Evaluating Multivariate Network Visualization Techniques Using a Validated Design and Crowdsourcing Approach

Supplementary Material

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Contents

1 Participant Demographics

This section presents the demographic information for our participant pool, including distribution of age, sex, highest degree achieved, browser used, and self-assessed visualization proficiency.
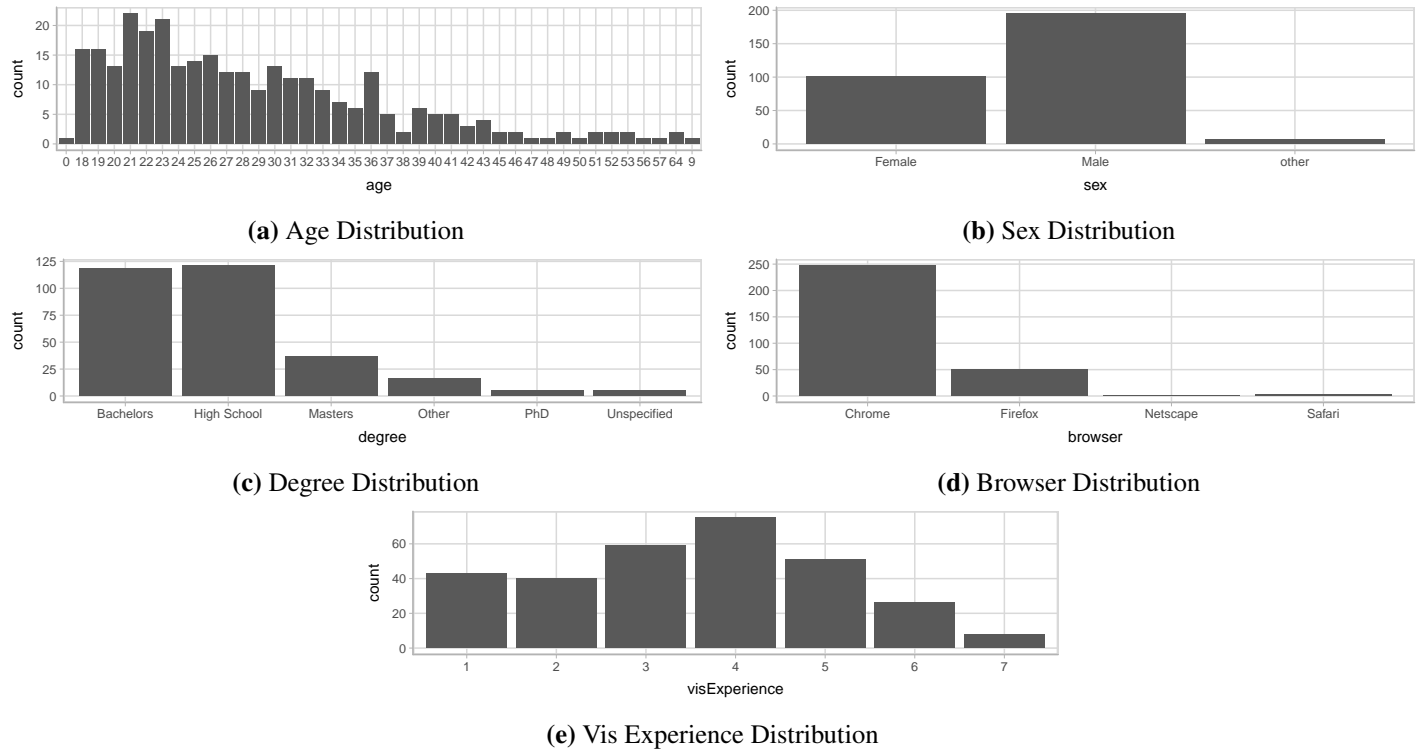

(a) Age Distribution

(b) Sex Distribution

(c) Degree Distribution

(d) Browser Distribution

(e) Vis Experience Distribution

Figure 1: Participant Demographics.

2 Tasks

The following section contains, for each task, the task prompt, which hypothesis it was meant to investigate, the visual configuration shown to the user depending on their assigned condition, how we scored for accuracy on that task, and results. We also provide links to the interactive visualizations with task instructions and stimuli.

The result plot caption contains the following statistical parameters: Wilcox Test (W), p-value (p), Cohen's d for Effect Size (d), and Median value + 95% confidence intervals (M).

	Task Name	Task Prompt	Properties	Topology Target	Hypothesis
T01	Node Search on At-tribute	Find the North American with the most tweets.	Large 2NA	Single Node	Distractor, Attribute Sort-ing
T02	Node Search on At-tribute with Distractors	Find the European person or institution with the least likes.	Large 6NA	Single Node	Distractor, Attribute Sort-ing
T03	Node Search on Topol-ogy and Multiple Attributes	Which person has many interactions (edges) in this network, several followers, but few tweets and likes in general?	Large 4NA	Single Node	Scalable Attributes
T04	Neighbor Search on Attribute.	Find all of Lane's European neighbors.	Large 1NA	Neighbors	Distractor
T05	Neighbor Search on Attribute with Distrac-tors.	Find all of giCentre's North American neighbors.	Large 6NA	Neighbors	Distractor
T06	Neighbor Search on Edge Attribute.	Who had the most mention interactions with Jeffrey?	Large 2EA	Neighbors	Edge Attributes
T07	Neighbor Overview on Edge Attribute.	Does Alex have more mention interactions with North American or European accounts? Who does he have the most mentions interactions with?	Large 1NA2EA	Neighbors	Edge Attributes
T08	Attribute of Common Neighbors.	Among all people who have interacted with both Jef-frey and Robert, who has the most followers?	Large 1NA	Neighbors	Common Neighbor
T09	Edge Attributes.	What is the most common form of interaction between Evis19 and Jon? How often has this interaction hap-pened?	Large 2EA	Neighbors	Edge Attribute
T10	Node Attribute Comparison.	Select all of Noeska's neighbors that are people and have more friends than followers.	Large 3NA	Neighbors	Within-node Comparison
T11	Node Attr. Comparison on Small Network.	Select the people who have interacted with Thomas and have more friends than followers.	Small 3NA	Neighbors	Within-node Comparison
T12	Cluster and Attribute Estimation	Select all the people who are in a cluster with Alex. Estimate the average number of followers among the selected people.	Large 1NA	Cluster	Cluster
T13	Attribute along Shortest Path	What is the institution on a shortest path between Lane and Rob? What is its continent of origin?	Large 2NA	Path	Path
T14	Attribute along Shortest Path on Small Network.	What is the institution on a shortest path between Jason and Jon? What is its continent of origin?	Small 2NA	Path	Path
T15	Attribute on Multiple Paths	Of the North Americans who are two interactions away from Sereno, who has been on twitter the longest?	Large 1NA	Paths	Path
T16	Free Explore	Please explore the network freely and report on your findings. Is there anything surprising or particularly interesting in the network?	Large 6NA	NA	Insight Generation

Table 1: Summary of tasks, the configrations, the topology target, and the associated hypothesis.

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2.1 Task 1: Node Search on Attribute

Instruction: Find the North American with the most tweets.

Properties: Large Network, 2 Node Attributes, Topology Target: Single Node.

Hypothesis: Distractor Effect Hypothesis, Sorting Attribute Hypothesis.

Scoring: Full score for T.J. 0.5 points for the NA with the second most tweets (Arvind).
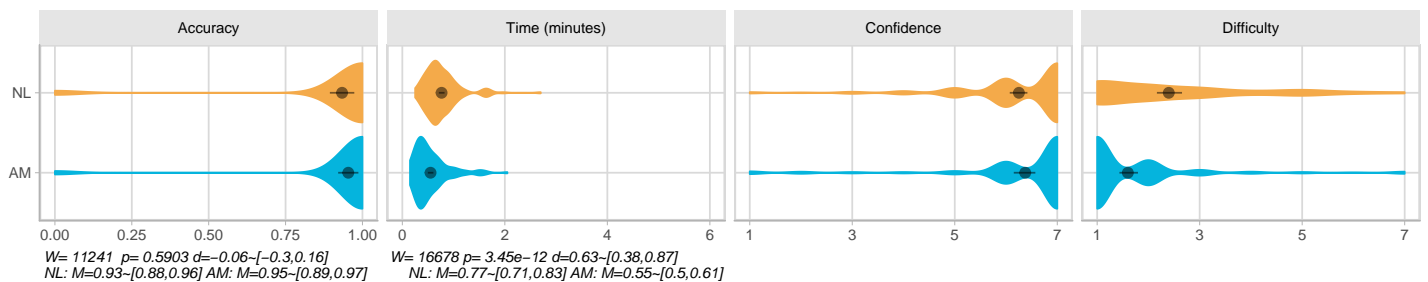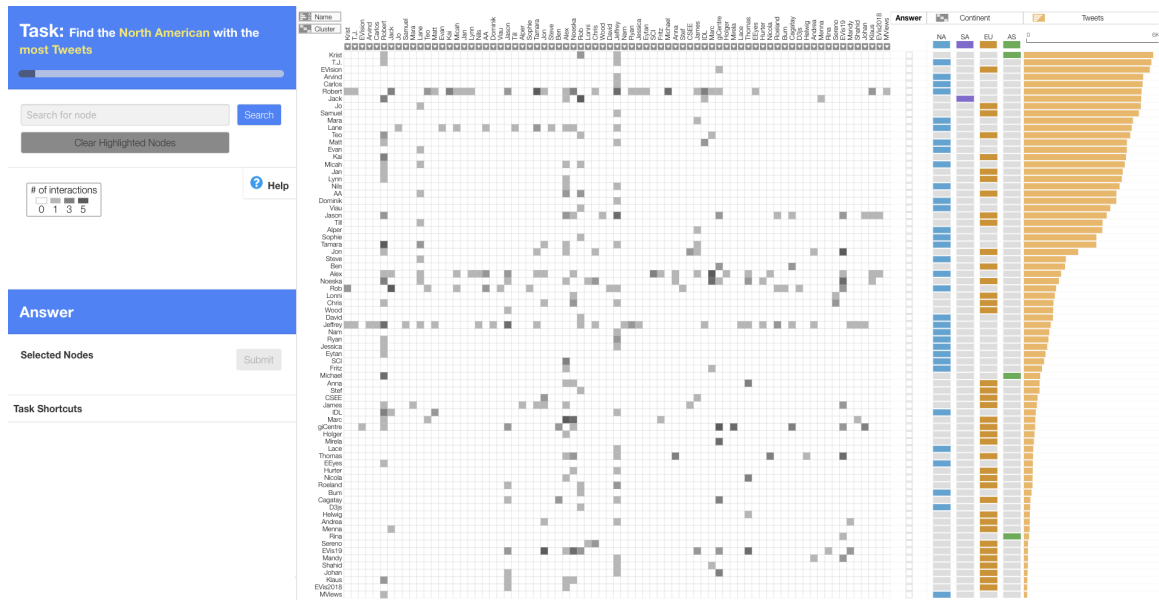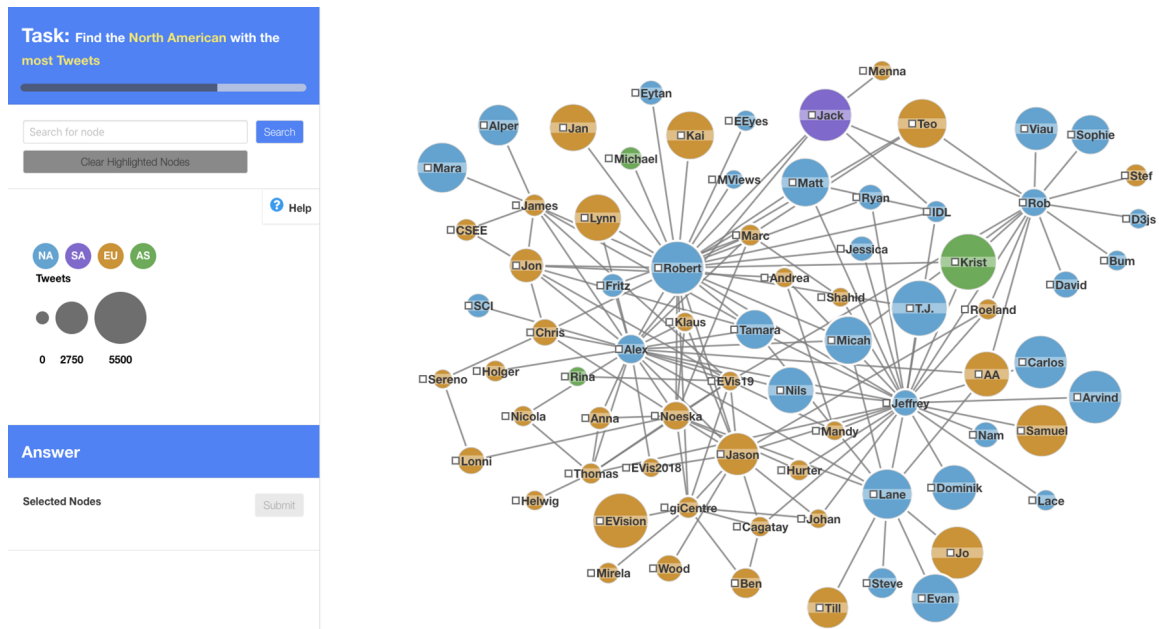
Links: NL, AM

W= 11241 p= 0.5903 d=-0.06~[-0.3,0.16]
NL: M=0.93~[0.88,0.96] AM: M=0.95~[0.89,0.97]

W= 16678 p= 3.45e−12 d=0.63~[0.38,0.87]
NL: M=0.77~[0.71,0.83] AM: M=0.55~[0.5,0.61]

Figure 2: Task 1 configuration and results.

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2.2 Task 2: Node Search on Attribute with Distractors

Instruction: Find the European person or institution with the least likes.
Properties: Large Network, 6 Node Attributes, Topology Target: Single Node.
Hypothesis: Distractor Effect Hypothesis, Sorting Attribute Hypothesis.
Scoring: .5 points for the two Europeans with the second least likes (Jason/Evision).
Links: NL, AM
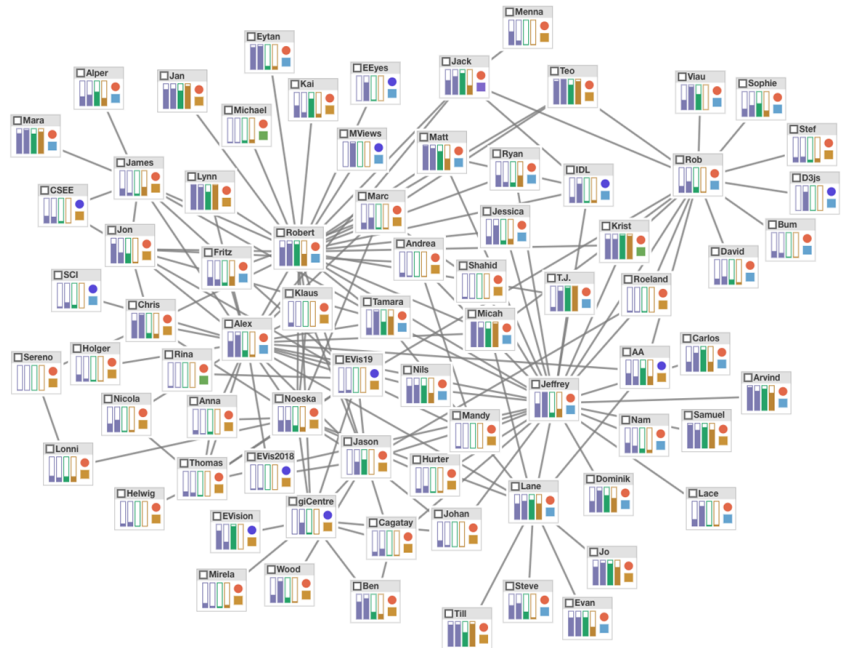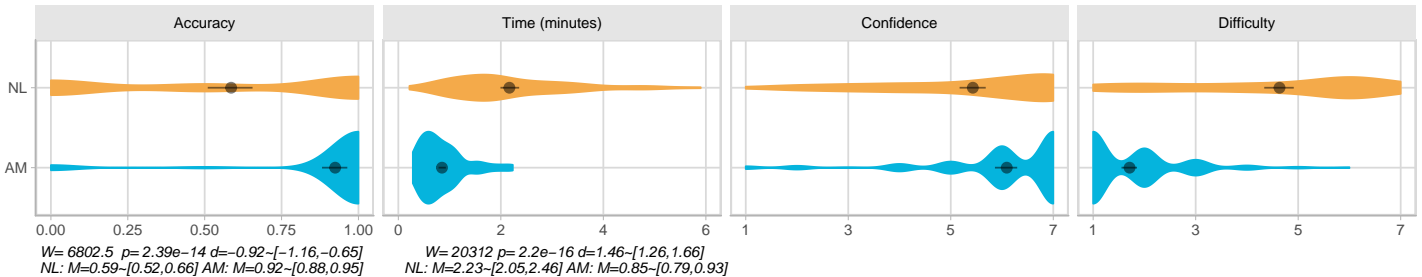
Figure 3: Task 2 configuration and results.

2.3 Task 3: Node Search on Topology and Multiple Attributes

Instruction: Which person has many interactions (edges) in this network, several followers, but few tweets and likes in general?

Properties: Large Network, 4 Node Attributes, Topology Target: Single Node.

Hypothesis: Scalable Attributes.

Scoring: This task didn't ask for a precise answer. We gave 1 point for Jeffrey and Alex, 0.5 points for Noeska and Rob.
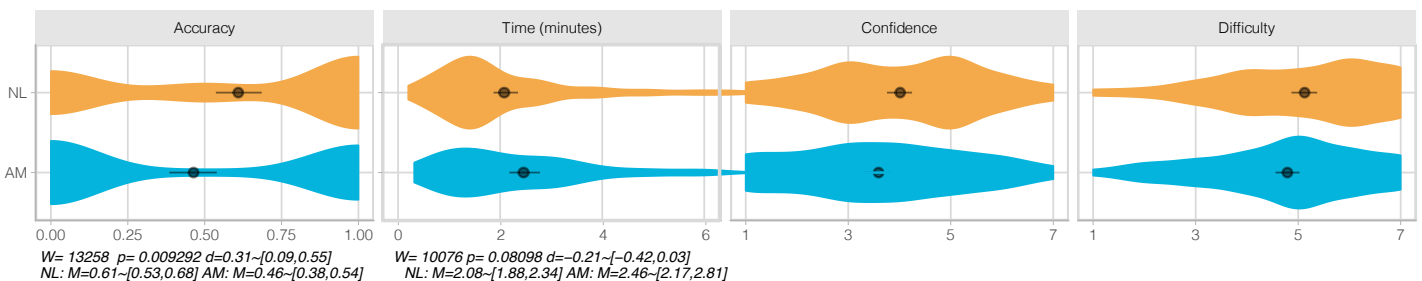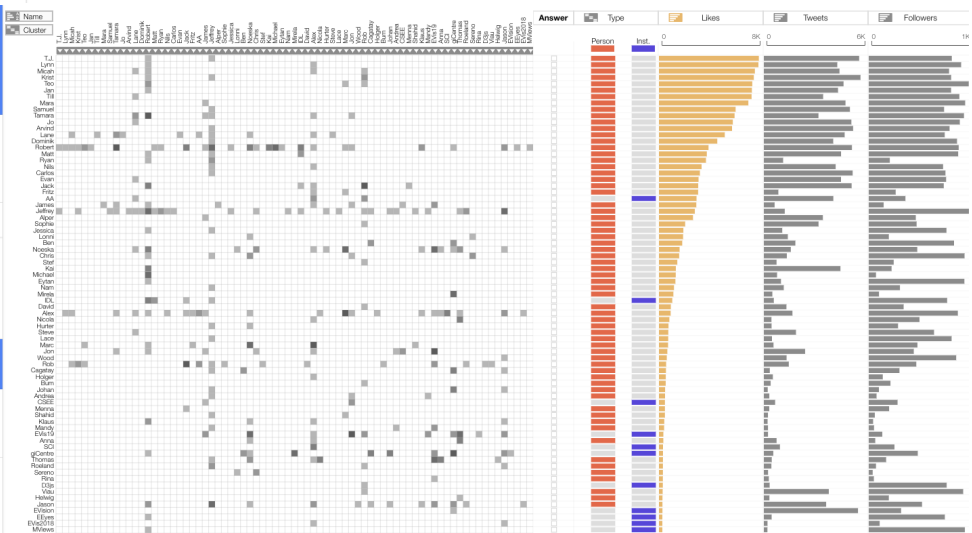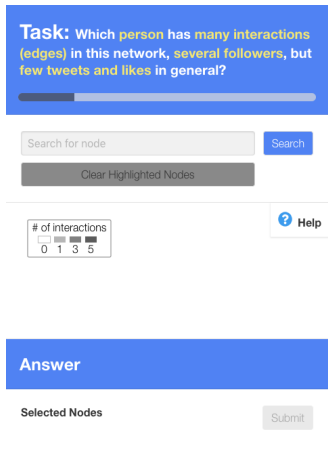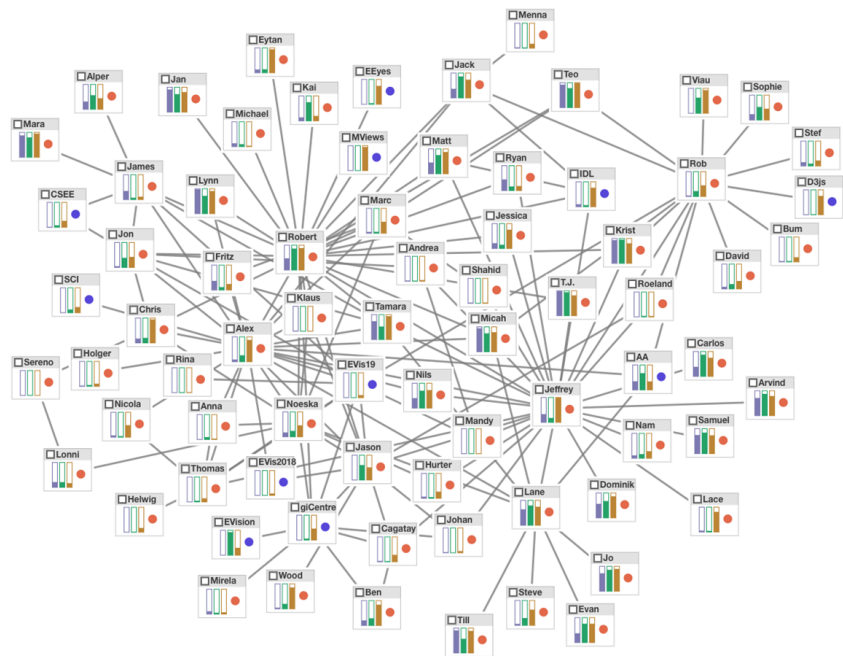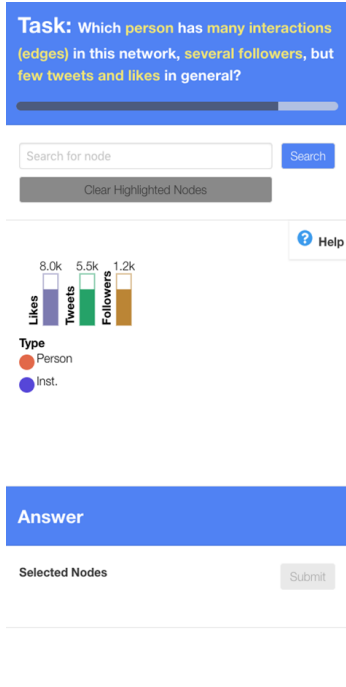
Links: NL, AM

Figure 4: Task 3 configuration and results.

2.4 Task 4: Neighbor Search on Attribute

Instruction: Find all of Lane's European neighbors

Properties: Large Network, 1 Node Attribute, Topology Target: Neighbors.

Hypothesis: Distractor Hypothesis.

Scoring: Correct answer is AA, Noeska, Till, and Joe. 1/4 point for each correct answer. -1/4 point for each incorrect answer.
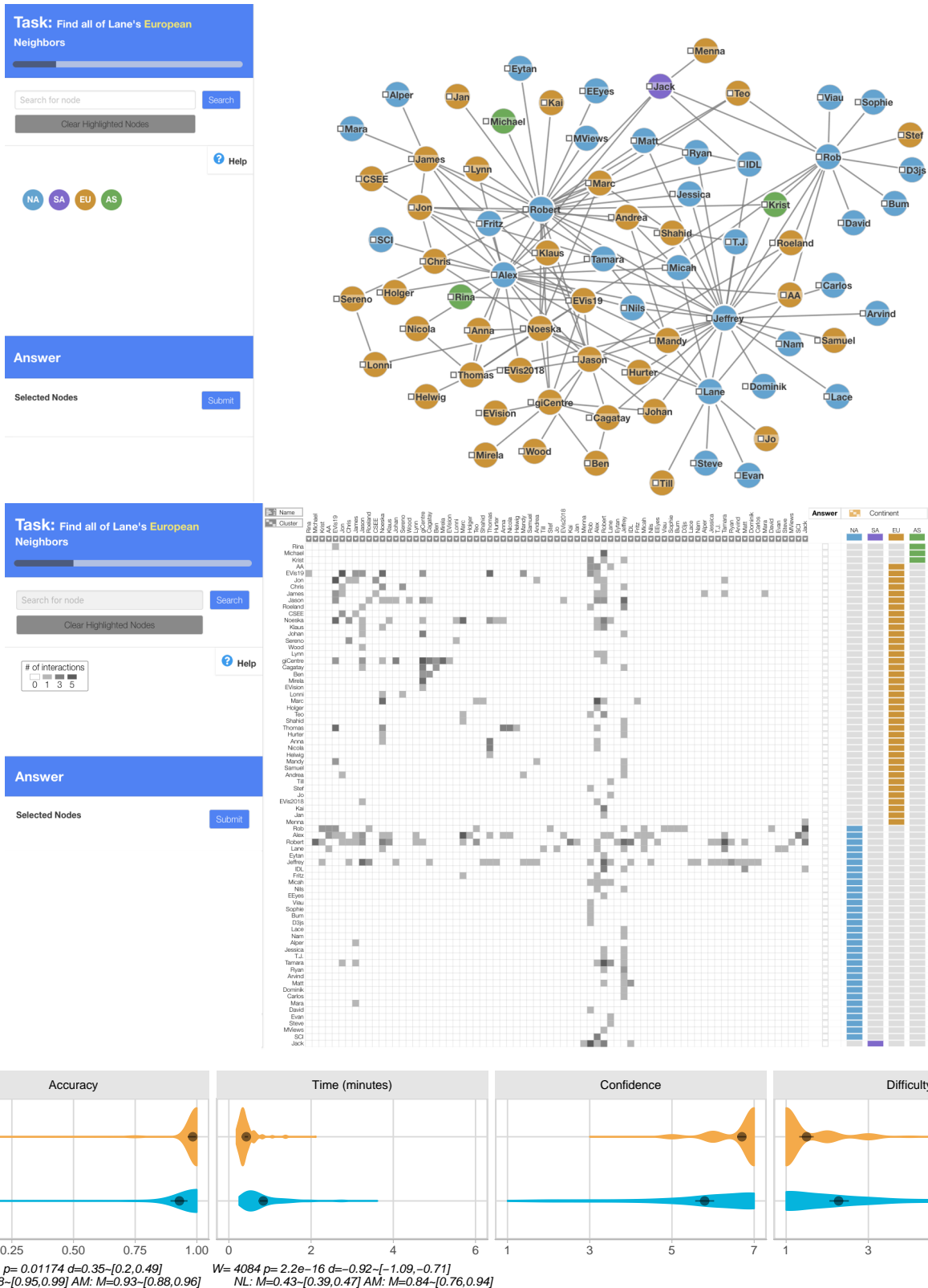
Links: NL, AM

Figure 5: Task 4 configuration and results.

2.5 Task 5: Neighbor Search on Attribute with Distractors

Instruction: Find all of giCentre's North American neighbors
Properties: Large Network, 6 Node Attributes, Topology Target: Neighbors.
Hypothesis: Distractor Hypothesis.
Scoring: Full score for only Robert. 0 otherwise.
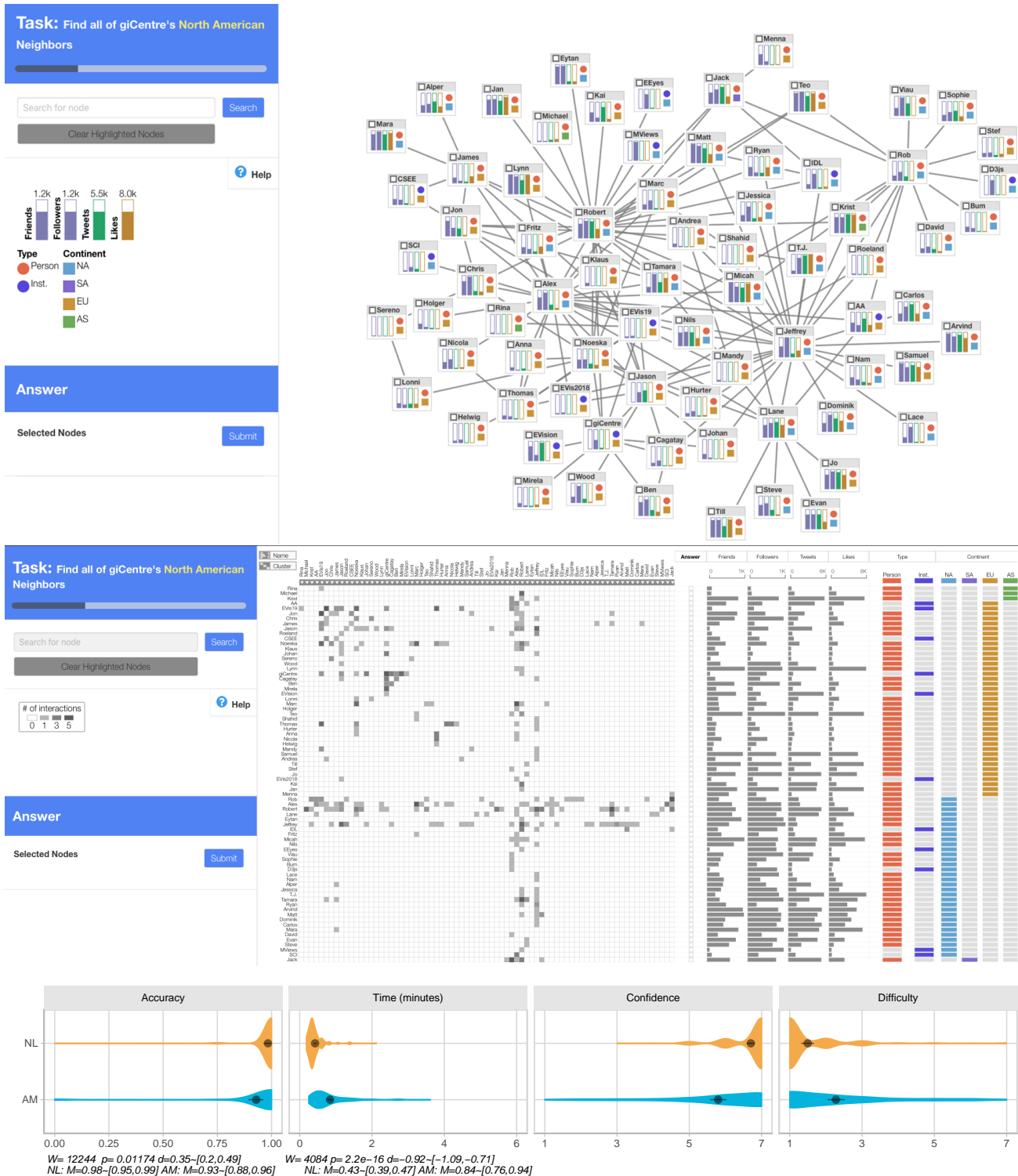**Links:** NL, AM

Figure 6: Task 5 configuration and results.

2.6 Task 6: Neighbor Search on Edge Attribute.

Instruction: Who had the most mentions interactions with Jeffrey?
Properties: Large Network, 2 Edge Attributes, Topology Target: Neighbors.
Hypothesis: Edge Attributes.
Scoring: Full score for only Robert. 0 otherwise
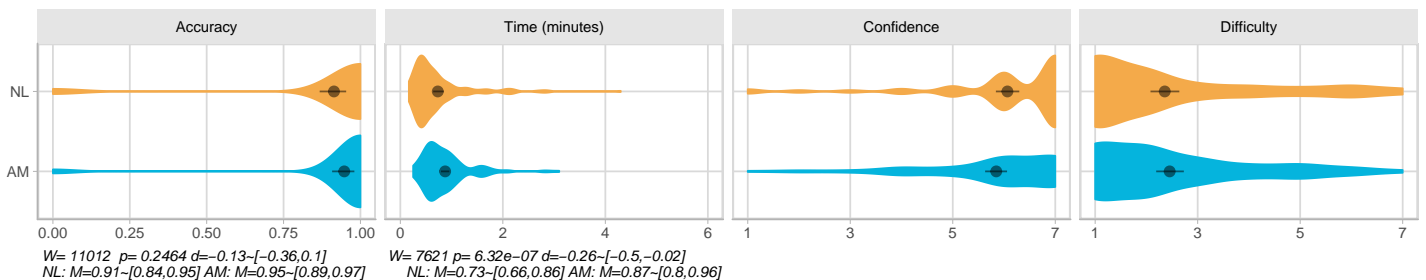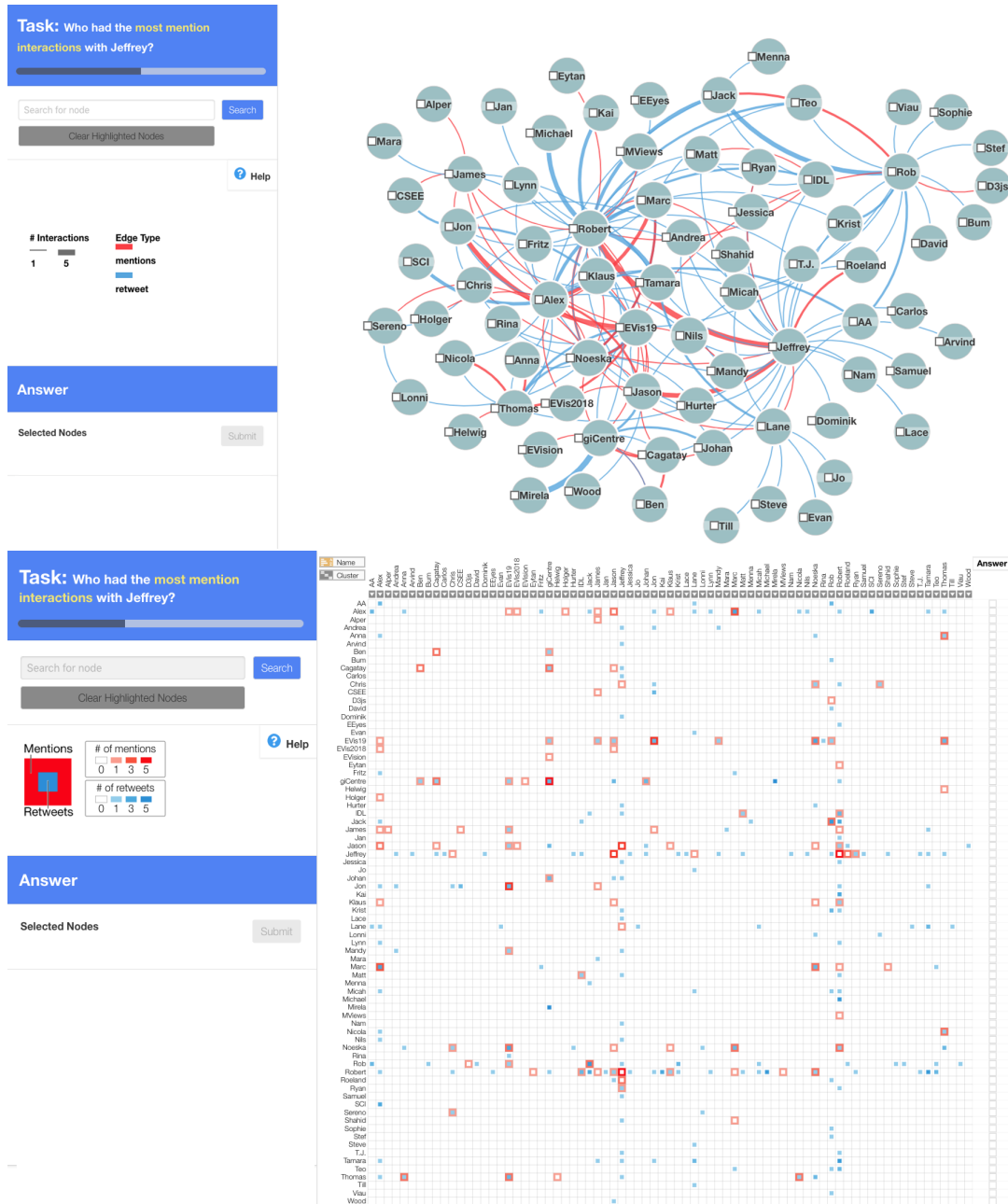**Links:** NL, AM

Figure 7: Task 6 configuration and results.

2.7 Task 7: Neighbor Overview on Edge Attribute

Instruction: Does Alex have more mention interactions with North American or European accounts? Who does he have the most mentions interactions with?

Properties: Large Network, 1 Node Attribute, 2 Edge Attributes, Topology Target: Neighbors.

Hypothesis: Edge Attributes

Scoring: European (worth .5 points). Marc (worth .5 points).
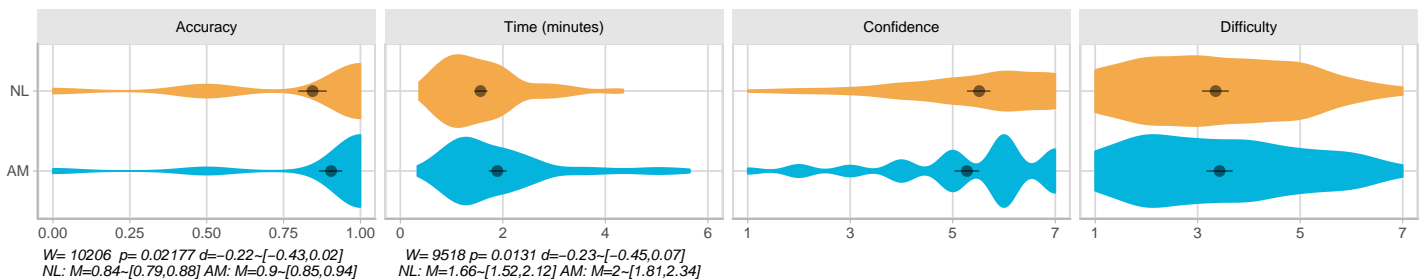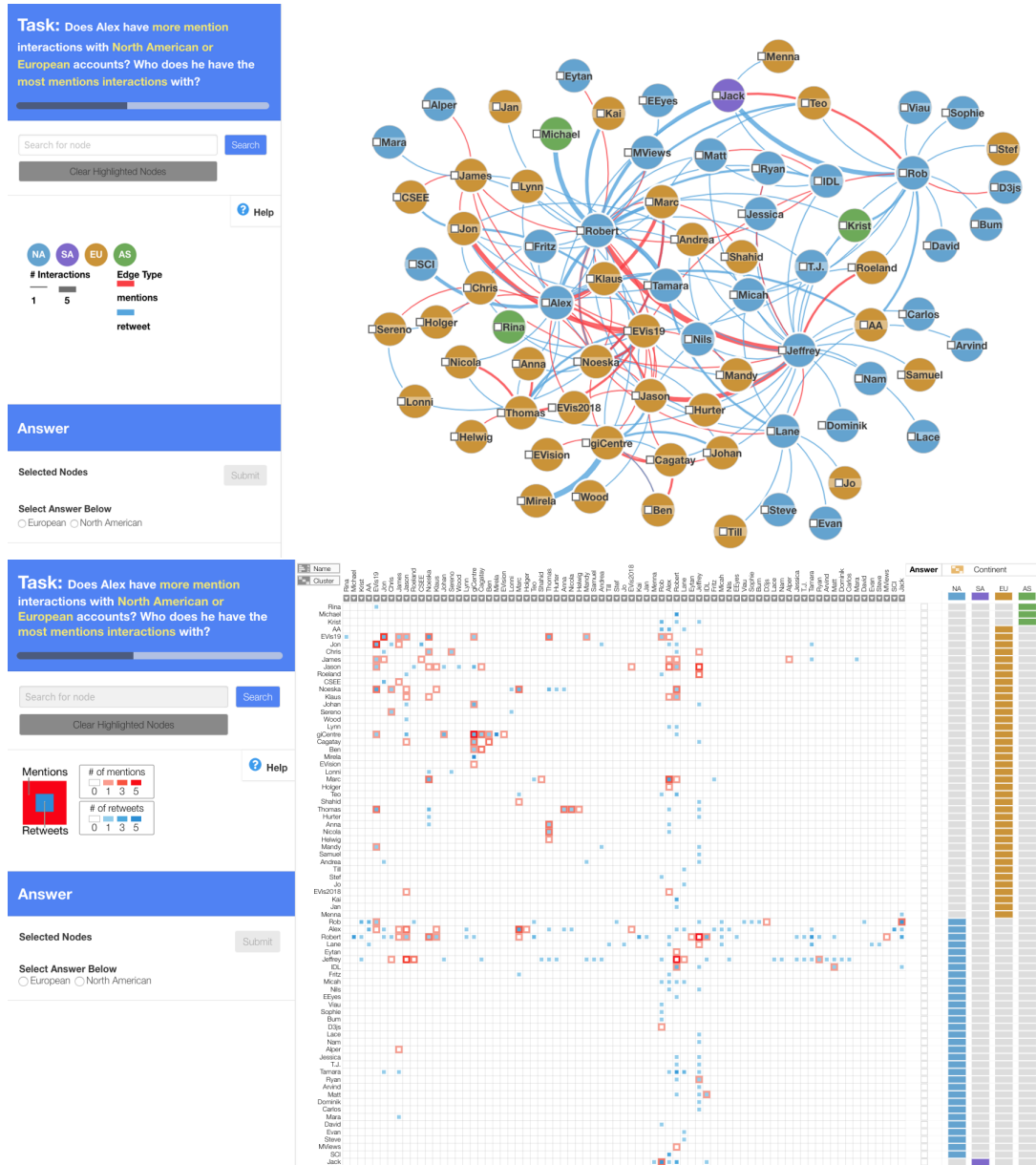
Links: NL, AM

Figure 8: Task 7 configuration and results.

2.8 Task 8: Attribute of Common Neighbors

Instruction: Among all people who have interacted with both Jeffrey and Robert, who has the most followers?
Properties: Large Network, 1 Node Attribute, Topology Target: Neighbors.
Hypothesis: Common Neighbor Hypothesis
Scoring: Full score for Chris, .5 point for Tamara.
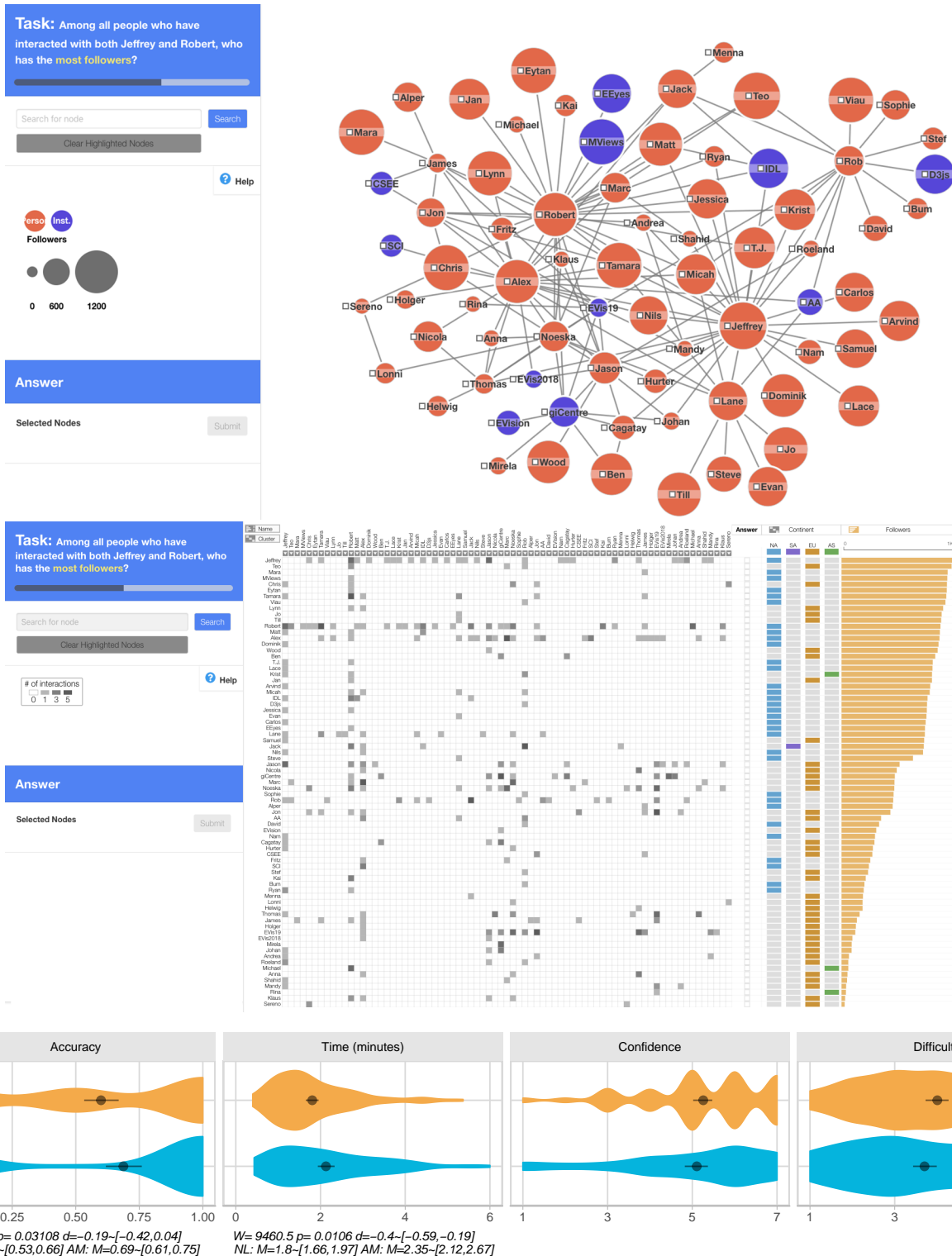**Links:** NL, AM

Figure 9: Task 8 configuration and results.

2.9   Task 9: Edge Attributes

Instruction: What is the most common form of interaction between Evis19 and Jon? How often has this interaction happened?

Properties: Large Network, 2 Edge Attributes, Topology Target: Neighbors.

Hypothesis: Edge Attributes

Scoring: Most common interaction is 'Mentions', worth .5 points. The number of times it has happened is 4, worth .5 points if part A was correct.
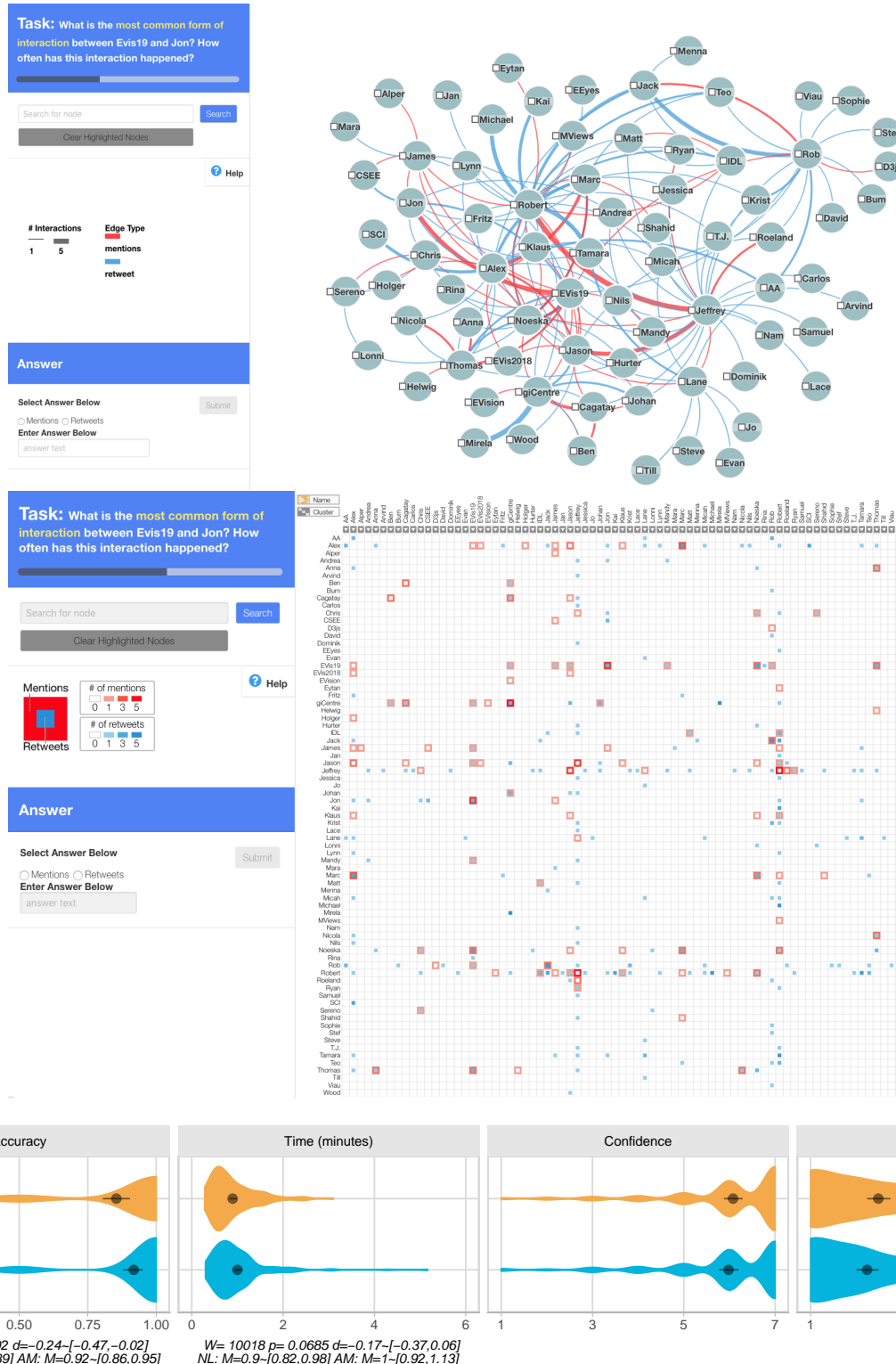
Links: NL, AM

Figure 10: Task 9 configuration and results.

2.10 Task 10: Node Attribute Comparison

Instruction: Select all of Noeska's neighbors that are people and have more friends than followers.

Properties: Large Network, 3 Node Attributes, Topology Target: Neighbors.

Hypothesis: Within-Node Attribute Comparison Hypothesis

Scoring: Correct answers are Lonni, Thomas, Anna, and Klaus. 1/4 point for each correct answer. -1/4 point for each incorrect answer.
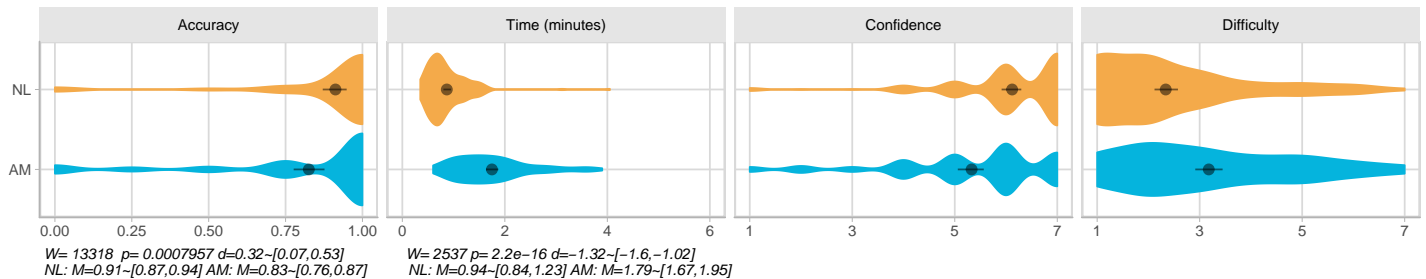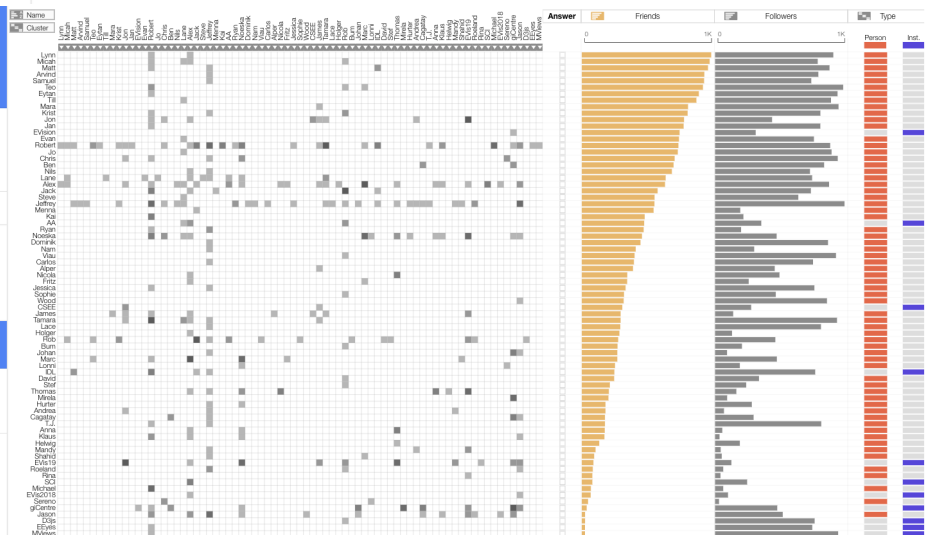
Links: NL, AM
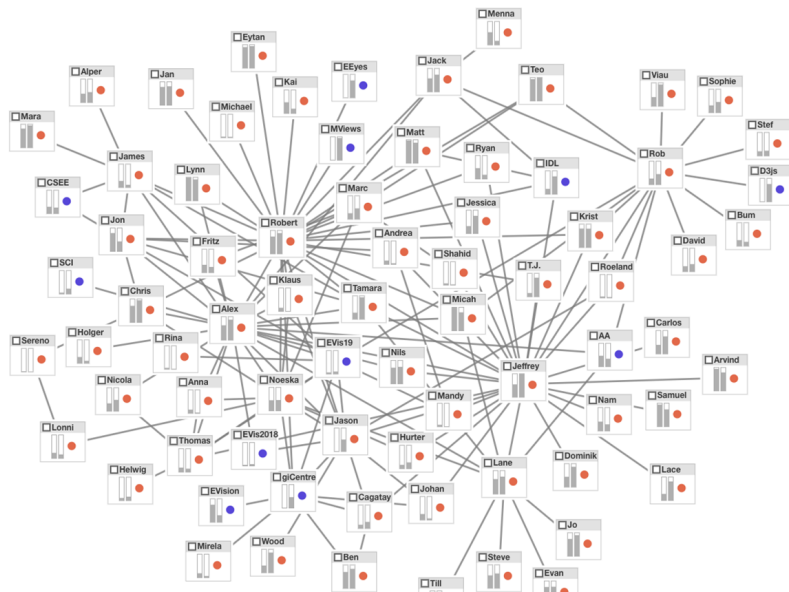
Figure 11: Task 10 configuration and results.

2.11 Task 11: Node Attribute Comparison on Small Network

Instruction: Select the people who have interacted with Thomas and have more friends than followers.
Properties: Small Network, 3 Node Attributes, Topology Target: Neighbors
Hypothesis: Within-node Attribute Comparison Hypothesis
Scoring: Correct answer is Anna. Full score for only Anna, 0 otherwise.
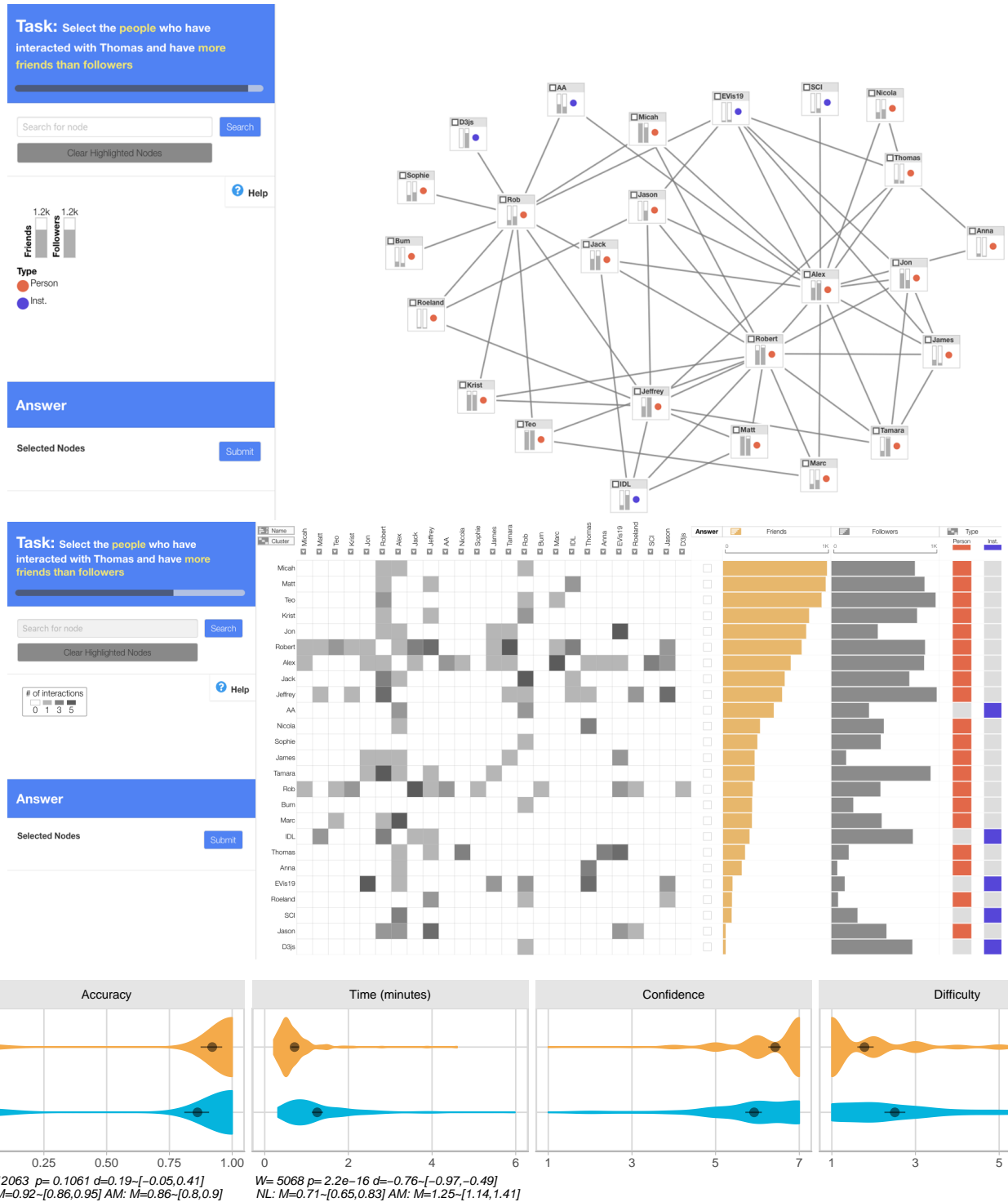**Links:** NL, AM

Figure 12: Task 11 configuration and results.

2.12 Task 12: Cluster and Attribute Estimation

Instruction: Select all the people who are in a cluster with Alex. Estimate the average number of followers among the selected people.

Properties: Large Network, 1 Node Attribute, Topology Target: Cluster.

Hypothesis: Cluster Hypothesis

Scoring: For subquestion 1, we determined clusters by two different methods: using a network clustering plugin to Cytoscape [2], and a seriation algorithm (optimal leaf clustering) [1] for the adjacency matrix. Based on these algorithmically defined clusters, we inspected the NL and AM to identify which nodes are distinctly in clusters in both visualizations and in the cluster results from the algorithms. Based on this, we defined a core cluster containing Alex, Robert, Noeska, and Jason. There are other members of the core cluster, but they are institutions, not people. The cluster score was then defined by the edit distance to the correct answer, with the following exceptions: As Alex was the node asked for in the question, including it doesn't get points, leaving it out doesn't incur a penalty. We also defined an extended cluster that contained people nodes that could reasonably be included in the cluster. This extended cluster includes Tamara, James, Jon, Marc and Klaus. These nodes were excluded from calculating the edit distance, i.e., including them did not incur a benefit or penalty.

For subquestion 2, the average number of followers of the cluster members, we averaged the number of followers for the nodes selected by the user in part A and computed the standard deviation of those values. The score was weighted from average -1/2 std dev to average +1/2 std dev, with full score given for the average, going to 0 at the extremes. The score for the combined task was the score for part A multiplied by the score for part B.
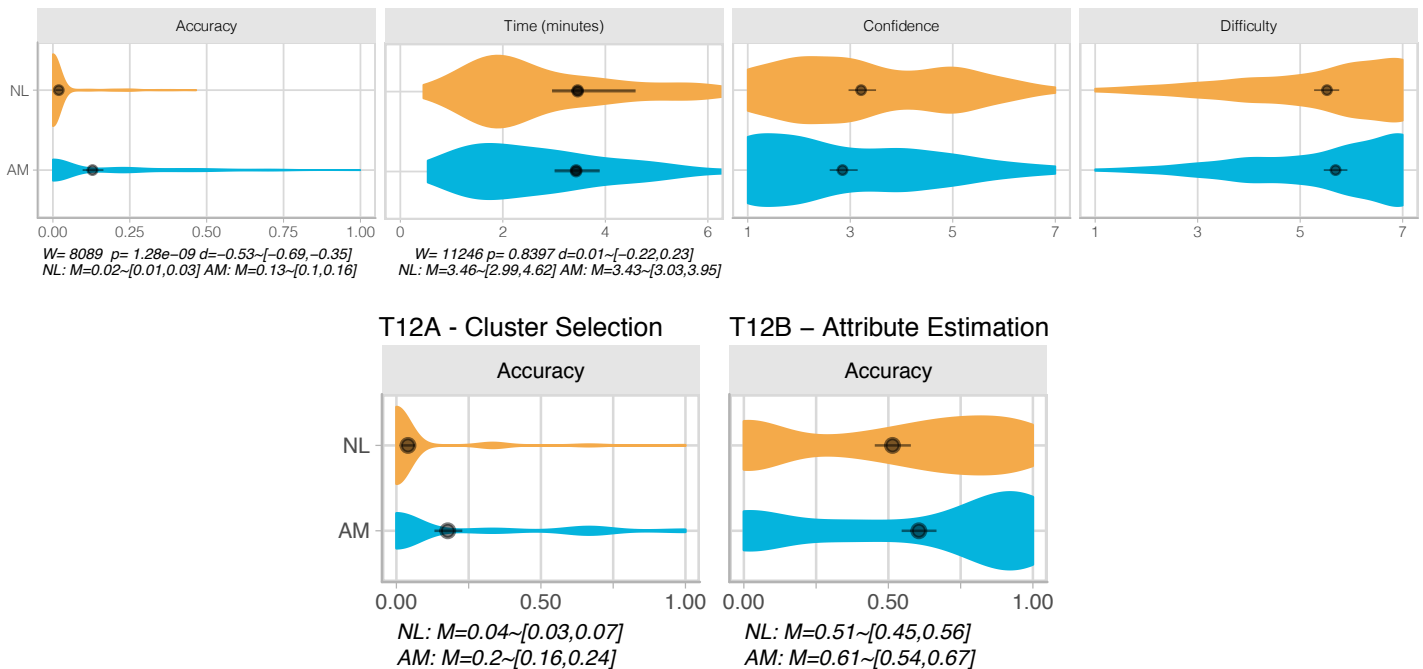
Links: NL, AM

Figure 13: Task 12 results.
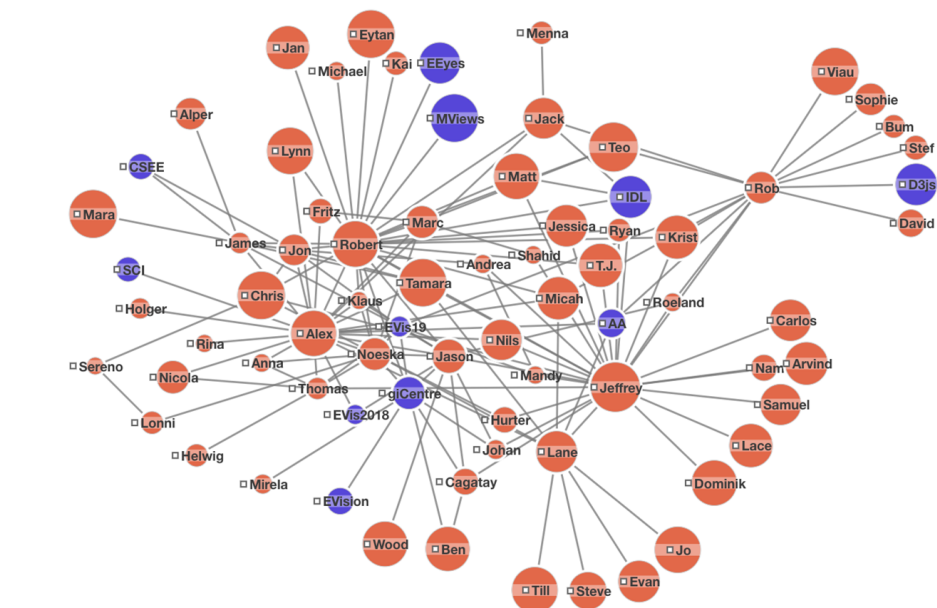
Figure 14: Task 12 configuration.

2.13 Task 13: Attribute Along Shortest Path

Instruction: What is the institution on a shortest path between Lane and Rob? What is its continent of origin?
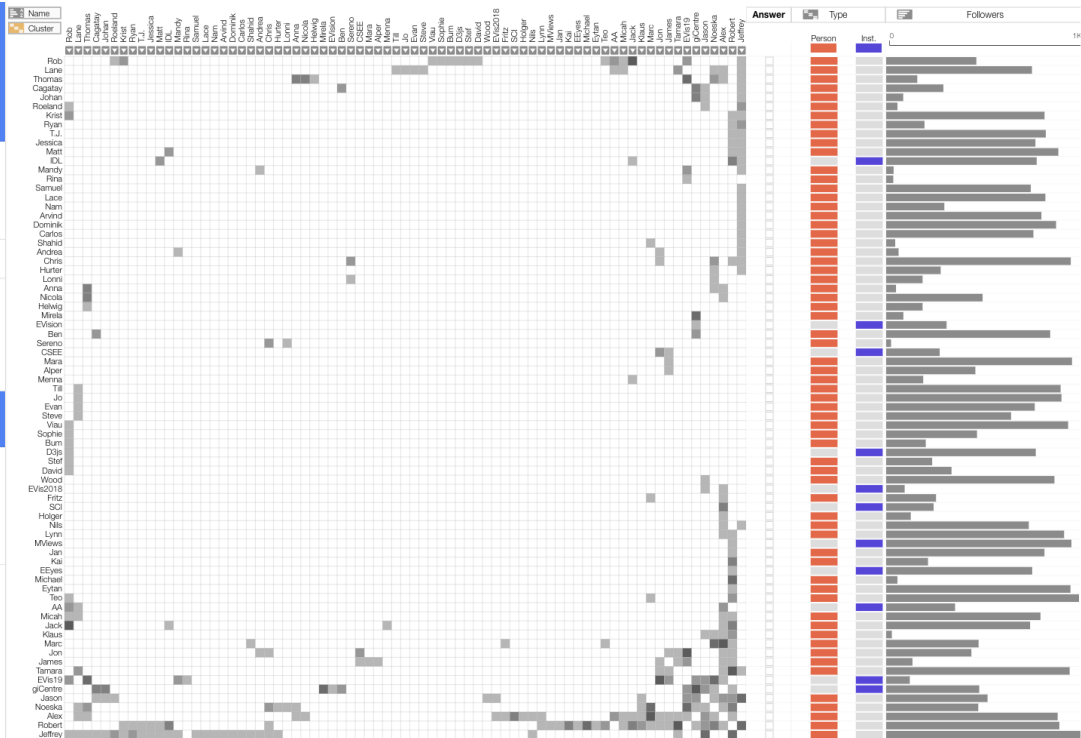
Properties: Large Network, 2 Node Attributes, Topology Target: Paths.

Hypothesis: Path Hypothesis

Scoring: The answer to subquestion 1 is AA, for which the user is awarded .5 point. Anything else is 0. If the user got the first part right, the continent of origin is EU, worth another .5 points.
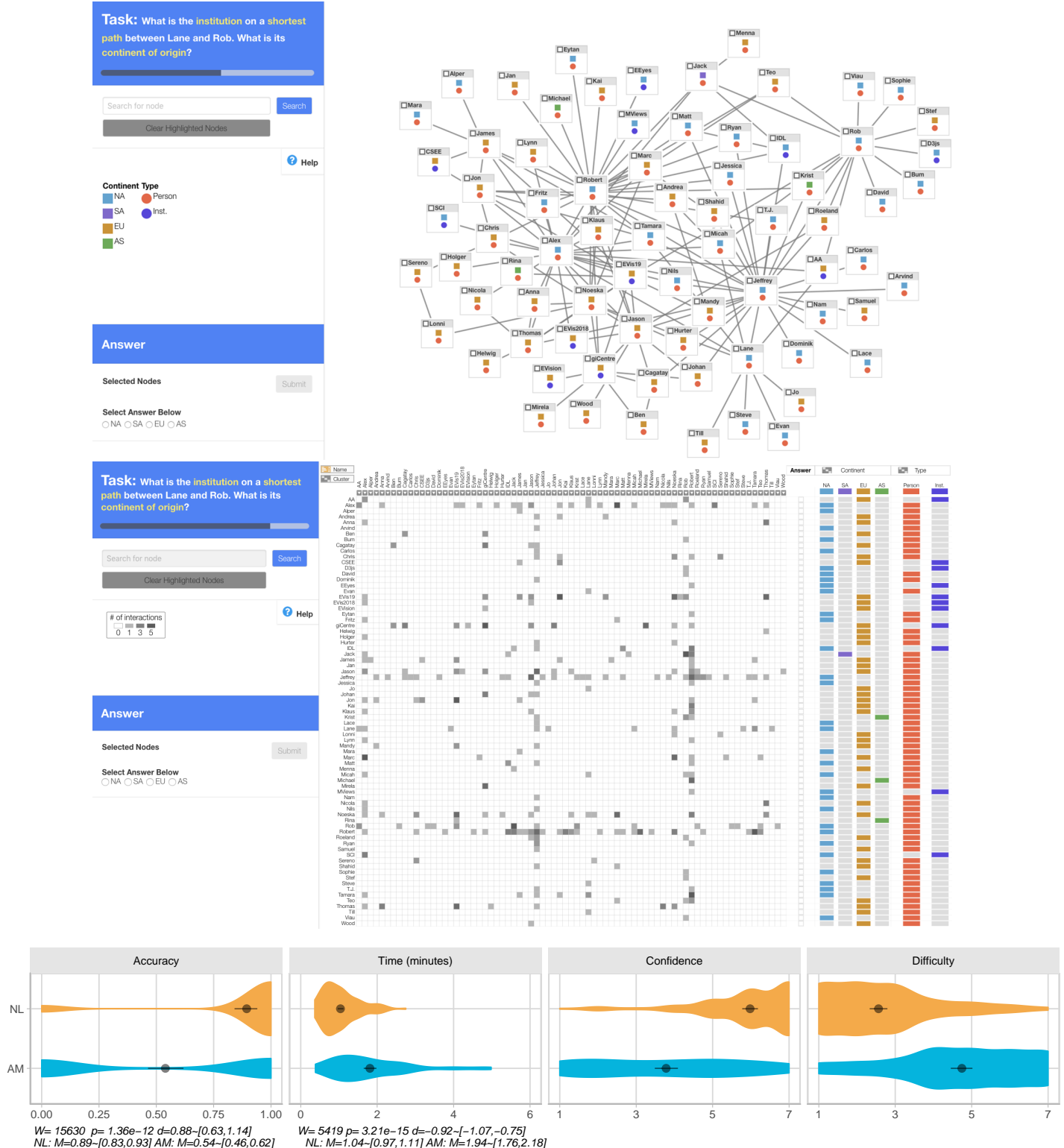
Links: NL, AM

Figure 15: Task 13 configuration and results.

2.14 Task 14: Attribute Along Shortest Path on Small Network

Instruction: What is the institution on a shortest path between Jason and Job? What is its continent of origin?
Properties: Small Network, 2 Node Attributes, Topology Target: Paths
Hypothesis: Path Hypothesis
Scoring: The answer to subquestion 1 is EVis19, for which the participant is awarded .5 point. Anything else is 0. The answer to subquestion 2 is EU. If the participant got subquestion 1 right, and then got subquestion 2 right, they got another 0.5 points.
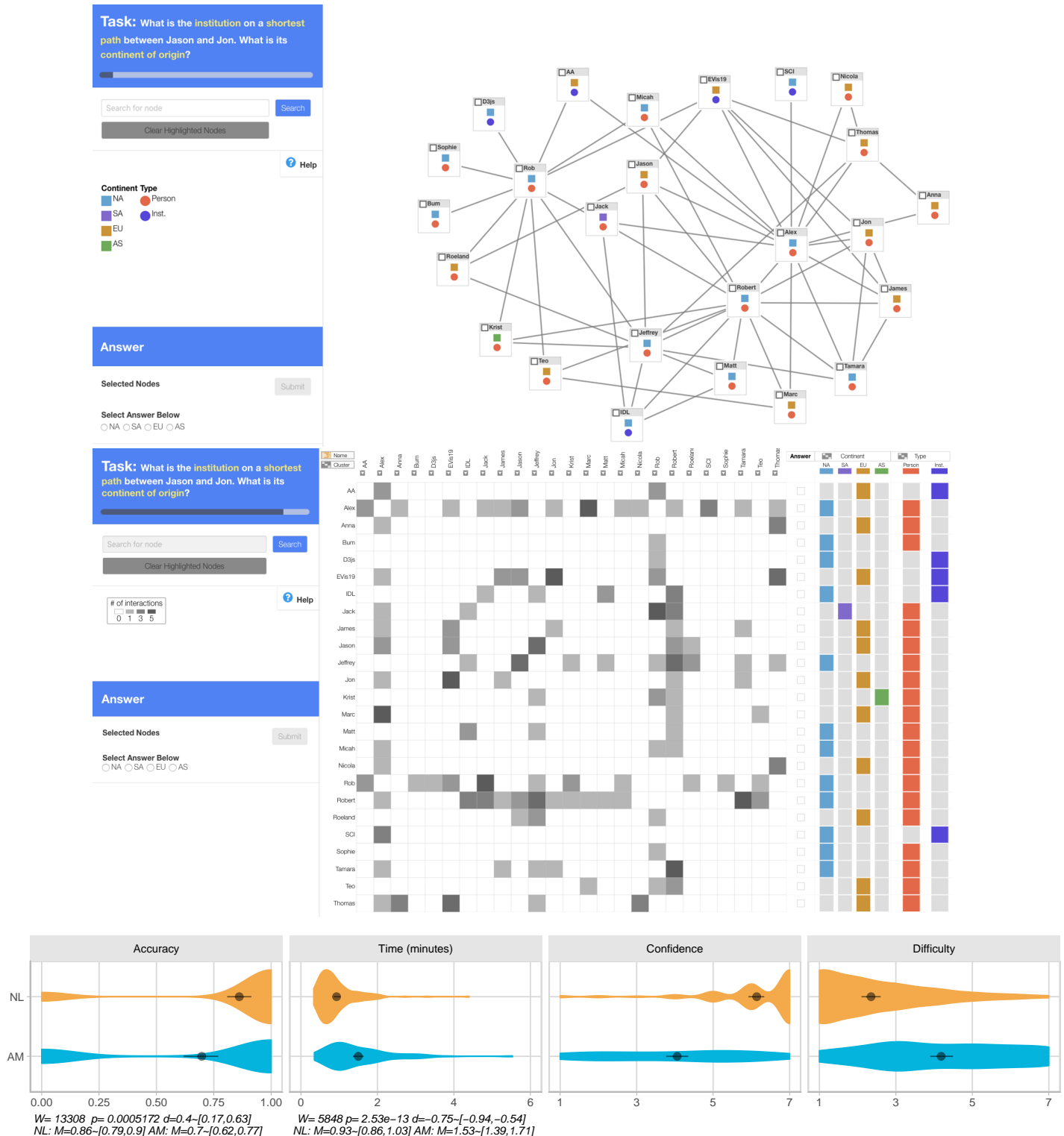**Links:** NL, AM

Figure 16: Task 14 configuration and results.

2.15 Task 15: Attribute on Multiple Paths

Instruction: Of the north americans who are two interactions away from Sereno, who has been on twitter the longest?

Properties: Large Network, 1 Node Attribute, Topology Target: Paths

Hypothesis: Path Hypothesis

Scoring: The answer is Robert. 1 point Robert, 0 otherwise.
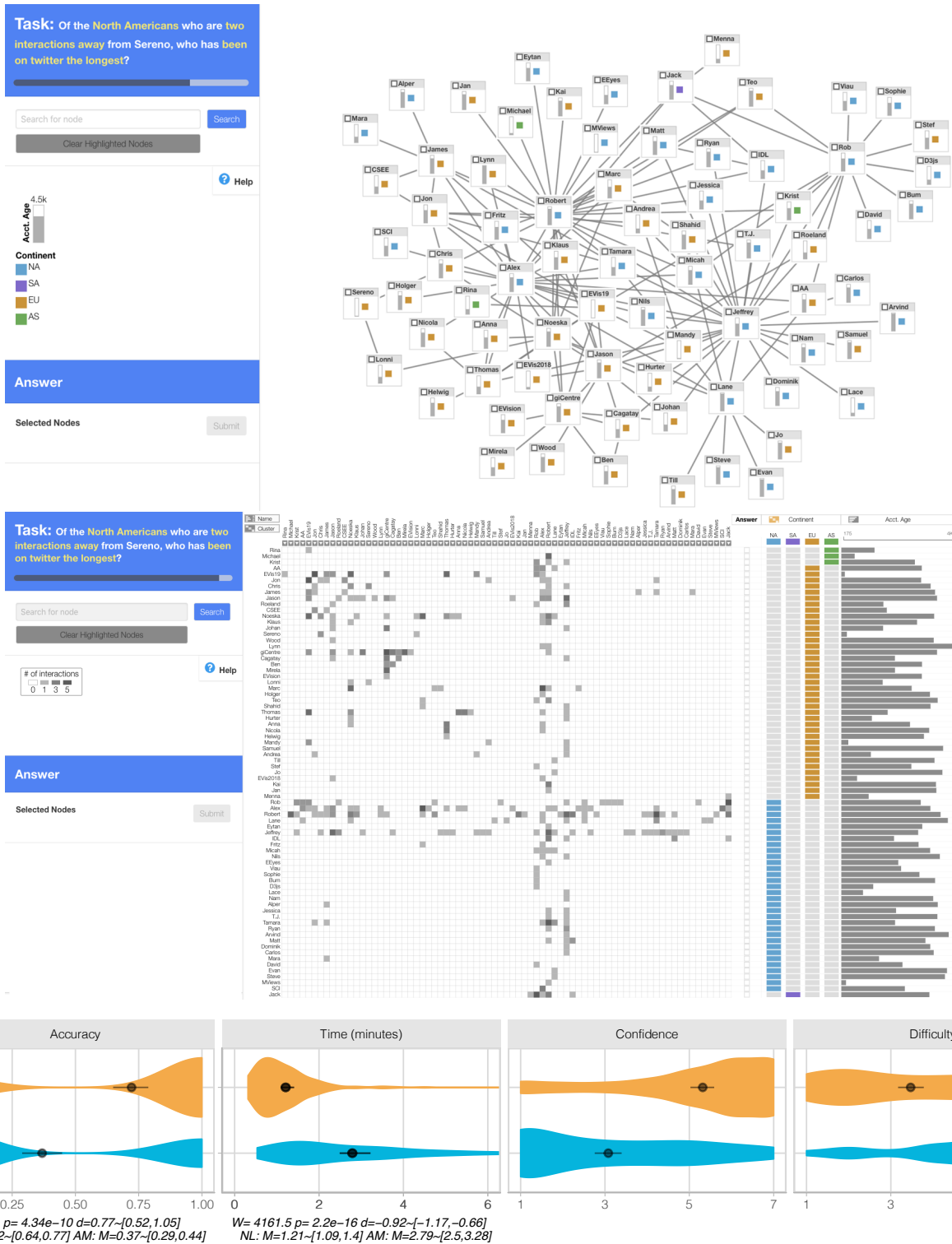
Links: NL, AM

Figure 17: Task 15 configuration and results.

2.16 Task 16: Free Explore

**Instruction:** Please explore the network freely and report on your findings. Is there anything surprising or particularly interesting in the network?

Properties: Large Network, 6 Node Attributes, Topology Target: NA

Hypothesis: Insight Generation Hypothesis

Scoring: Qualitative coding based on answer types..

Links: NL, AM

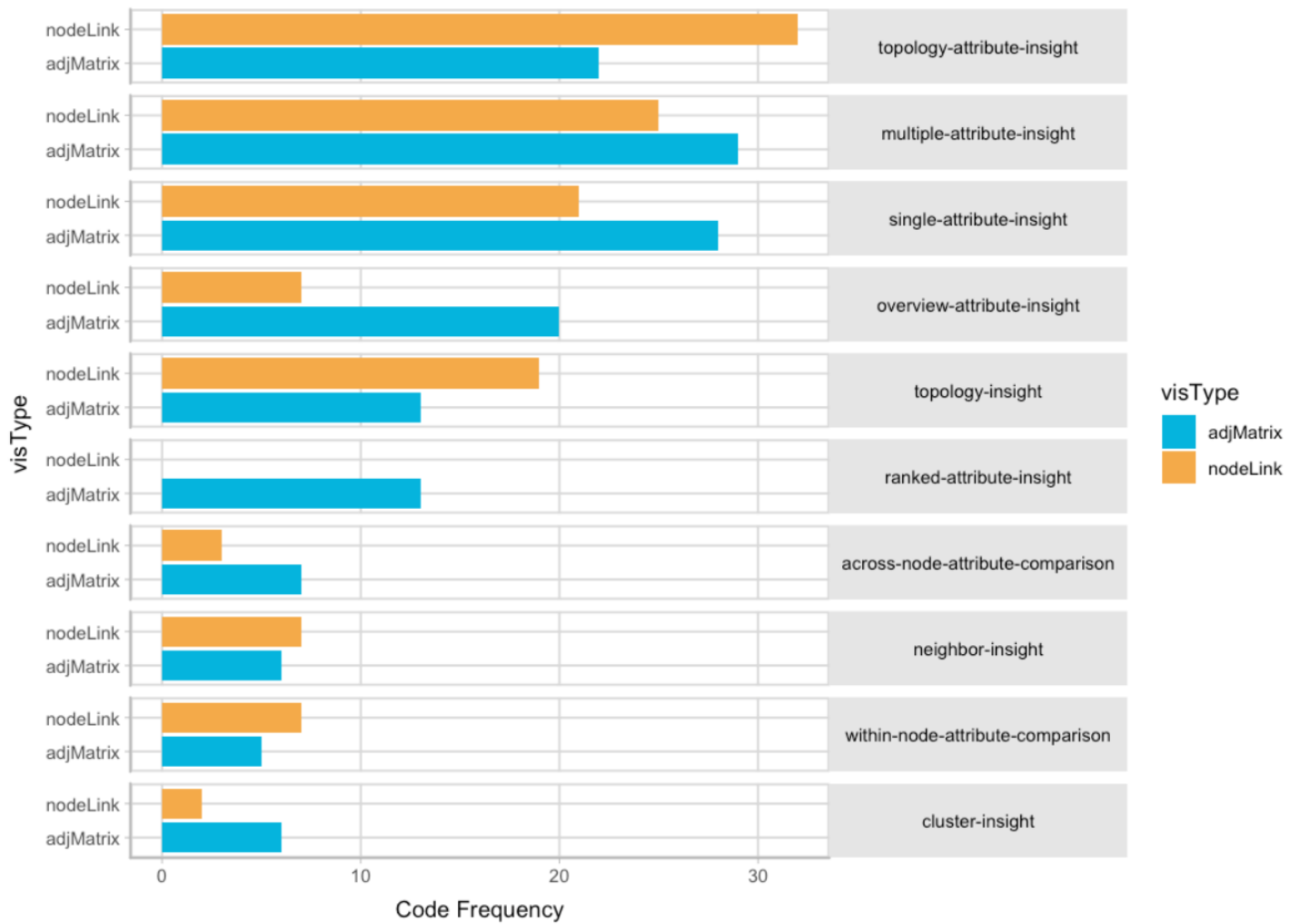**Figure 18:** Task 16 configuration and results.
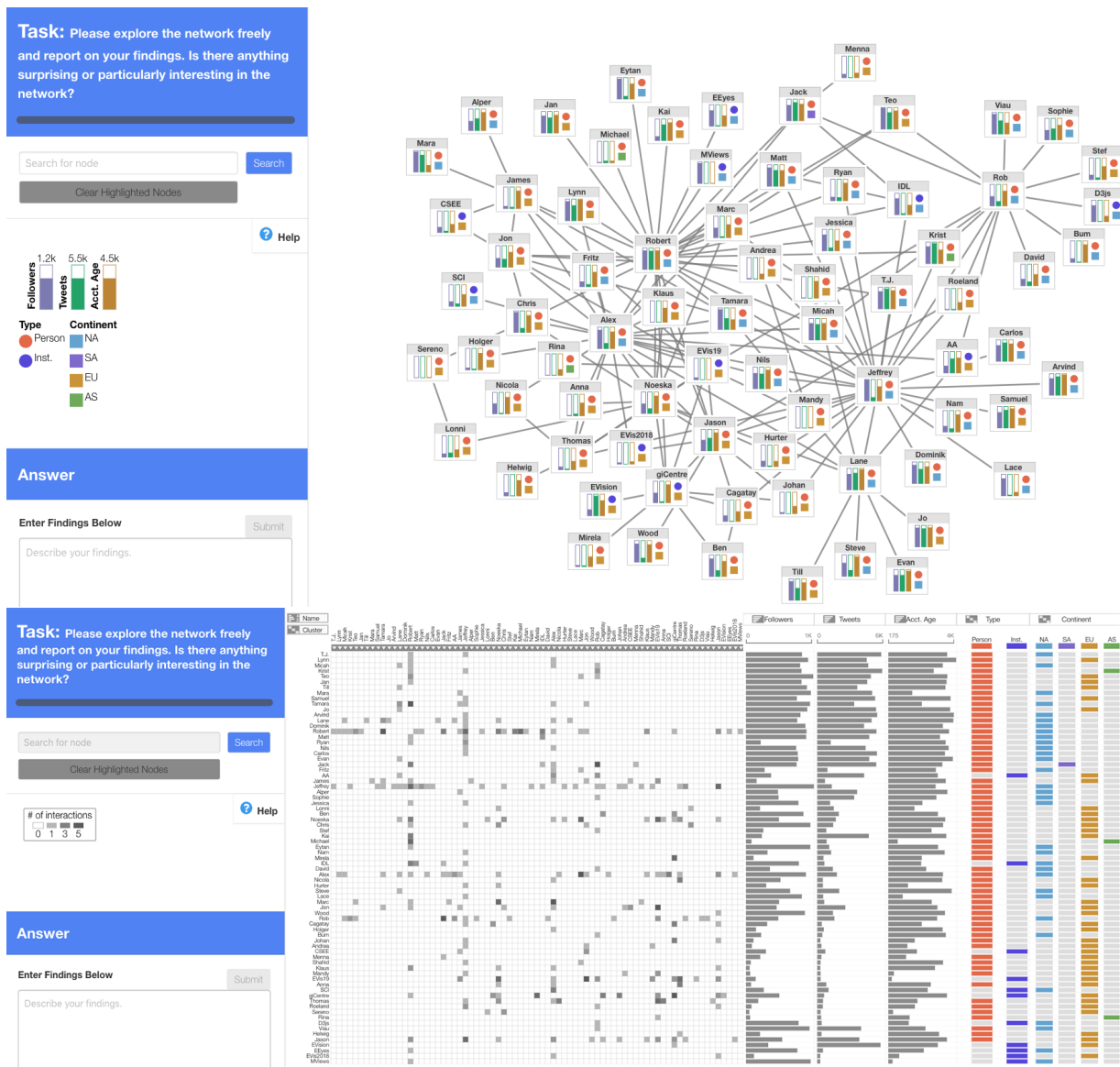
Figure 19: Frequencies of insights faceted by type of insight and condition.

3 Provenance

We tracked various types of interactions using a provenance framework. The following figures show the frequency of selected interactions. We used custom visualizations to inspect the provenance data, which is available at https://vdl.sci.utah.edu/mvnv-study-analysis/.
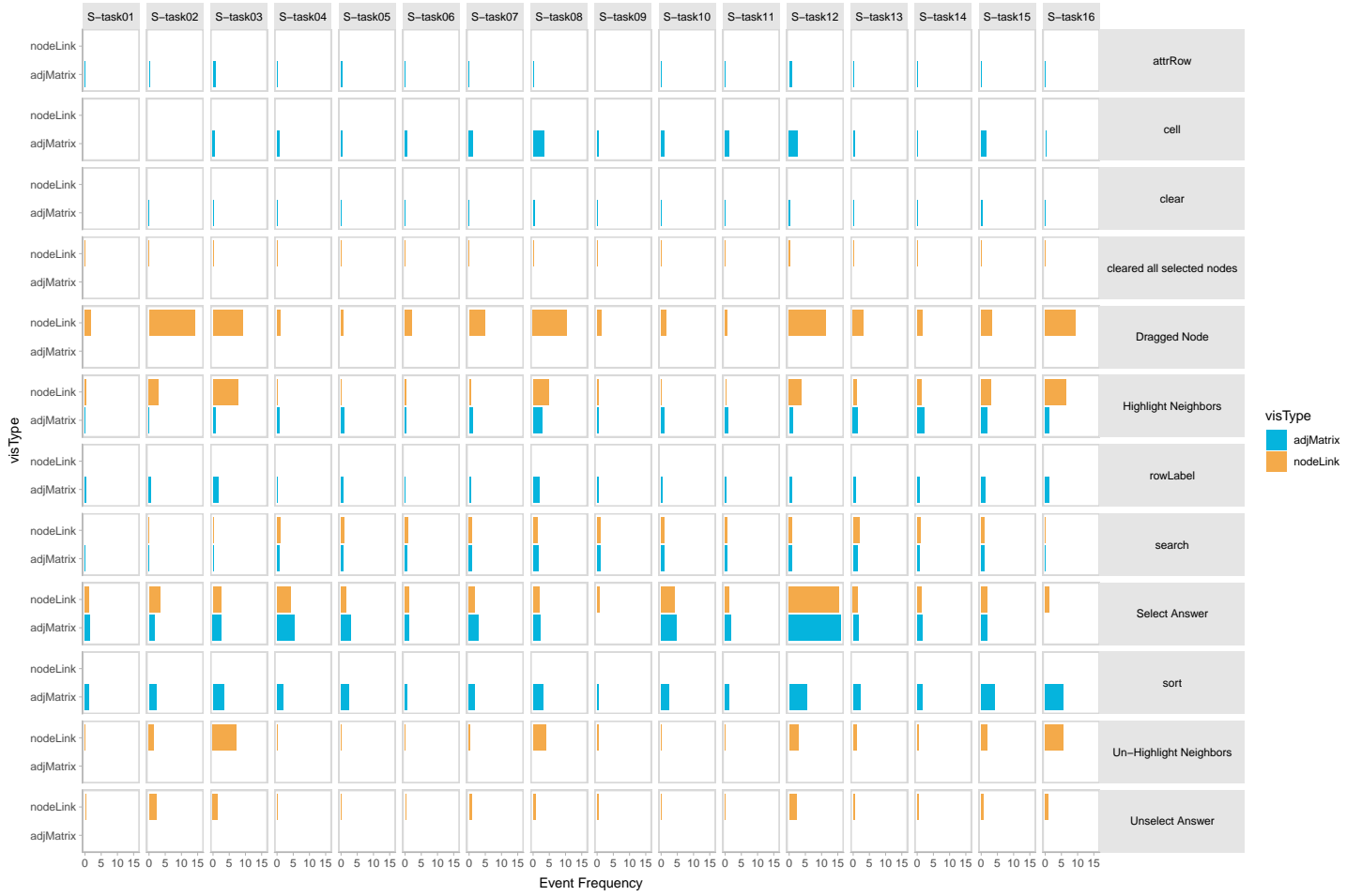

Figure 20: Interaction count per participant as a function of task and specific interaction type.
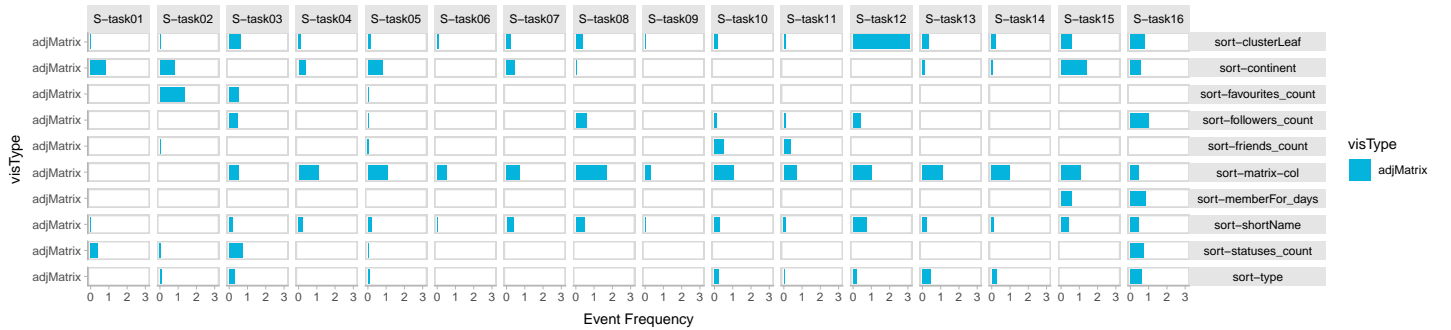

Figure 21: Interaction count per participant for sorting interactions in the Adjacency Matrix.

4 Design Guidelines

For a sparse network with few attributes, we recommend a design similar to our node-link diagram with bubbles. Global tasks on a single numerical attribute are about as well supported as in the AM. Most topology tasks are supported about equally well, with the exceptions of path-related tasks, which are much better supported in NL, and cluster tasks, which are better supported in AM. We believe it is important to provide the ability to selectively show attributes of interest in NL, so that bubble size can be leveraged and nested charts can be avoided. Interactions such as node dragging and neighborhood highlighting were extensively used, and a system should certainly provide them.

For sparse networks with attributes that need to be analyzed simultaneously, and any dense network, we recommend a design similar to our adjacency matrix. While performance on the task that had the most attributes but also considered topology (T3) was slightly more accurate with the NL, the AM performed well on global discovery tasks (e.g., T1) and resulted in a lot of overview insights. The AM is clearly the method of choice for discovering clusters or communities and characterizing their attributes, but is also competitive for neighborhood and common neighbour tasks. As far as interaction is concerned, sorting was extensively used in the matrix, and is clearly an important feature for any implementation.

References

[1] Jean-Daniel Fekete. 2015. Reorder.Js: A JavaScript Library to Reorder Tables and Networks. In *IEEE Symposium on Information Visualization*. Chicago, United States, 3.

[2] Min Li, Jian-er Chen, Jian-xin Wang, Bin Hu, and Gang Chen. 2008. Modifying the DPClus Algorithm for Identifying Protein Complexes Based on New Topological Structures. *BMC Bioinformatics* 9, 1 (Sept. 2008), 398. DOI:http://dx.doi.org/10.1186/1471-2105-9-398