5-2013

Effects of Curved Lines on Force-Directed Graphs.

Marshall Couch
East Tennessee State University

College of Business and Technology: Honors-in-Discipline

Effects of Curved Lines on User Perception of Graphs

By

Marshall Couch

ETSU Computer Science

Honors in Discipline

Table of Contents

Abstract

The most common methods for simplifying force-directed graphs are edge-bundling and edge routing. Both of these methods can be done with curved, rather than straight, lines which some researchers have argued. Curved lines have been offered as a solution for clarifying edge resolution. Curved lines were originally thought to be more aesthetically pleasing. 32 computer science students were surveyed and asked questions about straight and curved line graphs. Research conducted by Xu et al. and this study suggests that curved lines make a graph more difficult to understand and slower to read. Research also suggests that curved lines are no more aesthetically pleasing than straight lines. Situations may exist where curved lines are beneficial to a graph's readability, but it is unclear due to uncontrolled variables in this study. Further study could reveal circumstances when curved lines would be beneficial.

Introduction

Over the last 20 years information visualization has become an active area of research. As noted by Shneiderman nearly 17 years ago, the increasing size of datasets has challenged people's ability to understand what those datasets signify. (1996) Information visualization is the study of how to present information visually in ways that allow users to absorb that information effectively. This includes both quantitative aspects, the graph itself, and qualitative aspects, how the graph is viewed. (Faisal et al., 2008)

The research presented here is the result of a study of how curved lines in force-directed graphs affect user perception of the information that these graphs present. Force-directed graphs are drawn by calculating forces between nodes and simulating them pushing against each other using line length as an indicator of force. (Finkel, 2004) This research was inspired in part by a similar study by Xu et al., which aimed to determine if curved lines were more aesthetically pleasing than straight lines, and how they affected graph readability. (2012) Xu et al.'s study was done in two parts. The work described here differs from Xu et al.'s in three primary ways. Xu et al. used node counts of 20, 50, and 100 for the first part of the study and 50, 100, and 200 for the second part of the study. This study uses node counts of 10 to 60 Xu et al. randomly generated graphs with curved lines in the first part of the study. In a second part the lines were curved using a Lombardi method which emphasizes angular termination of an edge at a node. This study uses graphs generated randomly much like the first part of Xu et al.'s study. Xu et al. asked participants whether connections existed and recorded the time for the response. (Xu et al., 2012) This study asked participants an estimated distance between two points, and about the clutter and readability of the graph.

This research seems to confirm Xu et al.'s findings, in that they suggest that curved lines tend to distort a dataset's semantic content. Curved lined graphs had more variation in answers than their straight line counterparts, though not often at a significant level. The low number of participants (32), along with a lack of a random selection process, precludes any definitive claims about these results. Further research with larger sample sizes, better sampling methods, and other strategies for realizing force-directed graphs would be needed to confirm these results.

Related Work

There is currently a large body of literature on information visualization, including entire conferences devoted to the subject. (Xu et al., 2012; Green, Ribarsky, & Fisher, 2009; IEEE)Visualization studies often focus on a specific set of data or a specific type of visualization. Studies range from extremely specific studies that focus on specific visualization tools such as force-directed graphs to more general visualization concepts that can be applied universally. Fewer studies have been done on the internalization process, which is the process of how users understand data. Internalization is much more complex than physical aspects of visualizations and difficult to quantify into simple aspects. (Faisal et al., 2008)

Best Practices in Visualization

While visualizations should always be custom tailored to their data as suggested by Pretorius and Van Wijk in 2009, research has uncovered a set of best practices that apply to different types of visualizations. Generally these principles, some of which are presented below, are not concerned with the graphs that represent the data, but, rather, with how users interact with the visualization. (Kelleher & Wagener, 2011)

Information visualizations should be kept as simple as possible. An information visualization should only include one style of data representation at a time: i.e., detailed or summary. Redundant and unnecessary information distract from a visualization's intent making interpretation more difficult. When portions of a visualization overlap, prominent information should be maintained.

Large amounts of data should be separated into several simple visualizations. When multiple visualizations are in use, they should be labeled with similar scales to allow for more intuitive comparisons. This helps to keep information from overwhelming the user. (ibid.)

A visualization's contents should match the type of data it represents. Lines and points should represent exact values, while color and size should represent general or trending information. Graph units should be used to represent the data's scale and the scale tailored to the range of values represented. Aspect ratios should be adjusted to reflect the data. One-to-one ratios are often ideal, but depending on scale, values and scaling strategies, such as logarithmic, should be adjusted to make the graph's image squarer. Smaller points and lines or transparency should be used to ensure each value is preserved in dense areas. Sequential data should be connected, while non-sequential data should not be connected; this includes unrelated values in time plots. The end result should show connections between items while not accidentally implying new connections. When large amounts of data are separated into multiple graphs, the scale of the graphs should be kept similar. (ibid.)

Designers of visualizations use two main strategies to increase the amount of data per area unit that an image conveys. The one, interactive graphs, allow users to manipulate images to focus on areas of interest. The other, edge-routing, minimizes edge intersections by moving nodes into different configurations. A third method, edge-bundling, groups related edges together and separates unrelated edges. When possible, this includes grouping edges from a single node and separating edges with no nodes in common. Curving a graph's edges can also make them easier to view and distinguish across intersections. (Luo, et al., 2011)

In *The Eyes Have It* Ben Shneiderman gives guidelines for creating information visualizations from his experience and from other studies. His key point is "Overview first, zoom and filter, then details-on-demand." (Shneiderman, 1996) Visualization structure and navigation can be classified into seven aspects: overview, zoom, filter, details-on-demand, relate, history, and extract. These seven aspects create a guideline to give a user the power to navigate through the information. He also lists seven major data types to group representation style.

A visualization should have an initial, overview state that represents all data. This state should allow a user to zoom into points of interest in order to limit its content to information that the user wishes to see. It should allow users to view detailed information about elements by selecting them. Relationships among the visualizations element should be clear. The visualization should have a method for tracking the history of a user so their actions can be undone or repeated if necessary. Finally the visualization should have options to export information to allow a user to easily share her findings. (ibid.)

Data can be classified into seven major data types: one-dimensional, two-dimensional, three-dimensional, multi-dimensional, temporal, tree, and network. One-dimensional data is information that can be viewed linearly, using structures like a list. Two-dimensional data includes data that conveys location and area: such data can be presented as maps. Three-dimensional data represents "real-world objects such as molecules." (Shneiderman, 1996) Higher-dimensional data, or data with four or more attributes, requires multiple views for adequate representation. Temporal data represents time and is often represented using a timeline. Trees are hierarchies where the important relationships are between children, parents and sibling nodes. Networks are similar to trees but can be linked to several items and can be non-directional, and cyclic. "These seven data types reflect [an] abstraction of [reality]." (ibid.)

Color can add emphasis or an extra dimension to a visualization: for example by visually connecting related but non-adjacent data such as temperature data. Color should be added only as needed and should not complicate the graph. (Kelleher & Wagener, 2011) An image's colors should be limited to seven. Fewer colors are better, due to a "user's ability to discriminate between colors and a user's ability to remember the meaning of each color..." (Silva, Santos, & Madeira, 2011) Linear data should be represented with a scale of colors: i.e. by using saturation or luminance with a monochromatic scale or blending multiple colors by changing hue. Colors that represent discrete data should themselves appear to be discrete and of the same saturation to avoid confusion of importance. For example, shades of red should not be used for unrelated points on a graph, or a dark shade of red and a light shade of blue for similar points. If the data is in countable steps, then the colors should reflect the distance of those steps using similar steps of saturation or scale. This allows relationships to be characterized in terms of distance between points, as well as distance between shades. (ibid.)

When colors overlap the best method to use is weaving "by representing the individual colors side-by-side, in a high frequency texture which fills the region." (ibid.) Using weaving rather than transparency allows people to better determine the amount of each color in a region. Colors in spatial data must be chosen carefully due to natural perception effects. Highly saturated colors are often overestimated in size. Eyes will also usually be drawn to brighter colors such as yellow. The number of steps used in a color scale for spatial data are best limited by the number of sections in the space. The larger the number of separate spaces, the fewer saturation differences can be detected. In spatial data colors of similar hues are often perceived as being grouped together. (ibid.)

Color should only be used to enhance visualizations; it cannot be relied on to fully represent important information. Hardware imperfections may cause different devices to display colors in different ways. Certain colors have different connotations depending on the data and the audience's culture: red for example can imply danger or just a need to pay attention. An audience, moreover, may include people who are color blind. Colors can be useful but they should be used carefully. (ibid.)

User internalization

The increasing complexity of contemporary datasets has created an interest in how people internalize content. Techniques for designing visualizations do not yet completely account for end users' cognitive processes, which are complex and not fully understood. (Green, Ribarsky, & Fisher, 2009)

Green, Ribarsky, and Fisher relate internalization of visualization to people's abilities to adapt to and accommodate new information. According to Green et al. humans process information that fails to fit into categories they understand by creating a new category for that information, and subconsciously marking it based on its similarity to categories they already understand. This allows humans to handle new situations without relearning known information in a new environment. "This process is effortless (that is, it does not demand attentional resources) for a human, it allows the reasoning process to advance despite incomplete information." (ibid.)

Humans also naturally solve problems in the simplest way with the smallest amount of resources. Eliminating known false values is often one of the first strategies for understanding a data set. "Because these models are based entirely on available (including previously held) information, it is imperative that all pertinent information is available to avoid the creation of incomplete mental models, which are, in turn, likely to be the basis of invalid rules." (ibid.)

While computers do not adapt to new information in the same ways as humans, they can process more data and also lack bias. Humans can only remember roughly seven major pieces of information at a time. (ibid.) Computers can be used to hold more information and augment a user's decision making. The information-processing strengths of both users and computers can be exploited by allowing users to control the addition of new links between data and computers to store those links for future use.

Using multiple views to present a dataset can help a user to perceive data more thoroughly, by reducing bias created by a given view and using a user's ability to do "multi-layered processing." (ibid.) The mechanisms for allowing users to interact with multiple views should make user interaction as natural as possible. A user's thought process should not be broken by having to think about how to navigate a visualization. When multiple views are available in a single screen the views should not break up the visualization. Side by side views should appear as a single view to maintain the user's flow.

Humans learn visually in sequences of "read-remember-read stop-and-go rhythm." (ibid.) A deeper understanding of this pattern could create less intrusive visualizations. Avoiding cognitive intrusions improves a user's ability to continuously read a visualization. Search boxes are an example of cognition intrusion. Switching focus to a search box breaks the rhythm of a user's thought. This is because a user has to consciously determine what they wish to search. Green, Ribarsky, and Fisher propose providing search criteria directly in a visualization by selecting an item or pattern of interest.

Developing an adequate model of how people internalize visualizations may require trial and error. The software process in visualization design can be changed to fully compliment a user's needs and abilities if users' thought processes are better understood. While processes will vary between users, process basics will be similar. (ibid.)

An image's readability can also be enhanced by attending to its preattentive features: i.e. properties like "orientation, length, closure, curvature, density, number, hue, luminance, intersections, terminators, 3D depth, flicker, direction of motion, velocity of motion, [and] lighting direction" that are processed within the first 0.2 seconds of seeing an object. (Healey & Enns, 2011) Treisman, the first researcher of "preattentive features," (ibid.) identified a continuum of preattentive properties. Certain preattentive features were processed closer to no time at all, while others were processed in closer to 0.2 seconds. It is faster to distinguish between severely differing items than somewhat similar items. The combining of preattentive properties into a single item, such as color, shape, and orientation, also results in preattentive processing. Images can include multiple preattentive features and still be perceived as preattentive.

Another perceptual phenomenon, change blindness, is the failure to perceive changes in an environment following a momentary distraction such as blinks. This phenomenon is not fully understood; as Healy and Enns note, "[T]here is no perception without attention." Data visualization, especially in presentation form, should avoid change blindness by placing an interrupt between similar information and forcing view attention: e.g., breaking up similar sets of data with other images and highlighting changes. The use of familiar settings and images as background directs viewer focus to those areas of an image where important information might be expected. View can also be directed by obscuring surroundings and oscillating an object's brightness. (ibid.)

Internalizing information may require several phases of perception and understanding, "for example formulating a new hypothesis, questioning its validity, elaborating on the hypothesis with detail, comparing alternatives." (Dadzie, Lanfranchi, & Petrelli, 2009) A good visualization accounts for these phases by allowing users to display information in different formats. Requirements for a visualization may also be affected by variations in a target audience's professional backgrounds and expertise along with the means of interacting with a visualization and the media through which a visualization is presented.

Visualization Experiments

Faisal et al. argue that data visualization cannot be solely rated on qualitative measures. How viewers internalize visualizations is subjective and should be studied as such using Grounded Theory. (Faisal et al., 2008) Grounded Theory is a method of research that draws conclusions based on comparisons between similar subjective responses to an experiment. The visualization process has two main parts: the designer who creates the visualization and a user who views it. Quantitative analyses of user interfaces, which record user reaction time and focus of a user, don't measure how users comprehend and remember information.

Faisal et al. used visualization software for author and publication information that allowed for hyperlinks between author citations and linked publications. Their study measured effectiveness, efficiency and satisfaction. Some participants acknowledged that the irrelevance of the information to their area of study affected their opinions of the visualization. (ibid.)

Problems with this process are the subjective nature of participants' responses, which only include conscious thoughts about the visualization, and the experimenters' analyses of the responses. Faisal et al. interviewed participants after "a high-level non-restrictive task" to determine "experiences and feelings" (ibid.) about the visualization. The task involved navigating a visualization of information on Dynamic Queries to identify the field's most beneficial authors. One user stated that using actions similar to other programs, like right-clicking to open a menu, made the software more natural. Another, however, expressed frustration about not being able to drag parts of the visualization. One user felt that navigation was much easier than a search engine.

Faisal et al. noted that users are prone to dislike a visualization if its benefits are not immediately apparent. The ability for a user to personalize a visualization also has an effect. The more users can move and change in a visualization the more prone they are to like it. (ibid)

Faisal et al. performed a follow-up experiment that combined methods of denoting direction. Tapered lines were combined with dark to light. Curved was combined with dark to light. Finally curved, dark to light and tapered were all combined as the final graph. The most effective combination was tapered and dark to light in terms of speed. The tapered and curved graph and tapered, curved, and dark to light both had the highest accuracy. Due to the low number of participants in the follow-up experiment it is unclear if the results were statistically significant. The results of the second experiment suggest an unclear relation between the method for denoting direction and a combination of methods. (ibid.)

Edge Management in Graph Visualizations

According to Wong et al., the management of edge representations in graph visualizations presents two main challenges for graph designers: routing edges around nodes and clarifying individual edges that connect to a node. (Wong, Carpendale, & Greenberg, 2003) Routing algorithms need to avoid introducing edge ambiguities, or unintended intersections of edges and node, into graphs. They should also clearly connect edges with their target nodes, a process known as edge termination or edge resolution. One aspect of edge termination is angular resolution, or the angle at which the edge terminates at a node with respect to other edges. Three edges with perfect angular resolution would reach the node 120 degrees from each other. (Duncan et al., 2011)

Wong et al.'s EdgeLens is an interactive application that removes clutter from a selected area of a graph. (Wong, Carpendale, & Greenberg, 2003) Using EdgeLens, Wong et al. experimented with edge-routing-based strategies for understanding complex relationships in force-directed graphs. The authors focused on edge routing because of their concerns about other methods for removing clutter. One, moving nodes could result in misrepresentation of the graph in the case where node location is meaningful. A second, filtering, removes "unimportant edges," which can result in a loss of context. A third, magnification, can be linear or fisheye which can cause distortion. Magnification may also not clear up edge ambiguity in the event the edge intersects the node. (ibid)

Two methods for reducing ambiguity through interactive edge routing are "the bubble approach" and "the spline approach" shown in Figure 1. (ibid.) The bubble approach only affects lines locally within a set radius around the point of interest. The spline approach curves the lines near the point of interest with a Bézier curve which affects the entire graph. EdgeLens was used to test which method allows for more accurate understanding. The spline method using a Bézier curve was in most cases clearer and could be understood more quickly. Comments about the spline were mostly positive, while comments about the bubble approach were mostly negative.

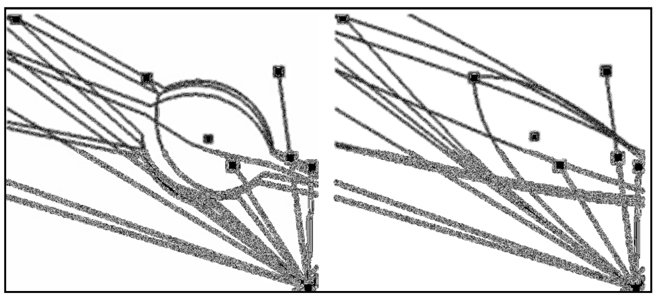


Figure 1. Bubble approach on left, Spline approach on right (Wong, Carpendale, and Greenberg, 2003)

After the experiments were completed the EdgeLens technique was improved using the spline method. The resulting mechanism provides a user with "a centre, a magnitude, and a radius of influence. A user can interact with an EdgeLens by placing and moving the EdgeLens centre." (ibid.) EdgeLens can also be set to maintain specific edges in relationship a user wishes to maintain. Multiple EdgeLens can be used simultaneously to clarify edges further. (ibid.) This is a good method for clarifying edge resolution in dense areas of a graph; unfortunately it requires a user's input, which could slow internalization.

In (2011), Cermak, Dokulil, and Katreniakova describe an original method for edge routing and bundling in order to maintain node location and clarify edge connection. Their algorithm splits a line into a poly-line at the location of an intersection (Figure 2. below). The two lines are connected outside of the node. Some checking is done to eliminate any unnecessary splits if one split removes two intersections. If two splits happen near the same location, they are separated to avoid ambiguity and edge intersection. Edge bundling was also done to remove clutter. Edges were only bundled from one node before being split to connect to their respective nodes. Edges that left the bundle were not routed into another bundle or even the same bundle. (Cermak, Dokulil, & Katreniakova. 2011)

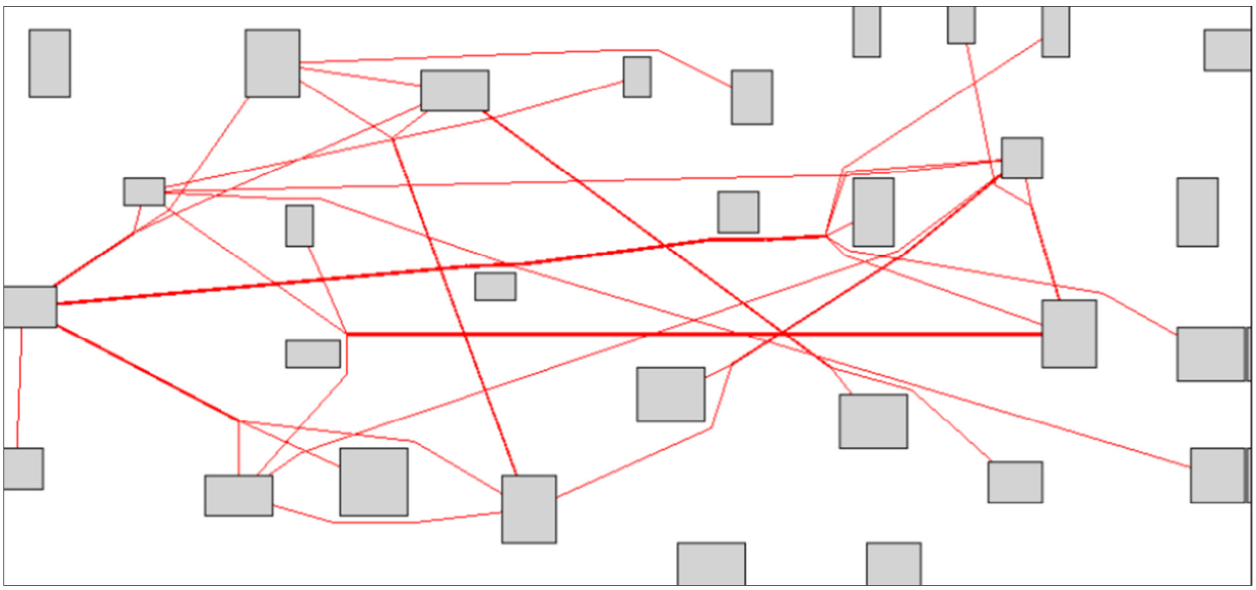


Figure 2. Edge bundling and routing (Cermak, Dokulil, and Katreniakova. 2011)

One method for making a graph aesthetically pleasing, a Lombardi drawing, draws edges "[as] circular arcs with perfect angular resolution: consecutive edges are evenly spaced around each vertex."(Duncan et al., 2010) The Lombardi drawing is named after American artist Mark Lombardi who created "drawings of social networks representing conspiracy theories." (Duncan et al., 2010) "[G]iven a fixed placement of the vertices of a planar graph, determining whether the edges can be drawn with circular arcs so that there are no crossings is NP-Complete." (Duncan et al., 2010)

Work done by Duncan et al. suggests that curves can improve the angular resolution while minimizing intersections. "Lombardi drawings" can ensure perfect angular resolution.

However, some graphs cannot be represented by a standard Lombardi drawing. (Duncan et al., 2011) Duncan et al. improve the Lombardi drawing by increasing the number of curves an edge might use to two. Every graph can be drawn in this 2-Lombardi drawing by drawing each line with two curves. The Duncan et al. method prioritizes the angular resolution of edges.

Chernobelskiy et al. seek to improve graph quality similar to Duncan et al. by increasing angular resolution. "Angular resolution has a significant impact on the readability of a graph." (Chernobelskiy et al., 2011)

Chernobelskiy et al. use two methods for creating Lombardi force-directed graphs. The first creates directed graphs using tangential and rotational force on nodes, rather than using a predefined force-directed algorithm followed by edge routing. The graph's requirements are relaxed so that perfect angular resolution does not have to be found for the graph to be complete. The second applies a force-directed algorithm to a graph, then applies Lombardi styling. This method uses temporary nodes to curve the edges to maximize angular resolution.

Finkel proposes a method using Bézier curves to improve edge angular resolution in KK-algorithm- and GEM-algorithm-constructed force-directed graphs. Both methods are shown in Figure 3. The primary graph types that can benefit from edge routing in this method are flat mapping methods that connect to physical locations. The GEM algorithm yielded better results when the curvilinear method was applied. The KK algorithm did not scale as well in performance, due to its $O(n^3)$ runtime. Finkel's curvilinear method greatly improved angular resolution as well as the edge separation (distance from edge to edge). This method appears to benefit smaller graphs more than larger graphs. The curvilinear method did not substantially improve edge crossings. Finkel notes that these are only two methods for generating force-directed graphs and more should be researched. (Finkel, 2005)

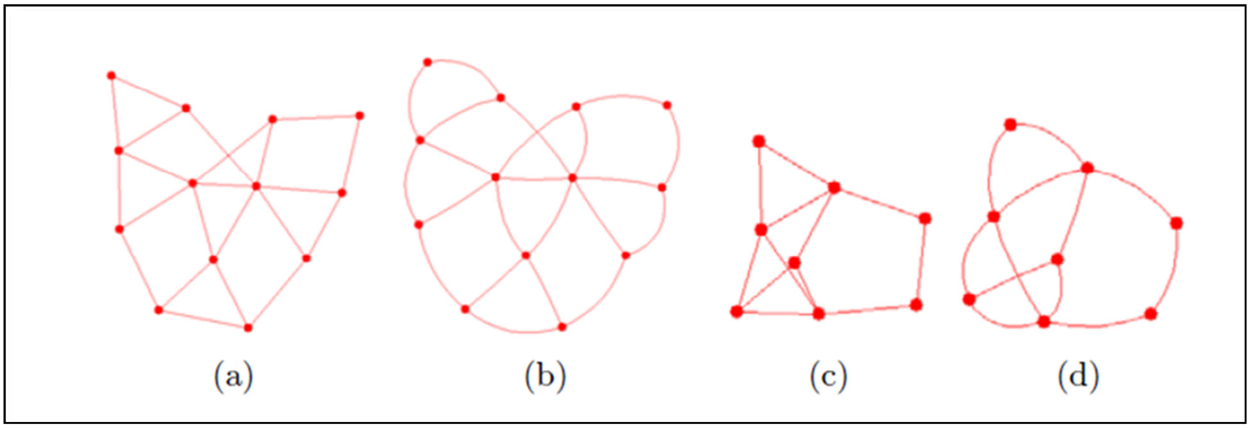


Figure 3. "Layout improvements obtained by our method: (a) straight-line drawing produced by the KK algorithm; (b) associated curvilinear drawing; (c) straight-line drawing produced by GEM algorithm; (d) associated curvilinear drawing." (Finkel, 2005)

Gauging the Effectiveness of Curvilear Edges in Graph Visualization

In 2012, Xu et al. researched the effectiveness of curved lines generated by methods like Finkel's on aesthetics and graph comprehension. While curved lines may be aesthetically pleasing to viewers, few studies have empirically evaluated the effectiveness of curved lines in graphs.

Xu et al.'s work focused on the effects of fixed curvature lines and varied curvature lines versus straight line graphs.

> Curved edges have been long used to illustrate self-loops and multiple edges between a pair of nodes, which are not possible with straight light segments. Examples include the 'Arc Diagram' in which all the nodes are placed on a horizontal line and half-circled lines are used to draw the connections among them. The PivotGraph is another example in which curved edges are used to draw the aggregated relationship between nodes. (Xu et al., 2012)

The first experiment conducted by Xu et al. studied the effects of three graph types: "straight, slightly curved, and heavily curved." The second used curves only in situations that improved angular resolution. "To understand the generic impact of edge curvature, we chose undirected abstract graphs instead of examples from a specific domain." (ibid.) The curves were generated using Bézier curves. The side to which the line was curved was assigned randomly.

The experiments' participants were asked if "a path of length two existed between two nodes." (ibid.) Differing node density did not affect the size of the nodes. The two reference nodes were drawn as orange while the rest of the nodes were black to highlight the nodes that were a given question's focus. The orange reference nodes were drawn 2 seconds before the rest of the nodes to highlight their location. All participants were volunteers and had "normal or corrected-to-normal" vision. (ibid.)

The "number of correct answers" and "time to answer" were the study's objective values. (ibid.) The straight line graph was better in both time and number of correct answers. Subsequent analysis failed to show any significant correlations between the results and number of edge crossings or the number of nodes. "This implies that path distance (i.e., the Euclidean path length) and 'smoothness' (i.e., the level of direction change at each intermediate node along a path) are more important factors in task performance." (ibid.) Participants also noted that the straight line graphs were more pleasing aesthetically, which was the opposite of what Xu et al. had predicted. Curves were generated totally randomly; this could have had some influence on the results.

The second experiment focused primarily on the use of curved lines to improve angular resolution. The number of nodes in graphs was also increased. The questions to complete were increased to four: Is there a path of length two between two random nodes, what is the shortest path between two randomly selected nodes, what is the number of connections to a random node, and "find the number of nodes connected to two selected nodes." (ibid.) Participants did all tasks on a single type of graph with varying number of nodes. The graph types used were straight, Lombardi layout resulting in improved edge resolution, and slightly curved, as the first experiment. (ibid.)

The second experiment found no significant difference between the effectiveness of the Lombardi style and straight line graph. The Lombardi style did yield more edge crossings. Participants also preferred straight line graphs. The aesthetic preference is completely against the hypothesis of Xu et al. while the effectiveness of curved versus straight lines is similar to what they originally believed. (ibid.) Since neither Chernobelskiy et al. nor Duncan et al. studied their graph design algorithms empirically, it is unclear to what degree good edge resolution improves readability, as Xu et al.'s findings suggest. Chernobelskiy et al. and Duncan et al. also focus on graphs that are mostly uncluttered.

Motivation for this Study

Edge bundling and edge routing are two of the most common methods for simplifying a graph's appearance. Edge bundling involves the grouping of edges that follow a similar path: typically, edges that terminate at a shared node. Edge routing involves either curving an edge or splitting it into multiple lines to create a polyline. Edges are then drawn so as to reduce clutter in a graph's congested subgraphs.

This research, like Xu et al.'s, sought to assess the usefulness of edge routing as a technique for simplifying force-directed graphs. Force-directed graphs use the distance between linked nodes to represent the strength of the relationship that the link depicts. It is unclear if redistributing a graph's components over the entire graph could be beneficial or harmful. Specifically, curving a graph's edges could distort users' perceptions of the relationships that those edges are meant to convey. While curved edges could be augmented with interactive content that clarifies significance, doing so could reduce a visualization's usefulness by making it harder to internalize data quickly.

Work by Xu et al. on graphs of upwards of 200 nodes suggests that curves hinder a graph's readability. (Xu et al., 2012) This study sought to determine the extent to which this result holds for smaller graphs, especially with regard to immediate observations of a graph's content. While this is not a study on the heuristics of reading distances in a graph, it does touch on how users quantify the distance between two nodes especially when the nodes are connected with curved lines.

Experimental Design

This research used randomly generated graphs of between 10 and 60 nodes to assess the effect of curved edges on graph readability. The 60-node limit was intended to limit clutter relative to display size. After 60 nodes relationships become difficult to identify with or without curved lines due to limited space and resolution. As node count increases whitespace also decreases, leaving fewer opportunities to curve edges into whitespace (shown in Figure 4). Xu et al. also note that the use of curves in graphs with more nodes increases the number of edge intersections. (Xu et al., 2012)

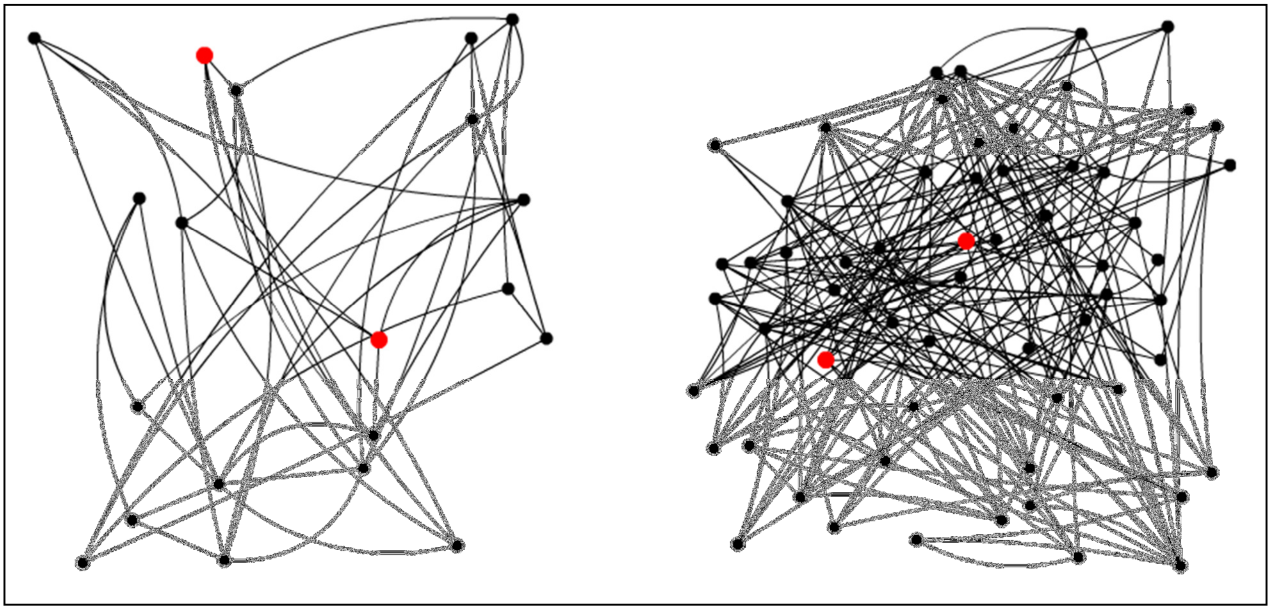


Figure 4. The graph on the left has 20 nodes; the graph on the right has 60. As the number of nodes increases the edge visibility decreases. The graph with 60 nodes is predominantly made up of straight lines because there is not enough whitespace to curve lines effectively.

Graphs were generated by first using a random number generator to position circular nodes on a 400 by 400 pixel grid. Each node had a radius of 2 pixels. A random number generator was then used to connect each node to roughly 10% of the graph's other nodes. The graph creation algorithm also ensures that every node is connected to at least two other nodes. While randomly connecting nodes does not guarantee that the resulting graphs will be fully connected, the chance of generating a disconnected node or set of nodes is insignificant. Graphs were also reviewed to ensure they were fully connected for use in the survey.

The use of randomly generated graphs ensures less bias from any previous knowledge by students being surveyed. It also allowed the focus on the study to be on the graph itself rather than on the information it represents. This method used for generating graphs is similar to Xu et al.'s method. The 400 by 400 pixel limit ensures that the graphs fit with a legend and a graph header number on a projector with a resolution of 1024 by 768 pixels. The graph was kept as a square due to Kelleher and Wagener's suggestion in 2011.

This research was limited by graph node count and graph interaction. The use of selection operations to determine the graph's properties (such as the true rather than the apparent distance between a graph's nodes) was avoided. While research by Shneiderman suggests that graph interaction is effective for clarifying ambiguities (Shneiderman, 1996), and further research by Wong, Carpendale, and Green demonstrated the value of filter-based graph interaction, this research was limited to the immediate observation of graph-based visualization. (2003) Graph size was limited due to space on the projector used for this survey. Also the method of graph connection, each node connected to 10% of the other nodes, causes large graphs to have far more connections than a graph with a static number of connections, each node always connected to 10 other nodes. This growth in connections also reduces readability giving another reason to limit graph node count.

Each graph was drawn twice: once with straight edge connections and once with curved edge connections. The corresponding graphs were placed 30 questions apart in a survey and presented using a slide show so participants could not revisit previous graphs or measure. These graphs were shown to 32 undergraduates, who were asked to estimate the distance between two nodes which were red and slightly larger than all other nodes on the graph. Red is a preattentive feature that allows for more time to process the distance rather than finding the nodes on the graph. (Healey & Enns, 2011) Xu et al. also used colored nodes in their studies of curved lines.

Questions about the aesthetics and qualitative aspects of the graphs were included to determine how students perceive each graph's readability and clutter. The use of these questions, which were added in order to obtain better insights into findings of Xu et al., was suggested in part by Faisal et al.'s observation (2008) that qualitative aspects of visualizations are equally important to the quantitative aspects. Following the survey, participants were asked overview questions about which graphs were easier to read, faster to use, and more pleasant to view. Acceptable answers included curved, straight, or neither.

Algorithm

Current Algorithm

The method used to curve edges was a Bézier curve. This type of curve was used for its simplicity in implementation and also its prior use in studies such as Xu et al. and Finkel. In 1998 Goodrich and Wagner created a framework using cubic Bézier curves. While Bézier curves are not the most versatile method for curving lines for the study of perception, they provide a time-effective method for generating graphs. Bézier curves used had only one control point which will be referred to as the Bézier anchor.

The algorithm used for curving an edge is based upon the closest nodes that lie on an edge's normal. The algorithm's primary goal is to avoid edge/node intersection. The algorithm curves the edge away from the closest node, called the anchor node, using the distance from the line to the closest point and the length of the edge to determine the curvature. The logarithmic basis used to curve lines ensures a degree of curvature that is inversely proportional to a line's proximity to its anchor node. The following equations shows the complete formula where DBA represents the distance from the line to the Bézier anchor, L represents the length of the line and DAN represents the distance from the line to the anchor node.

$$DBA = 10 * Log(L - DAN)$$

The curve is only applied if $L > DAN * 2$. Edges that pass a single close node are highly curved. Edges that pass by a more distant node are slightly curved, or not curved at all if the distance to the line from the node is greater than half of the edge's length. Edges are less curved if there is a second node that is near the edge on the opposite side; edges that pass between two close nodes are nearly straight. The following equation shows the alternate way to determine the DBA when there is a close node opposite the anchor node where DON is the distance from the line to the closest node opposite of the anchor node.

$$DBA = \frac{DON}{2}$$

The second equation is only used if the resulting DBA is less than the DBA from the Logarithmic method. This will cause highly crowded graphs to use straighter edges due to the likelihood of edges going between close nodes increasing.

Since Xu et al. in 2011 showed that number of intersections increases as node count increases, especially with curved lines, this algorithm reduces curvature as node count increases removing some intersections. While intersections are not a complete indicator of graph complexity, more intersections are correlated with more complexity. By reducing the curvature the number of intersections is also reduced. This results in a simpler graph even with high node counts. This benefits the graph by curving when it is appropriate and does not add to graph complexity.

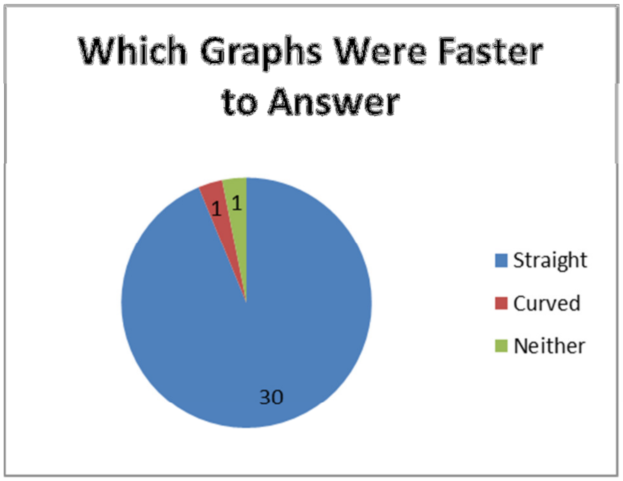
Improvements to the Algorithm

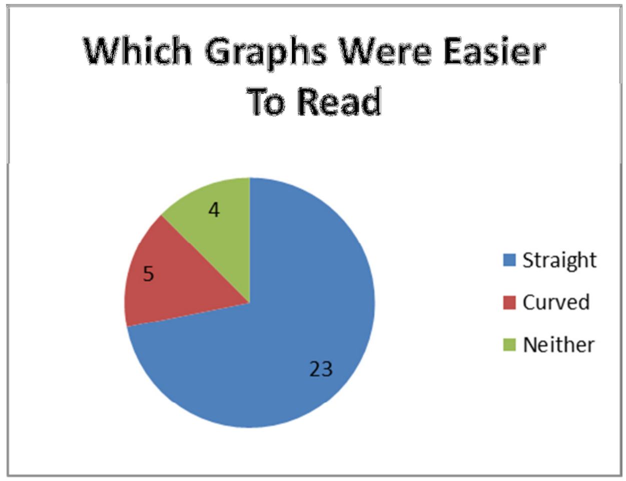
The algorithm could be improved by including edge bundling. Often when curved edges cause overlap it is near a node at which two or more edges terminate. Bundling edges would eliminate this overlap. Bundling could also eliminate some of the problems that Xu et al. encountered in 2011. Since the use of edge bundling with curved lines has not been studied, the benefit is unclear. The improvement would be that bundling may be less intrusive than intersections to the visualization since McGee and Dingliana in 2012 showed that edge bundling can inhibit users' ability to trace lines.

Another possible improvement is changing the location of the curve. A method that was abandoned for this study was curving edges dynamically from the point where the normal of the line intersected the anchor node. This meant a line was more curved around the anchor node. This would have created asymmetric curves which were beyond the scope of this study. A future study based on asymmetric curves could produce new understandings of the heuristics used by humans to understand connections and distances.

Results

There were 32 undergraduate students used in the survey. The self-reported levels of experience with visualization for these participants ranged from none to occasional, with only one saying often and two saying extensive. In responses to the other questions are shown in Figure 5. Responses to the overall questions of curved versus straight lines 30 out of the 32 said straight was faster than curved. 23 of 32 said that straight were easier to read. 16 out of 32 said that curved graphs were more pleasant to look at. Overall, the use of curved lines was not beneficial from a solely aesthetic view. While half the participants did find curved lines to be more aesthetically pleasing, the majority found them slower and more difficult to read. From a strictly perceptual standpoint curved lines appear to hinder a visualization much like Xu et al. found.





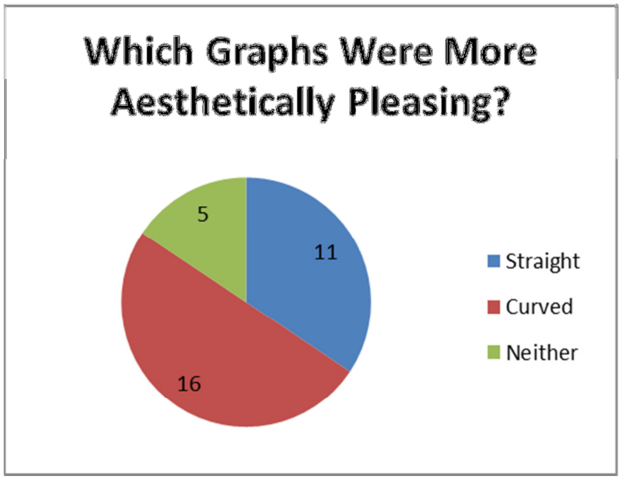


Figure 5. These pie charts show the distribution of responses to the overall speed, difficulty and aesthetics. Straight graphs appear to be faster and easier to read. Despite speed and difficulty, half of the participants still found curved lines to be more aesthetically pleasing.

The observations on graph clutter and readability (Figure 6) indicate that curved graphs did tend to be considered more cluttered but straight lines were not necessarily less cluttered. Curved graphs also tended to be more difficult to read. While this information is cumulative and not graph-specific it does suggest that the use of curved lines fails to unclutter graphs. The node count directly influencing the number of connections may have caused the clutter amounts to gravitate to “Very cluttered” and “Somewhat cluttered.” The same is also true for readability. Graphs with fixed connection counts may have had vastly different responses.

Overestimating or underestimating the distance on corresponding graphs is independent; thirteen of the graphs showed significance at a P =0.05 level in the chi-square test. There is no way to determine if a user is more likely to underestimate or overestimate a distance on a graph. This could mean that underestimating and overestimating distance is not predictable based on node configuration in a graph. It also suggests that estimated values have some amount of randomness involved.

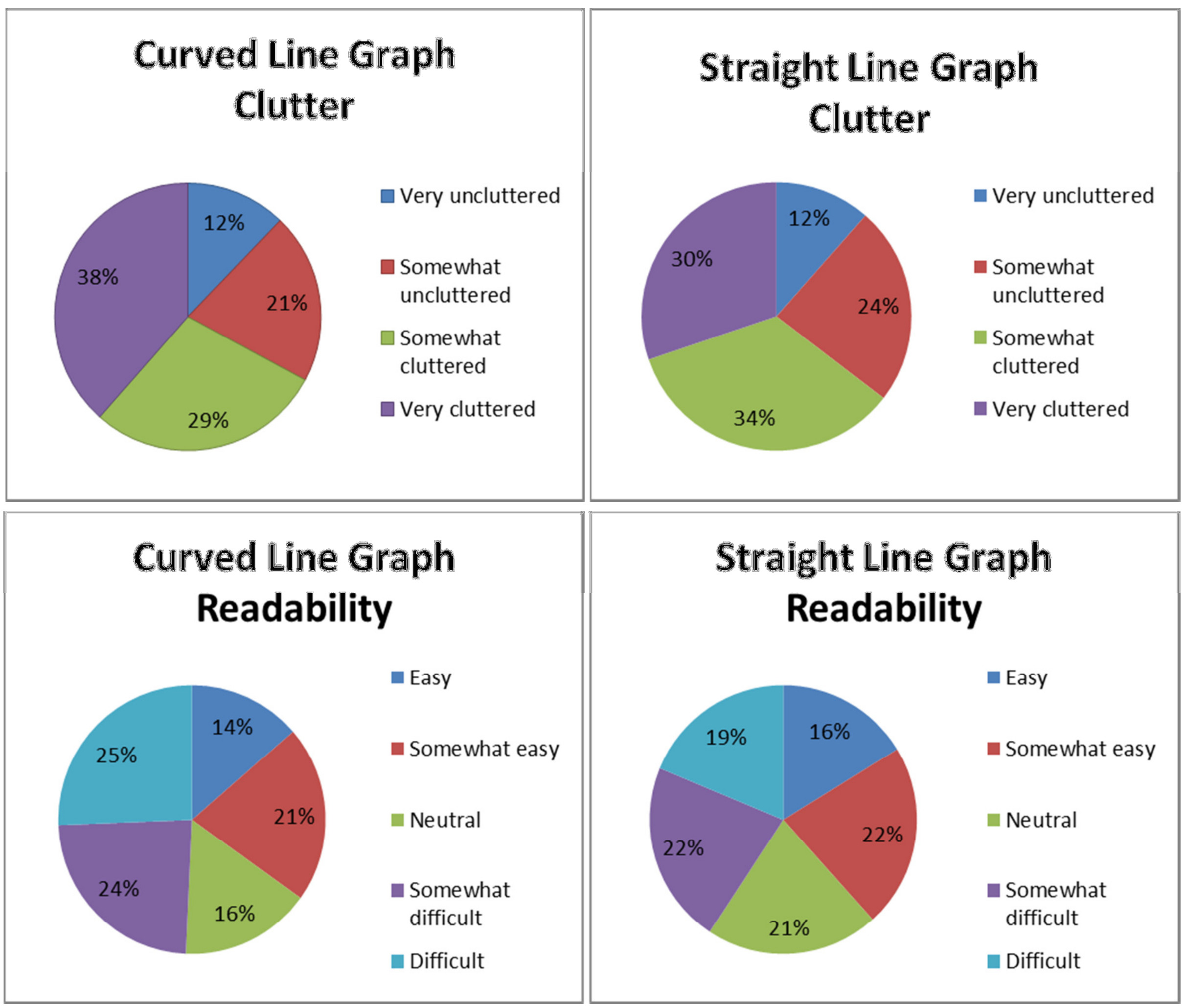


Figure 6. The top pie charts show how participants ranked graphs cluttered by curved and straight respectively. The bottom pie charts show how participants ranked graphs in readability in curved and straight

The data suggest that these observations about the lack of benefit for curved lines holds for all node counts. Even when there are few nodes and large amounts of whitespace available to curve lines curving the lines only adds clutter. Typically a participant would perceive a curved graph to be less readable and more cluttered if not the same than the straight line version. Instances where individuals found the curved version to be less cluttered or more readable were less common. This would suggest that curved lines inhibit readability.

Statistical analysis was done on the values estimated by participants. Their answers were compared to the actual values to determine the absolute relative bias. This bias shows the percentage of how wrong the participant was. The total average of every participant on every graph came out to 19.5% wrong on curved graphs and 19.8% wrong on straight graphs. So even though curved lines might inhibit the readability and clutter a graph they do not necessarily cause more incorrect estimations.

When the biases are averaged without the absolute value being taken the expected value would be close to zero, suggesting a balance between underestimations and overestimations. The average of the biases without the absolute value being taken was -12% for curved and -20% for straight. This would appear to show that straight lines are more likely to be underestimated than curved lines. This could be a result of estimating from the edge of the first node to the edge of the second node, rather than the nodes' centers. It could also suggest that humans are more prone to underestimate than to overestimate. Force-directed graphs drawn using exponential forces may be more effective in offsetting this tendency to underestimate. Since this study did not explore reasons for estimation failure, this observation is merely speculative.

On a more definitive note, three of the graphs did show significant evidence at a P = 0.05 level that curved lines cause worse estimations in distance. This supports the hypothesis that curved lines cause graphs to be more difficult to read beyond the perceived difficulty.

Even with minimal differences in user error curved lines appear to have little to no benefit over straight lines. Since the goal of visualizations is clarity, it does not appear that curved lines are effective for presenting connections in force graphs. Methods of interaction may be more valuable than a pre-curved graph for clarification.

There was also statistical significance showing independence of overestimating and underestimating with thirteen of the graphs. If a person overestimated the distance between two nodes on a curved line graph, that information does not predict whether they will overestimate or underestimate the same distance on a straight line graph or vice versa. This suggests that estimations have some amount of randomness involved or there are other uncontrolled factors that were not accounted for in this study.

Conclusion and Future Work

Future Work

Concerning the understanding of internalization of force-directed graphs with curved lines similar studies could be done asking different questions about relationships within the graph. While this survey asked participants to judge absolute distance, it may be more appropriate to ask relative distance of two nodes when compared with other attached nodes. This relative distance may in some force-directed graphs be more descriptive than the absolute distance between two nodes. Other questions relating to similarities relative to other nodes are possible areas of study. For example, marking three nodes in which all three nodes are connected in some form, and asking "which nodes are more similar based on this force-directed graph?" might lead to a better understanding of relative connections. Relative distances may also be more likely to be used for quick internalization under time constraints.

This study was also primarily on at-a-glance understanding. Other studies might be beneficial on understanding a slower internalization process where time is not an issue. The heuristics used for understanding curved versus straight lines may also be the same or even similar which could be an issue with curved lines. More studies could be done to understand if there is a specific heuristic used for distances between two points. (Green, Ribarsky, & Fisher, 2009)

The use of computer science students as the participants for this research may have yielded results that fail to generalize to other classes of observers. Using visualization experts who rely on force-directed graphs regularly could result in different values. Using students with little to no experience with force-directed graph gives a strong baseline but a person who would be concerned with distance and relationships in a force-directed graph would most likely have developed some amount of skill for estimating distance and connection. (Green, Ribarsky, and Fisher, 2009)

The effects of curved lines during interaction with graphs are another area for further study. Especially when using a pre-curved graph, a method such as EdgeLens might make graph internalization more difficult. Other interaction techniques could reduce the need for quick analysis of distance between two nodes, and even be faster than a user's best guess.

A graph's dimensions may also affect a users' perception of distance. Users, for example, may estimate distance based on the graph's absolute size. In a graph that is wider than it is tall, lines that are horizontal may be estimated as being longer than the same line drawn vertically. This could also be a possible heuristic that is used in estimating length.

Similar studies could also be done with higher node counts if the graphs were less connected. By connecting each node to only 2% of the graph 400 nodes could be generated each only being connected to roughly eight other nodes causing less congestion from lines. This could also be done if higher resolution and larger screen equipment was available. Professional displays for visualizations would allow for larger graphs with higher node counts. Even the use of a high definition monitor would allow for a graph four times the size of graphs used in this study.

The main aspects that can be further studied may be better studied on a per graph method. Absolute rather than relative distance can be of varying importance depending on the information represented. Other changes to the graph may also skew perception either negatively or positively. Other variables depend on the participants themselves which was beyond the scope of this research.

In summary, additional research on the effect of edges on information visualization could address multiple areas for further study, including size, absolute values, relative values, time, and experience. Isolating these aspects could lead to better understanding and showing other aspects that also need to be studied in isolation. This could prove valuable in understanding the internalization process and determining what heuristics are used when.

Conclusion

Xu et al.'s research was confirmed that curved lines appear only to inhibit internalization, although half of the participants in this survey did find curved lines to be more aesthetically pleasing. Curved lines appear to be harmful to understanding a visualization when absolute distance is important. In most cases they add clutter, even when there are few nodes. The benefits they might bring are not worth the perceived speed loss in almost all cases. At best curved lines are equally as useful as straight lines but will typically add clutter to a graph.

References

Cermak, M., Dokulil, J., & Katreniakova, J. (2011). Edge Routing and Bundling For Graphs With Fixed Node Positions. *Proceedings of the 2011 15th International Conference on Information Visualisation*, 475-481.

Chernobelskiy, R., Cunningham, K., Goodrich, M. T., Kobourov, S. G., & Trott, L. (2011). Force-Directed Lombardi-Style Graph Drawing. *GD'11 Proceedings of the 19th international conference on Graph Drawing*, 320-331.

Dadzie, A.-s., Lanfranchi, V., & Petrelli, D. (2009). Seeing is Believing: Linking Data with Knowledge. *Information Visualization*, 197-211.

Duncan, C. A., Eppstein, D., Goodrich, M. T., Kobourov, S. G., & Nöllenburg, M. (2010). Lombardi Drawings of Graphs. *GD'10 Proceedings of the 18th international conference on Graph drawing*, 195-207.

Duncan, C. A., Eppstein, D., Goodrich, M. T., Stephen, K. G., & Löffler, M. (2011). Planar and Poly-arc Lombardi Drawings. *GD'11 Proceedings of the 19th international conference on Graph Drawing*, 308-319.

Faisal, S., Craft, B., Cairns, P., & Blandford, A. (2008). Internalization, Qualitative Methods, and Evaluation. *Beyond Time and Errors: Novel Evaluation Methods for Information Visualization* (pp. 1-8). New York: ACM.

Finkel, B., & Tamassia, R. (2004). Curvilinear Graph Drawing Using the Force-Directed Method. *Proceedings of the 12th international conference on Graph Drawing* , 448-453.

Goodrich, M. T., & Wagner, C. G. (1998). A Framework for Drawing Planar Graphs with Curves and Polylines. *GD '98 Proceedings of the 6th International Symposium on Graph Drawing*, 153-166.

Green, T. M., Ribarsky, W., & Fisher, B. (2009). Building and Applying a Human Cognition Model for Visual Analytics. *Information Visualization*, 1-13.

Healey, C. G., & Enns, J. T. (2011, July 19). Attention and Visual Memory. *IEEE Transactions on Visualization and Computer Graphics*.

IEEE. (n.d.). *Welcome to Infovis*. Retrieved March 28, 2013, from IEEE Information Visualization(InfoVis): http://conferences.computer.org/infovis/

Kelleher, C., & Wagener, T. (2011, June). Ten Guidelines for Effective Data Visualization in Scientific Publications. *Environmental Modeling & Software, 26*(6), 822-827.

Luo, S.-J., Liu, C.-L., Chen, B.-Y., & Ma, K.-L. (2011, June 13). Ambiguity-Free Edge-Bundling for Interactive Graph Visualization. *IEEE Transactions on Visualization and Computer Graphics*.

McGee, F., & Dingliana, J. (2012). An Empirical Study on the Impact of Edge Bundling On User Comprehension of Graphs. *AVI '12 Proceedings of the International Working Conference on Advanced Visual Interfaces*, 620-627.

Pretorius, A. J., & Van Wijk, J. J. (2009). What Does the User Want to See? What Do the Data Want to Be? *Information Visualization*, 153-166.

Shneiderman, B. (1996). The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations. *Proceedings of the 1996 IEEE Symposium on Visual Languages*, 336 - 343.

Silva, S., Santos, B. S., & Madeira, J. (2011, April). Using Color in Visualization: A Survay. *Computers & Graphics, 35*(2), 320-333.

Wong, N., Carpendale, S., & Greenberg, S. (2003). EdgeLens: An interactive Method for Managing Edge Congestion in Graphs. *Information Visualization, 2003. INFOVIS 2003. IEEE Symposium on 21 Oct. 2003*, 51-58.

Xu, K., Rooney, C., Passmore, P., Ham, D.-H., & Nguyen, P. H. (2012). A User Study on Curved Edges in Graph Visualization. *Visualization and Computer Graphics, IEEE Transactions on Dec. 2012*, 2449-2456.