VizInteract: Rapid Data Exploration using Multi Touch and Interactive Construction of Multi-Dimensional Visualizations

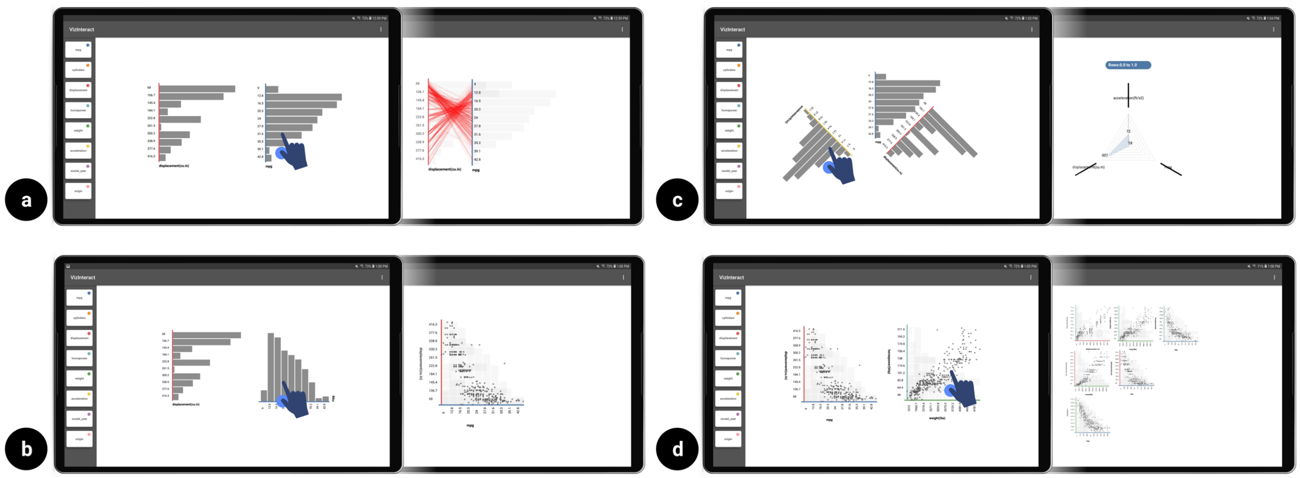

Figure 1 : VizInteract supports easy creation of multidimensional visualizations. a) Two vertically oriented dimensions combined to form a parallel coordinates plot. b) Two orthogonally oriented dimensions combined to form a scatter plot. c) Multiple dimensions loosely arranged at equal angles to each other combine to form a radar chart. d) Multiple scatter plots combined to form a scatter plot matrix.

ABSTRACT

We present VizInteract, an interactive data visualization tool for touch enabled displays. VizInteract affords rapid construction of multidimensional data visualizations through multi-touch gestures, which supports efficient data exploration. Creating and analyzing multi-dimensional data visualizations with current tools typically involve complex interactions. Building on primitive visualization idioms like histograms, VizInteract addresses the need for easy data exploration by affording the construction of multi-dimensional visualizations, such as scatter plots, parallel coordinate plots, and radar plots through simple touch gestures. Touch-based brushing and linking and attribute-based filter-bubbles also support diving down into the data and analysis. We conducted an explorative study to demonstrate the usability of VizInteract. We found that exploration techniques in VizInteract lead to an increased awareness of dimensional correlations and significantly improve data comprehension.

Author Keywords

Data visualization; Interaction; Gesture Interaction; Natural Interaction; Touch Interaction; Scatter Plots; Parallel Coordinate Plots; Radar Chart; Scatter Plot Matrix, Tablets.

ACM Classification

• Human-centered computing ~ Graphical user interfaces

INTRODUCTION

Data visualization is becoming ubiquitous due to the increasing availability of many forms of data and increased need for data consumption and analysis [5]. Thus, sensemaking, as a skill, is becoming essential to answer complex questions across all domains. For causal to expert users, there is a need for tools that facilitate easy data exploration [19]. Desktop tools like Tableau and Cognos offer a configurable interface for data exploration and analysis where users can combine multiple dimensions to produce visualizations. The challenge with such tools is the steep learning curve associated with their adoption [16]. These tools utilize interactions that revolve around traditional WIMP metaphors on desktop systems. Although the operations that users need to perform on data across all the tools are standardized [2], *post-WIMP* [25] implementations of data exploration tools have demonstrated significant improvements in maintaining a user's spatial understanding of data [22,35]. To enable easier data exploration on the rapidly growing set of touch enabled devices, we explore gesture-based interactions to facilitate construction of multidimensional data visualization, more specifically scatter plots (SCP) parallel coordinate plots (PCP), radar charts and scatter plot matrices (SPLOM) in this paper.

Studies have shown that touch-driven interaction is beneficial for a diverse range of plots, such as bar charts and stacked graphs [3,13]. However, these tools provide only limited capabilities for interactive and quick exploration of multi-dimensional data. These methods focus on simple visualization idioms that work well with single, specific data attributes. These interaction techniques do not utilize direct manipulation (DMP) for quick switching between primitive and higher order visualization idioms. Even though DMP has been extensively used for data transformation and filtering operations [22,44] like TouchPivot [22], which uses DMP to transform isolated idioms and PanoramicData [44], which uses gestures for chaining filter operations to quickly query data. These tools do not support rapid plot generation through DMP for quick multi-dimensional analysis workflows. In this paper we address these limitations by allowing primitive data plots to be combined into multiple standard multivariate data visualization idioms using DMP. DMP has also been used for chart authoring in iVoLVER [31], Data Illustrator [28] and Charticulator [34]. However, unlike iVoLVER which facilitates data extraction from nonstandard sources and giving them a visual form. VizInteract focuses on rapid explorative analysis through existing data visualization language. Data Illustrator and Charticulator on the other hand, are desktop visualization authoring tools that do not scale well to mobile screen sizes.

To cater to both novices and experts, VizInteract builds on commonly used and easy-to-learn interactions. The interactions make use of the rotation of individual dimensions and their proximity as a primary tool to combine and produce new views. Our goal was to facilitate rapid construction of multidimensional visualization idioms and provide easy-to-adopt interaction techniques for data analysis and queries. VizInteract currently supports 5 types of views: histograms (primitive plots), scatter plots, parallel coordinate plots, radar charts and scatter plot matrices. We conducted an exploratory user study with 16 participants to investigate how users interact with our tool. Our study shows that the ability to rapidly construct multi-dimensional visualizations led users to explore more correlations, patterns and trends in data. This led to an increased awareness in users about attribute relationships and improved data comprehension.

RELATED WORK

Our proposed system is informed by 3 broad categories of previous research: *Ad-hoc Visualization Construction*, *Touch-based Interaction for Visualizations* and *Interaction with Multidimensional Data Visualizations*. In this section we review the literature in each category.

Ad-hoc Visualization Construction

The most popular commercial tools in the visualization space that facilitate easy generation of charts are Microsoft Excel and Tableau. Microsoft Excel [45] with its PivotTable and PivotChart feature, provides a quick way to summarize large tabular data and generate on the fly visualizations. Tableau [46] on the other hand, abstracts data tables and supports quick creation of relationships between attributes as part of a larger set of data query specific operations. For more complex data processing and visualization workflows, Visualization Tool Kit [47] provides a graphics library that can connect to data sources and generate custom mapping views between the data and rendered visualizations. The limitation of these tools are the detailed specification requirements and lack of support for post-WIMP metaphors, which introduces barriers for rapid data exploration. VizInteract overcomes this limitation by using simple multi-touch gestures to rapidly construct charts. Our system enables gestural combination of similarly or differently oriented idioms to be combined into SCP, PCP, radar chart and SPLOM.

All aforementioned tools also require explicit visual transformations on selected attributes of the data. Tools like Voyager [42] remove this manual process and also provide recommendations for visualizations that showcase the most significant relationships between selected dimensions. APT [29] introduced an effectiveness criterion to rank visualizations and VizDeck [33] explored a gallery of recommendations based on statistical effectiveness of chart types. VizInteract contributes to exploratory data analysis [17] by providing a direct interface to rapidly construct primitive and higher order visualizations. There are no recommendations in VizInteract, as the primary aim is to assist users of all expertise to use the interaction mechanism to rapidly construct complex visualizations and discover relationships based on their workflow requirements.

Another way to perform data exploration is through filtering operations. Faceted metadata [43] used filters to dynamically reduce the working data size and then identify relationships between attributes. For working with significantly large datasets with coordinated views, C. Dunne et al. developed GraphTrail [14]. It allowed exploration through nodes and edge-based aggregation of data. It also facilitated tracking of user interaction history for easily resuming exploration sessions. The idea of filters can also be extended to multiple views. Snap-Together [32] introduced coordinate selection and filters across multiple views. VizInteract builds upon these works by using filter bubbles that are linked to each visualization and can be easily constructed, manipulated and duplicated to other visualizations through drag and drop. This allows for more dynamic filter operations in our tool.

Touch-based Interaction for Visualizations

Interacting with visualizations using gesture- or touch-based interfaces has been explored extensively. Isenberg et al. identified interactive tabletops and touch surfaces as a medium for effective data visualization [21]. Lee et al. also identified the importance of using *post-WIMP* metaphors and using more naturalistic interactions for sensemaking in visualizations [25]. A combination of pen and touch for object selection [18] has also been applied to data visualizations [7,11,26,40]. Interactive whiteboards and pen input have also been used to facilitate fluid and easy data exploration. SketchVis [7] in particular used sketching to transform data and perform filter operations. VizInteract builds on these ideas by offering touch gesture-based construction of visualizations without the need for auxiliary pen input and also provides a touch-based data filtering and querying operation.

Interaction with visualizations has also been explored on smaller form factor devices, such as multi-touch tablets. TouchViz [13] compared traditional WIMP based interface with their fluid gesture based interface for Visual Analytics on a tablet. TouchViz focused on data querying operations enabled through gestures while VizInteract utilizes touch gestures to construct many kinds of multivariate charts. Kinetica [35] used physics-based affordances for multivariate data exploration and filtering. Each filter query required the user to trace a significant portion of the canvas to make the data points reconfigure. Building upon this limitation, VizInteract uses a far simpler and quicker drag and drop interaction to add filters which can be manipulated and duplicated at any time. Multi-touch interactions have also been used for dynamic scatter plots in [38], but their gestural interactions were only limited to selection, filtering, selection and zooming in scatter plots. TouchWave [3] also used multi-touch gestures for interacting with only stacked graphs. All these tools incorporated interactive data exploration and transformation on a single type of chart. In contrast, VizInteract provides a canvas to construct and interact with multiple types of multi-dimensional charts. Sadana et al. had explored coordinating multiple views on a Tablet [36]. However, their MCV [36] interface focused on coordinating views for selection and filtering operation, whereas VizInteract explores rapid ad-hoc construction of higher order data visualizations and dynamic filters.

Interaction with Multidimensional Data Visualizations

Tukey et al. [39] introduced a graphical view called draftsman's view or a scatter plot matrix (SPLOM) that was used to explore multivariate data. It displays a scatter plot for all pair wise combination of dimensions. Scatter plot matrices are effective to quickly surface correlations between multiple attributes. Another form of visualization used for multivariate data exploration is PCPs. Inselberg et al. [20] introduced parallel coordinates plots for effective data exploration in a 2D space. The study also found that PCPs have very low representational complexity. This is because the number of axes required to plot the relationships is equal to the dimensionality of the data. These were strong motivations for us to include SPLOM and PCPs as a visualization idiom in VizInteract. This choice also potentially reduces the cognitive load for newcomers as our work builds on known chart types.

Wong et al. summarized a significant amount of multivariate data visualization research [41]. Visualizations that explore interactivity in multidimensional data visualization include Starfields [1] and parallel sets [23]. Data analysis operations like brushing and linking in multivariate scope have also been explored in the past [30]. DataMeadow [15] used a canvas of starplots, each having an interactive filter slider to adjust the distribution of a selected dimension in a query against the data. These interactive multidimensional visualizations were created primarily for mouse-based interfaces and have minimal DMP affordances. VizInteract expands on these works by introducing DMP interactions to explore multivariate data. In VizInteract, any number of dimensions can be selectively dragged and placed on the canvas and can be combined to produce different visualizations.

Flexible linked axes [8], utilized drawing to explore multi-dimensional data. The system had a canvas where users could draw mechanical lines between axes. Depending on the lines drawn between axes and axes configuration, the visualization generated was either SCP or PCP. ImAxes [9] used virtual axes that could be manipulated in 3D space and combined to produce sophisticated visualizations. One limitation of ImAxes was the need for the user to physically move to interact with the plots in the 3D space. This led to lot of walking, crouching and general movement for simple analysis. The authors suggested that a semantic zoom operation would allow isolating axes and overcome the abovementioned limitation. Our work is inspired by these interactive systems to generate visualizations [8,9]. However, instead of mechanically drawing links or drawing in 3D space, we modify the axes through simple gestures on a 2D canvas. We also provide a gesture-based zoom operation to facilitate isolated analysis of single plots. VisTiles [24] also used orientation and arrangement to produce different visualizations but it catered to a more collaborative VA workflow where multiple devices were spatially oriented and arranged to compose higher order views. On the contrary, our work focuses on a single user single device use case.

DESIGN GOALS

We developed VizInteract to address three design goals.

a) Afford multi-touch based direct manipulation to facilitate data exploration.
b) Offer an easy-to-learn set of interaction.
c) Empower novice users, but also provide room for advanced exploration by experts.

Multi-touch based DMP for data exploration

The VizInteract interface leverages the benefits of DMP [12] by supporting multi-touch gestures to construct and explore high dimensional data. This design choice applies learnings from instrumental interaction [4], where the domain objects are the visualizations and the interaction instrument is multi-touch input. Motivated by the encouraging results of using a tablet surface for a single type of visualization [38], we explore multi-touch affordances for constructing and exploring multiple types of visualizations. We explain the detailed interactions in the Interactions section below. In contrast to showing a predetermined selection of visualizations for a subset of dimension pairs like in [42], we provide explicit dimension selection through drag-and-drop gestures. The motivation for this decision is to support users who have been shown to prefer attribute selection and iterative data querying via simple chart types [16].

Easy to learn set of interactions

The VizInteract interface affords creation of multiple visualizations limited only by the computation power of the device. Unlike multiple coordinated views [37], we designed VizInteract to support independent interaction with each constructed visualizations. This was a design decision motivated by behavior of users to iteratively refine data mappings and ignore finer control [16]. The set of interactions supported by VizInteract are drag-and-drop, pinch to zoom, touch and drag, touch and hold, and two-finger drag and rotate. Drag and drop is used for adding dimensions to the canvas and also adding filters. The 'two finger rotation' gesture is used for modifying the orientation of dimensions. The orientation of the dimension determines the visualization that is generated when user combines these dimensions. Brushing and linking is achieved through one finger 'touch and drag'. One finger 'touch and hold' creates a magnifying lens view. This lens can be hovered over any data point or line to reveal its value. 'Pinch to zoom' gesture is for scaling the canvas and lastly two finger drag is used to pan the canvas. This design decision was motivated by the use of multiple axes to produce visualizations in previous research [8]. However, instead of sketching links or using sophisticated interactions, we utilize simple and easy to learn interactions to produce our higher order views.

Room for advanced operations.

To support workflows that require flexible and advanced data queries, we designed VizInteract to support brushing and linking, numerical and categorical filter operations, and duplication of filters. It also supports multiple copies of the same dimension to be present on the canvas, each of which can be interacted with and combined with other dimensions to generate corresponding visualizations. This together with the pinch-to-zoom gesture overcomes the view limitation of working with only single chart at a time on a tablet surface [36]. Taking inspiration from the benefits of using multiple PCPs [27], we allow linking of multiple dimensions oriented vertically and in close proximity to create multiple PCPs. The pattern of lines formed are useful for advanced visual analysis. There is no need to explicitly duplicate dimensions for constructing multiple PCPs. A single dimension can be paired with a dimension on each side to construct PCPs as shown in Figure 8. [27].

VIZINTERACT INTERACTIONS

After loading any dataset in VizInteract, the typical workflow involves 8 primary interactions.

1) Adding dimensions
2) Changing the orientation of dimensions
3) Combining dimensions to create SCPs
4) Combining dimensions to create PCPs
5) Combing dimensions to form Radar Charts
6) Combining scatter plots to form SPLOM
7) Filtering visualizations
8) Canvas operations.

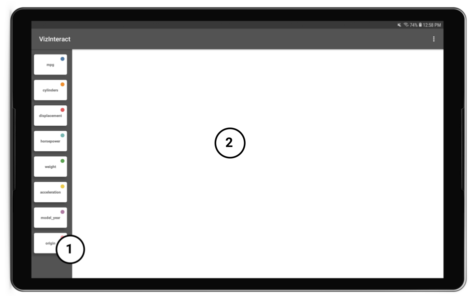

Figure 2: VizInteract Interface 1) Dimension Sidebar 2) Interactive Canvas.

Adding dimensions

The VizInteract interface consists of two main components, the dimension sidebar and the interactive canvas (shown in Figure 2). After loading a dataset using the popup menu on the top right, the sidebar is populated with the dimensions of the data set. The sidebar is a scrolling list showing all dimensions of the data. Each dimension is a draggable card with the name displayed on it. The user can simply touch a dimension card and drag it out on the canvas (See Figure 3). Each dimension also carries a color indicator mapped to it which is used for coloring its axis and the corresponding filter bubble color. At the location where the user drops the card, we construct a frequency histogram of that dimension. Any number of dimensions can be added to the canvas. To remove a dimension, the histogram on canvas needs to be dragged to the "trash" area at the bottom of the screen.

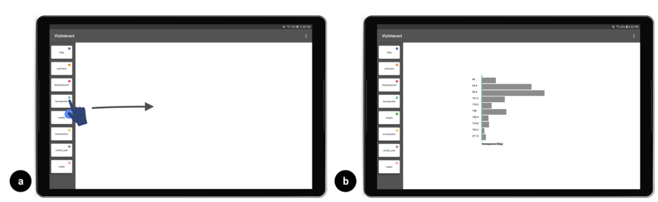

Figure 3: Dimension interaction a) Dragging dimension to canvas b) Default construction of a frequency histogram.

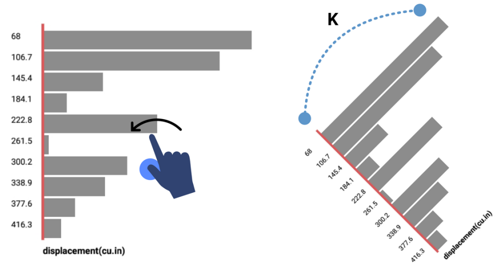

Figure 4: Default orientation is Vertical ($k = 0$). Angle K is a multiple of 45

Changing the orientation of an dimensions

VizInteract supports changing of orientation of primitive visualizations. The default orientation is vertical orientation (See Figure 4). The orientations can be changed using a rotation gesture (See Figure 4). A rotation gesture will smoothly transition the visualization into the nearest K degree orientation, where K is a multiple of 45. For horizontal orientation K is equal to 90.

Combining views to create scatter plots

Each histogram on the canvas can be re-located by simply dragging it on the canvas. The orientation of each histogram view guides the construction of multi-dimensional views when combined. The first compositional interaction is for SCPs. If two unique histograms with orthogonal orientations (one horizontal, one vertical) are overlapped, it creates a single SCP corresponding to the interacting dimensions (See Figure 5a). The histograms need to have an area overlap of 80 percent to trigger the SCP. To decompose the SCP, the user has to drag the SCP with a fast and swift movement (See Figure 5b). This will separate the SCP into its individual dimensions while retaining their origin al orientations

Combining views to create parallel coordinate plots

The second supported multidimensional view is PCPs. If two unique histograms with vertical orientation are brought close, a PCP is constructed between the interacting dimensions (See Figure 6a). The histogram opacity is also

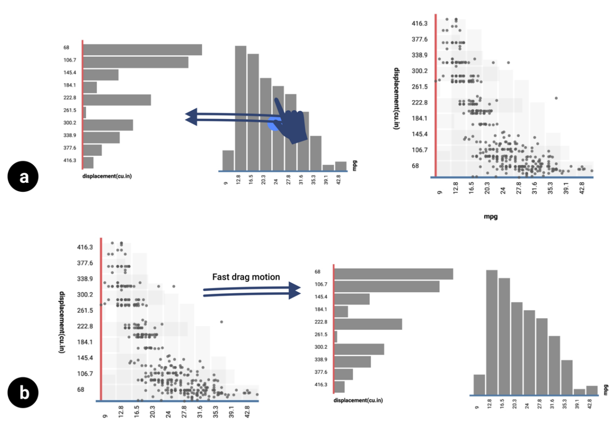

Figure 5: Scatter plot creation a) Combining histograms at orthogonal orientations to create a scatter plot b) Using fast drag to decompose scatter plot into dimensions

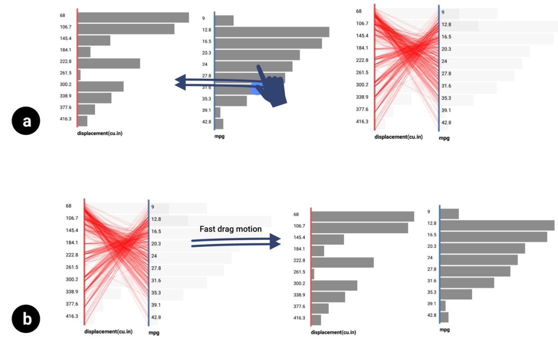

Figure 6: a) Combining views with vertical orientation b) Parallel coordinate created for dimensions.

reduced to 50 percent, to improve the visibility of the lines. All data point labels for the dimension on the right are rendered on the right side. This is to avoid values being hidden behind lines. The dimensions need to be at a minimum distance of $\frac{w}{2}$ to trigger the PCP, where w is width of the dimension. To decompose a PCP, individual histograms can be simply dragged with a fast drag motion (See Figure 6b). This is similar to the interaction used for decomposing SCP and keeps the interaction intention similar across the visualization types. VizInteract also allows chaining of dimension to create multiple PCPs (See Figure 7). The order of the PCP is based on the order of histograms being added. At any point of time, the dimensions can be reordered to dynamically alter the PCP.

Combining views to create radar charts

The third supported multidimensional view is Radar Charts. When two dimensions are in close proximity with one being vertically oriented, the other at any angle k, (where k is a multiple of 45) and a third dimension oriented at angle m (where m is multiple of 45 and $m \neq k$) is brought close to the group, it creates a Radar Chart (See Figure 8).

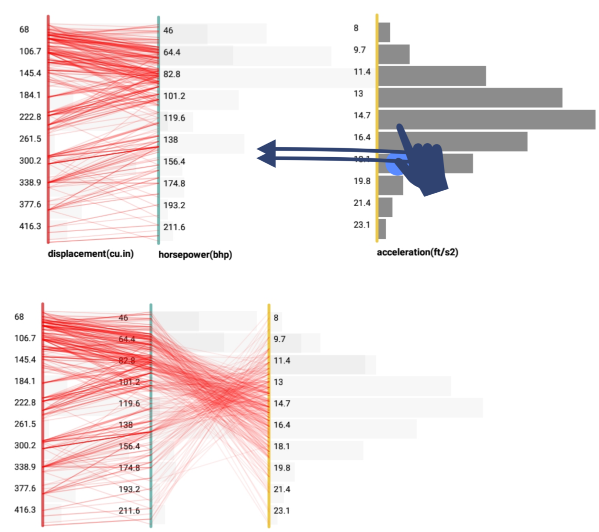

Figure 7: Dragging dimension to existing parallel coordinate plot to create multiple PCPs.

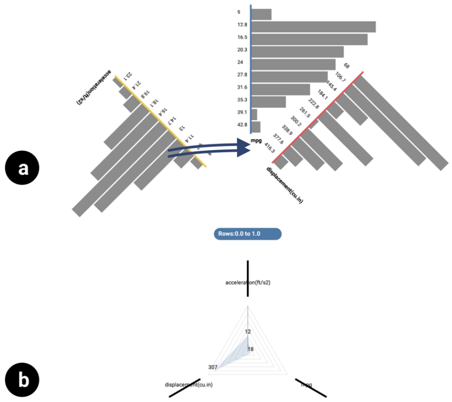

Figure 8: Radar Chart creation a) Adding third dimension to group of dimensions arranged as such b) Radar Chart is formed with axes representing each dimension

Attributes can be removed from the radar chart by dragging the corresponding axis out of the chart and dropped on the canvas. If after removing the attribute, the radar chart has less than 3 attributes remaining, the chart separates into individual histograms (See Figure 9a). For radar charts with more than 3 attributes, removing one renders the chart again with the reduced attribute set. Adding attributes to the radar chart is achieved through dragging additional histograms over the radar chart. (See Figure 9b). The dimension once removed returns to its pre-radar configuration. The radar plot by default shows only 1 data row but that can be changed to a maximum of 3 rows by interacting with the row change bubble displayed above the radar plot. The limit of 3 data rows is to sustain legibility from overlapping radar regions. Tapping on the row bubble shows a popup view with a slider that can be dragged to change the count (See Figure 10). The slider handle has a tap target of 50 pixels for easy detection.

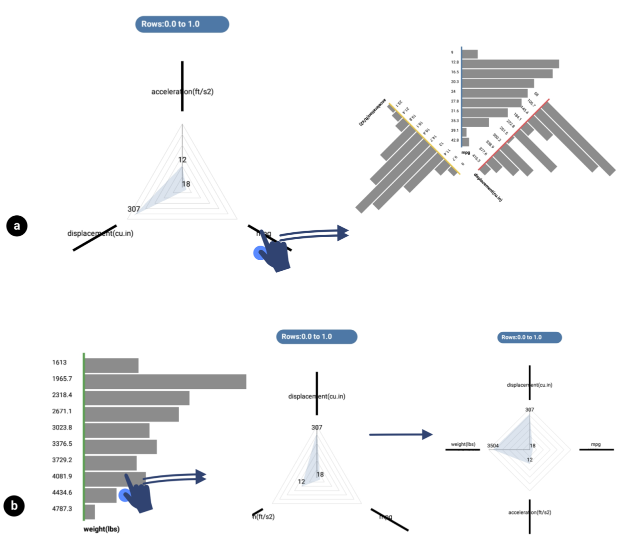

Figure 9: a) Decompose radar charts swiftly dragging axis out b) Adding dimension to radar chart by dragging dimension over it

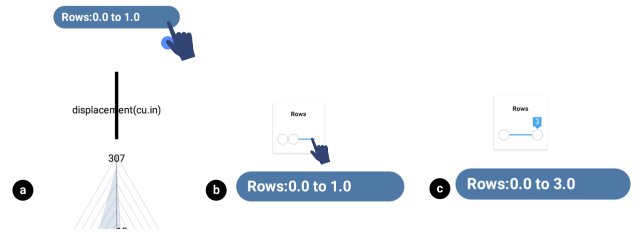

Figure 10: Radar Chart row count a) Tap on row bubble b) Drag the row slider (max =3) c) The chart updates

Combining views to create scatter plot matrices

The fourth supported multidimensional view is Scatter plot matrices. If multiple scatter plots are brought close to each other. It creates a SPLOM corresponding to the combined attributes (See Figure 11). Duplicate dimensions are considered just once, and the canvas scale factor is reduced to half its value to accommodate the whole SPLOM on the screen (if scale factor >1).

Filtering operations

All view types in VizInteract: Histogram, SCP, PCP, Radar chart and SPLOM have filter support. If a dimension is dragged out of the sidebar and dropped on an empty space in the canvas, it creates a histogram but if it is dropped over an existing visualization, it adds a filter on it corresponding to the dragged attribute.

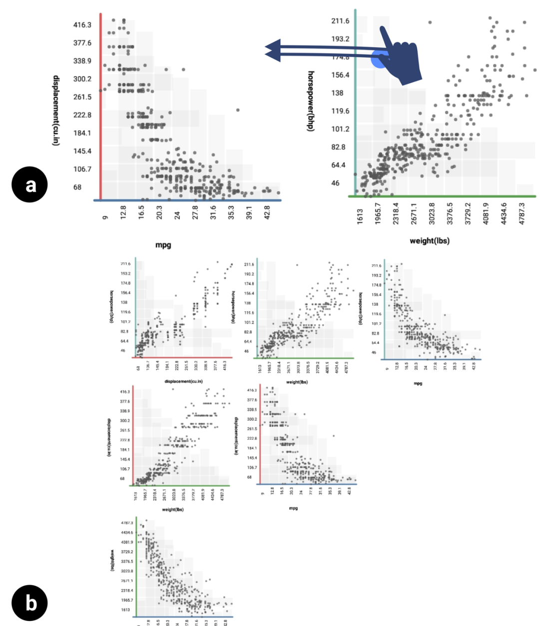

Figure 11: SPLOM creation a) Combine multiple scatter plots by dragging them to an overlap condition b) SPLOM corresponding to interacting attributes is created

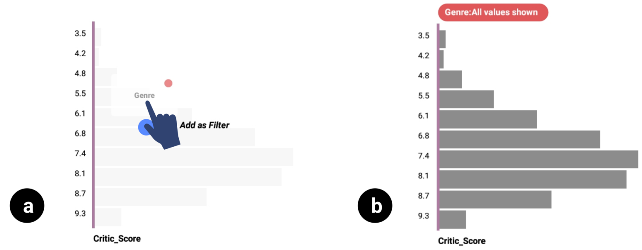

Figure 12: Filter Addition a) Add a filter by dragging a dimension from sidebar and placing over a chart b) The added filters are displayed as bubbles over the charts

While dragging out the dimension, hovering over any chart displays a message saying, “Add as filter” (See Figure 12). VizInteract supports both numerical and categorical attribute filters. Tapping on a numerical filter bubble brings up a range slider for setting the desired values (See Figure 13a).

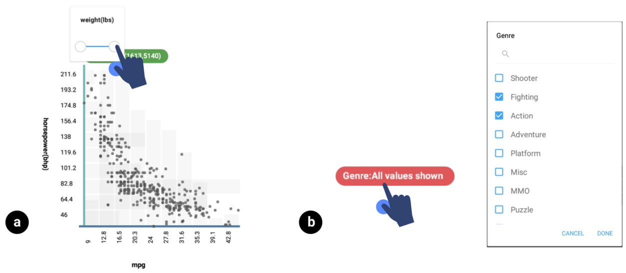

Figure 13: Filter Interaction a) Range Slider for numerical filters b) Searchable multi select list for categorical filters

Tapping on a categorical filter brings up a searchable multi select list where values can be selected to apply the filter (See Figure 13b). Filters can also be removed by dragging out of the charts to any empty space. If the filters are dragged over to any existing chart, it duplicates the filter (See Figure 14b).

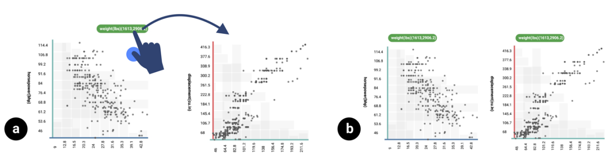

Figure 14: Filter duplication a) Drag out filter bubble to another chart, b) Filter gets duplicated with same values.

Canvas operations

VizInteract canvas supports brushing and linking. One finger drag over the canvas, creates a selection box that highlights the points in yellow to distinctly represent them. The linked values are highlighted in all other visualizations (See Figure 15a). A double tap on the canvas clears the selection. The VizInteract canvas allows any number charts to be constructed on it. To enable isolated analysis while maintaining the freedom to explore multiple views, we added the ability to *scale* the canvas. display size. We also provide a pan operation to move the canvas. The scale operation is afforded by a *pinch-to-zoom* gesture (See Figure 15b). The

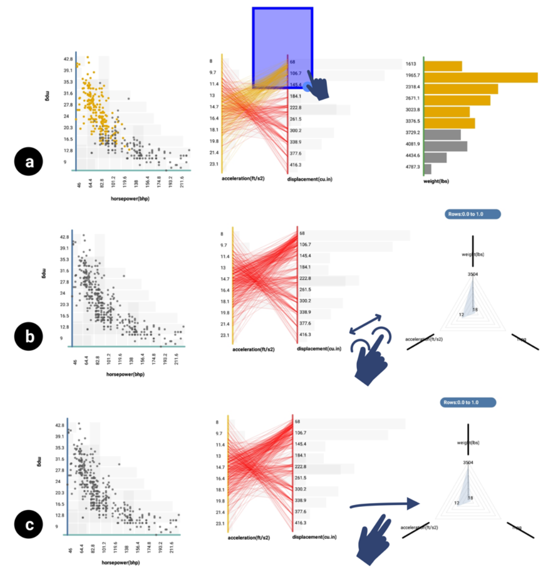

Figure 15: a) Brushing and Linking b) Pinch to zoom to scale canvas c) Pan canvas using ‘Two finger’ drag

pan is performed by dragging with two fingers (See Figure 15c). The final canvas operation supported by VizInteract is to trigger a lens view to read the data point/line values. A one finger ‘touch and hold’ interaction brings up a magnifying lens view that can be dragged around. As the lens hovers over data points, it displays the values above the lens (See Figure 16).

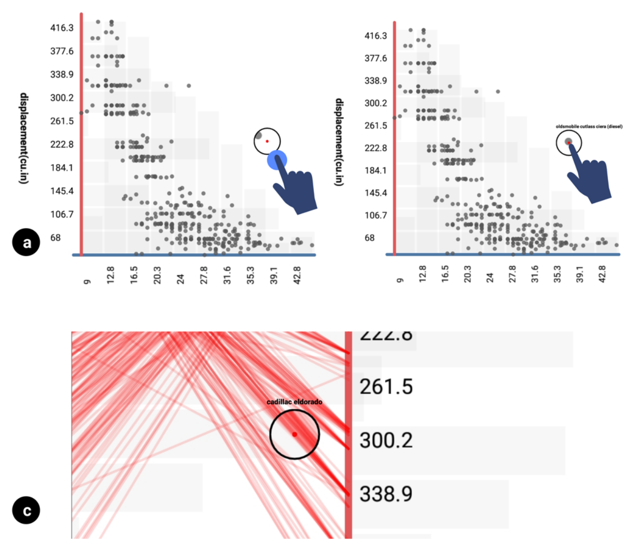

Figure 16: Lens View a) Singer finger touch and hold to bring up the lens b) Drag over data point to read the value c) Dragging over a line to read the value (PCP)

USER STUDY

We conducted an exploratory user study to understand how VizInteract supports data analysis activities. The goal of this study was to explore and understand how users can benefit from rapid interactive construction of multivariate data. We also wanted to evaluate the usability of the tool. The study aimed to answer two big questions.

- Q1: What usage patterns are observable while users complete visual data analysis tasks in VizInteract.
- Q2: Does a user find interacting with VizInteract to be easy and flexible?

A qualitative approach in the form of case study was used to understand the usage patterns emerging from data analysis in VizInteract.

Apparatus

VizInteract was developed as an Android application, running on a Galaxy Tab A 10” tablet. We used the Auto dataset from the ISLR package [48] for the training session, which includes data of 397 cars in 8 dimensions. For the formal analysis session, we used a subset of the Video Game Sales 2019 Dataset [49] that carries records for 600 games with 13 dimensions. The datasets were varied enough to permit nuanced exploration scenarios. The interactions were also video recorded and logged as per participants consent.

Participants

We ran the study with 16 participants, all aged between 22 to 28. All participants had experience with data visualization tools and were familiar with multidimensional data analysis. Participants received course-credit for the study.

Study design

We present the study design in 5 sections – participant preparation, tool demo, guided exploration, visualization tasks, and exploratory qualitative interview.

Participant preparation – 5 minutes

Participants first filled out an informed consent form, as well as a demographic questionnaire. A short freeform interview with each participant was used to assess their familiarity with visualizations, visual analytics and multi-dimensional data.

Tool demo and tutorial – 10 minutes

The experimenter then demonstrated the capabilities of VizInteract to the participant. The core functionality of system and its intended purpose were explained. All the possible interactions of the system were demonstrated step by step. The tutorial was done on the sample Cars Dataset.

Guided Participant exploration – 10 minutes

Subsequently, participants were given the opportunity to freely explore the data for 10 minutes. Here, the participants were given the Cars Dataset and some practice exercises to explore. They were asked to think-aloud while interacting with the tool. Assistance or guidance was provided, if participants got stuck or expressed a need for help with interactions. This time duration was enough for users to get an understanding of interactions afforded by both tools. This initial exploration also helped us in assessing the learnability of the tool.

Visualization tasks – Maximum 30 minutes

After the participant exploration, the main tasks were presented to the participant. A total of 5 visual analysis tasks (See Table 1) were given and the Video Games sales 2019 dataset was used for this session. All interactions were logged by the system and for each task the participant had to construct multi-dimensional charts. They were also asked to write down their insights and verbally explain their procedure of arriving at that insight once they completed the task

Question	Objective
Your colleague wants to add video games to their community pop culture store, but she is not familiar with video games and has asked you for suggestions. Show her some visualizations that can help her understand your choices for each of these below mentioned tasks.	Introducing the scenarios
Q1: Your friend wants suggestions on high selling and highly rated adventure or puzzle games. Create a chart for the same and write names of 3 such games	Explore how users create charts and use filter interactions
Q2: Her community has a lot of European residents. She is curious about impact on region specific sales? Specifically, what impacts the European game market	Explore how users analyze dimensional relationships
Q3: She wants to know how the North American game market compares to the global market, especially for adventure games?	Explore how users analyze dimensional relationships
Q4: She has a lot of vintage item collectors as her customer, so she wants to know if North American market has higher sales for an older platform like PS2 and NES compared to Japan and Europe.	Explore how users utilize views to find high performing variables
Q5: She has a specific requirement from her returning customers about titles published by EA and Nintendo which rank well on the game charts and are available only on PlayStation and Xbox platforms and have high market demand in North America. Does she have any options?	Check how users query for specific details and interact with numerical and categorical filters combined

Table 1: 5 Questions on the Auto dataset

Interview for ease of use – 15 minutes

The study ended with a semi-structured interview with each participant about their experience of using the tool. We focused on the usability of the interactions and the usefulness of the tool. The questions also asked about the usefulness of rapid SCP, PCP Radar Chart and SPLOM creation and the use of interactions for specific analysis. The open-ended part of the interview provided an opportunity for participants to reflect on their experience of using VizInteract and to provide additional feedback. We also captured the usability feedback of the system using a 7-point Likert type [10] questionnaire. Participants were also asked to suggest areas of improvement for VizInteract. The answers were recorded which were later encoded for analysis

Analysis

We took the interaction log from the tool for each participant and analyzed it. We then conducted a thematic analysis on the recordings to identify usage patterns. An open-ended coding style was used to broadly classify the patterns. The objective was to explore how participants were using the interactions to rapidly create multidimensional charts for completing the tasks. Each task was timed, and the correctness of each answer was validated manually. The Likert questionnaire and the interview data were used to analyze the overall usability of the tool.

Results

We narrowed our analysis to only the main interactions related to visualization construction and data querying and filtering. The interactions that were considered for the analysis were – SCP, PCP, Radar Chart and SPLOM creation, adding and manipulation of filters, brushing and linking. We identified and analyzed all such interactions from logs and the video to report a collective list of 3 patterns. We also report the findings on the learnability and usability and qualitative feedback of the tool.

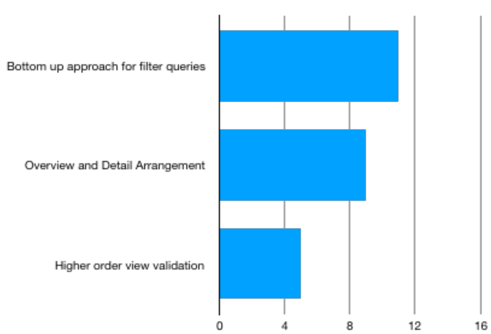

Figure 17: Number of participants that exhibited each usage pattern

Bottom up Approach for constructing filter-based queries

In this usage pattern, the participants construct and edit filters right on the histogram representation and combine the filtered representations to build the combinational views. They bring the dimension in question to the canvas and directly add filters to it rather than adding it on the multidimensional view which also supports filters. For example, for Q4, participant P7 brought in the 'NA_Sales' dimension and directly applied 'Platform' filter on it and then used that filtered dimension to construct a SCP with 'Global_Sales'. When asked for the rationale, the participant said, "*It is easy to construct the parameter at the beginning and then constructing its associations with other attributes*". Participant P3 also exhibited the same pattern for Q3 where they created the histogram, added the 'Genre' filter and then constructed a PCP. P11 mentioned that '*Focusing on the primary attribute and selecting values for the filters makes it easy for building up the query. This matches their thinking'*. This pattern was the most repeating pattern observed in 72% of the participants.

Overview and Detail Arrangement

Participants were observed to specifically arrange their constructed views in a repeating manner for many analytical tasks. While some participants isolated and analyzed singular charts on the canvas, many participants created a side by side arrangement of multidimensional views and singular representations. Participant P2 used such a setup for Q3 where on one side they placed 'Genre' frequency histogram and on the other side constructed a SCP for 'NA_Sales vs Global_Sales'. When asked for their motivation they said, '*it was easier to analyze in this way'*. P5 showcased the same pattern for answering Q1, where they kept 'Critic_Score' on one side and PCP of 'NA_Sales' and 'Global_Sales' on the other. They later added 'Genre' filter on the PCP and brushed the 2 highest intervals on 'Critic_Score'. This highlighted the corresponding values on the SCP and allowed P5 to complete the task. In the interview, P5 indicated that '*I wanted to see the distribution for the critic ratings before I made my selection*'. This was the second most repeating usage pattern with 56% of participants creating some kind of overview and detail arrangement.

Validating higher order views

Some participants were observed to construct a radar chart and then immediately couple it with multiple scatter plots. P6, P11 and P13 used a radar chart for Q4 where they each constructed a radar chart comprising of attributes 'NA_Sales', 'PAL_Sales' and 'Global_Sales'. P6 immediately followed it up with 3 scatter plots each representing a pairwise combination from the above-mentioned attributes. P11 and P13 interacted with the radar row sliders and then rearranged the dimensions to form individual SCPs. P13 mentioned in their interview that '*I didn't know if the radar web represented the properties of the whole table, I wanted to be sure before I answered*'. Similarly, for Q2, participant P4 constructed two SCPs 'PAL_Sales vs Critic Score' and 'Global_Sales vs Critic Score' and combined them to form a SPLOM. After adding a filter to see the impact of 'Genre' in the SPLOM, they immediately reset the canvas, constructed the two SCPs again and added the filter back to each SCP. P4 reported in the post task interview that '*I wanted to check if the filters were correctly applied to individual plots or not*'. This usage pattern shows that participants were somehow trying to validate the correlations visible in the higher order multivariate views. This pattern was observed in 31 percent of the participants.

Learnability & Usability

For VizInteract, the participants found that overall, the interactions were easy to learn. P8 mentioned that "*Not much* *explanation was needed for understanding the interactions*", P4 commented that only a single explanation was enough to understand the interactions, and P1 noted that "*only 5 minutes [were] needed to learn the interface and its capabilities*". Participants agreed in general with ease of interactions in constructing the multidimensional views. Participant P4 even commented that the Radar Chart and PCP interactions felt '*magical*'. On the 7-point Likert results, SCP (14 *strongly agreed* and *2 agreed*) and PCP (11 *strongly agreed* and 5 *agreed)* had the highest ratings for ease of use and learnability. Radar charts interactions were also comparatively easy to learn (μ=5.1, sd=0.83) and use (μ=5.31, sd=1.11). SPLOM had good ratings for learnability (μ=5.24, sd=0.74) but it suffered with the ease of use (μ=3.17, sd=1.04). We attributed this to the computational delay associated with loading all pairwise combinations on device memory and then rescaling the canvas. This feedback will be incorporated in our future iterations. Participants also liked the filter interactions. The filter interactions had a very high ease of use (μ=6.1, sd=1.21) and learnability rating (μ=5.9, sd=0.63). P8 remarked that "*I found the multiple option popup for selecting game genre really useful*". This shows that the interaction set for VizInteract were easy to use and learn.

Dimensional Awareness and Data Comprehension

As a response to the post task interview, many participants mentioned that the ability to easily create multidimensional views made them aware about the dimensional relationships. 10 out of the 16 participants commented with a feedback that resonated the same sentiment. Participant P7 said that "*Inter dependence of Video game sales in different regions and Genre makes sense now*". Participant P15 noted that "*it's visually very easy to see the relationships between the different attributes*". Another noteworthy observation was that users appreciated the comprehensiveness of supported views as it was helpful in catering to specific analysis tasks. P6 remarked that "*the different types of views are helpful, findings from a radar chart can be coupled with other view types to support your hunch*".

DISCUSSION AND FUTURE WORK

Our initial findings largely support our design goals, which is to provide easy to use and learn touch-based interactions for rapid multidimensional data exploration and identify how users interact with VizInteract while analyzing multivariate data. Participants successfully created multiple multidimensional views and were able to easily drill down for specific data queries. Our initial finding about using filters as a bottom up approach for constructing queries can be attributed to the fact that it matches the mental model of most users who follow an atomic VA workflow where view composition is delegated to be a second order step. Our findings on the 'overview and detail' style arrangement of visualizations also support our main hypothesis of allowing users to rapidly and interactively construct complex idioms. Users were able to correctly construct task specific visualization and also coordinate relationships between the attributes. The interaction set used in VizInteract did not come in the user's way of representing dimensional relationships and comprehending data.

Challenges

As noted in the usability study. There is scope for better motivation for users to construct filter queries on compositional views rather than singular representation. Further investigation on improving indication of filter support can be warranted here. Things like visual markers on multidimensional views can be explored. Our results also showed that many users compared two different representations at the same time. One view to do detailed analysis and another for an overview of correlations. This indicates that users might want to come back to certain visualizations in potentially intricate VA tasks. Therefore, a mechanism for saving and referencing saved representations can be coupled with these multi touch interactions to study how the usability changes. Based on our final usage pattern, users were found augmenting their findings from higher order multidimensional views like Radar Charts and SPLOMS with isolated primitive plots. A VA tool could enable quickly peaking at simpler representations of the contributing dimensions while users are exploring complex plots like Radar Charts and SPLOM. Finally, the bivariate visualizations in VizInteract have some missing auxiliary information like trend lines and sorting of dimensional axis and. This is something that we plan to implement in our subsequent versions.

Future work

As per the feedback from the initial study, we found that there is a potential to support additional multidimensional visualization idioms. The interaction set can be extended to support charts like Stacked bar charts, Streamgraphs, Node-Link Trees, Parallel Sets and etc. The scatter plots could also add color and glyphs size for representing higher dimensionality. Finally, because this tool is currently focusing on a single user, the aspect of collaborative VA tasks can be explored in the future, especially on a larger display setup.

CONCLUSION

In this paper, we introduced VizInteract, a visualization tool for tablets that uses multi touch interactions for rapid multidimensional data exploration. The system allows interactive construction of SCP, PCP, Radar Chart and SPLOM. We also implemented touch-based interactions for filtering, brushing and linking. We evaluated the usability through an exploratory user study with 16 participants. The findings from the study support our design goals of creating easy-to-learn interactions, which allow users to effortlessly explore multidimensional data.

ACKNOWLEDGMENTS

We thank all colleagues who provided helpful comments on early versions of this document.

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