Effects of Curves on Graph Perception

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Abstract

Curves have long been used for graph visualization with increased popularity in recent years. Curves are mainly used for two purposes: one is to increase readability and the other is to enhance visual aesthetic pleasingness. Although curves can be visually pleasing, the introduction of curves in graph drawing does not increase readability automatically. Attempts have been made to investigate the usability of curved drawings. However, the results on the effect of curves per se on human graph comprehension has not been conclusive. This paper presents a user study that is to examine the effect of curves when they are introduced to remove crossings. Twenty-six participants were recruited to perform typical graph reading tasks. Task performance and user preference data were collected for analysis. The results indicate that curves can be a useful alternative when crossings are to be present in straight-line drawings. The findings of the study are also discussed along with some of our future research activities in this paper.

Keywords: graph drawing, aesthetics, readability, visualization, curve edges, node-link diagrams.

Index Terms: H.1.2 [Models and Principles]: User/Machine Systems—Human Factors; H.5.0 [Information Interfaces and Presentation]: User Interfaces—Evaluation/Methodology

1 Introduction

Node-link diagrams have been used to visualize abstract graph data for the purpose of knowledge discovery and knowledge sharing. In this type of diagrams, dots are used to represent nodes of the graph and lines are used to represent links between them. Although links are often drawn as straight lines, curves have also been used in drawing graphs.

Historically, the use of curves can be traced back to as early as 1840s for hand-generated pictures mainly for ease and clearness of drawing while independent of graph drawing research [1]. Since then, curves have been used in a number of situations for a range of purposes. For example, American abstract artist Mark Lombardi [2] drew social networks using almost circular and evenly distributed edges as a form of artistic representations. Inspired by the work of Lombardi, nowadays in graph drawing, drawings with perfect angular resolution and circular edges are categorized as *Lombardi drawings* [3].

Curves have been used to draw special types of diagrams. For example, *arc diagrams* [4] in which nodes are placed along a line while edges are drawn as semicircles placed on both sides of the line. In *confluent drawings* [5], a set of edges are merged together and drawn as "train tracks" so that non-planar graphs can be visualized in a planar or crossing-free manner. *Edge bundling* [6] is also a popular technique that groups a set of edges connecting the same two clusters into a "bundle" to reduce visual complexity. Curves can also be seen in other visualization techniques such as Fisheye view [7] and curvilinear graph drawing [8].

Despite the wide use of curves for various purposes, the research on to what extent these curves serve their purposes or how effective curves help a specific visualization technique convey the embedded information to users is still a topic that requires further exploration. Intuitively, curves appear more visually pleasing in node-link diagrams and are often more preferable than straight lines [10]. Curves can also help improve layout aesthetics. For example, when two edges cross, crossing angles are more likely to be larger with curved edges than with straight-line edges. Angular resolution of nodes will also have better chance to be improved if curves are used. Further, curves can help to make edges more visually separate and more easily for viewers to distinguish between nodes and edges, thus avoiding possible confusion caused by visual clutters of dense edges and nodes.

Empirically, it has been found that people prefer objects with smooth and round contour to sharp-angled objects [12]. However, findings from studies with graph drawings have not been conclusive in support of using curves for better task performance and visual preference. Xu et al. [9] conducted a study that compared straight-line and curved-edge drawings. It was found that straight-line drawings induced better performance and stronger user preference, and that participants took significantly shorter time to complete tasks with both straight-line and Lombardi drawings than with slightly curved-edge drawings. On the other hand, in the study of Purchase et al. [10] that compared Lombardi and straight-line drawings, it was found that users preferred Lombardi drawings, but performed better with straight-line drawings. Further, in both studies, effects of curves was evaluated in terms of the curved-edge drawing as a whole. The aesthetics seemed to not have been controlled when edge type changed. For example, curved-edge drawings could also have more crossings. Therefore there is still a question to be answered about what the effect of curve itself is on human graph perception.

In an attempt to answer this question, we initiated a project that aims to systematically investigate the pros and cons of curves, and their impact on human graph comprehension in terms of task performance and task execution behavior. In this paper, we report on an initial study that was part of the on-going effort for the project. The main objective of this study was to investigate whether curves could be used to avoid crossings. And we found that users preferred curved non-cross drawings for aesthetic pleasingness while their task performance was best with curved crossing drawings.

2 Experiment

In this section, we present the details of our study design, participants, stimuli, tasks, procedure and hypotheses. The effect of curves on human graph comprehension was examined by

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IEEE Pacific Visualization Symposium 2016
19–22 April, Taipei, Taiwan
978-1-5090-1451-4/16/$31.00 ©2016 IEEE

comparing task performance and user preference for curved and straight-line drawings. We also examined the role of individual difference, such as age, gender, task experience and cognitive style (using the 40-item Rational-Experiential Inventory (REI-40) of Pacini and Epstein [11]). However, due to the page limit, the possible interaction between curves and individual difference is not reported in this paper.

2.1 Design

We randomly created a set of graphs with different sizes and asked users to perform typical graph reading tasks. Their task performance and preference with each graph were recorded for analysis. To produce stimuli, we draw a straight-line node-link diagram manually for each graph. Then based on this layout, we replace straight-line edges with curves to create three variations. As a result, we have the following four drawing versions:

1) Straight-cross drawing: this is the type that is the most commonly seen in graph visualization.
2) Curved-cross drawing: all straight-line edges are replaced by curves.
3) Curved-nocross drawing: all straight-line edges are replaced by curves. However, in this version, edge crossings are not permitted.
4) Mixed-nocross drawing: Only crossed edges are replaced with curves to remove crossings.

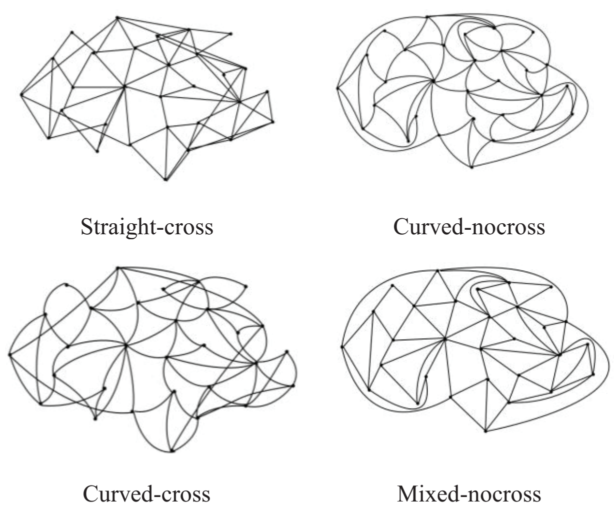

Figure 1: Four drawing versions of a graph.

The examples of these four versions are shown in Figure 1. As we mentioned in Section 1, it has been found that straight-line drawings outperform curved ones [9, 10], we do not consider non-crossing straight-line drawings in this study. Therefore, the central question we want to investigate is whether curves could be used as an alternative when crossings are presented in straight-line drawings and which of three curved versions are the most effective. When producing these drawings, following constraints are applied to control possible confounding factors and ensure accurate evaluation of impact of curves:

1) The layout of the four versions are the same. That is, the node positions are not changed when replacing straight-line links with curves.
2) Angular resolution of nodes are not changed whenever possible.
3) When producing curved-cross drawings, the crossing number and the crossing angle of the original straight-line drawing are maintained.
4) In producing mixed-nocross drawing, we ensure that the least number of straight lines were replaced by curves while eliminating crossings.
5) Further, to make these graphs of different sizes comparable and have a reasonable level of complexity for visual perception, these graphs each have a density ranging from 10% − 20%, calculated by $2 \times |E| / (|V| \times (|V| - 1))$, and their drawings all have the same crossing ratio of 40%, calculated by the number of crossings divided by the total number edges.

The experiment employs a within-subject design which means participants need to perform all tasks with all images. The independent variable is drawing version. The dependent variables include preference and task performance in terms of task time, accuracy and effort. Note that we used tasks of different types and graphs of difference sizes to make the experiment setting more representative, thus increasing the possibility of experimental results more widely applicable. However, for the purpose of this study, we were not interested in how task interacted with graph size or drawing version for simplification of analysis.

2.2 Participants

We recruited twenty-six university students on a volunteer basis. Twelve of them were female, and fourteen were male. These participants were aged from 18 to 40. They all had normal or corrected-to-normal vision at the time of the experiment. None of them had experience performing topology-related graph reading tasks with node-link diagrams although some of them reported to have seen application diagrams such as city train maps or organization diagrams.

2.3 Stimuli

Four graphs were randomly generated with sizes: 20, 30, 40 and 50. To avoid one specific layout helping or hindering tasks for a drawing version, we draw each version twice. In other words, two straight-line drawings were drawn for each graph. Then based on each drawing, three curved versions were produced. This resulted in 4 (graphs) × 2 × 4 (versions) = 32 stimuli in total. These stimuli were produced with pen tools in Photoshop. The curves were Bezier curves. The drawings of the graphs with size 50 were shown in Figure 1 as an example of the stimuli used in the experiment.

2.4 Tasks

Graph comprehension is a complex process consisting of small components. These small component can also be complex and can be broken into smaller tasks. A single user study cannot include all those tasks or components. Complex tasks require time and effort to complete, for which participants may react differently, such as get tired or exhausted, lose focus or interest, or start to give random answers. This in turn could introduce unwanted confounding factors and make experiments difficult to control. Therefore, only a small set of representative basic tasks (usually two to four) are used in graph evaluation. In this study the following three tasks that are varied in difficulty and typical components of graph comprehension tasks are used. These tasks were also used in previous studies [9, 10].

1) ShortestPath: what is the length of the shortest path between two highlighted nodes?

2) CommonNeighbour: How many common neighbors do the two highlighted nodes have?
3) Degree: which of the three highlighted nodes has the largest degree?

For the first task, the nodes are selected so that there is only one shortest path between them and the shortest length is between 3 and 6 inclusive.

Apart from graph reading tasks, the participants were also required to complete a short questionnaire that asked them to indicate their preference from 1 (least preferred) and 4 (most preferred) for the four diagrams of each graph based on two aspects: one is the overall aesthetic pleasingness and the other is performance of graph tasks.

2.5 Online System

A custom-built system was used to display stimuli. The system was designed to show the three tasks in a counter-balanced order across the participants. For each task, all 32 images were displayed in a random order with a constraint that the images of the same graph should not be displayed in one after another. Upon the start of the system, the first task is shown on the screen with brief instructions, the participant presses the space key on the keyboard for the first image to be shown. Immediately after the answer is found, the space key is pressed to record the task time and the answer screen is shown. On the answer screen, the participant uses the mouse to indicate his/her answer to the task and the effort devoted to the task from 1 to 5 with 1 indicating the least effort and 5 for the most effort. After this, the space key is pressed again to proceed to the next image. After all images are shown, the participant is required to have a short break and then the space key is pressed to the second task. This process is repeated until all tasks are completed.

2.6 Procedure

Before the formal study, a pilot study was conducted with two participants to ensure that the experimental design and the protocol were appropriate.

During the formal study, participants were first briefed about the purpose of experiment and the procedure. Then, a short tutorial was also given on knowledge of graphs and graph drawings, such as shortest paths, common degree, and aesthetics. Participants were instructed to perform tasks as quickly and as accurately as possible. They were also given chance to practice tasks and the system and ask questions so that they were ensured that they understood the tasks and knew what they were expected to do.

Once ready, the participant indicated to the experimenter to start the online system for performance of the three online tasks. After a short break, the online questionnaire was administrated to collect their demographical information, their preference of images, and their responses to the REI-40 items for their thinking style. This was followed by a short interview or discussion for their feedback of study and their behavior during the task performance. The whole session took about one hour per person on average.

2.7 Hypotheses

As the mixed version removes crossings and at the same time the total edge length is smaller than the curved-nocross version, we hypothesize:

- H1: The participants perform better with mixed-nocross drawings than all others. That is, the participants will take less time and less effort to complete tasks with higher accuracy.

As it is the common belief that non-crossings drawings with curves are visually more pleasing, thus more visually preferable, while straight-line and short edges are more beneficial for task performance, we hypothesize:

- H2: The participants prefer mixed-nocross drawings more than others for task performance.
- H3: The participants prefer curved-nocross drawings more than others for overall aesthetic pleasingness.

3 Results

Twenty-six participants performed the tasks with the thirty-two diagrams of the four drawing versions: curved-cross, curved-nocross, mixed-nocross and straight-cross. For each task, we recorded time, effort and accuracy. In our data analysis, when data were normally distributed, Analysis of variance (ANOVA) was used. Otherwise, a proper non-parametric testing method was used instead.

3.1 Time

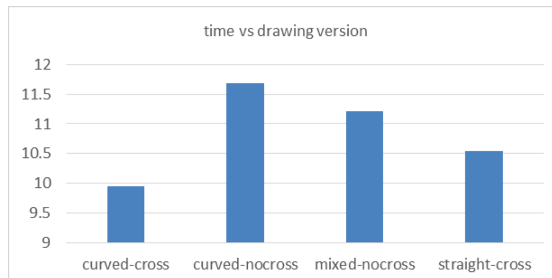

Figure 2: Average time data (seconds) for each drawing version.

The average time data for the drawing versions are shown in Figure 2. It can be seen that the participants took the shortest time with curved-cross drawings (mean = 9.95 second), followed by straight-cross and then mixed-nocross drawings. The curved-nocross drawings took students the longest time to complete the tasks (mean = 11.68 second). The ANOVA with repeated measures revealed that these differences were statistically significant (F=8.676, $p<0,05$). Further post-hoc pairwise comparisons indicated that all drawing version pairs were significantly different ($p<0.01$), except the pair of curved-nocross and mixed-nocross ($p>0.05$).

3.2 Effort

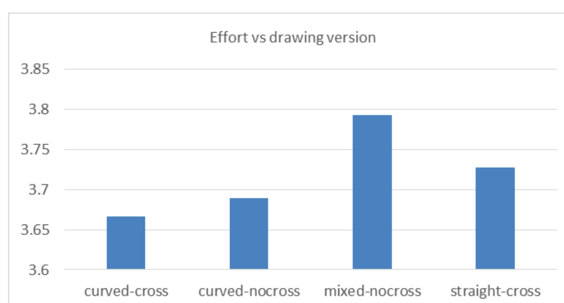

Figure 3: Average effort data for each drawing version.

The average effort data for the drawing versions are shown in Figure 3. It can be seen that the least effort was spent with curved-cross drawings (mean = 3.66), followed by curved-nocross and then straight-cross drawings. The mixed-nocross drawings took students the most effort to complete the tasks (mean = 3.79).

However, the non-parametric Friedman's test revealed that these differences were not statistically significant (χ^2=4.53, p>0.05).

3.3 Accuracy

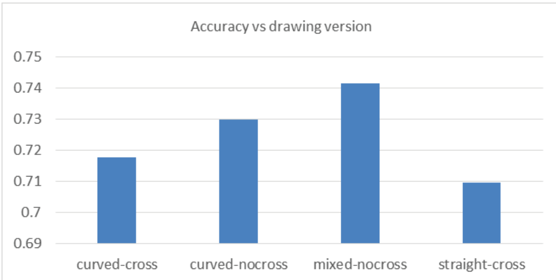

Figure 4: Accuracy data for each drawing version.

The accuracy data for the drawing versions are shown in Figure 4. It can be seen that the participants were most accurate with mixed-nocross drawings (mean = 74%), followed by curved-nocross and then curved-cross drawings. The participants made most errors with the straight-cross drawings (mean = 71%). However, the ANOVA with repeated measures revealed that these differences were not statistically significant (F=0.740, p>0,05).

3.4 Preference (task performance)

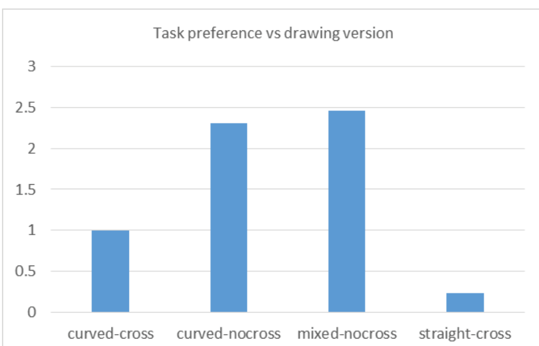

Figure 5: Average task preference for each drawing version.

The average data of the preference results for task performance are shown in Figure 5. It can be seen that mixed-nocross drawings were the most preferred (mean = 2.46), followed by curved-nocross (mean = 2.30), and then curved-cross (mean = 1.00). The straight-cross drawings were rated as the least preferred (mean = 0.23).

The non-parametric Friedman's test was conducted on the preference data and the results revealed that there was a significant difference in task preference among these drawing versions (χ^2=53.63, p<0.001). Further, post-hoc pairwise comparisons using Wilcoxon Signed Ranks test indicated that all pairs of drawing versions were significantly different (p<0.01), except the pair of curved-nocross and mixed-nocross (Z=-0.78, p>0.05).

3.5 Preference (aesthetic pleasingness)

The average data of the preference results for aesthetic pleasingness are shown in Figure 6. It can be seen that curved-nocross drawings were rated as most aesthetically pleasing (mean = 3.54), followed by mixed-nocross (mean = 3.07), and then curved-cross (mean = 2.11). The straight-cross drawings were the least preferred (mean = 1.19).

The non-parametric Friedman's test was conducted and the results revealed that there was a significant difference in aesthetic pleasingness among these drawing versions (χ^2=49.40, p<0.001). Further, post-hoc pairwise comparisons were conducted using Wilcoxon Signed Ranks test and the results indicated that all pairs of versions were significantly different (p<0.01), except the pair of curved-nocross and mixed-nocross (Z=-1.93, p>0.05).

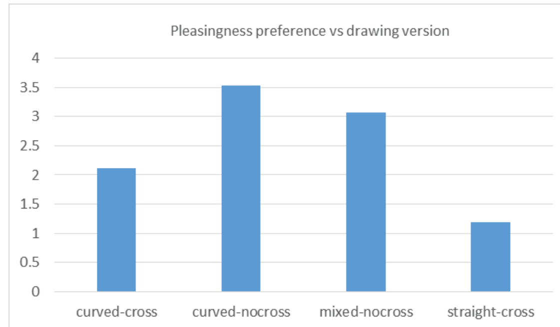

Figure 6: Average aesthetic preference for each drawing version.

4 Discussion and Future Work

Both H2 and H3 were supported by user preference data. That is, non-crossing drawings are more preferable than crossing drawings for both task performance and for visual pleasingness. However, it was surprising that H1 was not supported. There was no difference in either effort or accuracy between drawing versions. This indicated that the participants were focused on the tasks and paid more attention on correctness. Participants were quickest with curved-cross, rather than hypothesized mixed-nocross. This could be because despite crossings, crossing angle was larger with crossed curved edges. At the same time the curved edges in mixed-nocross were long and far away from the nodes of the interest. This also indicates that path length played more important role than crossings, which was consistent with the conjecture of Xu et al. [9].

In summary, our study indicated that curves could be used to avoid crossings to make pictures more visually pleasing. But for better human graph comprehension, it might be better to use curves to increase crossing angle, rather than to remove them. Increasing crossing angle will reduce the negative impact of crossings, while to remove crossings, the straight-line edges will have to be replaced with long curves. As demonstrated in this study, long curves are not desirable in this case as the impact of crossings would be overshadowed by the greater effect of long path length.

For future work, we are currently planning to conduct a further study using automatic algorithm drawn diagrams. This will allow us to use a larger size of drawing samples and calculate aesthetic values so that we are able to compare the layout quality of different drawing versions and evaluate their relations to task performance quantitatively and objectively. Further, given the importance of short path length and the best task performance with curved-cross drawings, we plan to introduce a new drawing version: mixed-cross. In this drawing version, if two edges are crossed in straight-line drawings, then these two edges are replaced with crossed curves. We also plan to use eye tracking technologies to understand exactly how visual queries were performed with straight-line and curved edges.

Acknowledgements: We thank Bridgette Kaminski for assistance with the study and all participants.

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