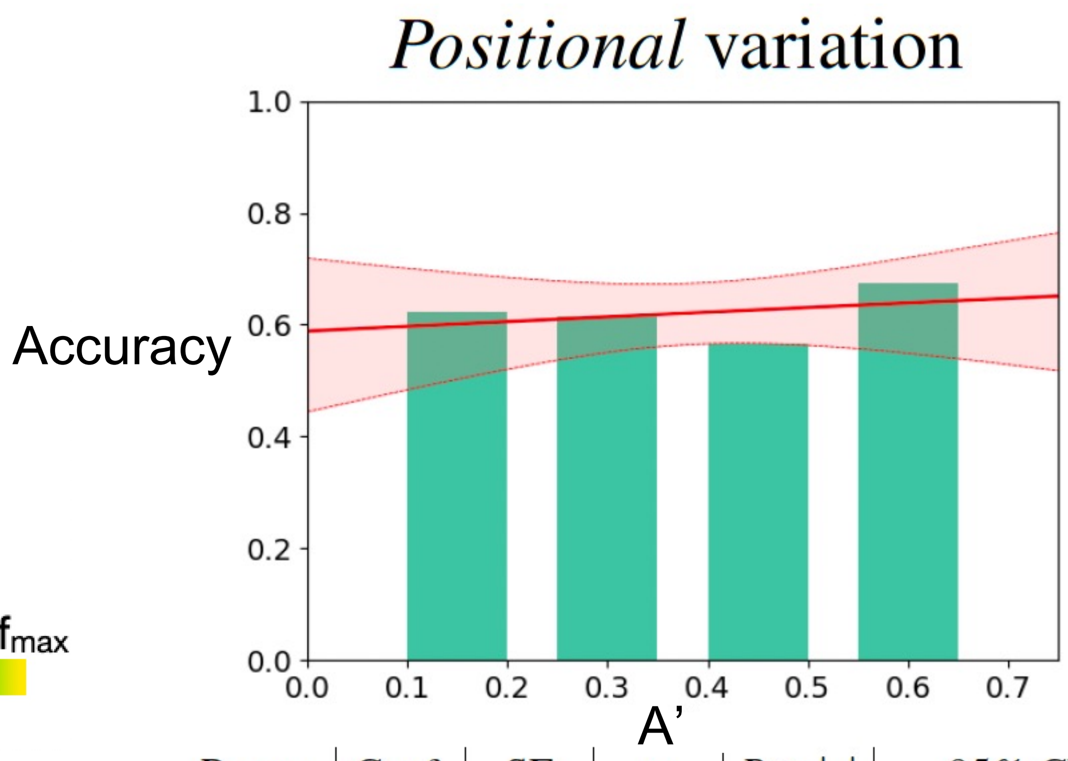
Reeb graphs displayed overall lower accuracy due to their discrete, high-frequency nature



Results: Color Map Sensitivity



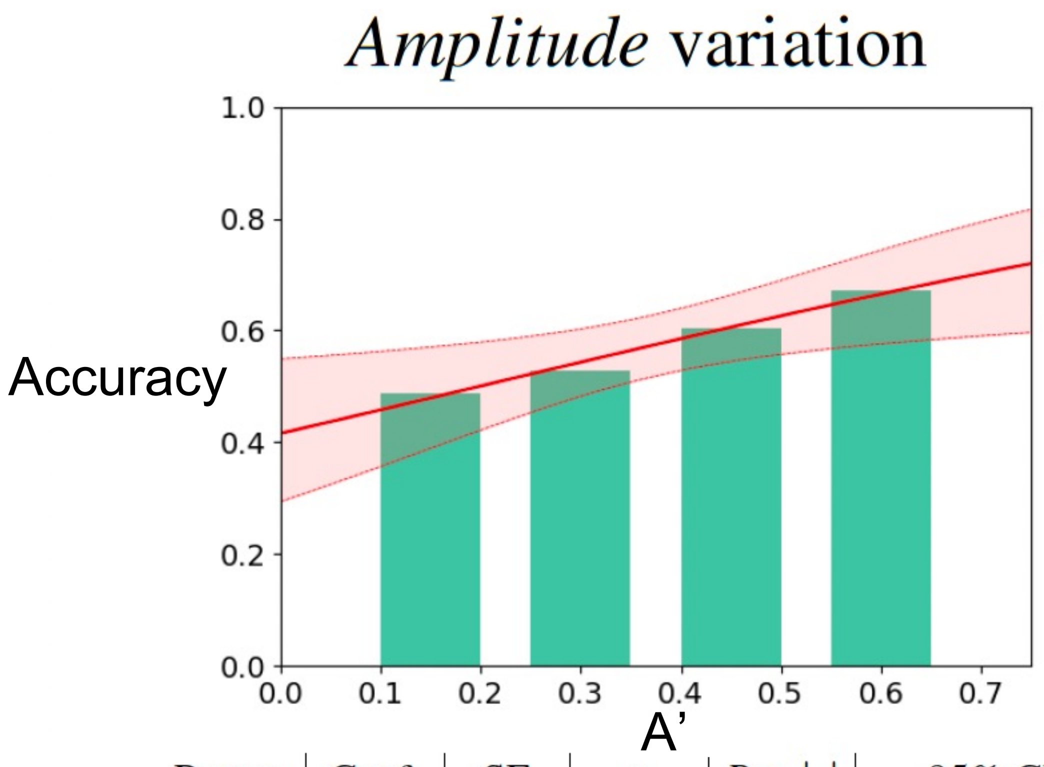


Param.	Coef.	SE	z	$P > \|z\|$	95% CI
A'	0.355	0.703	0.505	0.613	[-1.022, 1.732]
(intcp)	0.357	0.297	1.204	0.228	[-0.224, 0.939]

Color maps ($p = .613$)

Hypothesis: *sensitive*

hypothesis rejected



Param.	Coef.	SE	z	$P > \|z\|$	95% CI
A'	1.708	0.672	2.541	0.011	[0.391, 3.026]
(intcp)	-0.340	0.274	-1.241	0.215	[-0.876, 0.197]

Color maps (**$p = .010$**)

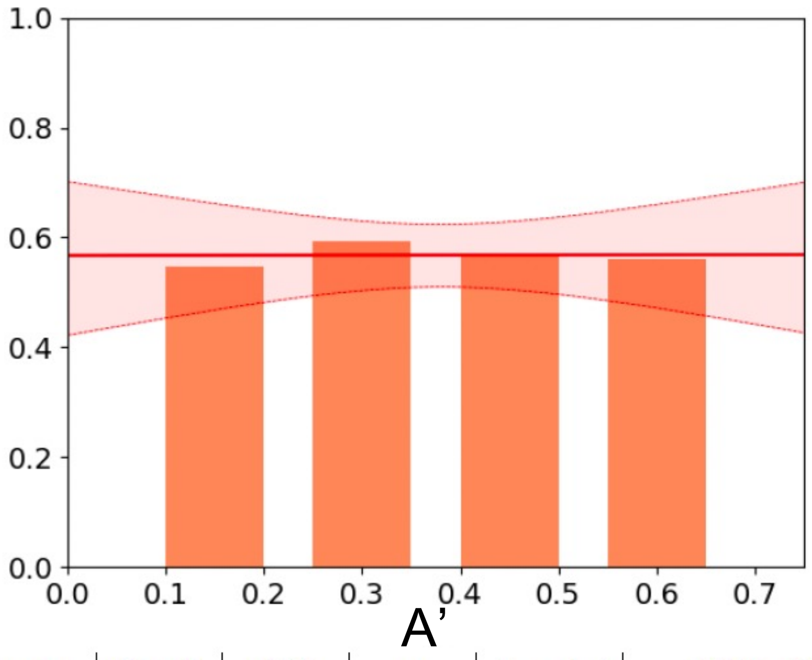
Hypothesis: *sensitive*

hypothesis validated

Results: Isocontour Sensitivity

Positional variation

Accuracy



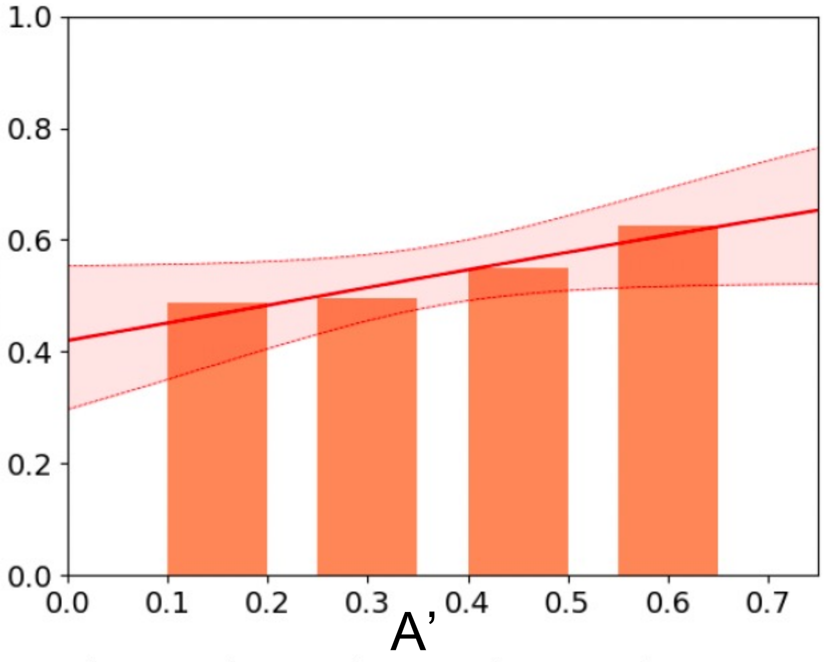
Param.	Coef.	SE	z	$P > \|z\|$	95% CI
A'	0.008	0.720	0.011	0.991	[-1.403, 1.419]
(intcp)	0.270	0.298	0.906	0.365	[-0.314, 0.855]

Isocontours ($p = .991$)

Hypothesis: *sensitive*

hypothesis rejected

Amplitude variation



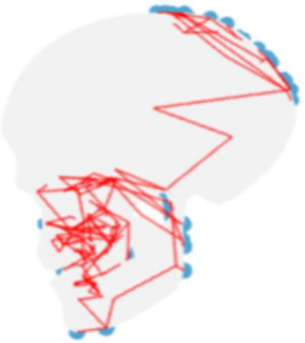
Param.	Coef.	SE	z	$P > \|z\|$	95% CI
A'	1.272	0.676	1.881	0.060	[-0.054, 2.598]
(intcp)	-0.323	0.275	-1.173	0.241	[-0.862, 0.217]

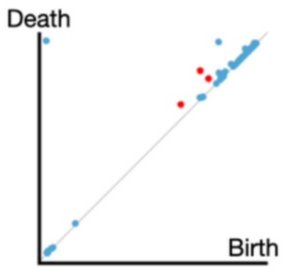
Isocontours ($p = .059$)

Hypothesis: *not sensitive*

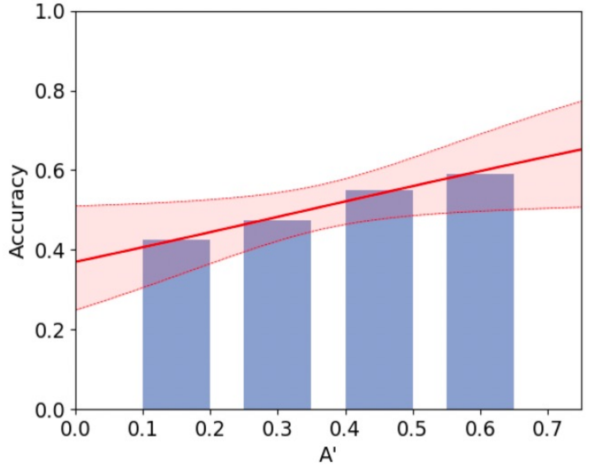
ambiguous result

Results: Reeb Graph and Persistence Diagram Sensitivity





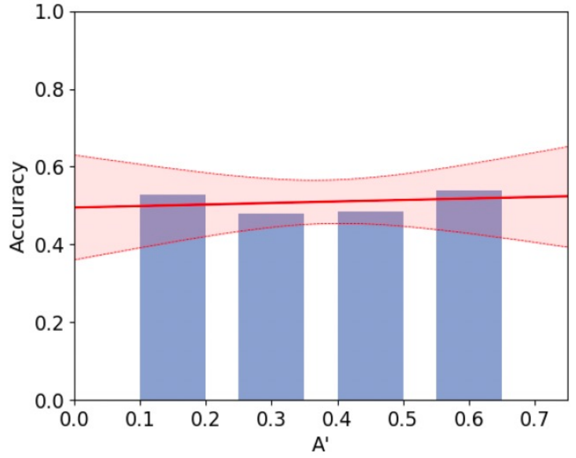
Positional variation



Param.	Coef.	SE	z	$P > \|z\|$	95% CI
A'	1.546	0.735	2.103	0.035	[0.105, 2.987]
(intcp)	-0.533	0.292	-1.823	0.068	[-1.106, 0.040]

Reeb graphs (**$p = .034$**)

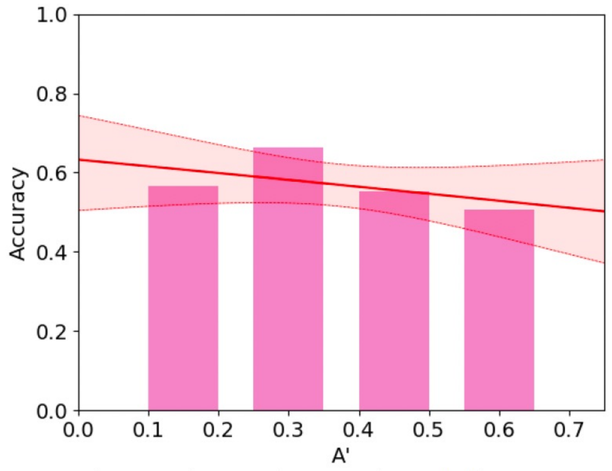
Amplitude variation



Param.	Coef.	SE	z	$P > \|z\|$	95% CI
A'	0.155	0.670	0.231	0.817	[-1.158, 1.467]
(intcp)	-0.020	0.282	-0.071	0.943	[-0.573, 0.533]

Reeb graphs ($p = .817$)

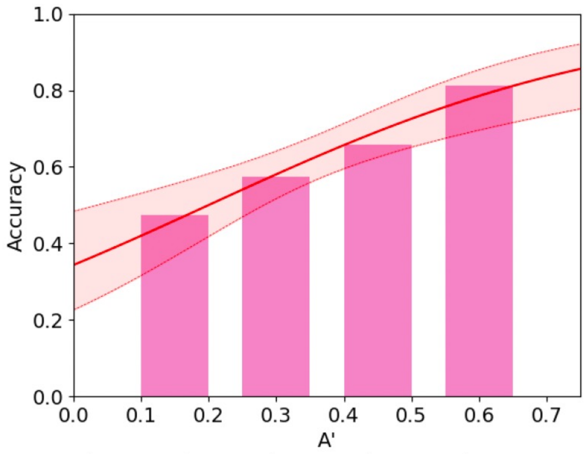
Positional variation



Param.	Coef.	SE	z	$P > \|z\|$	95% CI
A'	-0.712	0.655	-1.087	0.277	[-1.997, 0.572]
(intcp)	0.543	0.268	2.027	0.043	[0.018, 1.068]

Persistence diagrams ($p = .276$)

Amplitude variation



Param.	Coef.	SE	z	$P > \|z\|$	95% CI
A'	3.238	0.786	4.121	0.000	[1.698, 4.778]
(intcp)	-0.647	0.297	-2.176	0.030	[-1.230, -0.64]

Persistence diagrams (**$p < .001$**)

Hypothesis was validated in the all cases!

Observations and Implications

Hypothesis

Visualization Method	Position Sensitive	Amplitude Sensitive
Color map	Yes	Yes
Isocontours	Yes	No
Reeb graph	Yes	No
Persistence diagram	No	Yes

Observation

Visualization Method	Position Sensitive	Amplitude Sensitive
Color map	Yes	No
Isocontours	No	Maybe
Reeb graph	Yes	No
Persistence diagram	No	Yes

- No single visualization to rule them all!
- Need for multiview visualization or enhancement in existing visualization design for better portrayal of features and enhanced sensitivity

Limitations and Future Work

- **Task:**
  Limitation: Task of comparison of scalar fields.
  Future work: Study different tasks performed with scalar fields.

- **Participant Pool:**
  Limitation: Participant pool comprises mainly non-experts and can have effect on accuracy statistics. We note that experts may be influenced by familiarity bias (Dunning-Kruger effect [Kurger and Dunning, 1999])
  Future work: Cover more diverse pool of participants.

- **Data and Features Evaluated:**
  Limitation: Data is modeled as a mixture of isotropic Gaussian functions on 2D manifolds, scale and position variation for evaluation.
  Future work: Need study for non-isotropic Gaussian functions, 3D volumetric datasets, variations other than position and scale.

- **Visualizations Evaluated:**
  Limitation: Our study is limited to color maps (viridis), isocontours, Reeb graphs, and persistence diagrams.
  Future work: Other visualization variations, e.g., planer Reeb graphs, Morse complexes, Multiview visualizations yet remain to be investigated.

Thank you for your attention!

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