On Aesthetics for User-Sketched Layouts of Vertex-Weighted Graphs

Chun-Cheng Lin, *Senior Member, IEEE*, Weidong Huang, *Member, IEEE*, Wan-Yu Liu*, and Chang-Yu Chen

Abstract—Recent empirical works on graph drawing have investigated users' interpretation ability of adjacency lists of graphs as well as drawing behaviors. This is mainly done by asking participants to sketch these graphs on a tablet computer so that they can freely express their interpretation. However, previous works did not consider weighted vertices, i.e., assigning a weight to a vertex to reflect its importance. Therefore, this work extends the previous work to conduct an empirical graph drawing study with weighted vertices. More specifically, this work conducts an experiment and analyzes characteristics of the final graph layouts, participants' drawing processes and strategies and their drawing preferences. Results indicated that minimizing the number of edge crossings was still the most important aesthetic for participants, and that participants preferred the aesthetic of creating grid-like drawings in the condition with weighted vertices. Hence, this work suggested that aesthetics of minimizing number of edge crossings and creating grid-like patterns should be the main consideration for designing a graph drawing software application.

Index Terms—Graph drawing aesthetics, weighted vertex, user-sketched graph drawing, information visualization

1 Introduction

Early graph drawing algorithms [1], [2], [3] are usually determined by aesthetics that were proposed by algorithm designers based on their intuition. These designers claimed that graph drawings illustrated using their algorithms could be more easily understood and could help readers remember. However, graphs drawings are generated for users to understand the underlying graph data. Therefore, it is important to get end users involved to evaluate and validate the role of those aesthetics in making drawings effectively display and communicate data patterns and insights that are otherwise hidden in their original non-visual format.

In conducting evaluations, a typical approach of earlier research works was to invite participants to take part in an experiment and ask the participants to directly interpret a set of graph drawings generated by the researchers through an online system, and answer questions on every graph drawing according to experimental tasks [4], [5], [6], [7]. After the experiment was finished, the researchers collected data and conducted statistical analysis to evaluate possible effects of predetermined visual characteristics or aesthetics of the drawings on task performance such as the number of crossing edges on the shortest path. This kind of research methods, however, can create two problems. First, visual characteristics to be evaluated were all predetermined by the researchers, not proposed by participants; this reduces the possibility of developing new aesthetics that are preferred by users. Second, research results can be easily influenced by an unpleasing graph drawing design from the researchers. As a result, researchers have started to derive user-centered aesthetics based on drawings that are created by users, instead of visualization designers. The work in [8] asked participants in a user study to freely create their own graph drawings. They provided participants with different initial graph drawings and then asked the participants to freely move the vertices until they believed that a perfect presentation had been achieved. Afterwards, researchers analyzed visual properties of the final drawings produced by the participants to understand the drawing criteria used by users. A similar approach was also adopted by [9] in a study comparing user generated and automatic graph layouts.

Instead of asking users to generate layout based on initial drawings, experiments have been conducted to provide only adjacency lists of experimental graphs [10], [11]. Participants were asked to draw graphs from scratch based on the adjacency list provided. This method is superior for finding out what aesthetic criteria were used by participants as creating graph drawings from scratch could avoid possible impact of initial layout on users generating final graph drawings. A similar approach was also adopted by [12], [13] to investigate how users draw clustered and symmetric graphs.

Despite the fact that deriving aesthetics based on user-generated graph drawings has been demonstrated to be useful in previous user studies, most of the studies were focused on general abstract graphs in which all vertices and edges were treated equally. How users draw weighted graphs has not been investigated. In graph drawing, weight is an important concept and it is used to reflect the importance of vertices and edges [14]. Weight also has applications in real world datasets. For example, the work in [15] assigned different weight values to vertices to represent the degree of preference of users towards a webpage in a web graph.

Hence, we conducted a user study that was to expand the body of the current research on evaluating user-generated graph drawings to include user-generated weighted graphs. The study takes the approach of asking participants to draw graphs based on adjacency lists provided and investigates how the feature of weight is drawn by users and what criteria were considered when weighted graphs are drawn. Additionally, to better understand whether users' drawing criteria change according to information provided at hand, our study has four stages and in each stage, different pieces of information were provided. The contributions of this present study are stated as follows:

- An experiment was conducted to investigate how users drew weighted graphs and what aesthetic criteria were used when doing so.
- We divided the experiment into four stages for better understanding of user drawing behaviors and aesthetics preferences when different pieces of information were provided.
- We analyzed the area ratio of important vertices and other

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vertices, and found that to differentiate important vertices from others, a 2.21-times difference between the areas of the two vertex types was created by participants.

- Our experiment replicated the finding of prior research that aligning nodes and edges to an underlying grid is important and further showed that when there exist vertices with different weights, participants value the aesthetic of the grid-like pattern more, which can be used to inform the design of future drawing software tools.
- This study confirmed that minimization of the number of edge crossings is still an important aesthetic criterion valued by participants.

The rest of this paper is organized as follows. Section 2 gives a comprehensive literature review on this study. Section 3 gives experimental design of this study, and Section 4 shows experimental results and analysis. Section 5 gives discussion based on the results, and Section 6 conclusion this work with future works.

2 RELATED WORK

At the early stage of graph drawing research, algorithms were developed mainly based on the aesthetics determined by the researcher or designers themselves. This kind of algorithms, however, are not objective, because the drawing aesthetics emphasized by every designer are not consistent. As a result, there exist a considerable amount of difference across graph drawings generated by those algorithms. Hence, some researchers have started to undertake empirical user studies on validating existing or deriving new objective drawing aesthetics.

In order to validate existing aesthetics, the work in [16] conducted one of the first studies that involve users and tested three aesthetics items: edge bends, edge crossings, and symmetry. Afterwards, the work in [17] considered another two additional types of drawing aesthetics: maximizing the minimum angle between two edges, and presenting vertices and edges in a grid-like pattern. They compared the degree of importance of these five drawing aesthetics and the results of this study confirmed that these aesthetics had varying degrees of influence in aiding users to understand graphs, and that minimization of the number of edge crossings was the most important. As a result, there were many subsequent studies [18], [19] that dealt with how to minimize edge crossings. There was even some works that studied the angle between crossing edges [20].

Putting aesthetics in the context of software engineering, the work in [5] investigated which drawing aesthetics were most suitable to be used to design the algorithm of drawing UML diagrams. The experiment asked participants to answer questions specific to a set of pre-drawn UML diagrams displayed by a custom-built system, and was divided into two parts. The first part decided which types of drawing aesthetics existed in the UML diagram, while the second part was to find the best graph presentation method in reality. Experimental results also suggested that the same graph itself may require a different set of aesthetic criteria to be effective in different contexts or domains.

Taking a different approach, the work in [8] conducted a user study in which graph drawings were laid out freely by participants. Moreover, their experiment was changed to be conducted through the Internet; hence, a large number of participants could be invited to join. Given initial graph drawings, participants were requested to freely adjust graph drawings by rearranging the nodes until participants believed that the perfect layout had been achieved. The study found that that participants were able to detect grouping information and that they used distance between groups to reflect strength or weakness of group relationships. Arguing that the experiment in [8] could be subject to the potential limitation of the initial graph drawings such as labeling vertices by names, the work in [9] conducted another study in which vertices were labeled with consistent identical smileys. In this study, participants first were asked to optimize the layout of a set of graph drawings. Then the user generated drawings were compared with automatically generated drawings using force-directed, orthogonal and circular layout algorithms and it was found that user-generated layouts performed equally well with or better than force-directed layout.

The works in [10], [11] conducted a study in which participants provided with an adjacency list of the experimental graph. Participants began to commence drawing from scratch on a tablet computer with the use of a touch pen based on the adjacency list. By analyzing the visual features of user generated drawing and participants' drawing behaviors, it was found that removing edge crossings was considered the most important task and that participants tend to position nodes and edges in a grid format. The work in [21] asked participants to read each type of graphs with different characteristics, and then requested them to draw the graphs, which they read from memory. The objective of this study was to analyze which characteristics can be employed by participants. The results showed that three types of characteristics that had the greatest degree of influence are symmetry, colinearity, and grid-like pattern.

However, the works in [10], [11] did not consider the characteristics of weight. Graph is frequently used to represent transportation system [22], [23], communication system [24], [25], [26], social phenomenon [27], [28], etc. in real world applications. Vertices and edges have different weights in these real world systems. The works in [29], [30] in recent years have begun giving different weights based on the importance of the vertex or edge. To gain additional knowledge on how users draw weighted graphs, the current study considers the characteristics of vertex weight, which we describe in what follows.

3 EXPERIMENTAL DESIGN

The experiment was designed to answer the following three questions: 1) How will people present graphs, when a certain vertex in the graph has a higher importance? 2) What aesthetic criteria will be used by participants when they draw weighted graphs? and 3) Vertices connected with a larger number of edges are often regarded as important. However, if we designate vertices connected with a smaller number of edges as important, how will participants present the graphs?

In this experiment, we have two experimental graphs, called Graph A and Graph B respectively, as shown in Fig. 1. Graph A includes 10 vertices and 15 edges. Graph B includes 10 vertices and 14 edges. To add weight information to the graphs, the number of edges incident to vertex C has been made higher than other vertices in both graphs.

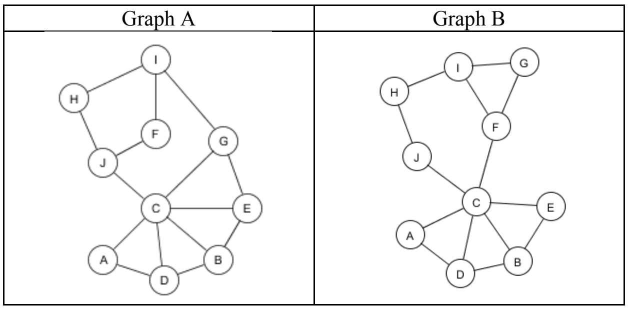


Fig. 1. The experimental graphs used in this study.

To address our research questions, our experiment was divided into four stages, or parts, with each part having different information provided and a different experimental task performed. Graph A was used in the first two parts while Graph B was used in the remaining two parts. The graphs were provided as adjacency lists shown in Table 1. Note that the order of edges and labels of the vertices were changed in different stages to make it difficult for participants to realize that the same graphs were used.

3.1 Apparatus and software

We chose the iPad 2 tablet computer [31], a product of Apple, Inc., as our experimental equipment. It is equipped with an iOS 6 operating system, A5 dual core processor, 9.7-inch Retina Display screen, and 32G storage capacity.

Table 1. The adjacency lists of the experimental graphs provided in the four parts of our experiment.

Stage	Edges
Part A	(A, D), (A, C), (B, D), (C, D), (B, C), (B, E), (C, E), (C, J), (C, G), (J, F), (F, I), (G, I), (J, H), (I, H), (E, G)
Part B	(B, D), (C, D), (G, I), (B, C), (B, E), (C, J), (A, D), (C, G), (J, F), (F, I), (I, H), (C, E), (J, H), (E, G), (A, C)
Part C	(A, D), (A, C), (B, D), (C, D), (B, C), (B, E), (C, E), (C, J), (F, G), (C, F), (F, I), (G, I), (J, H), (I, H)
Part D	(G, I), (B, D), (C, D), (J, H), (B, C), (C, E), (C, J), (F, G), (C, F), (F, I), (B, E), (I, H), (A, D), (A, C)

In order to conduct this experiment, we also have the following two software applications installed on iPad 2: a drawing software "OmniGraffle" [32] and a screen recorder software "Display Recorder (version 1.0.0)" [33]. The interface of "OmniGraffle" is easy to operate. Participants can draw a vertex through choosing the circle pattern and then touching the screen. The vertex can be labeled by double tapping on the vertex. Edge relationships can be established by choosing the line pattern and dragging it in between two vertices. The screen recorder software can record any action that the participant takes during the experiment into videos, which allows us to analyze information, e.g., what actions the participant takes, or how much time it takes for the participant to operate an action.

3.2 Experimental tasks

For each part of the experiment, participants are asked to draw the graph from scratch based on the given adjacency list of Graph A or Graph B. Before the experiment, participants were shared with a tip that "*graphs usually have certain vertices with higher importance, and therefore participants should endeavor to present the vertex with high importance to be clearly distinguished*". We did not inform participants, however, on the definition of "important vertex," but the intent of the hint was hoping that participants would consider the weight characteristics of vertices in the course of drawing. Specific tasks and graph information provided for each part are as follows:

- Part A: "*Please draw this graph as best as you can so to make it easy to understand*."
- Part B: "*Vertex C is an important vertex and must be enlarged. Please draw this graph as best as you can so to make it easy to understand*." Note that the important vertex here has a larger number of edges.
- Part C: "*Please draw this graph as best as you can so to make it easy to understand*."
- Part D: "*Vertex A is an important vertex, although it is connected with a small number of edges. Please draw this graph as best as you can so to make it easy to understand*." Note that different from Part B, the important vertex here has a small number of edges. In addition, we did not specifically ask participants to enlarge the important vertex in Part D.

Note that the first three parts were to address our first two research questions stated in the beginning of Section 3, while the fourth part was to address our third research question. More specifically the purpose of Part C was to understand whether participants would be able to learn from the experience of the prior drawing process after they finished the first two parts. We call this "learning effect". And the purpose of Part D was to understand how participants would draw the graph when the important vertex did not have many edges as normally expected.

3.3 Participants

A total of 34 participants were invited to take part in this experiment. Participants mainly come from masters' students of National Chiao Tung University and their circle of friends and relatives. Males and females each account for two halves of the participants. A majority of the participants studied Computer Science or were studying it. Nearly half of the participants had prior experience of drawing general graphs, but not drawing weighted graphs. In addition, all participants frequently utilized smart phones or tablet computes in their daily lives. Thus, these participants did not have any trouble in operation of touch technology.

3.4 Experimental procedure

Participants were asked to first read the experiment guidelines and informed of the whole experimental process and then sign a letter of consent. Afterwards, a pre-experiment questionnaire would be filled out to collect the participants' background information. Next, we played the instructional video which included a demonstration of how to operate the drawing software "OmniGraffle" on iPad 2 and a tutorial example on the adjacency list. Once they were ready, the participants started drawing graphs, performed tasks and going through the four stages.

After participants completed the experiment, we requested them to fill out a post-experiment questionnaire asking about how they interpreted the importance of vertices and what strategies they used for drawing, etc. Lastly, we scheduled additional time with each participant to conduct an interview. During the interview, it was possible to ask as many questions as possible, and seek clarification for doubtful parts.

3.5 Hypotheses

H1: for Part A task, because we did not give any specific information about important vertices, we expected that participants would follow common practices to draw graphs. That is, draw the graph with minimum edge crossings, important vertices near the center and a symmetric layout [7, 10].

H2: for Part B task, additional information was given. Participants were told vertex C was important as it has many connections and must be enlarged. Because of this, we expected that participants would follow the instruction by drawing vertex C in the center as a larger node, while keeping edge crossings low if possible.

H3: for Part C task, we expected that participants could learn to utilize the number of connections as an indication of importance to draw a graph with enlargement of nodes after the Part B task was completed, although the task for Part C did not specifically ask the participant to enlarge the important vertex.

H4: for Part D task, we told participants that vertex A was important but it did not have many connections. We expected that most participants would still draw the vertex as an enlarged node but might not emphasize its importance as much as they did in Part C.

4 Experimental Results

Our analysis is based on the data collected during the experiment, which includes final graph drawings, videos of participants drawing graphs and the data of questionnaires and interviews. Part of the experiment results are reported in [38]. This section reports the results concerning drawing aesthetics and drawing strategies of participants. Further, we name individual drawings according to the International Numbering Convention. For example, the drawing generated by Participant No. 5 in Part A is named as "5A"; the drawing generated by Participant No. 11 in Part C is thus named as "11C."

4.1. Drawing aesthetics of final graph layouts

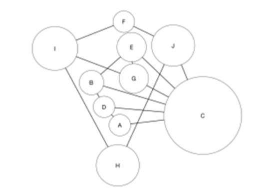
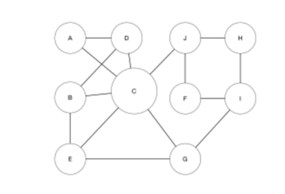
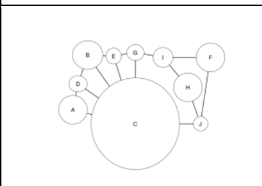
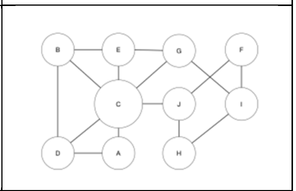
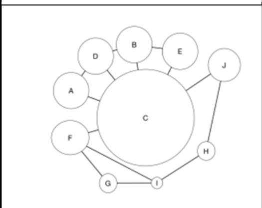
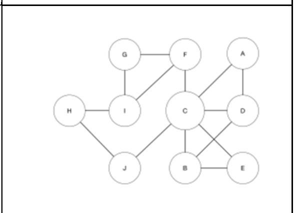
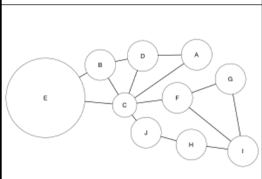
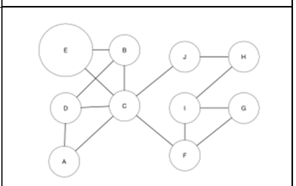
Thirty-four students participated in the experiment with four parts, and hence, 136 graph drawings were collected. Table 2 shows examples of those drawings.

Remind that one of the research questions was to find out how participants displayed the information of vertex importance in their final drawings. To answer this question, different from previous works, our user generated drawings are analyzed using the following characteristics:

- Area ratio of important vertex and other vertices: We calculated the area of the important vertex and a general vertex, respectively. The ratio can be obtained by dividing the two aforementioned values. In general, the larger the ratio is, the easier the important vertex can be visually distinguished.
- Whether or not the size of the important vertex is enlarged.

- Whether or not the important vertex is centered in the whole drawing: Our definition of "centered in the whole drawing" is to enclose the final drawing in a rectangular box, and then divide it into 9 grids (Fig. 2). If a majority of the important vertex circle falls within the central grid, then it is defined as "centered."

Table 2. Final drawings generated by Participant 5 and Participant 14.

	5	14
Part A		
Part B		
Part C		
Part D		

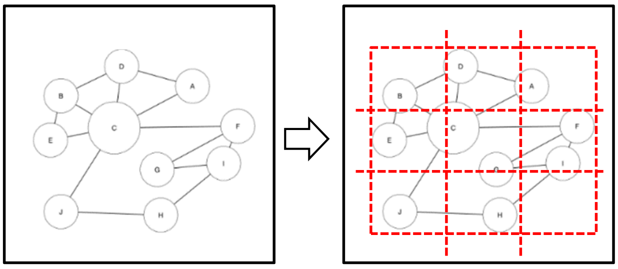


Fig. 2. Illustration of defining the centered important vertex.

In addition, we analyze the aesthetics of edge crossings and edge length distribution that are also important criteria for quality drawings have been investigated in previous empirical graph drawing studies [10].

4.1.1. Analysis of final graph drawings

First, we collected statistics for the two characteristics of "whether the important vertex is enlarged" and "whether the important vertex is centered" from participants' final drawings. The statistical results are shown in Table 3.

As can be seen from Table 3, in Part A, 53% of the vertices had enlarged the maximal-degree vertex. That is, without being told any information about important vertices, approximately a half of the participants could find the correct important vertex and present the vertex with an enlarged node in their graph drawings. In Part B, participants were specifically informed that "*vertex C is an important vertex and must be enlarged*." Therefore, 100% of the graph drawings had vertex C being enlarged.

Table 3. Statistics for whether participants enlarged and centered important vertices.

	Part A	Part B	Part C	Part D
The proportion of participants that enlarged the size of the maximal-degree vertex	53.0%	100.0%	82.0%	14.7%
The proportion of participants that centered the maximal-degree vertex	61.7%	73.5%	70.5%	50.0%
The proportion of participants that enlarged the size of the important vertex assigned in Part D	–	–	–	91.0%
The proportion of participants that centered the important vertex assigned in Part D	–	–	–	20.5%

In Part C, 82% of the participants enlarged the maximal-degree vertex. Note that the same information was provided in Part A and Part C. However, the portion of participants who enlarged the vertex increased from 53% to 82%, which is likely because they had performed the vertex enlargement task in Part B. We also performed a statistical paired t test on the two conditions under a 95% level of confidence, and it was found that there was a significant difference between Part A and Part C ($p < 0.001$). In Part D, participants were specifically informed that "*vertex A is an important vertex, although it is connected with a small number of edges*". The proportion of participants that enlarged the size of the important vertex accounted for 91%. Note that we did not ask them to enlarge the important vertex in Part C and D, and hence, they could emphasize this important vertex based on their own preference. There were two possibilities to explain this: 1) a majority of the participants believed that enlarging an important vertex indeed can help determine the importance of vertices, or 2) given that none of our participants had experience of drawing weighted graphs, it is likely they learnt from Part B and followed the same approach in the subsequent two parts.

Furthermore, we calculated the area ratio for all the drawings and used the software Minitab to generate the box-and-whisker plot, which is shown in Fig. 3. Note that the number shown beside the outliners is the participant ID. As can be seen from Fig. 3, Participant No. 5 enlarged the vertices at each stage of the experiment, while participants No. 7, 17, 18, and 20 enlarged vertices only in Part B. We further calculated the mean of the area ratio values and it was 2.21. That is, on average, an approximate 2.21-times difference between an important vertex and a non-important vertex was created by participants to make a differentiation between important and non-important vertices for human vision.

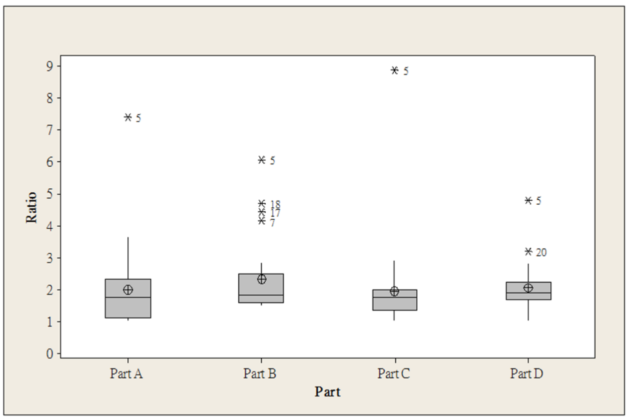


Fig. 3. Box-and-whisker plot for the area ratio of the important vertex and other vertices.

The statistical results in Table 3 indicate that in Part A, 61.7% of graph drawings have a centered maximal-degree vertex, 73.5% for Part B, and 70.5% for Part C. To understand why participants put important vertices in the center, we found from interviews that aside from being easily distinguished by readers, another important reason is that it can lead to fewer edge crossings. Thus, minimization of the number of edge crossings is the aesthetic that participants valued highly. However, in Part D, only 20.5% of graph drawings have the important vertex centered in their layout. This is likely because the important vertex was "artificial" here and was not the vertex connected with many edges. In order to avoid edge crossings, most of the participants had chosen not to place the "artificial" important vertex at the center of the drawing. Instead, in most cases, the important vertex was placed at a corner, or at isolated peripheral positions without other vertices surrounding them. All this indicates that participants believed that the number of edge crossings was more important than centering important vertices.

Furthermore, we observed that overall, approximately 28.6% (39/136) of graph drawings had grid-like patterns. This proportion is close to that found in the work in [10]. In addition, as shown in Table 4, a certain proportion of vertical edges and horizontal edges still exist in non-grid drawings. More specifically, vertical edges and horizontal edges in Part A accounted for 19.4% of all edges, 37.2% for Part B, 33.9% for Part C, and 39.4% for Part D. The fact that the proportion is clearly lower in Part A may be because at this stage, many participants could not detect the weight characteristics of vertices.

Table 4. Statistics of characteristics of final graph drawings.

Class	Characteristics	Part A	Part B	Part C	Part D
Important vertex	Centered	21	24	23	8
	Area ratio	1.995	2.310	1.952	2.046
Edge crossing	Total number of edge crossings	22	27	13	7
	Number of non-edge-crossing drawings	24	25	31	29
Vertical/ horizontal edge	Percentage of vertical/horizontal edges	19.4%	37.2%	33.9%	39.4%
	Number of grid-like drawings	3	11	10	15
Edge length	Average variance of edge lengths	0.43	0.55	0.79	0.74

Lastly, we also observed that some participants adopted edges with similar lengths for each drawing. The variance of edge lengths in each of their drawings is very small. This shows that participants preferred to adopt edges with similar lengths, which is consistent to the findings of previous studies [8], [10]. More specifically, as shown in Table 4, the largest variance among the four drawing stages is 0.79 only, with 0.43 being the smallest.

4.1.2. Comparing differences between experiment parts

By means of hypothesis testing methods, we compared whether significant difference exists among the experiment parts. P-value is calculated through the repeated measures ANOVA using the statistical software Minitab and the results are shown in the last column of Table 5. Under the 95% confidence level, while there was no difference in edge crossing or edge length variance across the four experimental parts, there existed a statistical significance for each of the following four graph drawing characteristics:

- Important vertex enlarged ($p < 0.001$): The number of drawings that enlarge the important vertex in Part A and Part C is smaller compared to other three parts.
- Important vertex centered ($p < 0.001$): The number of drawings that center the important vertex in Part D is the smallest compared to other three parts.
- Grid-like pattern graph drawing ($p = 0.012$): The proportion of participants who drew the graph with the grid-like pattern in Part A is the smallest compared to other three parts.
- Percentage of horizontal edges/vertical edges ($p = 0.050$): The proportion of participants, who utilized vertical edges/horizontal edges, is the smallest in Part A compared to other three parts.

Table 5. ANOVA analysis of final graph drawings.

Class	Characteristics	P-value
Important vertex	Centered	< 0.001
	Area ratio	0.902
	Whether the important vertex is enlarged	< 0.001
Edge crossing	Total number of edge crossings	0.373
	Percentage of crossings among all edges	0.429
	Number of non-edge-crossing drawings	0.110
Vertical/horizontal edge	Percentage of vertical/horizontal edges	0.050
	Number of grid-like drawings	0.012
Edge length	Average variance of edge lengths	0.879

In summary, although in Part A and Part C, participants received the same information, Part C was conducted after Part B and in Part B, they were asked to enlarge the important vertex. This have had impact on how they drew graphs in Part C; drawings with the characteristic of enlarging the important vertex in Part C accounts for 82%, which is significantly larger than that in Part A.

The significant difference in the number of grid-like drawings between Part A and other parts indicates that participants preferred the aesthetic of the grid-like pattern more when additional vertex importance inform was provided. Note that the proportion of vertical edges/horizontal edges was also higher in other parts of the experiment as shown in Table 4. However, how vertex importance is related to grid-like pattern is worth further investigation.

Furthermore, only a small portion of participants placed the artificial important vertex at the center in Part D. Based on the feedback that we received from interviews, this is largely related to participants' preference of drawing aesthetics. Even if the vertex in consideration is important, it does not have many edges and placing it at the center easily causes the graph drawing to generate edge crossings. In the end, a majority of the participants chose to move the artificial important vertex to a peripheral position to avoid the existence of edge crossings. What is surprising is that some participants derived another type of method to emphasize importance. That is, placing the artificial important vertex at an isolated position, where it could be easily spotted at a single glance.

4.2. Drawing strategies

A screen recorder software tool was used to video record the drawing process of participants on the tablet computer. With the videos recorded, we were able to observe each action taken by the participants from the start to the completion of the final graph drawing and a lot of logical drawing processes can be discovered.

4.2.1. Analyses of drawing process

From the experiment video of the participants, we can observe that participants adopted some logical drawing strategies. First, there are three types of drawing strategies as shown in Table 6:

- Draw all vertices from the start, and then connect the vertices with edges based on the adjacency list (17B of Table 6).
- Draw the important vertices first, and then gradually draw other vertices based on the adjacency list (24A of Table 6).
- Always draw vertices according to the convenience of the participant based on the adjacency list (14A of Table 6).

Second, we also observed three types of preferences of the participants in their drawing process:

- Prefer to adopt vertical edges/ horizontal edges.
- Prefer to adopt edges with similar lengths.
- Prefer to plan ahead before drawing a graph.

The statistics of the logical drawing strategies and preferences in the drawing processes of participants are shown in Table 7. First, we can observe that on the condition of informing participants of the important vertex, a majority of the participants adopted "first draw the important vertex" strategy. More specifically, participants tended to place important vertices at conspicuous positions so that they can be easily distinguished from the start. Under a condition where participants were not informed about the important vertex, most participants preferred the other two types of strategy to illustrate vertices, with relatively more participants employing the strategy of "drawing vertices based on the participant's convenience in drawing".

Table 6. Various drawing strategies of participants.

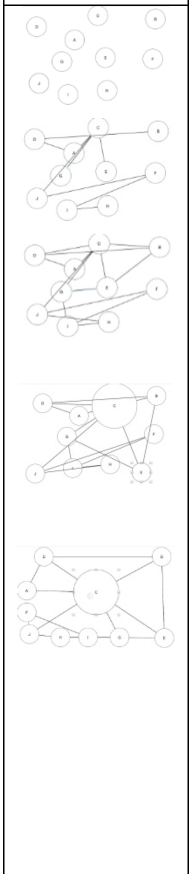
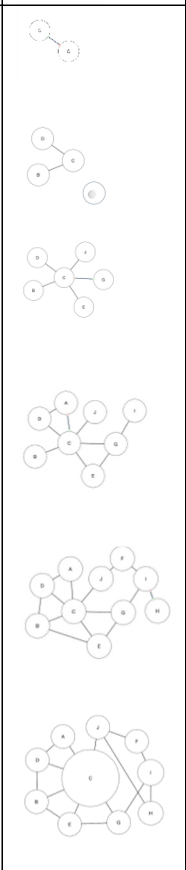
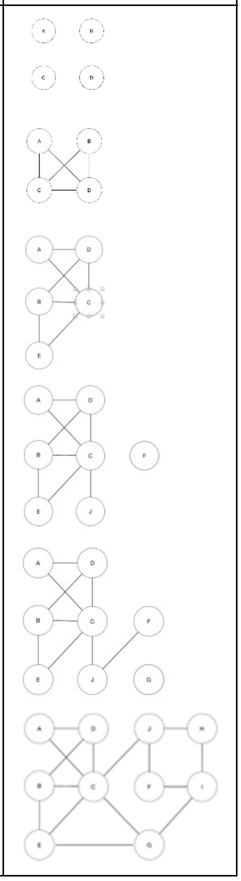
17B	24A	14A
		

Table 7. Drawing strategies and preferences adopted during the drawing process.

Strategy	The important vertex is not informed	The important vertex is informed
Drawing vertices		
Drawing all vertices first	10*	9*
Drawing the important vertex first	3*	22†
Drawing vertices based on the participant's convenience in drawing	23	6
Drawing preference in the drawing process		
Preferring to draw vertical/horizontal edges	15‡	18†
Preferring to draw edges with similar edge length	26	28
Plan how to draw before drawing the graph	3	3

* One participant adopted different drawing strategies in different parts.
† Two participants adopted different drawing strategies in different parts.
‡ Three participants adopted different drawing strategies in different parts.

Concerning the preference of participants in the drawing process, nearly half of the participants preferred utilizing vertical edges and horizontal edges to illustrate. However, the more vertices and edges are drawn for a given graph, the more edge crossings are easily created. Therefore, participants are more likely to move around vertices in order to avoid edge crossings, which can be seen in the videos. As a result, the proportion of vertical edges/horizontal edges would reduce. This drawing process indirectly verifies the previous research results of [17] that the number of edge crossings is the most important aesthetic criterion. Furthermore, a majority of participants preferred utilizing edges with similar lengths. The advantage of adopting this aesthetic is that visually, the judgment on the importance of the vertices will not be subject to the influence of differences in edge length. Lastly, there were three participants who analyzed the adjacency list and planed ahead before drawing the graph. Although they spent some time at the early stage of the experiment, we can see that these participants spent relatively less time in moving around the vertices. Therefore, the overall drawing time did not significantly increase.

4.2.2. Comparing the differences in the situations of informing participants of important vertices or not

By means of hypotheses testing, we compared differences of the two situations of "informing the important vertex" and "not informing the important vertex." Through the statistical software Minitab, ANOVA was performed to calculate the P-value, as shown in last column of Table 8. Under a 95% confidence level, two drawing strategy results have significant differences:

- First drawing the important vertex ($p < 0.001$): Compared with the situation of not informing about the important vertex, more participants under the situation of being informed about the important vertex chose this strategy (Fig. 4).
- Drawing vertices based on the participant's convenience in drawing ($p < 0.001$): Compared with the situation of being informed, more participants under the condition of not being informed chose this strategy (Fig. 5).

Concerning the aforementioned significant differences, we can arrive at one main conclusion as follows. Under the condition of informing participants on the important vertex, participants clearly prefer to adopt the "first drawing the important vertex" strategy. However, on the condition of not being informed of the important vertex, participants practically will not choose this strategy. This is because an overwhelming majority of participants does not plan ahead. Therefore, they cannot find the important vertex at the start, thus, reducing the probability of adopting this strategy.

Table 8. ANOVA analysis of the drawing strategies.

	Strategy	P-value
Drawing vertices	Drawing all vertices first	0.307
	Drawing the important vertex first	< 0.001
	Drawing vertices based on the participant's convenience in drawing	< 0.001
Drawing preference in the drawing process	Preferring to draw vertical/horizontal edges	0.474
	Preferring to draw edges with similar edge length	0.556
	Plan how to draw before drawing the graph	1.000

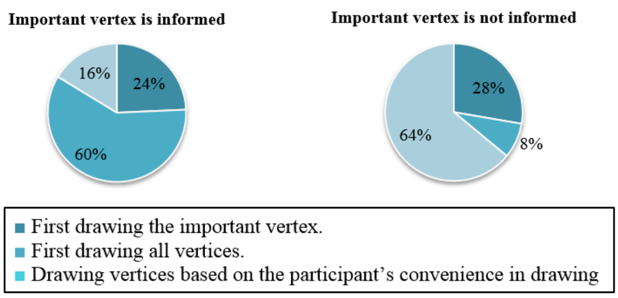


Fig. 4. Pie chart for distribution of participants that adopted each drawing strategy adopted by participants.

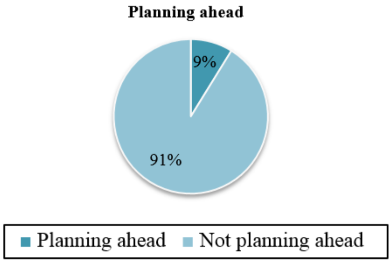


Fig. 5. Pie chart for distribution of participants that planned ahead or not before drawing the graph.

5 Discussion and Concluding Remarks

This present study divides the experiment into four drawing experimental parts: Parts A, B, C and D. We provided different information to participants at different stages. In Part A, we did not provide participants with any additional information. Nearly a half of the participants did not discover that vertices had weight differences. Further, three participants failed to identify the correct important vertex. With regards to presentation of the important vertex, only approximately 53% of the participants adopted the characteristics of enlarging the important vertex. This is less than what we expected, because we thought that enlarging the important vertex is a natural method. Further, approximately 62% of the participants adopted the approach of centering the important vertex, and participants commonly acknowledged that the "centered" position attracts attention. Concerning drawing aesthetics, among all drawings produced by the participants, only four had more than one edge crossing. This shows again that minimization of the edge crossing number is important. However, the aesthetic of the grid-like pattern is not significant at this stage. Therefore, our hypothesis H1 was only partly supported.

In part B, we directly informed participants the important vertex and asked them to enlarge it. The intent was to hint participants that more edges signifies that vertices are more important, and we hoped that they would utilize the characteristics of enlargement to illustrate important vertices in graph drawings. And this is reflected in the result; as it can be seen from the resulting drawings, at this stage, graph drawings all had a phenomenon of enlarging the important vertex. Furthermore, because the important vertex was explicitly pointed out, it avoided judgement errors of the participants, and the probability of a centered important vertex increased to 73.5%. Concerning drawing aesthetics, out of all drawings, 6 had more than one edge crossing, which is higher than that in part A. This may be because participants focused on emphasizing the existence of the important vertex and slightly neglected the aesthetics of minimization of the number of edge crossings. Thus our second hypothesis H2 was supported. Moreover, at this stage, the number of vertices and edges that were presented as a grid-like pattern had clearly increased. Thus, we infer that when participants knew that there existed different weights for the vertices, they preferred to adopt the grid-like pattern aesthetic in graph drawing.

The graph in Part C is an all-new experimental graph. Similarly, we did not inform participants of any additional information. However, participants can identify the correct important vertex and utilize the characteristics of enlargement to present it. Our analysis revealed that approximately 82% of graph drawings presented important vertices by means of enlarging the important vertex. And the statistical ANOVA test indicates that this percentage was significantly different from that in Part A. We attribute this difference to the learning effect as they were told to enlarge the important vertex in Part B. Therefore, our hypothesis H3 was supported. The only participant that did not find the correct important vertex at this stage is Participant No. 8. We tried to understand the participant's behavior through post-experiment interview. This participant believed that when illustrating the graph drawing based on adjacency list, vertex G fell at the center of the drawing, and thus the participant believed that it was the important vertex. On the other hand, all other participants could identify the important vertex through observing the number of edges incident to each vertex. Further, in addition to locating the important vertices, Participants No. 5 and 7 also expressed the importance of the characteristics of "propagation," i.e., the more directly a vertex is linked to the most important vertex, the higher its importance, and vice versa.

In Part D, even if the graph used was the same experimental graph as that is Part C, we directly informed the participants that a certain vertex (i.e. vertex E), which had the least number of edges, was the artificial important vertex. The results showed that 91% of the participants chose to enlarge the artificial important vertex, rather than the vertex with the most number of edges. This was consistent with our expectation (H4). A majority of the participants, however, would place the vertex with the most number of edges at the center, and not the artificial vertex. We observed that even if the artificial important vertex had a high importance, placing it at the center is the initial choice of the participants, but after the participants completed the graph drawing, they noticed that edge crossings were presented, and then started to the artificial important vertex around. In the end, participants chose to place the vertex with the most number of edges at the center.

Further, based on our observations and analysis, it is clear that even if this study added the attribute of vertex weight, crossing minimization is still the aesthetic criterion that participants value the most. Furthermore, when a graph has vertices with different weights, participants would value the aesthetic of the grid-like pattern more. Therefore, we recommend that in future drawing software design, more attention should be paid to these two aesthetics. In other words, when vertices and edges are entered, the drawing software should be able to place them in a grid-like pattern, and at the same time avoid the creation of edge crossings. Afterwards, users can adjust the graph drawing based on their needs and personal preferences, until they believe that the optimal layout of the graph structure has been achieved.

It is also worth noting that although graph size is not a testing condition in our experiment, graph size could be a factor that effects participants' drawing behaviors and final drawings. Although exactly how graph size affects drawing of weighted graphs is beyond the scope of this study, research has shown that size of graphs can have impact how people perceive the quality of drawings and how they achieve the balance of conflicting ascetics in a single graph drawing of large graphs [7], [8], [9], [39].

Finally, it is important to note that our experiment has limitations, and cautions should be taken to generalization of the findings [34], [35], [36]. In the future, we plan to conduct more rigorous user studies with a larger number of participants on graphs of various structures and contexts to further investigate and derive user behavior based aesthetics to inform the design of graph visualizations.

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