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Perspective Charts

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Abstract

Bar charts are a popular and commonly used tool for the interpretation of datasets. However, representing datasets with a large range is challenging in a bar chart due to limitations in viewing space. To address this challenge, we introduce three novel data visualizations, called Perspective Charts, based on the concept of size constancy in linear perspective projection. Each of our designs focuses on the static representation of datasets with large ranges. Through a user study, we measure the effectiveness of our designs in representing these datasets in comparison to traditional and state-of-the-art methods. The evaluation reveals that our designs allow pieces of data to be visually compared at a level of accuracy similar to traditional visualizations, and demonstrates advantages when compared to state-of-the-art visualizations designed to represent datasets with a large range.

CCS Concepts

• ***Human-centered computing*** → ***Information visualization;***

1. Introduction

Today we are faced with large amounts of data with varying complexity [War12]. This makes the visualization of large datasets challenging, especially when viewing space is limited. Different tools and charts are suited to different types of data [Mun14]. Bar charts are well-known tools for comparing datasets, and they are one of the most commonly used data visualizations as they are simple and easy to interpret. However, if the range of data is too large, there are unique challenges with representing the data in a chart. Examples can commonly be found in population data, as illustrated in Figure 1, which shows population data for several Canadian cities. The vertical limitation of the viewing space requires a large scaling factor to be applied to the data, which makes differences between values less readable. For example, in Figure 1, the largest value is the population of Toronto; the scale of the chart needs to be adjusted in order to accommodate such large values. Showing Toronto's population in the same chart as smaller cities such as Guelph and Kingston makes it difficult to measure the population of the smaller cities. When the scaling factor increases, it becomes more difficult to make comparisons between pieces of data with close values. In this paper, we introduce a novel method for bar chart visualization that can represent datasets with large ranges.

The limitation that we focus on is the readability of charts that represent datasets with a large scaling factor. The linear mapping between the range of the data and the vertical size of the viewing space may result in undesirable compression of the charts. One potential solution is to use a non-linear mapping, such as a logarithmic function (see Figure 1, center). However, this type of non-linear mapping is difficult to read and understand in comparison with simple linear mappings. How do we find a more natural solution to mapping data with a large scale onto a small viewing space? This question has been answered in artistic paintings, engineering drawings, and geometry through the use of perspective projection. Humans naturally perceive perspective, and are naturally able to estimate the size of distant objects through a property known as size constancy [Car10]. Using simple linear perspective, geometric proportions can be used to measure the size and relative differences of objects [Erk13]. Our new charts are inspired by, and built based on, linear perspective projection.

Our first design simply shows a bar chart that is slanted backwards from the viewing plane, such that it is viewed in perspective. We call this the *Slanted Perspective Chart* (See Figure 1, right). As the lower part of the graph appears closer to the reader, small values in the dataset become easier to read in comparison to a traditional bar chart.

The main problem with the solution of slanting a traditional bar chart is that larger values in the dataset become compressed due to the perspective projection. This may make large values more difficult to read and compare.

Our next chart is designed to address the issue of scaling large values in our Slanted Perspective Chart, while also improving the readability of small values. In bar charts, space in the middle of the chart is often wasted due to large differences in values from the dataset. We can reduce the amount of wasted space by visualizing this area in an extreme slant. This puts only the less important range of the data at an extreme angle; each bar's value is still measurable in an area that is perpendicular to the view (see Figure 2, left).

We call this chart the *Stepped Perspective Chart*. This design is intended to resemble a staircase; we can insert multiple bends in

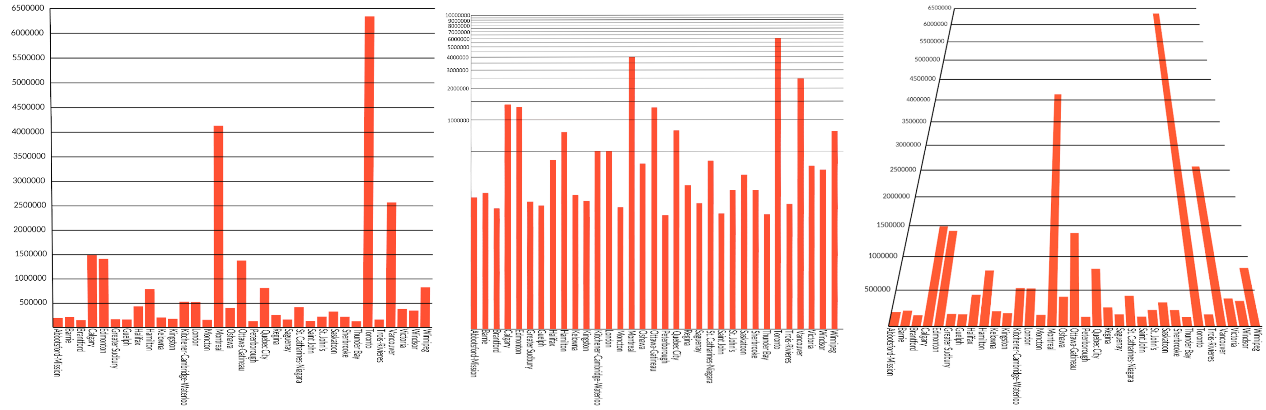

Figure 1: *Canadian cities with a population of more than 150,000, in a traditional bar chart (left), a bar chart with a logarithmic scale (center), and a Slanted Perspective Chart (right).*

the axis in a single chart to compress multiple areas of the chart and eliminate multiple areas of unused space (see Figure 2, right). Since the tops of the bars are not slanted or foreshortened in the Stepped Perspective Chart, the values are emphasized more strongly than in the Slanted Perspective Chart.

The Stepped Perspective Chart is conceptually similar to a traditional broken-axis bar chart (see Figure 3), which also addresses the issue of wasted space in areas where there are large gaps in the data. However, since a broken-axis bar chart essentially cuts out a portion of the graph, the ability to visually estimate and compare data is lost, unlike in our Stepped Perspective Chart.

Both our Slanted Perspective Chart and Stepped Perspective Chart may result in some wasted space around the upper corners of the viewing space. To eliminate areas of unused space wherever possible, we introduce a third type of Perspective Chart, called the *Circular Perspective Chart* (see Figure 4, left). Our design for this chart is inspired by the impression of looking up at tall buildings and skyscrapers from a low vantage point, as shown in Figure 4, right. The horizontal axis of the chart is mapped to a circle, with the vertical axis extending away from the reader's view. This chart occupies a consistent viewing space regardless of the scale of the data or the number of entries in the dataset.

In information visualization, two-dimensional views are preferred to three-dimensional ones [Mun14], so we prefer to hide the three-dimensional aspects of our charts and display only certain fixed views. The data visualization challenges that we discuss related to readability in large datasets can be addressed using dynamic visualization methods, such as focus-plus-context; however, we focus on a static method of addressing these issues. We introduce a new class of charts comparable to traditional static bar charts, and note that commonly used interactive techniques for bar charts can also be used with our Perspective Charts.

To evaluate our visualizations, we conducted a user study with twenty-four participants. The purpose of the study was to quantitatively measure the speed and accuracy with which users could read data from our charts in comparison to traditional and state-of-the-

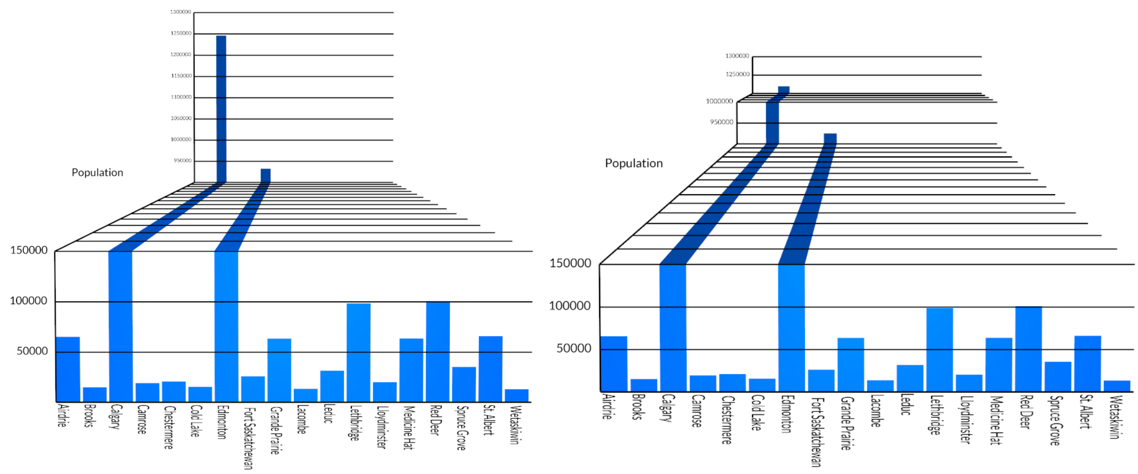

Figure 2: *Left: A Stepped Perspective Chart. Right: A Stepped Perspective Chart with multiple bends in the axis.*

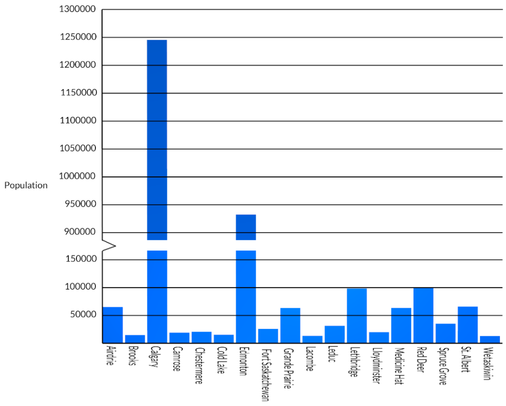

Figure 3: *A broken-axis bar chart.*

art methods of data visualization. We also performed a qualitative evaluation of our three designs. Participants generally responded favorably to our visualizations, and were able to read data from them as accurately as with the traditional methods in fifteen out of seventeen task types, and performed more strongly than a state-of-the-art method in three out of four tasks.

Our contribution is the introduction of three novel data visualizations, called Perspective Charts, that use perspective projection as a tool for simple mapping of datasets with a large scale.

In the following section, we provide an overview of related work. Next, we describe and provide design rationale for our three types of Perspective Chart, as well as some implementation details. We then describe the methodology and results of our user study.

2. Background and Related Work

Given the increasing size and complexity of available datasets, finding clear and readable methods for visualizing these datasets is becoming more challenging [KMSZ06]. Traditional visualization methods such as bar charts are not always a practical choice when visualizing datasets with a large range [KHDH02]. In this section, we first provide a short review of research on visualizing complex datasets using variations of large scale bar charts. Since we use perspective projection in our charts, we provide a short review on the literature about the role that perspective plays in human perception.

2.1. Large Scale Bar Charts

Bar charts are a conventional method for representing categorical data with rectangular shapes, whose heights are proportional to the scale of the category. Bars may be oriented either vertically or horizontally depending on the application and viewing space limitations. Diverging stacked bar charts [HR*14] are a well known example of a bar chart with the bars displayed horizontally.

As the number of represented categories increases, the width of the bars must decrease to allow the chart to fit into the viewing space. When a range of data is mapped to a bar chart, a scaling factor is applied such that all of the data can be represented in the viewing space. Although high data density in a chart is not inherently undesirable [TGM83], when the range of the data is sufficiently large, it may not be possible to fit the chart into a limited viewing space without applying scaling that decreases legibility. To address this problem, in some applications, alternatives to bar charts are used.

Traditional alternatives to bar charts include broken-axis bar charts, radial bar charts, and stacked bar charts [Rib]. However, Goldberg and Helfman suggest that user performance with radial graphs is weaker than with linear graphs for some use cases [GH11]. A broken-axis bar chart eliminates areas of unused space between values in a bar chart; this is visualized as a discrete jump in values in the axis. We compare broken-axis bar charts to our Stepped Perspective Chart in our evaluation.

Charts scaled with a logarithmic function are also sometimes used to represent datasets with a large range. However, this type of scale is not typically used in bar charts, and may be difficult to interpret given that it is non-linear [HSBW13].

2.2. Variations of Bar Charts

There exist several proposed solutions to common problems with bar charts. Pixel bar charts [KHDH02] introduce a new technique for visualizing multivariate data with traditional bar charts. In this technique, each data point is mapped to one pixel of display. Hlawatsch et al. compare their scale-stack bar charts with logarithmic and broken bar charts for the visualization of datasets with a large scale [HSBW13]. Another variation of bar charts, called the Bar-Chart Chip [LXX*15], is used in point-of-care diagnostics and allows authors to create categorical positive or negative results as visual ink bar charts.

Variations of bar charts are commonly used when visualizing multivariate comparable datasets. Demir et al. use bar charts to visualize multiple volume datasets in their multi-charts [DDW14]. They introduce a hybrid visualization that incorporates bar charts and line charts in a three-dimensional setting.

Skau et al. evaluate the impacts of adding visual embellishments in bar charts [SHK15], taking into account human perception and aesthetic factors in their analysis. The results of this evaluation showed that simple embellishments like rounded or triangular bars have strong effects on human perception, and in some tasks will negatively affect performance. Their evaluation found that humans rely on strong lines at the ends of the bars to accurately estimate values. In our Stepped Perspective Charts, we keep the tops of the bars visible and perpendicular to the view in each cluster of the data.

A potential application for the use of Perspective Charts is geospatial data visualization, where datasets such as population or the pollution levels of cities, countries, etc. are spatially presented on a map. The use of charts for visualizing geospatial datasets has a long history in data visualization. Examples such as [LSC08] highlight attempts to bring charts into spatial data visualization. The use of bar charts in spatial data visualization often results in issues relating to properly managing the available viewing space. Hence, designing a new mapping for bar charts will be useful for multidimensional and spatial data visualizations.

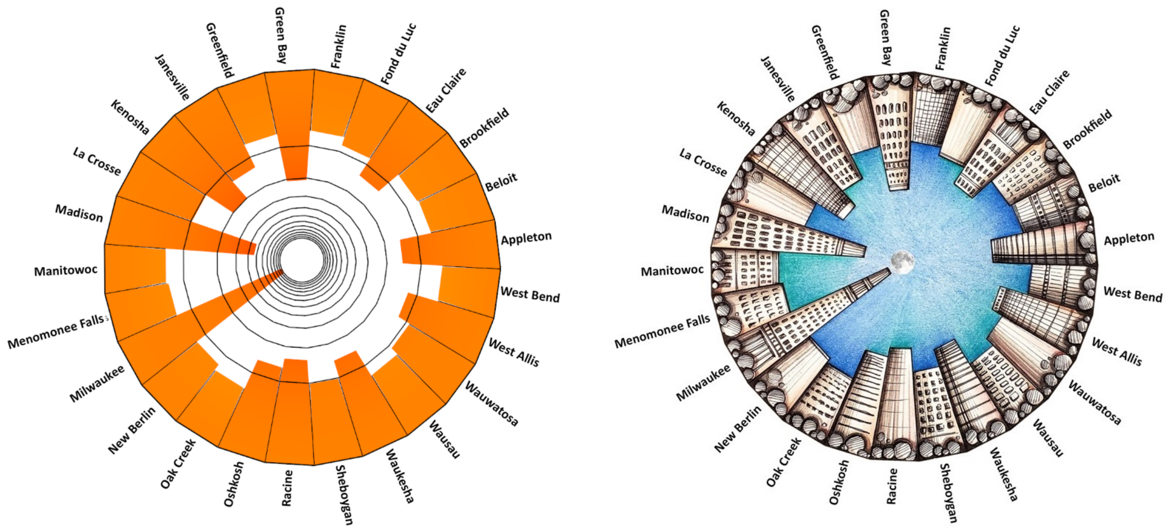

Figure 4: *Left: Population of cities in the state of Wisconsin in the United States, in a Circular Perspective Chart. Each line marks an increment of 50,000. Right: An artistic representation of our Circular Perspective Chart.*

Figure 5: *A photographic example of single-point perspective. Due to the effect of size constancy, we perceive the height of the statue in the red box to be the same as the height of the statue in the blue box. In image space, the statue in the red box is half the height of the statue in the blue box.*

2.3. Human Perception

Graphical representations of data have a strong effect on human perception [CM84]. As described by Tufte [TGM83], graphical representations of data must have several points of focus, encouraging the eye to compare pieces of data. Perspective, in combination with lighting, distance and angle, also has a strong effect on human perception [Gib60].

The visual shape and size of objects changes as the object's distance and orientation relative to the viewer changes [Shl00]. However, the concept of *size constancy* explains that perception of an object's size does not change with the distance of the object from the viewer [PPC97]. This is true even for two-dimensional representations of three-dimensional scenes (see Figure 5). This is because of humans' natural ability to account for perspective and the reduction of the projected size of an object when estimating its size [TK04]. Size constancy is one of the types of natural constancy in human perception of distance and scale of objects. We use this feature of perception in the design of our Perspective Charts.

Three-dimensional perspective is used by Mackinlay et al. [MRC91] in their technique called the Perspective Wall. This interactive technique explores a method of addressing data with "wide, inefficient aspect ratios" by placing the area of focus on a flat plane, with surrounding contextual data placed on planes that appear to be slanted away from the viewer. Other aspects of human perception, such as those described by Gestalt psychology [Kof35], are used in the design of various hierarchical data visualizations [KY93, EBB*14, NCA06].

3. Methodology

We propose the use of perspective as a mapping of bar charts in three different designs: the Slanted Perspective Chart, Stepped Perspective Chart, and Circular Perspective Chart. In this section, we present design rationale and methods for creating our three different Perspective Charts.

3.1. Slanted Perspective Charts

Slanted Perspective Charts, as shown in Figure 1, are similar to traditional bar charts, but have the vertical axis of the chart slanting

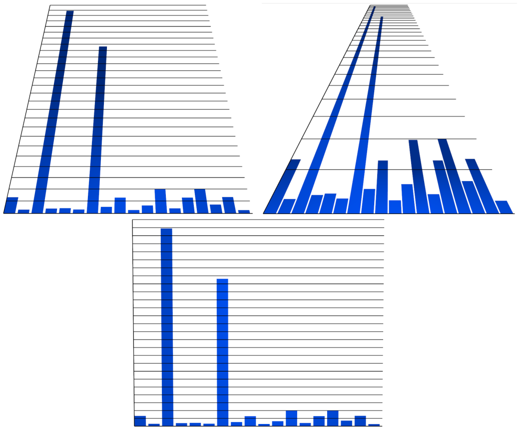

Figure 6: *A comparison of methods for slanting a traditional bar chart (bottom). The left chart's vertical axis is slanted away from the viewer at an angle of* 30°*, stretching the axis in the process. The chart on the right is slanted at an angle of* 60°.

away from the viewer. This design is inspired by drawings and images that portray one-point perspective, i.e. images with a single vanishing point, as shown in the photograph in Figure 5. We use a simple 3D environment and set a predefined camera setup to avoid user input for 3D interaction. Slanting the chart brings smaller values closer to the viewer, while moving larger values away.

The slant in the vertical axis of the chart can be achieved either by viewing the chart from a lower angle, or by maintaining the same viewpoint and instead slanting the chart plane backwards from the viewer in three-dimensional space. We choose the latter option of slanting the vertical axis of the chart, in order to maintain a consistent viewing space. Slanting the chart moves large values in the chart away from the viewer, and decreases the space between scale lines.

We control the foreshortening ratio in order to limit the compression of large values as they move away from the viewer. The foreshortening ratio measures how objects viewed at an angle appear to be shorter than their true measurement. We slant the vertical axis of the chart at a fixed angle θ. The slanting angle θ controls the foreshortening ratio, f_r, of the slanted line L compared to the viewing plane V:

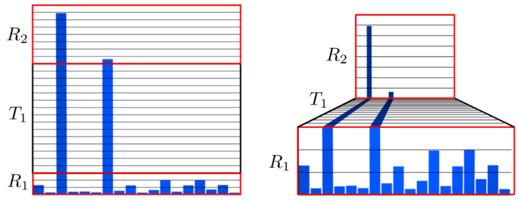

Figure 7: *A simple example of a dataset with two clear clusters* R_1 *and* R_2*, and a transitive range* T_1.

$$f_r = \frac{L}{V} = sec(\theta).$$

For example, when $\theta = 60^\circ$, the foreshortening ratio f_r is 2. In general, $1 \leq f_r < \infty$ where $0 \leq \theta < \frac{\pi}{2}$.

We avoid slanting the chart at extreme angles in order to control the foreshortening ratio f_r and maintain readability of large values. Figure 6 demonstrates how a change in θ impacts foreshortening.

3.2. Stepped Perspective Charts

Our Stepped Perspective Chart, as seen in Figure 2, is designed to resemble a staircase showing various "tiers" of data. According to these tiers, we divide the range of the data into subranges $R_1, T_1, R_2, T_2, \ldots, R_n$ (see Figure 7) where each R_i is a cluster of the data and T_i are transitions. Each of these subranges represents a rectangular region of the chart. To create the Stepped Perspective Chart we use a vertical view plane with a view angle $\theta_v = 0^\circ$ for the R_i, and an extreme slant ($\theta_v = 60^\circ$ for Figure 7) for the transitive regions T_i.

The Stepped Perspective Chart is comparable to traditional broken-axis bar charts, which are also intended to address the issues associated with large gaps between values in a dataset. However, the use of broken-axis bar charts is discouraged in data visualization because it disrupts the sense of scale that can be valuable when representing a wide range of values. In a traditional broken-axis bar chart, without the use of labels, it is impossible to visually

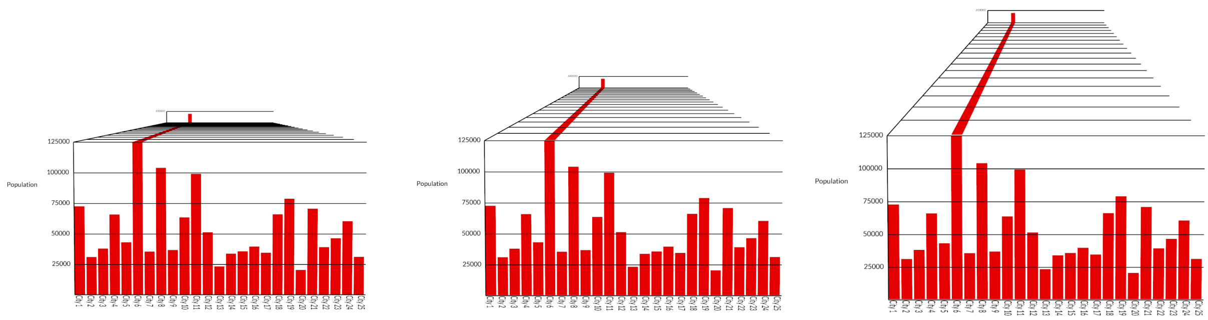

Figure 8: *A Stepped Perspective Chart viewed at three different heights, resulting in varying view angles and amounts of viewing space occupied by the transitional region of the chart. Left:* $\theta_v = 80^\circ$*. Center:* $\theta_v = 60^\circ$*. Right:* $\theta_v = 40^\circ$

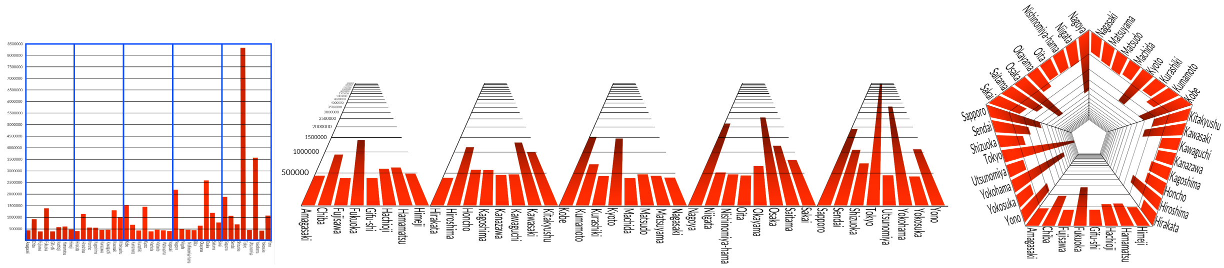

Figure 9: *The Circular Perspective Chart is created by grouping sections of a large chart into several smaller sub-charts. In this example we have five sub-charts. Each of the sub-charts is individually slanted, then rotated to form a closed polygon.*

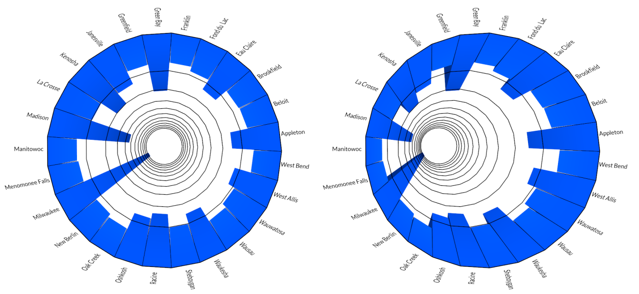

Figure 10: *The vanishing point of the Circular Perspective Chart can be adjusted.*

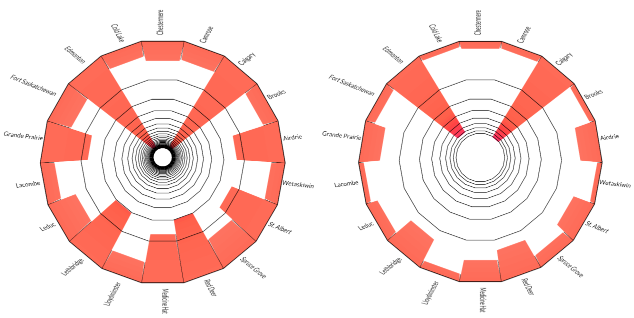

Figure 11: *A Circular Perspective Chart showing population of cities in Alberta, with two different scaling factors. In the top chart, each line marks an increment of 50,000. In the bottom chart, each line marks an increment of 150,000.*

compare values on opposing sides of the break in the axis. In the Stepped Perspective Chart, the area within the gap is still visible, as it runs along a different axis rather than being cut out of the chart entirely (see Figure 7). This way, visual estimation is still possible, and the reader is able to perceive the approximate size of the gap.

The amount of the transitional region of the chart that is visible can be adjusted. Figure 8 shows varying heights from which the chart can be viewed. While the axes are always bent at an angle of 90°, the height of the camera affects the view angle. A height that is too low results in a high view angle, with scale lines positioned so closely together that they are no longer readable, while a low view angle lessens the impact of the separate regions of the chart. We choose a height that is just high enough to allow the viewer to distinguish between scale lines. This is dependent on the resolution and size at which the chart is viewed.

3.3. Circular Perspective Charts

As seen in Figure 4, our Circular Perspective Chart is inspired by the perception of tall buildings as viewed from a low vantage point, converging on a singular vanishing point. In this chart, the bars are placed in a closed polygon and extend away from the viewer, converging at a vanishing point at the center of the polygon.

We create our Circular Perspective Chart by bending the horizontal axis to remove areas of unused space and accommodate a larger number of values in a limited viewing space. We can imagine that the entire bar chart is divided into multiple smaller sub-charts that are slanted individually (see Figure 9). The slanted sub-charts are then rotated to form a closed polygon. In the extreme case, each sub-chart is allocated to only one single value (see Figure 4). When there is no preferred clustering to create sub-charts, we use this extreme case as the main design of our Circular Perspective Chart. By wrapping the horizontal axis of the chart to form a closed polygon, the chart is contained within a consistent view.

The vanishing point of the Circular Perspective Chart can be adjusted, as shown in Figure 10. This modifies the foreshortening ratio of bars in the chart. Bars that are closer to the vanishing point have a more extreme foreshortening ratio, while bars that are farther from the vanishing point have a lower ratio. In Figure 10, values on the right-hand side of the chart are less compressed and more easily readable. This technique could be used in interactive visualization as a tool to enhance certain parts of the data or emphasize small values.

The vantage point of the viewer is another potential handle to use in interactive visualization using the Circular Perspective Chart. Figure 11 shows an example of a low and a high viewing height for the chart shown in Figure 4. In the left chart, each scale line represents an increment of 50,000 for a total of twenty-four scale lines. The right chart's scale lines represent an increment of 150,000 for a total of eight scale lines. To make the most efficient use of space in the Circular Perspective Chart, the scaling factor should be chosen such that bars are compressed as little as possible while avoiding the issue of closely converging scale lines. The occurrence of this

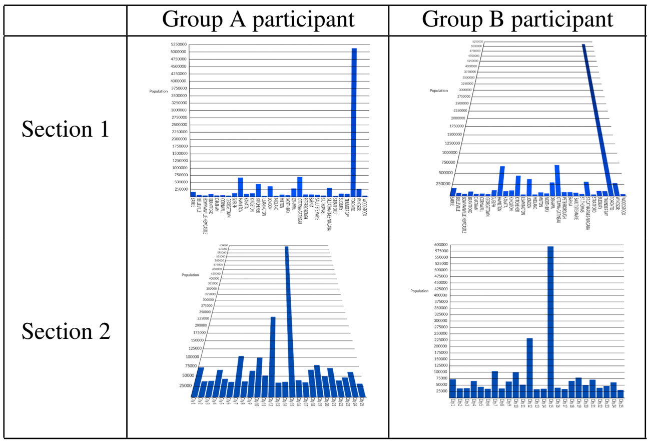

Figure 12: *An example of the task flow in our evaluation. A participant in group A completes a set of tasks in Section 1 with dataset A using a traditional bar chart, and then a set of tasks for Section 2 with dataset B using the Slanted Perspective Chart. A participant in group B completes the same set of tasks, using the same datasets, with the type of chart swapped for each set of questions.*

issue is dependent on the size and resolution at which the chart is displayed.

4. Evaluation

We conducted a user study to evaluate the readability and novelty of Perspective Charts as a data visualization tool. The study quantitatively measures the accuracy and speed with which users answered a series of questions based on data shown in various charts, and also collects the participants' opinions of the three types of Perspective Charts in a qualitative study.

4.1. Study Design

Methodology: Studies were performed on an individual basis over the course of approximately 60 minutes per participant. Each participant was shown a series of various types of charts and answered a list of questions based on the data in these charts. Each participant performed tasks such as value reading, determining magnitude differences, determining range, and filtering based on common visualization task taxonomies [AES05, TSA14]. Each participant answered questions based on a traditional bar chart, a radial bar chart, a broken-axis bar chart, a state-of-the-art approach (Scale-Stack Bar Charts) [HSBW13], and our Slanted, Stepped, and Circular Perspective Charts.

In our evaluation, we performed pairwise comparisons between each of our Perspective Chart designs and other types of visualizations, either traditional or state-of-the-art. We compare our Slanted Perspective Charts to traditional bar charts by having participants perform tasks of specific taxonomies, such as reading a small value from the chart, In both types of chart. The dataset and specific questions vary between the charts, but the tasks use the same taxonomies for both charts.

In order to reduce potential bias caused by the structure of particular datasets, participants were divided into two groups. Participants in both groups answer the same questions using the same datasets, however the type of chart used is swapped. Half of the participants answered the first set of questions using a traditional bar chart, and then the next set of questions using a Slanted Perspective Chart. The other half would use a Slanted Perspective Chart followed by a traditional bar chart. An example of this task flow is shown in Figure 12.

We used this format to pair our Stepped Perspective Chart to broken-axis bar charts and to the Scale-Stack Bar Chart, since each of the three types of chart feature some sort of break or discontinuity in the chart's axis. We also paired the Circular Perspective Chart with a radial bar chart and a traditional bar chart. We chose the radial bar chart in order to compare the Circular Perspective Chart against another type of closed-form circular visualization.

After the main set of tasks were completed, participants answered a short post-study questionnaire asking them to evaluate each type of chart used in the study. This was followed by a short verbal interview portion where we further gathered their opinions on the charts used in the study.

Participants. We recruited 24 participants (12 female, 12 male) using posters distributed across our local campus as well as via word of mouth. 22 participants were students at the time of the study; 16 participants worked or studied in the fields of science, mathematics or engineering, while the remaining participants worked or studied in arts, business or social sciences.

Datasets. Since the tasks were divided into ten different sections for each participant, ten unique datasets were used. We chose real datasets that satisfied our use case of clusters of data across a large range. Six datasets showed population data across various regions, two represented pollution data, and two represented precipitation data. We used data that was likely to be unfamiliar to the participants to reduce potential bias resulting from preexisting knowledge about the data. This was done either by using data from regions that were not geographically close to the location where the study was performed, or by obscuring the names of the locations in the datasets ("City 1" instead of "Vancouver", etc.).

Tasks. Tasks were designed based on several common information visualization taxonomies: retrieving values, determining magnitude differences, determining range, filtering, and sorting. Example tasks for Figure 4, left, with their corresponding taxonomies, could include:

"What is the population of Franklin?" (Retrieve small value)

"How much larger is Milwaukee than Oak Creek? (For example, 2x larger, 3.5x larger)" (Determine magnitude difference, small and large values)

"What is the range of the data? (Smallest population to largest population)" (Determine range)

	Traditional	Slanted
RV (small value)	13.45	13.45
DMD (two small values)	29.08	17.34
DMD (small & large values)	14.53	6.84
DR	2.44	8.65
Filter	9.09	12.88

Table 1: *Median percentage of error for the first group of tasks, evaluating the Slanted Perspective Chart compared to a traditional bar chart. Results are grouped by the taxonomy of the tasks. (RV = Retrieve Value, DMD = Determine Magnitude Difference, DR = Determine Range)*

	Scale-Stack	Stepped
RV (small value)	31.41	13.14
DMD (two small values)	29.64	**10.04**
DMD (small & large values)	48.72	**11.87**
DR	12.12	**0.53**

Table 2: *Median percentage of error for the second group of tasks, evaluating the Stepped Perspective Chart compared to the Scale-Stack Bar Chart. Bolded cells indicate that the result was statistically significant compared to its paired chart. (RV = Retrieve Value, DMD = Determine Magnitude Difference, DR = Determine Range)*

4.2. Study Results

We compare percentage of error and task completion time between sets of tasks. The Shapiro-Wilk test indicates that our data does not follow a normal distribution, so comparison of methods was performed using a Mann-Whitney's U test and we examine the median error rate for each task.

Between a traditional bar chart and our Slanted Perspective Chart, median error rate was lower for tasks related to determining magnitude difference between two small values and between small and large values with the Slanted Perspective Chart. However, this result was not found to be statistically significant, and no significance was shown in the difference in error rate between tasks performed with a traditional bar chart and with our Slanted Perspective Chart, or for tasks performed with a traditional bar chart and our Circular Perspective Chart. There was also no significant difference demonstrated in accuracy between a broken-axis bar chart and our Stepped Perspective Chart. Tasks were not shown to be completed significantly more quickly with traditional visualizations than with our visualizations.

	Broken	Stepped
RV (small value)	5.08	5.15
RV (large value)	0.50	1.39
DMD (two small values)	14.71	15.42
DMD (small & large values)	10.38	8.89

Table 3: *Median percentage of error for the third group of tasks, evaluating the Stepped Perspective Chart compared to a broken-axis bar chart. (RV = Retrieve Value, DMD = Determine Magnitude Difference)*

	Radial	Circular
RV (small value)	**0.00**	5.56
DMD (two small values)	0.68	2.60
DMD (two large values)	7.08	12.66
Sort	**0.00**	8.33

Table 4: *Median percentage of error for the group section of tasks, evaluating the Circular Perspective Chart compared to a radial bar chart. Bolded cells indicate that the result was statistically significant compared to its paired chart. (RV = Retrieve Value, DMD = Determine Magnitude Difference)*

	Traditional	Circular
RV (small value)	2.78	4.17
DMD (two small values)	19.23	23.08
DMD (small & large values)	7.72	12.38
Filter	9.09	0.00

Table 5: *Median percentage of error for the fifth group of tasks, evaluating the Circular Perspective Chart compared to a traditional bar chart with a large vertical scale. (RV = Retrieve Value, DMD = Determine Magnitude Difference)*

The Stepped Perspective Chart significantly outperformed the Scale-Stack Bar Chart ($p < 0.04$) for tasks related to determining magnitude difference between values and determining range, and was also significantly faster.

Compared to the Circular Perspective Chart, tasks related to retrieving values and sorting were completed with significantly more accuracy using a radial bar chart. Our quantitative results are separated into five categories, one for each pairwise comparison made in the evaluation. Median results are shown in Tables 1 to 5. Visualization of these results is shown in Figure 13.

Responses to the post-study questionnaire are shown in Figure 14. The two most common visualizations, the traditional bar chart and the broken-axis bar chart, were the most well-received. The other types of visualizations were less familiar to participants and received lower scores, with the Circular Perspective Chart receiving slightly less favourable scores.

The Circular Perspective Chart received the most "very hard to use" scores out of all the types of visualizations; nine out of twenty-four participants indicated that it was difficult for them to retrieve large values from the Circular Perspective Chart.

P10: "With the circular chart, with lower values it was easier to calculate, but I kept losing count when the perspective got smaller for the higher numbers."

However, two participants felt that the Circular Perspective Chart was a good choice for an artistic representation of data:

P6: "The Circular Perspective Chart isn't the greatest for just reading values, but for giving a perspective on how large or *small a value is compared to others, it's good when you want to make an impact."*

Several participants indicated that they struggled to use the Scale-Stack Bar Chart because they felt that its design was complicated.

P10: "With the Scale-Stack Bar Chart, I kept tripping myself up about what each value was, and where I was actually supposed to be looking at with the different scales. It was hard to go back and forth."

Overall, participants felt that the ease-of-use of the Slanted and Stepped Perspective Charts were comparable to a radial bar chart and the Scale-Stack Bar Chart. The results of the evaluation indicate that the use of perspective does not have a significant effect on the ability to perform tasks using the Slanted Perspective Chart and the Stepped Perspective Chart, despite our visualizations being unfamiliar to the participants at the beginning of the evaluation. The Stepped Perspective Chart outperformed the comparison state-of-the-art method, the Scale-Stack Bar Chart, in three out of four task taxonomies and was also significantly faster to use. However, the Circular Perspective Chart showed less accurate results than a radial bar chart in two out of four taxonomies, and nine out of twenty-four participants felt that the effect of the perspective was too extreme in the Circular Perspective Chart.

5. Conclusion and Future Work

We have introduced three novel chart designs, called Perspective Charts, to address limitations of traditional bar charts caused by undesirable scaling factors and a fixed viewing space. Our designs can open up new possibilities for visualizing large and complex datasets using the natural perception of size constancy. We provide design rationale for our three chart designs and evaluate their usability in a user study.

Evaluation showed no significant difference in performance (accuracy and timing) between traditional visualizations and our Slanted and Stepped Perspective Charts. Tasks were performed significantly more quickly and accurately with the Stepped Perspective Chart than with the Scale-Stack Bar Chart, another recent visualization design intended to represent datasets with a large scale, in three out of four task taxonomies. The Circular Perspective Chart showed less accurate results than a radial bar chart for some tasks.

Future work. The research could be expanded to explore the use of interactive tools for visualization. Various design parameters could be modified by users based on their desired design for a particular Perspective Chart, based on the features of the dataset. For example, the number of steps or the viewing angle in the Stepped Perspective Chart could be modified. In the Circular Perspective Chart, the position of the vanishing point could be moved to place a stronger emphasis on various sections of the data, or the height of the vantage point could be dynamically adjusted to change the context of the data, as shown in Figure 11.

We would also like to add support for time-varying data sets. This may be useful for visualizing information such as changes in population over the course of several years.

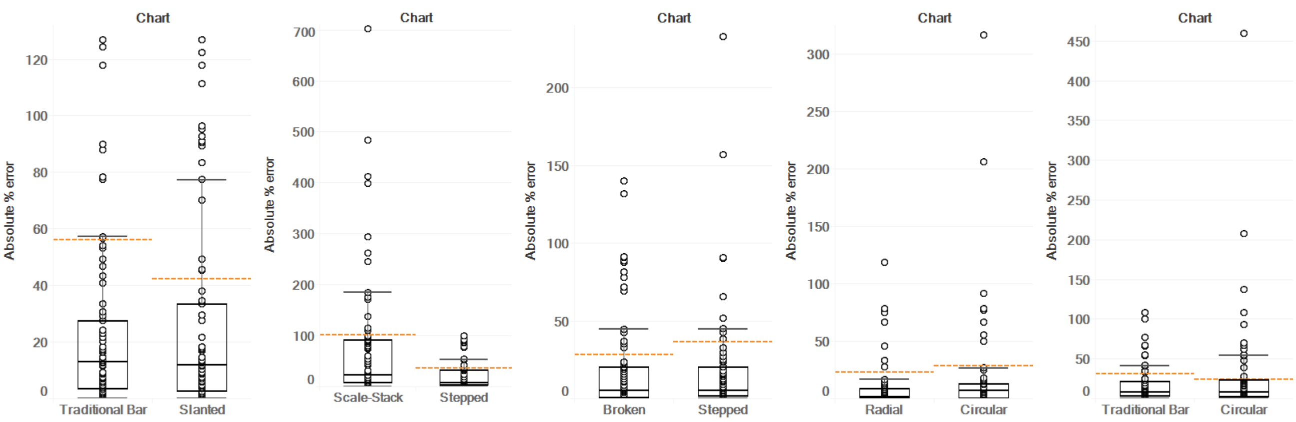

Figure 13: *Aggregate task accuracy results for the evaluation, showing the groups of pairwise comparisons in the tasks. The mean error rate is represented by the orange bar. Each type of chart had one to five outliers with a value greater than 750%, which exceeded the scale of the chart.*

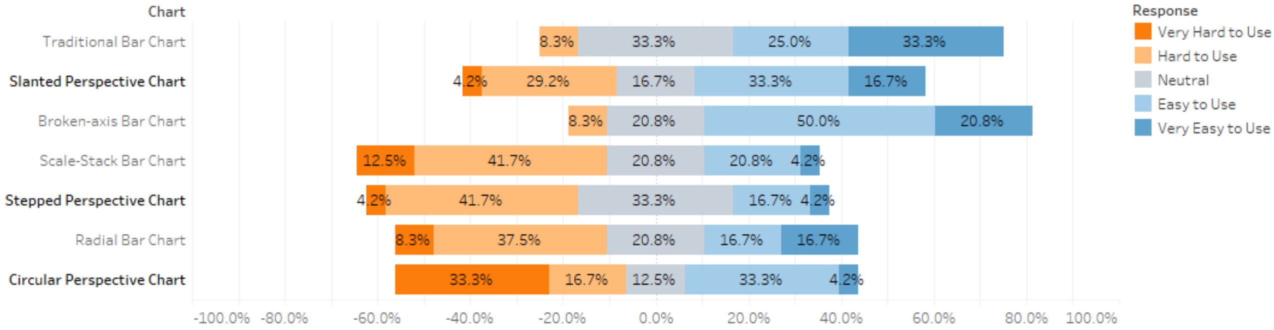

Figure 14: *Qualitative results of our user study evaluation. Our methods are indicated in bold.*

References

[AES05] AMAR R., EAGAN J., STASKO J.: Low-level components of analytic activity in information visualization. In *Proceedings of the Proceedings of the 2005 IEEE Symposium on Information Visualization* (Washington, DC, USA, 2005), INFOVIS '05, IEEE Computer Society, pp. 15–. URL: https://doi.org/10.1109/INFOVIS.2005.24, doi:10.1109/INFOVIS.2005.24. 7

[Car10] CARLSON N.: *Psychology: The Science Behaviour*, 4 ed. Pearson Canada Inc, 2010. 1

[CM84] CLEVELAND W. S., MCGILL R.: Graphical perception: Theory, experimentation, and application to the development of graphical methods. *Journal of the American statistical association 79*, 387 (1984), 531–554. 4

[DDW14] DEMIR I., DICK C., WESTERMANN R.: Multi-charts for comparative 3d ensemble visualization. *IEEE Transactions on Visualization and Computer Graphics 20*, 12 (2014), 2694–2703. 3

[EBB*14] ETEMAD K., BAUR D., BROSZ J., CARPENDALE S., SAMAVATI F. F.: Paisleytrees: A size-invariant tree visualization. *EAI Endorsed Trans. Creative Technologies 1*, 1 (2014), e2. 4

[Erk13] ERKELENS C. J.: Computation and measurement of slant specified by linear perspective. *Journal of Vision 13*, 13 (Nov. 2013), 16–27. 1

[GH11] GOLDBERG J., HELFMAN J.: Eye tracking for visualization evaluation: Reading values on linear versus radial graphs. *Information Visualization 10*, 3 (2011), 182–195. URL: https://doi.org/10.1177/1473871611406623, doi:10.1177/1473871611406623. 3

[Gib60] GIBSON J. J.: Pictures, perspective, and perception. *Daedalus 89*, 1 (1960), 216–227. 4

[HR*14] HEIBERGER R. M., ROBBINS N. B., ET AL.: Design of diverging stacked bar charts for likert scales and other applications. *Journal of Statistical Software 57*, 5 (2014), 1–32. 3

[HSBW13] HLAWATSCH M., SADLO F., BURCH M., WEISKOPF D.: ScaleâĂŘstack bar charts. *Computer Graphics Forum 32*, 3 (2013), 181–190. 3, 7

[KHDH02] KEIM D. A., HAO M. C., DAYAL U., HSU M.: Pixel bar charts: a visualization technique for very large multi-attribute data sets. *Information Visualization 1*, 1 (2002), 20–34. 3

[KMSZ06] KEIM D. A., MANSMANN F., SCHNEIDEWIND J., ZIEGLER H.: Challenges in visual data analysis. In *Tenth International Conference on Information Visualisation (IV'06)* (2006), IEEE, pp. 9–16. doi:10.1109/IV.2006.31. 3

[Kof35] KOFFKA K.: *Principles of Gestalt psychology*. Routledge, 1935. 4

[KY93] KOIKE H., YOSHIHARA H.: Fractal approaches for visualizing huge hierarchies. In *Proceedings 1993 IEEE Symposium on Visual Languages* (1993), IEEE, pp. 55–60. 4

[LSC08] LUBOSCHIK M., SCHUMANN H., CORDS H.: Particle-based labeling: Fast point-feature labeling without obscuring other visual features. *IEEE Transactions on Visualization and Computer Graphics 14*, 6 (Nov. 2008), 1237–1244. 3

[LXX*15] LI Y., XUAN J., XIA T., HAN X., SONG Y., CAO Z., JIANG X., GUO Y., WANG P., QIN L.: Competitive volumetric bar-chart chip with real-time internal control for point-of-care diagnostics. *Analytical Chemistry 87*, 7 (2015), 3771–3777. 3

[MRC91] MACKINLAY J. D., ROBERTSON G. G., CARD S. K.: The perspective wall: Detail and context smoothly integrated. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 1991), CHI '91, ACM, pp. 173–176. 4

[Mun14] MUNZNER T.: *Visualization analysis and design*. AK Peters/CRC Press, 2014. 1, 2

[NCA06] NEUMANN P., CARPENDALE M. S. T., AGARAWALA A.: Phyllotrees: Phyllotactic patterns for tree layout. In *EuroVis* (2006), vol. 6, Citeseer, pp. 59–66. 4

[PPC97] POLACK J. A., PIEGL L. A., CARTER M. L.: Perception of images using cylindrical mapping. *The Visual Computer 13*, 4 (1997), 155–167. 4

[Rib] RIBECCA S.: The data visualization catalogue. https://datavizcatalogue.com/index.html. Accessed: November 2019. 3

[SHK15] SKAU D., HARRISON L., KOSARA R.: An evaluation of the impact of visual embellishments in bar charts. *Computer Graphics Forum 34*, 3 (2015), 221–230. 3

[Shl00] SHLAHOVA A.: Problems in the perception of perspective in drawing. *Journal of Art & Design Education 19*, 1 (2000), 102–109. 4

[TGM83] TUFTE E., GRAVES-MORRIS P.: The visual display of quantitative information, 1983. 3, 4

[TK04] TYLER C., KUBOVY M.: The rise of renaissance perspective. *Science and art of perspective* (2004). 4

[TSA14] TALBOT J., SETLUR V., ANAND A.: Four experiments on the perception of bar charts. *IEEE Transactions on Visualization and Computer Graphics 20* (2014), 2152–2160. 7

[War12] WARE C.: *Information visualization: perception for design*. Elsevier, 2012. 1