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Evaluating Cognitive Load: Force-directed Layout vs. Chord Layout

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Abstract

Understanding cognitive processes during the interaction with visualizations, specifically limitations of working memory, opens a new perspective on evaluations and encourages a more user-centric design approach. In a user study we evaluated two graph data visualization approaches (i.e., the force-directed layout and the Chord layout) using a cognitive load questionnaire to assess the three load types: intrinsic, extraneous, and germane load. Tasks were designed to encourage insight and sensemaking in the participants during the evaluation. This type of evaluation helps to assess the users' mental processes during sensemaking and graph reading in the underlying layouts. Further, such study findings would help visualization designers in choosing the appropriate layout type for their graph data.

Categories and Subject Descriptors (according to ACM CCS): H.5 [Information interfaces and presentation]: - [-]: —-H.5.2[User Interface]: Evaluation/methodology

1. Introduction and Background

As information visualizations continue to grow in complexity with the need to represent more complex data, human attributes, such as limited working memory and cognitive load capacities, need to be taken into greater consideration [HEH09]. Cognitive load theory was postulated by John Sweller in the field of instructional design, with tools and methods being developed to measure the load of lessons and assessing learning [Swe88]. Current findings in the theory support a three factors approach: **intrinsic load** (the load associated with the material or subject matter), **extraneous load** (the load type predicated on the design, instructional and task complexity), and **germane load** (the load type measuring the elements contributing to learning) [DM08]. These three load types contribute to load experienced in working memory. In general, cognitive load theory is based on a limited working memory capacity, which is utilized during information processing [vMS05]. Exploring the impact of cognitive load during the use of information visualizations is important as the amount of load experienced by users can reveal reasons for differences in performance and uncover areas for improvements in the design or task structure [HHE06].

In the field of Information Visualization, the force-directed layout [Ead84] and the Chord layout [KSB*09] are used to depict graph data, e.g., social network data. In this paper, we focus on a user study conducted in a controlled lab environment with 24 participants in a *between-subjects* design. The purpose of the study was to evaluate the force-directed layout and the Chord layout depicting an ego social network from the three-factor perspective of cognitive load. Participants of the study completed eighteen tasks structured according to the insight-gaining process by Yi et al. [YKSJ08]: "provide overview, adjust, detect pattern and match mental model". After each section of tasks, participants were asked to fill out an adapted version of the cognitive load questionnaire by Leppink et al. [LPVdV*13] to assess the cognitive load of the last section. Overall, cognitive load measurements of each section demonstrated lower intrinsic load ratings for the force-directed layout group and higher germane load ratings for the Chord layout group. Extraneous load ratings were higher for the Chord layout group, except after the last section of tasks.

2. The User Study

We designed the user study as a controlled laboratory study to evaluate the mentioned layouts, while focusing on the cognitive load ratings of the participants' interaction. We used the web-based tool PerSoN-Vis [EHAE16], to facilitate the depiction of an ego network in a force-directed layout and a Chord layout (see Figure 1). PerSoN-Vis is based on web technologies and provides manifold interaction methods (such as zooming and panning, point and click, etc.) to enable easy information extraction. An ego network in current social media is a personal social network of a user on social media that usually consists of their family members, friends, and acquaintances of acquaintances [ML14]. We used an ego network consisting of 58 nodes and 144 edges, derived from a dataset by Mcauley and Leskoves collected from a Facebook app [ML14].

In our study, 24 participants (13 females) with an age range of 20 to 55 years (M = 29.41) interacted with either the force-directed layout or the Chord layout in a *between-subjects* manner, where participants solved 18 tasks encouraging insight and sensemaking.

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The tasks were presented with the help of the Qualtrics online survey environment and recorded with the integrated Qualtrics timer. This was achieved first with five tasks to gain an *overview* of the network, four tasks requiring *adjusting* the point of view of the network, four tasks to *detect patterns* in the network, and the last five tasks centering on the participant's *mental model*. After the completion of each of the four sections of tasks, participants were asked to fill out a questionnaire rating their cognitive load on an eleven-point scale from 0 to 10 for each item. We formulated the following hypothesis: *The Chord layout, because of its improvements over the force-directed layout, would result in lower ratings of extraneous load and higher ratings of germane load:* ***EL(FD) > EL(CH)*** *and* ***GL(FD) < GL(CH)***.

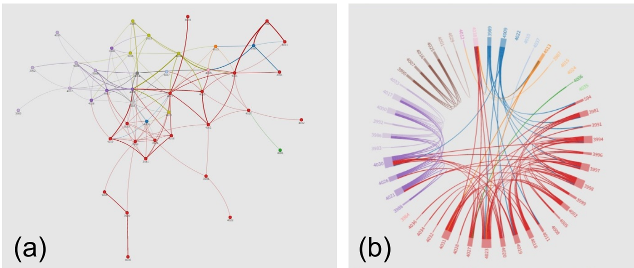

Figure 1: *The force-directed visualization (a) and the Chord visualization (b) of the used ego-network in the study.*

3. Results

In the case of accuracy and efficiency, the force-directed (FD) group achieved an overall average accuracy of 85.68% with an average time of 53.69 seconds spent on all quantitatively measured tasks (i.e., an average of 83% with 44.83 sec., 93.75% with 54.70 sec., 83% with 71.17 sec., and 83% with 44.02 sec. in all four sections respectively) compared to an overall average accuracy of 88.40% with 59.46 seconds spent on all quantitatively measured tasks (i.e., an average of 91.67% with 53.68 sec., 93.75% with 64.36 sec., 89% with 71.58 sec., and 79.17% with 48.24 sec. in all four sections respectively) by the Chord (CH) group.

Based on cognitive load theory's differentiation between the three loads, a minimum rating of extraneous load (EL) and a maximum rating of germane load (GL) is preferred in the results [LPVdV*13]. Intrinsic load (IL) is load imposed by the inherent difficulty of the subject matter and cannot be influenced by the design of the visualization. Figure 2 shows the average score results of the cognitive load factors in all four sections of tasks. Based on the cognitive load ratings of extraneous and germane load for each section of tasks, differences between the groups can be noted. The first section of tasks ('Overview') resulted in similar EL ratings for the FD group (M = 3.39) and the CH group (M = 3.44) and equal average GL ratings (M = 5.13). The second section of tasks ('Adjust') showed similar EL ratings for the FD group (M = 3.00) and CH group (M = 3.06), but significantly higher average GL ratings for the CH group (M = 6.08) than the FD group (M = 4.96), $p < 0.05$. The third section ('Detect Pattern') showed significant differences for the EL ratings in favor of the FD group (M = 2.86) compared to the CH group (M = 4.22), $p < 0.05$. Comparing average ratings for the last section ('Match Mental Model') resulted in significantly higher GL ratings for the CH group (M = 5.79) as opposed to the FD group (M = 4.46), $p < 0.05$. Overall, by averaging the ratings of each load type across sections of tasks, a significantly higher germane load rating was given by the CH group (M = 5.66) as opposed to the FD group (M = 4.82), $p \leq 0.001$. The intrinsic load, which is based on the expertise of the participant and complexity of the subject matter, was also observed. Results of an independent t-test of the two groups and their intrinsic ratings showed a significantly lower average rating given after the third section with an average of 2.61 for the FD group and 4.03 for the CH group, $p < 0.05$. The cognitive load measurements were hypothesized to show an opposing relationship between the lower extraneous load ratings and higher germane load ratings, which was confirmed by the results. Also, the Chord layout's germane load ratings for most sections were higher than the force-directed ratings. Extraneous ratings were lower for the force-directed layout, except in the last section, where the Chord layout's ratings were lower.

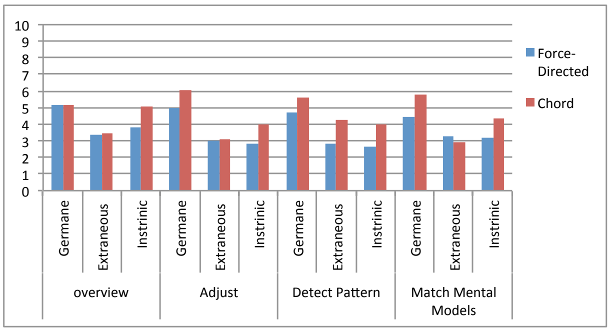

Figure 2: *Average factor scores for the four sections of tasks.*

4. Concluding Remarks and Future Work

Based on our results, some recommendations on the use of each layout can be made. For example, we found that the Chord layout provides a higher effectiveness than the force-directed layout. As with larger data set sizes errors become more likely, the usage of the Chord layout should be in clear favor. This finding is supported by the cognitive load ratings, specifically the germane load ratings, given by each group. The last section of tasks, which was higher in complexity than previous sections, averaged a higher extraneous load for the force-directed layout, indicating a higher load caused by the tasks or visualization. Germane load, load caused by schema acquisition or learning, was higher in the Chord layout group, pointing to a higher level of learning occurring during solving of these tasks. This could lead to better results when dealing with more complex data. Smaller datasets are less prone to errors, so that the force-directed layout would provide a better depiction, due to its at times higher efficiency and its lower extraneous load ratings in the first three sections. In the future, we aim to conduct further user studies with different graph sizes as well as with different network types in order to generalize our findings and to investigate the impact of these three types of cognitive load on users while working with both visualization layouts.

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