OA-Graphs: Orientation Agnostic Graphs for Improving the Legibility of Charts on Horizontal Displays

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ABSTRACT

Horizontal displays are emerging as a standard platform for engaging participants in collaborative tasks. Little is known about how groups of people view visualizations in these collaborative settings. Several techniques have been proposed to assist, such as duplicating or reorienting the visual displays. However, when visualizations compete for pixels on the display, prior solutions do not work effectively. We first ran an experiment to identify whether orientation on horizontal displays impacts the legibility of simple visualizations such as charts. The results reveal that users are best at reading a chart when it is the right side up, taking them 20% less time to read than when it is upside down. This insight led us to develop the *Orientation Agnostic Graph (OA-Graph)*, making use of a radial layout designed to be legible regardless of orientation. In a second experiment we found that users can read OA-Graphs better than when the graphs are upside down but less well than traditional graphs in the right side up. The design of our novel visualization, informed by radial visualization methods will assist designers in developing charts that are not easily affected by user orientation, an issue that is prevalent in collaborative tabletop systems. Certain tasks such as observing relative differences can benefit from OA-Graphs.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces. - Graphical user interfaces.

General terms: Design, Human Factors, Experimentation, Theory.

Keywords: View perspectives, tabletops, orientation graphs, information visualization.

INTRODUCTION

Tabletop displays take advantage of flat surfaces such as a table or desk to provide an effective platform for collaboration. Researchers have developed techniques and interfaces to support and assist the collaboration process in tabletop environments [9,11,12,16,17,22]. In face-to-face settings, collaboration involves sharing information placed on the tabletop surface including objects, documents, pictures, and charts. Due to the nature of face-to-face cooperative work on tabletop surfaces, orientation and view perspective cannot be neglected [8,9]. For a single user at a tabletop, orientation may not be a crucial problem. Objects can be displayed and adjusted toward the user. However, for groups of users gathered around a tabletop, object orientation becomes critical. In such a setting, users do not share a common perspective of the displayed information. Instead, their perspective is strongly correlated with their location around the tabletop. Since users will be viewing the information from different positions, the information will be differently perceived. Figure 1 shows an example of such a situation.

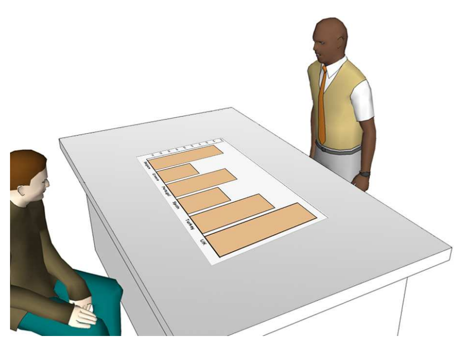

Figure 1: The user on the left views the chart in the right direction. The user on the right side of the tabletop views the chart up-side-down. Different viewing orientations negatively impact graph legibility which we have addressed with our proposed Orientation Agnostic Graphs.

The visual representation of information is a key factor that plays an important role in the perception, and more specifically, the readability performance of participants. When viewed on a tabletop, commonly used and popular visualizations such as charts are unidirectional, meaning that only one person will see the object in the right view. More attention to techniques for migrating standard visual representations for data on a traditional desktop to a tabletop is required. Designers need to consider the challenges involved in working collaboratively in tabletop environments when developing interfaces and displays for charts. The interfaces provided and the representations of data have to appropriately consider scenarios for single user or multiple user views.

Our goal was to investigate the orientation effects of particular objects such as charts in a tabletop setting. We examined charts that have been used widely in many common applications and that would typically benefit from collaborative input. Results of a first experiment suggest that graph orientation can negatively impact the readability of charts. Based on this result we introduce the *orientation agnostic graph (OA-Graph)* as an alternative presentation for charts. The design of the OA-Graph is inspired by radial visualizations and is targeted at improving the legibility of charts across different orientations. In a second experiment we compare OA-Graphs against traditional chart representations. Our results demonstrate that the radial design improves legibility over upside down graphs particularly for tasks selected here, such as observing relative differences between parts of a chart.

In the next section, we describe how researchers have addressed orientation issues and categorize their solutions. Next, we explain our experimental design. We build on our results to design the OA-Graph and report results of an experiment designed to evaluate OA-Graph visualization. We summarize by introducing an implementation of OA-Graph interaction techniques as well as transforming different types of charts into OA-Graphs. Our work contributes to the intricate understanding of the effect of chart orientation in collaborative settings among users.

RELATED WORK

Several design guidelines for co-located tabletop collaboration have been offered through a number of studies [7,14,16,25]. With respect to orientation, tabletop interfaces have to support different kinds of activities with flexible user interaction from a variety of positions around the table. One of many common practices designed to reduce the effect of orientation is to use manual and/or automated object rotation [14]. As a result, a number of techniques have been developed to provide users with the ability to orient objects in order to achieve effective collaboration in these environments [3,14,19,20,24]. Researchers have looked at the effect of text and object orientation in group interaction in tabletop settings. Not surprisingly, studies have shown that participants have preference for the “right way up” for both reading text and viewing objects [27]. These investigations also indicate that participants tend to exercise less straight-on orientation during collaboration sessions.

A majority of tabletop interfaces use several approaches to address orientation issues [9]. Kruger categorized these approaches into *fixed orientation*, *manual orientation*, *multiple copies*, *person-based automatic orientation*, and *environment-based automatic orientation* [9]. In the fixed orientation approach, objects are oriented to one direction due to the assumption that users will be seated shoulder-to-shoulder with other participants [3]. Manual orientation is a more comprehensive way to orient objects since it simulates traditional rotating of objects (i.e. paper) to some extent. With the limitation of current input devices, interaction with objects on a tabletop could be unnatural and difficult. Multi-touch tabletops may be a better alternative for input devices for manual orientation tasks [7,26]. Replicated copies of shared information are another way to solve orientation issues. Each user on each side of the tabletop has their own independent copy of the objects [12,24]. Yet, using such an approach would introduce another issue: consumption of the space for displaying data. For example, consider four users sitting around a tabletop wanting to compare three documents or charts. Using a multiple copy approach will require the display of twelve objects in the limited space provided. In person-based automatic orientation tabletops, the interface automatically orients the object toward the user at the edge of the tabletop who has recently accessed an object [19,24,25]. In this approach, the assumption is that users always will be positioned sitting at the edge of the table. Environment-based automatic orientation, on the other hand, orients objects based on object position relative to the user. The object would be oriented towards the outside of the tabletop since a user on the edge has the advantage to view the object there [20,23].

All of these approaches do not consider the view angle for object visibility in tabletop environments [13]. In a tabletop setting, users view the content from oblique angles. Nacenta *et al.* [13] introduced a system that identifies the location of a user in order to model the appearance of the object (e.g. windows, text) and change the view angle of it to be perpendicular. The model changes the shape and orientation of the object so that it appears perpendicular to one user at a time. Nevertheless, the user has to use different interaction techniques to share information with other users and requires specialized hardware. Hancock *et al.* [6] show that for 3D projections, errors in judging object orientation increase as the centre of projection diverges from the observer’s viewpoint. These errors are considerably lower when the centre of projection is directly above the table [3,6]. Tabletop interfaces must support flexible collaborative tasks and comprehensive data representation by supporting multiple views of information. *Lark* [26] and the prototype outlined by Isenberg and Carpendale [7] are two systems that facilitate the coordination of interaction with information visualization. Both provide the user with an ability to change the collaboration style and the information representation. Such information representation needs to be validated. Wigdor *et al.* [28] examined the perception of basic graphical elements as proposed by Cleveland and McGill. They found that distortion has less impact on some graphical elements than others. As a result of this work they introduced design recommendations for visualizing graphical information in tabletop environments. Using these design recommendations for more complex and common visual presentations (e.g. charts) may reduce the effects of orientated views. Empirical evidence is needed to support this assumption.

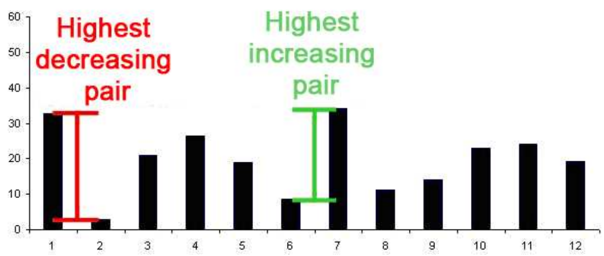

Figure 2: A chart could have one of two types of questions. Each participant was asked to identify the maximal decreasing pair (shown as points 1 to 2) or maximal increasing pair.

GOALS OF THE PRESENT WORK

Charts can use different presentations for data (i.e. Area, Bar, Line, Scatter). The most common charts, which use the data encoding system outlined by Wigdor *et al.* [28], are still used on tabletops. We conducted two experiments to critically evaluate the readability of charts on tabletops in terms of *completion time* and *accuracy*. In this study, we explore one task, among many others that could be employed for testing our hypotheses. The task involves one of finding relative differences between values in a chart, a task that is nonetheless common on the types of visualizations we selected. In the first experiment, we focused on chart orientation, type, and range of dataset values to observe their effect on user performance. The second experiment extended the goals of the first experiment by comparing a new chart representation (an OA-Graph) using the same experimental protocols as those used in experiment 1.

EXPERIMENT 1

The purpose of the first experiment was to investigate the impact of chart orientations on user perception in a tabletop setting. Readability performances were observed in terms of completion time and accuracy. We chose a task that requires searching and filtering to find predefined patterns [1]. This task is commonly practiced by different financial analysts when viewing different finance charts. For example, when user reads stock charts where he/she needs to identify the pattern of the stock or peaks in duration of time. We introduced similar tasks to participants in the experiment. There were two types of patterns each participant had to identify in a chart. In the first exercise, each participant was asked to compare all pairs of consecutive points in a chart to identify where the largest difference between two points occurred. To illustrate, in a pair of two consecutive points, when the first point has a higher value than the second point, this pattern was called a *decreasing pair*. When the first point has a lower value than the second point, this pattern was called an *increasing pair*. The location of the *decreasing* and *increasing* pairs were randomly generated in the chart. In the chart provided, only one pair of points would have a highest (or maximal) increasing or decreasing pair (Figure 2).

Hypotheses

Based on our preliminary exploration of the issues, we formulated the following hypotheses:

H1: As the chart is oriented in a different view other than the 0º angle, both completion time and error rate will increase.

H2: Chart type has an effect on performance.

H3: The difference between pairs of points in a chart has a significant effect on completion time and error rate.

Participants

We recruited a total of 40 university student participants (34 male and 6 female). Each experiment session lasted about 30 to 45 minutes depending on individual performance. The age of the participants ranged from 21 to 35. None were colour blind. Participants sat on an adjustable chair at the centre of a tabletop edge. The relative position and angle of the head for each participant was not controlled to emulate real-world scenarios in collaborative settings.

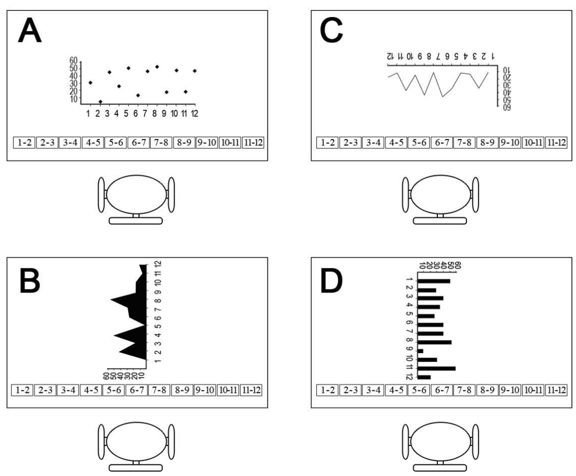

Figure 3: A bird's eye view of tabletops with different types of charts and orientation angles. Tabletop A shows a Scatter chart with a 0º orientation. Tabletop B shows an Area chart with a 90º orientation angle. Tabletop C shows a Line chart with a 180º orientation angle. Tabletop D shows a Bar chart with a 270º orientation angle. The buttons, shown here, were aligned along the edge closest to the user.

Apparatus and Display Configurations

Participants sat on a chair at a height of 48cm in front of a tabletop. The tabletop itself was 80cm off the floor, oriented in a "landscape" position with size of 153cm x 113cm. The tabletop projector has a resolution of 1152x864 pixels. The contrast and the brightness of the projector were adjusted and all charts were shown in black and white. Participants used a mouse for input. Each task was completed by answering a question related to a chart displayed on the tabletop. The chart was placed directly in front of the user.

Charts

We selected the most common chart types that can be found in popular charting software. The four charts type we used were Scatter, Line, Area, and Bar. These charts were generated randomly. The dataset in each chart was generated with consideration to the differences between at least two pairs of points with 4, 6, or 10 pixel values. Each chart type was oriented with an angle of 0°, 90°, 180°, and 270°. The chart size was 84cm x 49cm. Figure 3 shows examples of the different orientations and chart types we used.

Task and Procedure

The tabletop interface used in the experiment had four components: a chart with eleven pairs of points, eleven buttons that contained a reference to all point pairs, a question associated with the chart for the participant to answer, and a timer to make the user aware of the task completion time. The question was presented in a different colour depending on what was being asked. It was red if the question was to find the highest decreasing pair and green if the question was to find the highest increasing pair. Participants were first briefed on the task and were shown each type of chart with all the different possible orientations. A practice session was provided where each subject was given the opportunity to read the question and select an answer for each trial. The system provided feedback on accuracy to the subject after each practice trial. Subjects were given the ability to choose more trials with different charts and orientations until they felt they understood the task requirements.

During the experiment, each participant had 40 seconds to complete the task. The reason for choosing a 40 sec timeout was to allow participants enough time to search the pattern and finish the tasks. This limit was based on pilot tests. When the timer reached the last 10 seconds, the timer background colour turned red. The trial was considered missed if the participant did not select an answer during the 40 seconds. The next trial appeared after the user made a selection or the timer expired. Each individual had to indicate one of the two patterns in a chart (highest increasing or highest decreasing pair) by clicking on the button that identified the correct pair of points for the question. The subjects were given a five minute break in the middle of the experiment. The order of displaying chart orientation was counterbalanced to account for learning effects, making orientation order a within-subject control variable in our design. Our experimental design can be summarized as:40 participants × 4 chart types ×4 orientations ×3 different difference values ×2 trials (per condition) =3840 trials.

Results

A univariate ANOVA was computed with Orientation, Chart Type, and Difference in Value as independent variables and completion time and accuracy as dependent variable. The Tamhane test was used for all post-hoc tests.

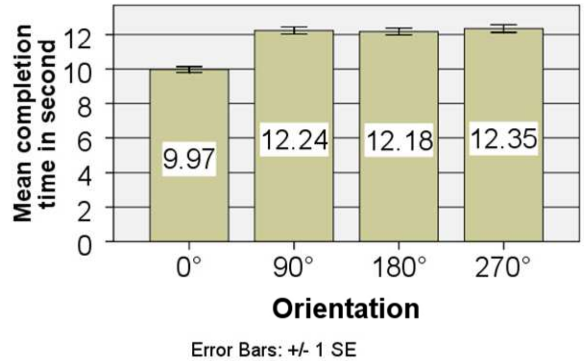

Figure 4: Mean completion times for all charts for angle orientations of 0°, 90°, 180°, and 270°.

Completion Time. A total of 3034 trial points were used as a result of removing outliers (-3 < std. < 3) as well as wrong and missed answers for the analysis of completion time (212 trials or about 5% of total number of trials were outliers). Average completion time by Orientation is shown in Figure 4. Our analysis indicates that there is a significant effect of chart orientation on completion time ($F_{3,117}$ =68.401, p=0.001) (support for H1). There was also a significant main effect of chart type on completion time ($F_{3,117}$ =20.359, p=0.001) with mean completion time of 11.46s, 11.52s, 12.02s, and 12.81s for Area, Bar, Line, and Scatter chart types respectively (support for H2). Similarly we found a main effect for the Difference in pairs on completion time ($F_{2,78}$ =301.359, p=0.001) with mean time of 14.16s, 11.36s, and 10.06s for 4, 6, and 10 pixels respectively (support for H3).

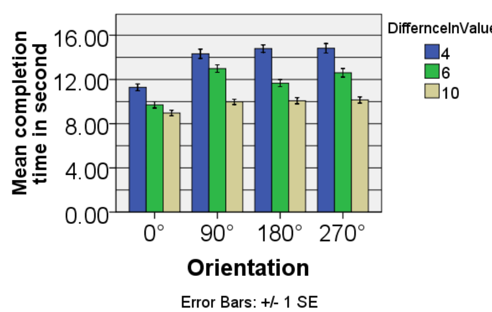

Figure 5: Mean completion times for 4, 6 and 10 pixel maximal differences in pairs of points for chart orientation angles 0°, 90°, 180°, and 270°.

In terms of interaction effects, we found that chart orientation interacts with chart type ($F_{9,1251}$=4.294, p=0.001) with differences mainly occurring at the 90º and 180º angles. Similarly, chart orientation interacts with difference in value between pairs of points ($F_{6,834}$ =11.095, p=0.001).

Post-hoc pair-wise comparisons on Orientation show that certain chart orientations vary in their performance. Readability at the 0º angle is significantly faster than all other orientations (all p=0.001). For other orientations we did not find any significant differences. Post-hoc pair-wise comparisons of chart type also yielded significant difference in completion time for pairs in Area and Line graphs (p=0.004), as well as all other graphs with Scatter (all p<0.05) (i.e. readability with Scatter is significantly slower than other types).

Post-hoc pair-wise comparisons of differences between pairs of points in the charts indicated significant differences in terms of completion time. When the difference between a pair of points increases, the completion time decreases (Figure 5). Participants were faster when the maximal difference between point pairs was 10 pixels than at 6 and 4 pixels (both p=0.001). Also, the maximal difference of 6 pixels yielded a faster completion time than 4 pixels (p=0.001).

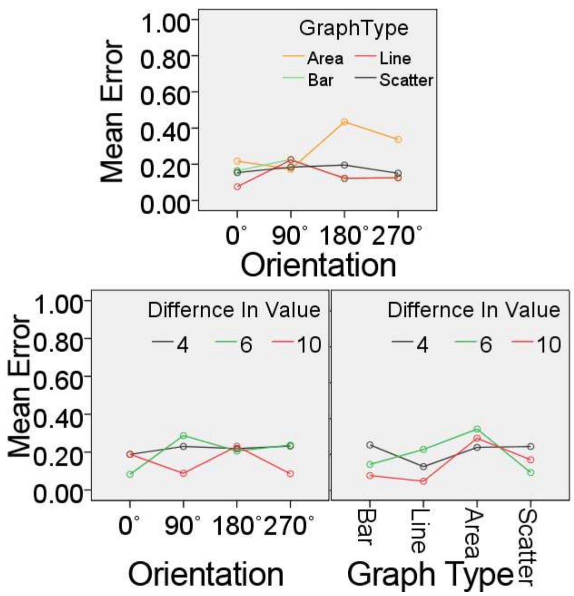

Figure 6: Upper graph shows the mean error for four chart types for four orientation angles. The lower left graph shows the mean error for four differences in pairs of points of size 4, 6, and 10 pixels for each orientation. The lower right graph shows the mean error rate for four differences in pairs of points of size 4, 6, and 10 pixels for each chart type.

Error Rate. Univariate ANOVA revealed that orientation had a significant effect on the error rate ($F_{3,11}$=5.550, p=0.001) with mean error rates of 0.15, 0. 20, 0.21, and 0.18 for orientation angles of 0º, 90º, 180º, and 270º respectively. This supports our hypothesis H1. In support for hypothesis H2, we found that there was a significant effect of chart type on the error rate ($F_{3,117}$ =36.096, p=0.001) with mean error rates of 0.29, 0.16, 0.13, and 0.17 for Area, Bar, Line, and Scatter chart types respectively. In favour of hypothesis H3, differences in values between pairs of points in a chart turn out to have a significant effect on the error rate ($F_{2,78}$ =19.288, p=0.001) with mean error rates of 0.217,0.203, and 0.149 for maximal point separation of 4, 6, and 10 pixels respectively.

Focusing on interaction effects between independent variables, we found that chart orientation interacts with chart type ($F_{9,1251}$ = 13.772, p=0.001). Figure 6 shows that chart orientation significantly interacts with relative differences on error rate ($F_{6,834}$ =21.805, p=0.001). Additionally, we found that chart type significantly interacts with difference in value between pairs of points ($F_{6,834}$ =18.570, p=0.001). Figure 6 summarizes the interaction between the chart type and Differences in pairs of values.

Post-hoc pair-wise comparisons of orientations indicated significant differences in error rate. We noticed that at an orientation angle of 0º chart orientation is significantly less than when the angle is 90º and 180º (p = 0.04, p= 0.002). There was no significant difference between angle orientation 0º and 270º (p = 0.573). Post-hoc pair-wise comparisons of chart type show significant differences in error rates. We found that the Area chart type has a higher error rate than Line, Bar, and Scatter chart types (all p=0.001). We did not find any significant difference between Line, Bar, and Scatter chart types. Post-hoc pair-wise comparisons of differences in value between a pair of points indicated significant differences in error rates. The only significant one is that 10 pixels had an error rate smaller than 4 and 6 pixels (p=0.001, p=0.002).

Discussion

Our results support all of our hypotheses. Interestingly, we found that the legibility of some of the most basic charts are affected by the user's orientation around a tabletop. While some differences exist between each chart type, in general we find that participants are capable of reading charts much faster and with fewer errors when presented at a 0º angle (or right-side up) than at the other angles, including 180º or upside down. These results corroborate and can partly be explained by the findings of Wigdor *et al*. [28] that orientation affects our visual interpretation of primitive graphical elements. Since most graphs are created based on a composition of primitive elements, it is interesting to see this result hold for higher orders of visual complexity. What remains to be known is whether basic charts can be created in a manner to increase legibility regardless of user position around a shared surface.

The OA-Graph

We introduce the Orientation Agnostic Graph, or OA-Graph that we hypothesize will improve legibility of simple graphs, such as charts, in difficult-to-read orientations. The OA-Graph is inspired by some of the earlier radial-based visualizations such as *SunBurst* [21,26], *Hyperbolic Browser* [10], *Radial Tree* [7], *Radial Cladogram* [26], and visualizations outlined by Isenberg and Carpendale [7] and Tobiasz *et al.* [26]. To our knowledge, these radial-based visualizations have not been empirically tested to validate their legibility in horizontal displays. For a thorough survey of radial methods for information visualization we refer to Draper *et al.* [5]. These visualizations, while designed for single user and desktop use, have several interesting properties. They do not have an implicit orientation (i.e. there is no face that is right-side up) unlike other common visualizations. As a result, they lend themselves naturally to the type of problem we are investigating here. Additionally, all points on the radius are equidistant to the centre of the graph. As a result, no one user can claim to have easier or harder access to interact with the graph (with the exception of the constraints set by the physical structure of the table). Finally, the radial arrangement provides a flexible layout for placing items of interest. As we describe below, various designs of the OA-Graph are available for representing chart data.

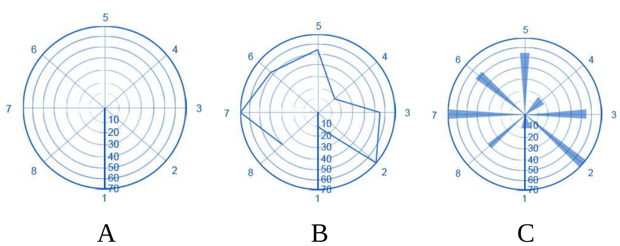

Figure 7: OA-Graph based on a radial layout. (a) the point of reference is at the centre and the graph is read counter-clockwise. (b) A line-based OA-Graph; (c) a bar-based OA-Graph.

We used the above described properties to design different OA-Graphs. The OA-Graph simply folds up a basic chart into a radial layout Figure 7-A. A line delineates the point of reference and the values are read in a counter-clockwise manner. This choice was arbitrary. Interestingly, a line-based OA-Graph has some interesting analogy to the spidergram [15] with the exception that the spidergram uses various different axes. Our initial investigation has considered line and bar graphs, as these are common and also severely affected by orientation as seen from our first experiment. As our finding from the first experiment showed, Bar and Line graphs are more robust than Area and Scatter. This motivated us to concentrate our observation on their robustness when converted to our OA-graph. The line-based OA-Graph and bar-based OA-Graph are presented in (Figures 7-B and 7-C). With our layout we had two different candidate designs. In the first, the x-axis is defined by the outermost concentric ring (called reference out). In the second, the axis starts from the centremost point of the graph (called reference in). Figure 8 shows both variations.

EXPERIMENT 2

The second experiment was designed to evaluate our OA-Graph design. We compared traditional graphs against our orientation agnostic graphs in terms of their effect on user perception. Orientation agnostic graphs have an advantage over linear graphs since all users will view a portion of the chart towards them. Readability performances in terms of completion time and accuracy were measured using the same searching and filtering tasks as in the first experiment. Each participant was asked to identify predefined patterns in a graph. The experimental configuration for the second experiment was the same as the first experiment.

Hypotheses

Based on the objective of the second experiment, we formulated the following hypotheses:

H1: OA graphs perform better than traditional graphs that are orientated at 180º on completion time and error rate.

H2: The difference between a pair of points in a linear graph and an OA-Graph has significant effect on completion time and error rate.

H3: Using Bar and Line chart types in linear and OA-Graphs will have no effect on completion time and error rate.

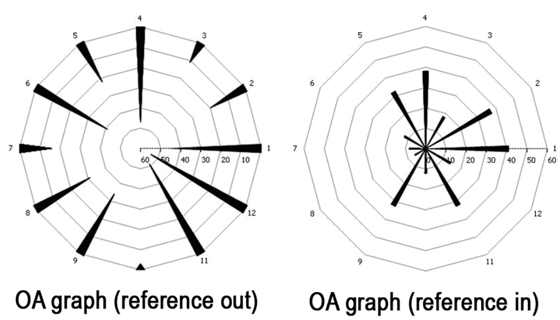

Figure 8: Two types of OA graphs. The graph on the left plots the value of each category along a separate axis that starts in the outer ring of the chart and ends in the centre of the chart. The graph on the right plots the value of each category along a separate axis that starts in the centre of the chart and ends on the outer ring.

Participants

We recruited a total of 30 first year and fourth year university students (20 male and 10 female). The age of the participants ranged from 18 to 30. Each experiment session lasted about 30-48 minutes depending on the performance of the participant. Half of participants sat on adjustable chairs in the centre of the tabletop edge at height of 48cm in front of tabletop. The other half were asked to do the experiment while standing. We measured the display view angle from the centre of the tabletop (Figure 1). We used the right angled triangle formula (Tan θ = Opposite / Adjacent) where Opposite is the distance from user's eye to the edge of the tabletop and Adjacent as the distance from the centre of the tabletop to the edge of the tabletop. The view angles of participants who did the experiment seated ranged from 21º to 30º (an average of 25.5º). For the other group who did the experiment standing the viewpoint ranged from 41º to 50º (an average of 45.5º).

Charts

We used two types of charts and two orientations to compare the linear charts with OA-Graphs. The Bar and Line chart types and Down and Up for chart orientation. For the chart type, our selection was based on best performance from the first experiment in completion time with highest number of correct answers. For the OA-Graph, we used Bar and Line graphs. We have chosen two orientations (0˚, and 180˚) in order to examine the chart performance in the best and worst scenario of reading chart as the analysis of the first experiment reveal. The OA-Graph is a radial-like graph. We evaluated both types of OA-Graphs: Reference-In and Reference-Out as shown for a Bar graph in Figure 8. Charts were generated randomly for the traditional chart style. The same data was then used to create the OA-Graph. Each chart was generated with consideration for differences in value between at least two pairs of points with 4, 6, or 10 pixel values. For the traditional charts, both the Line and Bar charts were oriented with an angle of 0° and 180°.

Task and Procedure

In the second experiment, we used the same tabletop interface and components as in the first experiment. We introduced both traditional and OA-Graphs to users. All subjects did practice sessions until they were familiar with the task and the kinds of charts involved. Each trial was timed to last for 40 seconds. The next trial appeared when the user chooses an answer or the timer expires. Each participant had to identify the chart pattern and then click the correct pair of points for the question. A five minute break was provided in the middle of the experiment. The order of chart orientation display was counterbalanced to account for learning effects, making orientation order a within-subject variable in our design. Our experimental design can be summarized as: 30 participants × 2 chart types (Bar, Line) × 4 orientations (Down, Up, Reference-In, Reference-Out) × 3 values different (4, 6, 10) × 3 trials (per condition) = **2160** total trials.

Result

A univariate ANOVA was applied to the average completion time and error rates. Tamhane tests were then used for post-hoc tests.

Completion Time. A total of 1846 trials were used as a result of removing timeouts, errors and outliers (-3 < std. dev. < 3).

Our analysis revealed a significant effect of orientation on completion time ($F_{3,87}$ =115.302, p=0.001) which supports hypothesis H1. We found that both OA-Graphs performed better than traditional charts with an orientation angle of 180º and slightly worse than traditional charts with an orientation angle of 0º. The overall results for completion time for each orientation is shown in Figure 9.

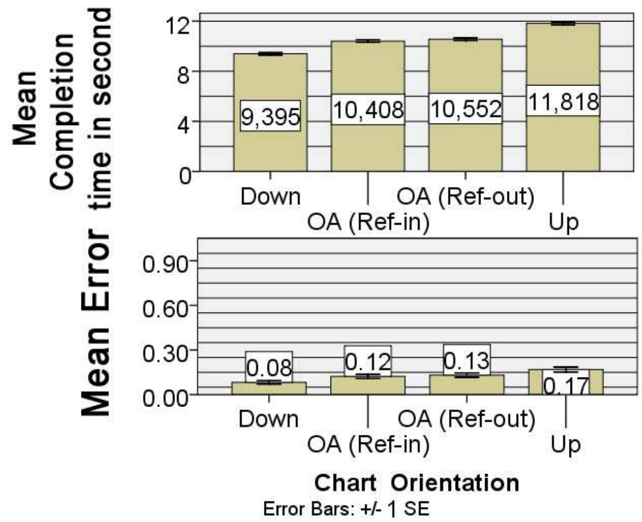

Figure 9: The upper graph shows the mean completion times. The lower graph shows the mean error rates.

In support for H2, we had expected to find an effect from the difference in pairs of points on the completion time. Our finding indicated that there was a significant main effect of the difference in pairs of points on the completion time ($F_{2,58}$ =257.022, p=0.001). When the maximal range of values of point pairs is 4 pixels, participants spent more time to complete the task. As the range of values increased, the completion time of the task decreased. The mean completion times for the 4 pixel, 6 pixel, and 10 pixel point pair differences were 11.877s, 10.736s, and 9.269s respectively.

We did expect to find an effect for the chart type as we expressed in hypothesis H3. We anticipated that the Bar and Line chart type in all orientations would perform equally well based on the results we found in Experiment 1. However, there was significant main effect of chart type on the completion time ($F_{1,29}$ =27.728, p=0.001). The mean completion times for the Bar and Line charts were 10.380s and 10.874s respectively.

We were interested to see the effect of the view angle of a chart on the completion time to determine if it is better to view a chart while standing or seating. The results revealed that view angle of chart has a significant main effect on the completion time ($F_{1,29}$ =8.427, p=0.004). The group of participants who performed the experiment while standing had a mean completion time of 10.491s, while the group who did the experiment seated had mean completion time of 10.764s.

Post-hoc pair-wise comparisons of orientation yielded significant differences (all p< 0.001) in task completion time for all pairs. When the orientation angle of the chart was 0º, participants performed significantly faster than the OA-Graph (Reference-In), OA-Graph (Reference-Out), and the linear graph with an orientation angle of 180º or when the graph is upside down. Both OA-Graphs have better readability than the upside down graph (both $p<0.001$). Post-hoc pair-wise comparisons of the maximal difference in pair values chart shows a similar pattern as we saw in the first experiment. Significant differences (all $p<0.001$) in trial completion times for all pairs (4, 6, and 10 pixels) were observed.

Error Rate. We used a total of 2111 trial data points in the analysis after removing outliers (-3 < std. dev. < 3). We found significant main effects of orientation, chart type, and difference in value on the error rate. However, the chart point of view turned out to have no effect on the error rate. In favour of hypothesis H1, the ANOVA test revealed that orientation had a significant effect on the error rate ($F_{3,87}$ =60610, p=0.001). The mean error rates when the orientation angle of the chart was 0º, OA (Reference-In), OA (Reference-Out), and upside down (180º) were 0.08, 0.12, 0.13, and 0.17 respectively. These results are shown in Figure 9.

We found that differences in point pairs in a chart have an effect on the error rate ($F_{2,58}$ =31.891, p=0.001). Therefore, the higher the value of at least one pair of points the lower the error rate is. Moreover, we found that there was significant effect of chart type on the error rate ($F_{1,29}$ =15.888, p=0.001) with a mean of 0.099 and 0.155 for Bar and Line charts respectively. This finding allows us to reject hypothesis H3 for the error rate. The viewpoint of the chart did not have a significant effect on the error rate ($F_{1,29}$ =0.426, p=0.514). Surprisingly, we did not find any significant interaction between the independent factors.

Looking into pair-wise comparisons of orientation we found that the chart orientation angle 0º was not significantly better than both OA (Reference-Out) and the chart orientation angle 180º (All p>=0.281). The difference for OA (Reference-In) was not significant (p=0.281). This is an interesting finding considering that the view with OA-Reference-In is slightly more distorted than the right side up view. Similar type pair-wise comparisons of chart type showed a significant difference in error rate where Bar, with mean of 0.099, has a lower error rate than Line, with a mean of 0.155 (p=0.001). In addition, the range of value variance in a chart has an effect on the error rate. A 4 pixel variance had a higher error rate than 6 pixels, which was higher than 10 pixels (All p<= 0.049).

TRANSFORMING OTHER GRAPH TYPES

Our experiments have shown that OA-Graphs perform better than linear charts with an orientation angle of 180º and perform slightly worse (only in performance but not error rate) than linear charts with an orientation angle of 0º. Providing the user with the ability to switch between different representations to support single and multiple views can be beneficial. Due to the several interesting properties of radial-based visualization, we consider transforming of commonly used and more complex charts such Bar and Line with several datasets, Parallel Coordinate, and Gantt charts (see Figures 10, 11, and 12).

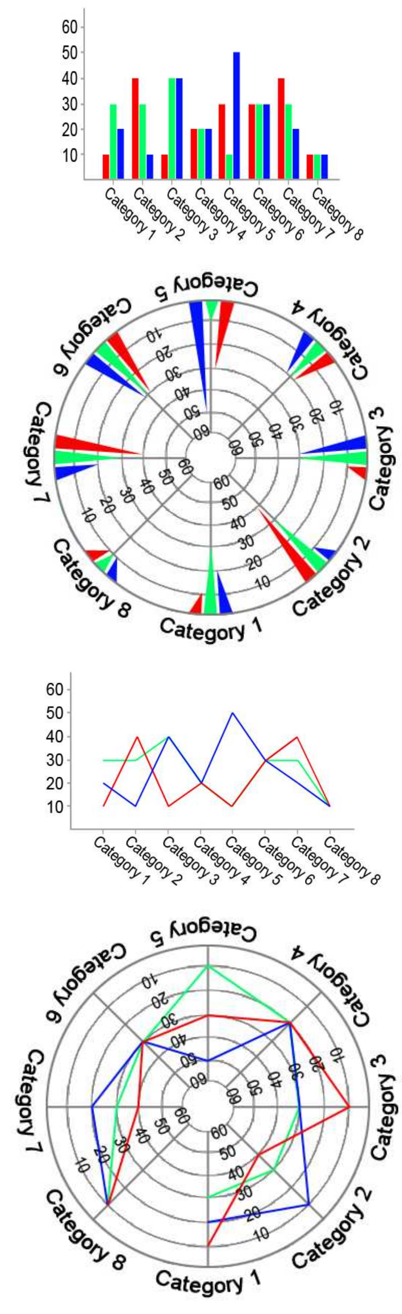

Figure 10: Commonly used charts: Bar and Line. Below each one, an equivalent OA-Graph is shown.

DISCUSSION AND LIMITATION

Our study confirms and builds on previous studies that orientation in tabletop settings has an adverse effect on perception. In our case, chart readability was negatively affected when viewed upside down. A tabletop display interface should support both ease of interaction and flexible data representation in order to reduce the effect of orientation. This is even more critical when a group of users perform a highly collaborative task such as reading a chart, where everyone is susceptible to the adverse effects of orientation on data perception. For a single user it is ideal to view a chart with an orientation angle of 0º. For a group of users, the ideal chart orientation is one that is Orientation Agnostic. One observation that we noticed during both experiments is that some users tend to move their heads to adjust the chart view for linear chart styles. It was observed that with OA charts these head movements significantly decreased. Also, during the practise session some users asked if they had the choice to do the experiment while standing, as that was their preference.

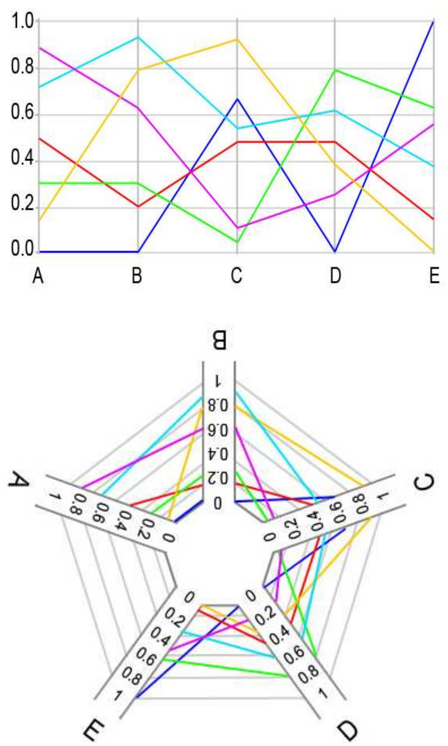

Figure 11: Parallel Coordinate graph on top chart, and equivalent OA-Graph below.

Orientation in tabletop settings is still a challenging issue and this can be seen in tasks that require reading of text. When an individual reads a chart, they look for patterns and trends and then look for labels to refer to corresponding values. Different label placement strategies are used to facilitate orientation-independent reading in visualization interfaces. One example is to warp labels in a circular or arc fashion. Although we did not address text orientation in this study, we do see it as an important focus for future investigation in tabletop environments. The main focus of the research in this paper was to examine the visual coding system in tabletop settings to achieve a better understanding of the effect it has on chart readability with consideration of orientation of displayed data.

Unlike previous work, this study assessed both visual representation issues and interaction techniques in an effort to address orientation issues with visualizations in tabletop settings. For linear chart styles we found that Line and Bar charts are more robust. However, Bar charts turn out to be more robust than Line charts when represented as OA charts. The variance of value in a chart dataset also has an effect on the completion time. Users are able to more quickly identify patterns in a chart when a range of difference in values in a chart is large.

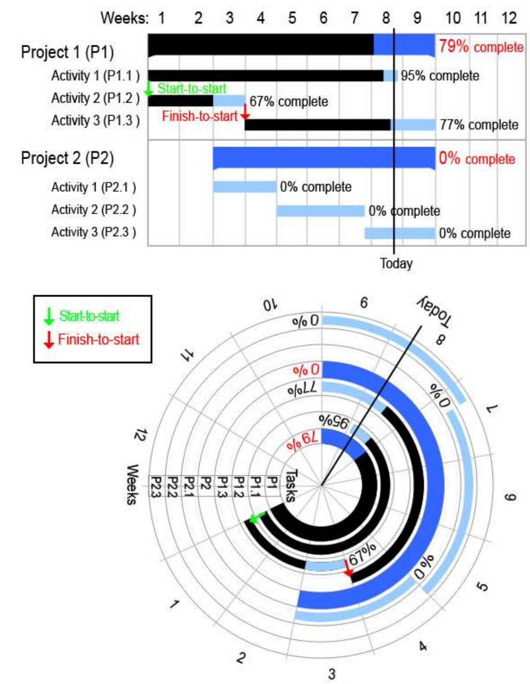

Figure 12: The upper chart shows the Gantt chart. The lower graph shows the OA-Graph version of it.

CONCLUSION

Orientation on tabletop displays remains a critical issue that needs to be effectively addressed. Our study demonstrates that a range of factors affect chart readability such as chart type, chart style, variance in pairs of points, and angle of view. It also demonstrated that the negative effects of orientation can be reduced. Tabletop interfaces should adopt different interaction scenarios when there is a need for data sharing and collaboration. We studied the effect of chart orientation on tabletop surfaces as it related to chart readability using common chart types in different viewing orientations. In an attempt to address the orientation issue, we compared linear chart styles with Orientation Agnostic (OA) charts. Our findings demonstrate that the readability of a chart can be improved using OA charts in certain circumstances. OA charts can be used to support multiple users with an optimal view of a chart.

We are currently investigating designs to convert some of the more common visualization techniques, such as parallel coordinates and tree visualizations so that they are orientation agnostic. These implementations will allow us to develop rigorous design guidelines to assist in the development of other types of orientation independent visualizations on tabletop surfaces. Additionally, we intend on evaluating existing interaction techniques used on graphs in tabletop settings to identify parameters to make these independent of orientation.

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