VizInteract: Rapid Data Exploration through Multi-Touch Interaction with Multi-Dimensional Visualizations

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Abstract. Creating and editing multi-dimensional data visualizations with current tools typically involves complex interactions. We present VizInteract, an interactive data visualization tool for touch-enabled displays. VizInteract supports efficient multi-touch data exploration through rapid construction of and interaction with multi-dimensional data visualizations. Building on primitive visualization idioms like histograms, VizInteract addresses the need for easy data exploration by facilitating the construction of multi-dimensional visualizations, such as scatter plots, parallel coordinate plots, radar charts, and scatter plot matrices, through simple multi-touch actions. Touch-based brushing-and-linking as well as attribute-based filter bubbles support "diving into the data" during analysis. We present the results of two explorative studies, one on a tablet and another on a large touchscreen and analyze the usage patterns that emerge while participants conducted visual analytics data exploration tasks in both conditions.

Keywords: Visualization; Visual Analytics; Multi-touch; Large Touchscreen.

1 Introduction

With the increasing availability of data and need for analysis, data visualization is becoming ubiquitous [8]. Thus, sensemaking, as a skill, is becoming essential to address complex data-related questions across all domains. From novice to expert users, there is a need for tools that facilitate easy data exploration, a critical component of sensemaking [28]. Visual Analytics (VA) focuses on analytical reasoning facilitated by interactive visual interfaces [13]. Desktop VA tools like Tableau or Cognos offer powerful user interfaces for data exploration and analysis, but have a steep learning curve [24]. Most current VA tools are based on traditional WIMP metaphors. Although the operations that users can perform on such tools are overall standardized [3], post-WIMP [34] implementations of data exploration tools have demonstrated significant improvements in maintaining a user's understanding of data [31, 45]. To facilitate data exploration on the growing set of touch-enabled devices, we use multi-touch interaction to enable easier and faster construction of and interaction with multi-dimensional data visualizations. To cater to both novices and experts, we leverage the power of commonly used and easy-to-learn multi-touch interaction techniques in VizInteract to allow users to quickly compose primitive visualizations into multivariate data visualizations (Fig.1).

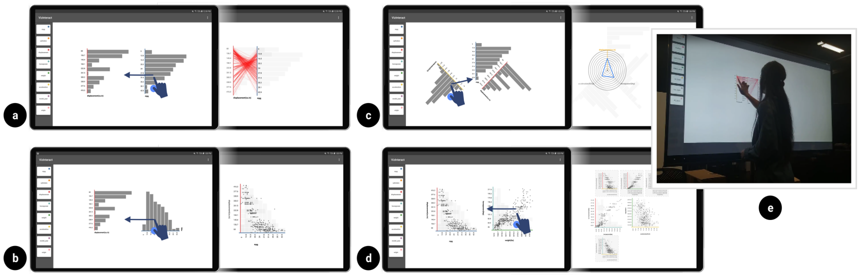

Fig. 1. VizInteract affords rapid and easy creation of multi-dimensional visualizations through a multi-touch interface on a tablet. a) Dragging two vertically oriented data dimensions into proximity creates a parallel coordinate plot, b) two orthogonally oriented dimensions combine into a scatter plot, c) multiple dimensions at other angles form a radar chart, and d) multiple scatter plots combine to a scatter plot matrix. e) Participant using VizInteract on a large touchscreen.

The interface leverages the proximity of individual dimensions and their orientation to produce new visualizations. For an example, two orthogonal histograms brought close together generate a scatter plot. VizInteract currently supports five types of visualizations: histograms (corresponding to a single data dimension), scatter plots (SCPs), parallel coordinate plots (PCPs), radar charts, and scatter plot matrices (SPLOMs). As such, visualizations can be easily and rapidly created and modified in VizInteract, and the system thus facilitates analytical reasoning on the underlying data.

We conducted two exploratory user studies to investigate how users interact with our tool. Our goals were to: a) observe user strategies and their progress with simple touch-based interaction on a tablet during VA tasks and b) investigate data exploration behaviors while users interact with VizInteract on a large touch display.

2 Related Work

2.1 Ad-hoc Visualization Construction

Even though Excel [60] offers quick ways to create charts with its PivotChart feature and Tableau [61] supports quick chart creation through query operations, none of these tools support multi-touch for rapid chart construction. In contrast, tools like Voyager [54], reduce the manual interaction required to create visualizations. Such systems instead recommend visualizations to display significant relationships. APT [38] ranked visualizations with an effectiveness criterion. VizDeck [43] showed a gallery of recommendations based on the statistical effectiveness of chart types.

Faceted metadata [56] dynamically reduced the data dynamically through filters and then identified relationships between attributes. OnSet [46] explored set relationships for elements through logical operations on grid cells, where each cell represents the same item in two different sets. GraphTrail [20] enabled exploration through nodes and edge-based aggregation of data. The idea of filters can also be extended to multiple views. Snap-Together [42] introduced coordinate selection and filters across multiple views and DynDash presented filter bubbles [41]. For more complex data processing and visualization workflows, toolkits, such as d3.js [58] or VTK [63], provide application programming interfaces that programmers can use to connect to data sources and generate custom visualizations. The limitation of these toolkits is that they require programming skills and that the authoring of visualizations requires detailed specifications.

2.2 Touch-based Interaction for Visualizations

Interacting with visualizations using gesture or touch-based interfaces has been widely explored. Isenberg et al. identified interactive tabletops and touch surfaces as a medium for effective data visualization [30]. Lee et al. recognized the importance of using post-WIMP metaphors and using naturalistic interactions for sensemaking in VA [34]. The combination of pen and touch for object selection [25] has also been used in data visualization [10, 16, 35, 52]. Further, interactive whiteboards and/or pens can facilitate fluid and easy data exploration. SketchVis [10] used sketching to transform data and perform filter operations. VizDom [17] also used pen and touch to support conducting interactive visual data analysis on a whiteboard. SketchInsight [35] proposed drawing simple charts on a whiteboard to explore data. VisWall [1] explored construction of multivariate visualizations using attributes of previously created visualizations on a large display. It combined collaborative touch-based interactions and visualization recommendations. TouchViz [19] compared traditional WIMP-based interface with their gesture-based interface for VA on a tablet. It focused on gesture-based data querying operations. VizInteract builds on these ideas by supporting touch-based visualization construction without the need for auxiliary input devices and providing data filtering and querying operations. Kinetica [45] used physics-based affordances for multivariate data exploration and filtering. Each query required the user to trace a significant portion of the canvas. VizInteract uses simpler drag-and-drop interactions to manipulate filters. Multi-touch interaction have also been used for dynamic scatter plots [48]. TouchWave [6] offered multi-touch gestures for interacting with stacked graphs. All these tools offer only touch-based interactive data exploration with a *single* type of chart. In contrast, VizInteract's canvas allows the user to construct and interact with multiple types of multi-dimensional charts.

2.3 Interaction with Multi-dimensional Data Visualizations

Tukey et al. [51] introduced scatter plot matrices (SPLOMs) for exploring multivariate data, which display scatter plots for each pair-wise combination of dimensions. Another popular visualization for multivariate data is parallel coordinate plots, PCPs. Inselberg et al. [29] introduced PCPs for effective data exploration in a 2D space, and found PCPs to have low representational complexity. Wong et al. surveyed much multivariate data visualization research [53]. They identified visualizations that explore interactivity in multi-dimensional data visualization, including Starfields [2] and parallel sets [32]. Common data analysis operations like brushing-and-linking in multivariate visualizations have also been explored in the past [39]. DataMeadow [21] used a canvas of starplots, each with an interactive filter slider to adjust the distribution of a selected dimension in a query. All these interactive multi-dimensional visualizations were designed primarily for desktop-based user interfaces and have minimal multi-touch affordances. VizInteract expands on these works by introducing multi-touch interactions to explore multivariate data. In VizInteract, any number of dimensions can be selectively dragged and placed on the canvas and combined to produce new visualizations.

With Flexible Linked Axes [11] users can draw lines between axes on the canvas to explore multi-dimensional data. Depending on the lines drawn and their configuration, the system generated either a SCP or PCP. ImAxes [14] relied on virtual axes that could be manipulated in 3D space and combined to produce 2D and 3D visualizations. One limitation of ImAxes was the need for the user to move their body to interact with the plots in the 3D space. This led to lot of walking, crouching, and general movement to perform even simple analysis. The authors suggested that a zoom operation might permit the user to isolate axes, which would overcome the abovementioned limitation. VisTiles [33] also used orientation and arrangement to produce different visualizations but was designed for a collaborative VA workflow where multiple devices are spatially oriented and arranged to compose higher order views. The additional step of introducing multiple devices increases the friction between creating visualizations and generating insights. For ease of access, our workflow focuses on a single display.

3 Design Goals

Informed by our main research goals for VizInteract, which are to observe (a) users' VA behaviors with simple touch-based interactions on a tablet and (b) data exploration behaviors on a large touch display, we developed VizInteract with three main design goals in mind: (1) allow rapid multi-touch composition and editing of visualizations, (2) leverage easy-to-use and -learn interactions, and (3) provide a flexible yet powerful interface. In the following, we discuss these design goals in detail.

3.1 Rapid multi-touch composition and editing of visualizations

Studies have shown that touch interaction is beneficial for a diverse range of plots, such as bar charts and stacked graphs [6, 19]. However, all presented methods work only well for single data attribute visualization and do not allow for rapid switching between primitive and higher-order visualization idioms. Touch interaction has also been used for data transformation and filtering operations, e.g., in TouchPivot [31] and PanoramicData [57]. However, these tools do not support rapid visualization composition for easy multi-dimensional analysis workflows. Some tools like iVoLVER [40], Data Illustrator [37], and Charticulator [44] facilitate both visualization creation and editing. Instead of transforming data from multiple sources or providing a new visual language, VizInteract focuses on rapid data exploration via existing visualization paradigms. Also, many desktop VA tools do not generalize well to touchscreens, e.g., Data Illustrator and Charticulator. VizInteract's interface leverages the benefits of direct manipulation [18], which suggests avoiding menus, forms, and toolbars, whose profusion can increase the complexity of any application. VizInteract affords multi-touch interaction as a first-class construct to enable rapid and easy exploration of high-dimensional data. Motivated by the encouraging results of using a tablet for interacting with a single type of visualization [48], we explore multi-touch affordances for constructing and editing multiple types of visualizations on touch-enabled displays. Examples include interactions like adding filters or altering the configuration of individual dimensions.

VizInteract currently supports SCPs, PCPs, Radar charts, and SPLOMs. SCPs offer a simple visual representation of two-dimensional data as they show every data point individually. As a result, they easily highlight groupings, outliers, and trends [12]. PCPs have relatively low representational complexity [29] and are effective for multi-dimensional data visualization. Radar charts support many variables next to each other, with each variable having the same resolution [23]. SPLOMs are simple to evaluate perceptually, as they show scatter plots for all combinations of dimensions. Thus, analyzing bivariate correlations, classifications, clusters, or trends is relatively easy with SPLOMs and they are appropriate for both novice and expert user [36].

3.2 Easy-to-learn set of interactions

Unlike many VA tools that use complex gestures for interacting with multiple visualizations (such as Tangere [47] and its touch-based hold-and-swipe gesture), VizInteract relies on the same simple interaction vocabulary that most touch-based systems support, which most users are intricately familiar with. We rely on the Direct Combination interaction paradigm [26], which focuses on pairs of interaction objects, in our case (initially simple) visualizations that are then combined to form more advanced ones. VizInteract also affords the frequently used brushing-and-linking method of multi-dimensional visualization systems [7] through a simple single-finger touch-and-drag operation. As the barrier to construct, edit, or remove visualizations is thus very low, users can quickly correct any mistakes in their choices. VizInteract also supports rapid modification of the visual mappings, which encourages users to explore different data configurations. This design decision was motivated by documented user behaviors, which show that they iteratively refine data mappings and tend to ignore finer control [24]. Novice users have also shown a tendency to think about data attributes and visual structures separately [24]. A blank canvas where data attributes can be independently placed and visualized thus enables the users to compose the elements as visual structures. As identified by Grammel et al. [24], participants want to link the data space with the visual space, as they are generally aware about the need to create links between the two. VizInteract builds on the metaphor of providing independent attributes which can be ‘linked’ easily, through simple composition with multi-touch interaction.

3.3 Flexible yet powerful interface

Our last design goal was to build an interface for a range of expertise levels, from novice users to experts with advanced VA requirements. To support workflows that require advanced data queries, we added brushing-and-linking, numerical and categorical filters, and functionality for the duplication of filters in VizInteract. Our design builds on previous work on filter bubbles [41] that are linked to visualizations, which can be easily constructed, manipulated, and duplicated to other charts through drag-and-drop. Multiple copies of the same dimension can be present on the canvas, each of which can be manipulated and combined with others. Together with the pinch-to-zoom interaction this design overcomes the limitations of working with only single chart at a time [49] and thus provides a simple canvas that still supports advanced workflows. VizInteract also supports visualizations like radar charts and SPLOMs for advanced VA queries. Unlike the axis representations for immersive analytics proposed by Fonnet et al. [22], which cater to advanced data querying use cases but require a 3D grid-based representations of coordinate systems, VizInteract uses a simple, infinite 2D canvas, where the orientation of each dimension can be chosen freely. This design affords more freedom while at the same time providing flexibility for detailed VA tasks. Our work is also inspired by interactive systems to generate visualizations [11, 14]. However, instead of mechanically drawing links or in 3D space [14], we manipulate the axes through touch on a 2D canvas. We also support a touch-based zoom operation to facilitate isolated analysis of single plots. As the 3D grid of Fonnet et al. [22] had a negative impact on speed for retrieving coordinate information, we believe that in contrast a 2D interactive canvas reduces the barriers for data exploration, by reducing friction between ideation and constructing visualizations for advanced queries.

4 VizInteract Interactions

A typical workflow for data analysis in VizInteract involves eight primary interactions: A user loads a .csv file and *adds dimensions from the sidebar* onto the canvas which show up as frequency histograms.

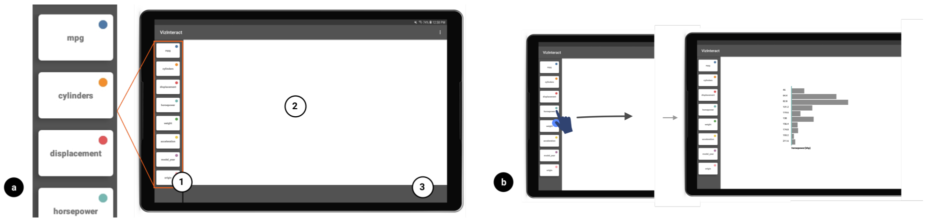

Fig. 2. a) VizInteract Interface: 1) dimension Sidebar, 2) interactive Canvas, and 3) trash area at bottom b) dragging a dimension onto the canvas constructs a frequency histogram.

Each histogram can be *rotated to change its orientation*. To visualize correlations between two dimensions, a user *combines two orthogonal histograms to create a scatter plot*. For visualizing data relationships as *parallel coordinate plots, they combine multiple parallel attributes*. Another option is to *combine multiple dimensions at varying orientations to form a radar plot*. To get an overview of the correlations of four or more attributes, they can form two scatter plots and bring them in proximity to *form a scatter plot matrix*. During their analysis, *they add numerical or categorical filters* by dropping dimensions as filter attributes onto a chart. Throughout, they *can freely zoom and pan the canvas* to fluidly explore the data.

4.1 Adding Dimensions

The two main components of the VizInteract interface are the dimension sidebar and the interactive canvas (See Fig 2). After loading a dataset through the top-right popup menu, the (scrolling) sidebar is populated with the dimensions of the data set. Each dimension also has an associated color, used for axes or filter bubbles. Both categorical and numerical attributes are listed in the sidebar. Dragging a dimension's name onto the canvas creates the corresponding frequency histogram (See Fig 2). Histograms can be dropped into a "trash" area at the bottom of the screen to remove them (See Fig 2).

4.2 Changing the orientation of a histogram

The default orientation for a histogram is vertical, but its orientation can be changed through a two-finger touch rotation gesture to any multiple of 45° (See Fig 3a).

4.3 Combining views to create scatter plots

Combining histograms creates multi-dimensional views, depending on the orientation of each histogram. If two different histograms with orthogonal orientations are overlapped (by more than 80%), VizInteract creates a single SCP with the interacting dimensions (see Fig 3b). To decompose a SCP, the user swiftly drags across the SCP. That separates the SCP into the individual dimensions, which revert to histograms (and similarly for other plots below). This retains the fluid nature of composition and decomposition of visualizations in VizInteract.

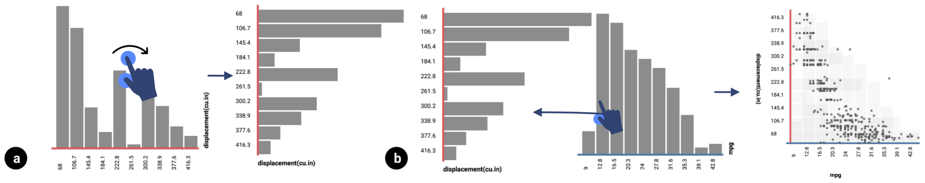

Fig. 3. a) Rotate dimension to change orientation, b) create scatter plot by combining histograms at orthogonal orientations.

4.4 Combining views to create parallel coordinate plots

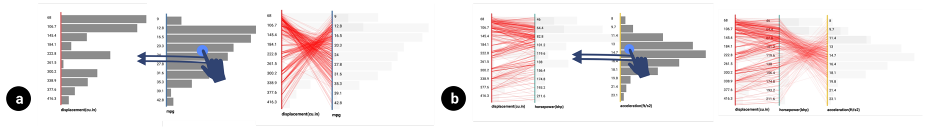

Fig. 4. a) Combining vertically oriented dimensions results in a PCP, b) adding a 3rd dimension.

If the user brings two unique histograms with vertical orientation into proximity, a PCP is constructed between the interacting dimensions (see Fig 4a). To improve the visibility of the PCP lines, each histogram is shown at 50% transparency. When creating larger

PCPs, users can chain dimensions in the desired order (see Fig 4b). A swift drag across a PCP dimension affords not only removal of that dimension, but also reordering.

4.5 Combining dimensions to create radar charts

If two dimensions are brought into proximity without being orthogonal or parallel, VizInteract creates a radar chart (See Fig 5a). Dimensions can be added by dropping them onto the chart or removed by dragging them away (See Fig 5b). Radar charts also support a filter to specify how many data points are shown.

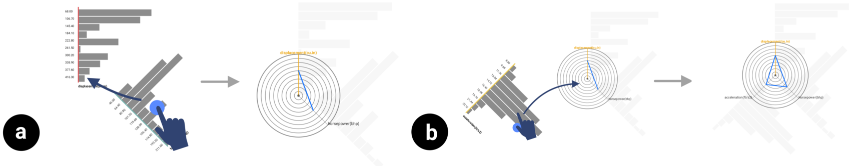

Fig. 5 a) Creating a radar chart, b) Adding attributes to a radar chart.

4.6 Filtering operations

All charts in VizInteract support filters. If a dimension is dragged directly onto an existing visualization, VizInteract adds a filter corresponding to the dragged attribute to the visualization.

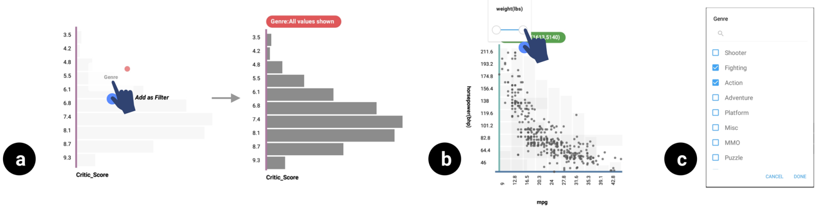

Fig. 6. a) Filter addition – drag dimension to visualization to add filter bubble, b) filter interaction through range slider for numerical, and c) searchable multi-select list for categorical dimensions.

As a visual aid, hovering over any chart displays a temporary popup “Add as filter” while dragging a dimension (see Fig 6a). VizInteract supports both numerical (with a range slider, see Fig 6b) and categorical filters (with a searchable multi-select list, see Fig 6c). If an existing filter is dropped over a chart, VizInteract duplicates the filter. Filters can be removed by dragging them onto empty canvas space.

4.7 Combining views to create scatter plot matrices

VizInteract also supports SPLOMs. If two SCPs are brought close to each other, the system generates a SPLOM corresponding to the combined attributes (See Fig 7). Removing any participating SCP destroys the SPLOM.

4.8 Canvas Operations

VizInteract allows the user to use a one-finger drag on the canvas for brushing-and-linking, which creates a rectangular selection box that highlights all selected points in yellow that are then also highlighted in all other visualizations (See Fig 8a). To clear the selection, the user can double-tap on the canvas.

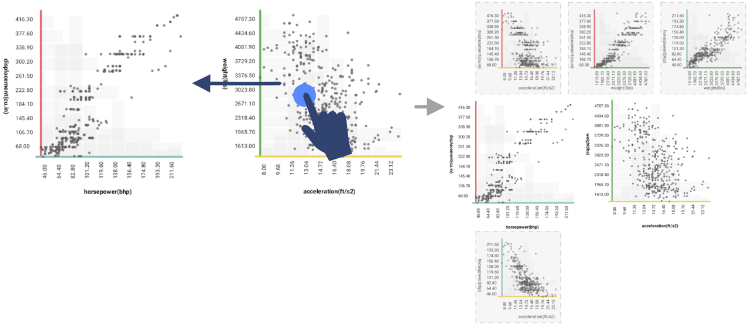

Fig. 7. Combining multiple SCPs by dragging them to overlap creates a SPLOM.

A pinch-to-zoom gesture on the canvas scales or a two-finger drag pans it. A 'touch-and-hold' on the canvas triggers a lens view to make it easier to read individual data point/line values, which brings up a magnifying lens view that can be dragged around. Values contained in it are displayed above the lens (See Fig 8b).

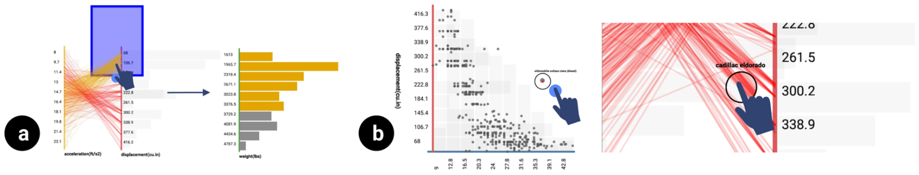

Fig. 8. a) Brushing-and-linking with rectangle selection, and b) single finger touch-and-hold to bring up a lens view to read values.

5 User Study I

We conducted an exploratory study to investigate how and how well VizInteract supports data analysis activities. The goal was to understand how users benefit from rapid interactive construction of multivariate data visualizations and how they use touch-based interaction to solve VA tasks. We also wanted to evaluate the usability of VizInteract. The study aimed to answer the following two main questions. **RQ1.1**: What usage patterns are observable while users complete visual data analysis tasks via VizInteract's interactions to construct charts and add or edit filters on the visualizations? **RQ1.2**: Do users find interacting with VizInteract to be easy and learnable?

5.1 Participants

We recruited 16 participants for the study, seven females, aged between 22 and 28. Ten were undergraduate students who participated for course credit, others were graduate students. We pre-screened participants to ensure familiarity with interpreting data from visualizations. All participants had some experience with basic multi-dimensional data analysis and multi-touch interactions. To minimize potential biases, we made sure that participants had not participated in any VA studies using touch-based visualization systems before. On average participants were familiar with at least one and at most two desktop visualization systems, e.g., Tableau, Microsoft Excel, or Power BI.

5.2 Apparatus and Datasets

All studies were performed before the COVID-19 pandemic. VizInteract ran on a 10”, 1920x1200 pixel Galaxy Tab A tablet running Android O. We used the Auto dataset from the ISLR package [59] for the training session (397 cars with 8 dimensions) and a subset of the Video Game Sales 2019 dataset [62] (600 games with 13 dimensions) for the main session. With user consent, we recorded user interactions using a camera. The software also logged all user interaction, but we used an auxiliary computer to record survey answers and a digital audio device to record the post-task interviews.

5.3 Study design

First, participants filled out an informed consent form and a demographic questionnaire. A short freeform interview with each participant was used to assess their familiarity with visualizations, VA, and multi-dimensional data. The experimenter then demonstrated the capabilities of VizInteract. The tutorial used the Cars dataset. Subsequently, participants were given the opportunity to freely explore this dataset for 10 minutes, guided by practice exploration tasks. Then, the main tasks were presented. For this part of the session, we used the Video Games sales 2019 dataset, with a total of five tasks.

- Q1: Your colleague wants to add video games to their community pop culture store. She wants suggestions for high-selling and highly rated adventure or puzzle games. Create a chart for this and record the names of 3 such games. *(Scenario Introduction)*
- Q2: Her community has a lot of European (EU) residents. She is curious about factors that impact EU game sales *(Explore how users create charts and use filters)*
- Q3: She wants to know how the North American (NA) game market compares to the global market for adventure games. *(Explore how users analyze relationships)*
- Q4: She has a lot of vintage game collectors as customers. Thus, she wants to know if the NA market has higher sales for an older platform like PS2 and NES, compared to Japan and EU. *(Explore how users analyze relationships)*
- Q5: Some customers requested top-ranking titles published by EA and Nintendo for PlayStation and Xbox platforms with high sales in NA. Does she have any options? *(Explore how users utilize views to find high performing variables)*

We chose these tasks to explore a range of multi-dimensional data queries. The questions also probe the usefulness of rapid SCP, PCP, radar chart, and SPLOM creation and the use of interactions for specific analysis. We asked participants to write down each insight they gathered and, once a task was completed, also to verbally explain their approach for arriving at that insight. The study ended with a semi-structured interview with each participant about their experience when using VizInteract. We focused on the usability of the interactions and the usefulness of the tool. The open-ended part of the interview encouraged participants to reflect on their experience with VizInteract and to provide additional feedback. We also captured usability feedback using a 7-point Likert type [15] questionnaire. Participants were also free to suggest areas of improvement for VizInteract. Answers were recorded and later encoded for analysis. As several studies had already established the benefits of touch-based visualization tools over desktop tools [39, 43, 55], we chose not compare VizInteract with a desktop-based system.

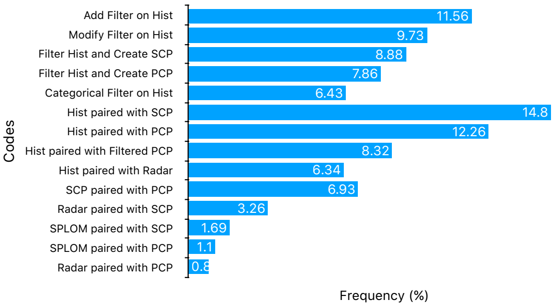

Fig. 9. Low Level Interaction codes and their frequency for Study 1.

Table 1. Coded Findings for Study 1.

Initial Codes	Focused Theme	# Particpants
Add or modify Filter on Hist, Filter Hist and Compose SCP or PCP, Categorical Filter on Hist	Bottom-up approach for filter-based queries	12
Hist paired with SCP, PCP, Filtered PCP, or with Radar	Overview-and-detail arrangement	9
SPLOM with SCP or PCP, Radar with SCP, SCP with PCP	Validating higher-order visualizations	5

5.4 Results

To answer our research questions, we narrowed our analysis to focus only on the main interactions related to visualization construction, data querying, and filtering. We considered for this analysis: creation of charts, adding and manipulation of filters, and brushing-and-linking. We identified and analyzed all such interactions (See Fig 9). The group of filter-based interactions represented the most frequently used actions, followed by the creations of different types of plots. Histogram and SCP/PCP arrangements were also frequent. Individual Histograms were also paired frequently with PCPs, and the histograms often had filters on them. Further analysis led us to the identification of a set of three over-arching patterns (see Table 1).

Bottom-up approach for constructing filter-based queries. In this usage pattern and rather than adding filters on multi-dimensional visualizations, the participants first constructed and edited filters right on a *histogram* and then combined filtered representations to build combined views. For example, for Q4, participant P7 brought in the 'NA_Sales' dimension and directly applied the '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 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 my thinking.*' This pattern was the most frequent pattern, observed in 12 of the participants.

Overview-and-detail arrangement. We observed that for many analytical tasks participants arranged their charts in a repetitive manner. While some participants analyzed individual, isolated visualizations on the canvas, many created a side-by-side arrangement of histograms and multi-dimensional charts. Participant P2 used such an arrangement for Q3, where they placed the 'Genre' frequency histogram on one side of the display 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 [the data] in this way*". P5 showcased the same pattern for answering Q1, where they kept 'Critic_Score' on one side and a PCP of 'NA_Sales' and 'Global_Sales' on the other. They later added a 'Genre' filter on the PCP and brushed the two 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 repeated usage pattern, with nine participants creating a kind of overview and detail arrangement.

Validating higher-order views. Some participants first constructed a Radar chart and then immediately coupled it with multiple SCPs. P6, P11, and P13 each constructed a Radar chart for Q4 comprising of attributes 'NA_Sales', 'PAL_Sales', and 'Global_Sales'. P6 immediately followed up with the construction of three SCPs, using all combination of the above attributes. P11 and P13 interacted with the radar data filter and then rearranged the dimensions to form individual SCPs. P13 mentioned 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 attempting to validate correlations visible in the higher-order multivariate visualizations. This pattern was observed for five participants.

Learnability and usability. Participants stated that VizInteract's interactions were overall easy to learn. P8 mentioned that "*Not much explanation was needed for understanding the interactions*", P4 said that only a single explanation was enough, and P1 noted that "*only 5 minutes needed to learn the interface and its capabilities*". Participant P4 even commented that the radar chart and PCP interactions felt 'magical'. On the used 7-point Likert scales, SCP (14 strongly agreed and 2 agreed) and PCP (11 strongly agreed and 5 agreed) had the highest ratings in terms of ease-of-use and learnability. Radar chart interactions were also comparatively easy to learn (μ=5.1, sd=0.83) and use (μ=5.31, sd=1.11). The SPLOM had good ratings for learnability (μ=5.24, sd=0.74) but ease-of-use was not as strong (μ=3.17, sd=1.04). We attribute this at least partially to the computational delay associated with constructing SPLOMs and the subsequent automatic rescaling of the canvas. Participants also liked the filter interactions, which 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 confirms that VizInteract's interaction set is easy-to-use and easy-to-learn.

Dimensional awareness and data comprehension. In the post-task interview, 10 participants mentioned that the ability to easily create multi-dimensional views made them (better) aware of the dimensional relationships. Participant P7 said that *"[the] interdependence 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 the supported charts to address the 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*".

5.5 Discussion

Our findings for VizInteract largely support our overall design goals to build a tool that provides: D1) rapid multi-touch composition and editing of visualizations, D2) leverages easy to use and learn interactions, and D3) a flexible yet powerful interface. For our research question RQ1.1 (*What usage patterns are observable while users complete visual data analysis tasks*), we found that participants successfully created multiple multi-dimensional charts and were easily able to "drill down" into the data for specific queries. Interestingly, we also identified that participants frequently used filters in a bottom-up approach for constructing queries. We believe this behavior matches the mental model of users who follow an atomic VA workflow, where visualization *composition* is a second-order step. This finding supports our design goal of providing a flexible yet powerful interface (D3). We also found people utilized an 'overview-and-detail' style arrangement of charts while rapidly and interactively constructing complex visualizations to address their data queries. VizInteract's interaction set did not seem to have hindered the user's processes for visualizing dimensional relationships and comprehending the data. This rapid and fluid composition and editing of visualizations using multi-touch interactions validates our first goal (D1). The participants also identified that the interactions were easy to learn and agreed in general with the ease-of-use for the interactions for constructing multi-dimensional visualizations. This confirms RQ1.2 *(Do users find interacting with VizInteract to be easy and learnable?*) and demonstrates that VizInteract's interaction set is easy-to-use and easy-to-learn (D2).

6 User Study II

Study II targeted the use of VizInteract on a large touch display. Building on related work [4,5], our main research question was: how does a larger display change user data exploration strategy while they are rapidly constructing and editing visualizations? And with the interactions afforded by VizInteract, do they exhibit different usage patterns on the large display?

6.1 Apparatus and Participants

We used an 85" Samsung 4K 60Hz display with a PQ Labs G5 multi-touch panel, connected to a PC running a bootable USB image of Android X86. We patched the OS to add support for the PQ Labs panel (now part of the Android X86 distribution). Interaction logs were saved to the USB drive. With user consent, a video camera was used to record interactions. An auxiliary computer was used to record survey answers and an audio recorder for post-task interviews. For the training and free exploration phases, we used the same dataset as in Study I [59]. For the main session, we used a subset of the Video Game Sales 2019 Dataset [62]. We ran the study with 16 new participants. Twelve were undergraduate students who took part for course credits, while the rest were graduate students. We pre-screened participants to ensure that they had familiarity with data visualization. To mentally prepare them for study, participants were told that they would be required to stand for 40 minutes. The display was mounted on a movable stand, adjusted to a comfortable height for every person.

6.2 Study Design

The participants were asked to fill a consent form and answer basic demographic questions. We then conducted a short freeform interview to assess their familiarity with visualizations, VA tasks, multi-touch interaction, and multi-dimensional data analysis. This whole phase lasted 5 minutes. Then we introduced the experimental setting and demonstrated VizInteract's interactions. The tutorial used the sample Cars dataset and participants were then given a set of practice tasks to explore the system. For the main part of the study overall task objectives were similar to Study I (See Appendix **Table**) and participants had 30 minutes to perform five tasks on a subset of the Video Games sales dataset. Even though the attributes involved in the tasks differed slightly from Study I, we believe that this difference did not affect the outcomes in a notable way. After all, we did not focus on task completion nor performance metrics, but on user behaviors when interacting with VizInteract. Once participants completed a task, they were asked to explain their approach to arrive at each insight. After the tasks, we conducted a semi-structured interview with each participant, to understand their experience when using VizInteract. We focused on their opinions on the usability of the interactions and the usefulness of the tool. We quantified some of the feedback through the System Usability Scale [9]. If consent to record had been given, audio and video recordings were later encoded for thematic analysis.

6.3 Results

In this section, we report our qualitative findings for the usage patterns and list the interaction codes observed in Fig 10.

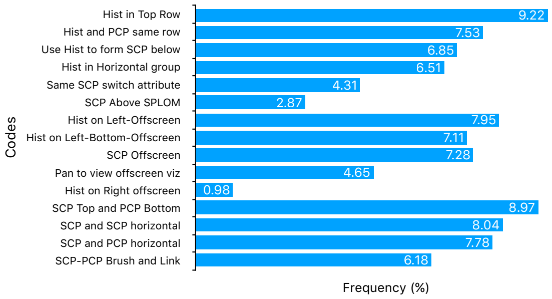

Fig. 10. Low-level Interaction codes and their frequency for Study II.

Table 2. Coded Findings for Study 1.

Initial Codes	Focused Theme	# Particpants
Hist in Top Row, Hist and PCP same row, Use Hist to form SCP below, Hist in Horizontal group, Same SCP switch attribute, SCP above SPLOM	Staging visualizations	10
Hist on Left- Offscreen, Hist on Left-Bottom-Offscreen, SCP Offscreen, pan to view offscreen viz, Hist on Right Offscreen.	Docking visualizations	8
SCP top and PCP bottom, SCP and SCP horizontal, SCP and PCP horizontal, SCP-PCP brush and link	Simultaneous PCP and SCP analysis	7

The primary spatial arrangement observed was individual histograms placed above a SCP. Two or more histograms were often placed on the same "upper row" and were brought "down" individually to construct or edit a SCP below. We also saw that off-screen space was utilized to temporarily store visualizations. Additionally, we observed a specific arrangement for the pairing of SCPs and PCPs, where frequently a SCP was on top and a PCP at the bottom. Pairs of SCPs, however, were arranged side-by-side. Through further analysis, we identified three major emerging themes, see Table 2.

Staging visualizations. We observed that participants constructed visualizations by bringing histograms for the attributes involved in the task into a single row, high up on the display, in a "staging" area. This allowed users to later take these histograms and combine them into desired multi-dimensional visualizations below that row. For example, for Q2, participant P3 brought in 'Critic rating', 'Global sales', and 'NA_Sales' attributes as histograms one beside the other. They then paired attributes into SCPs below the histogram staging row. When questioned, P3 said, "*Having attributes separated makes it easy to quickly replace the dimensions in the charts*". For Q4, P6 put 'Console', 'Europe_Sales', 'NA_Sales', 'JP_Sales' histograms into a row. Then, they created 3 SCPs below the row before arriving at their conclusion. They said that "*It's like a mental map where [I] save these attributes that [I] want to analyze for later*".

Docking visualizations. Another observed behavior concerned the way participants 'docked' their visualizations beyond the viewport. They created a visualization, moved it offscreen, brought other attributes into the empty space, and then constructed new visualizations. Later, they would bring the offscreen visualization back to refer to it or to compare it with the current one before drawing conclusions for the task. For Q3, participant P7 constructed a 'Genre' vs 'Europe Sales' SCP, docked it to the left side, and then created 'Europe Sales' vs 'Global Sales' with a 'Genre' filter on it. When asked about it, they remarked "*I want to know if there are peculiarities with the way Europe reacts to different categories of the games. I spotted [that] co-op games have [a] higher frequency count. I was curious and wanted to compare it to global but have 3 attributes in the equation, that other visualization was for cross referencing*".

Simultaneous PCP and SCP. Most pairings that combined PCPs and SCPs involved an arrangement with the PCP for correlational insights on top and the SCP on the bottom. P2, P10, and P14 used a PCP for Q3 where they made a PCP for 'Europe_Sales' and 'Genre' at the top and then constructed a SCP for 'Europe_Sales' vs 'Global_Sales' with a filter at the bottom. P10 followed this up with a two-finger canvas move operation to vertically align the plots at the center. This pattern supports the benefits of pairing a SCP with a PCP for data analysis [27]. P2 and P14 also rearranged the dimensions between the PCP and SCP, but the layout still remained a vertically separated PCP and SCP. P14 mentioned in their interview that "*The dots view gives me a better detailed picture but having the patterns in the connected lines be visible at the same time is useful*". P2 reported in the post task interview that "*The scatter plot has some advantages but pairing it [with] another view validates your instinct about the pattern*".

Temporal patterns. When we analyzed the temporal distribution of actions during the tasks, some additional behavioral patterns emerged. Every dimension drop was almost always followed by brushing-and-linking. Analyzing such interactions in more detail via the trace log and video also identified that participants preferred brushing on isolated histogram ranges and linking on existing SCPs. It is also interesting that the press-and-hold interaction to bring up the lens view mostly happened when a visualization was constrained by filters. Also, the frequency of lens interactions kept increasing towards the end of a task, which might suggest that even somewhat less common touch interactions, such as the press-and-hold, quickly can become routine. We also saw that people spent more time on filter modification with PCPs than SCPs.

Learnability and usability. With VizInteract running on the large display, participants found the interactions easy-to-learn and easy-to-use. P7 found the interface to be fluid and remarked that "*Seeing correlations so quickly from a dataset is good, user-experience wise*". P13 commented that not having a lot of "*calls to action"* (buttons) makes it a "*one-step process*" to think about the problem and create relevant visualizations. P4 claimed that it "*only took a single demonstration to get the hang of each interaction*" and they found the quick creation of charts exciting. In their words *"The number of steps from thinking about the problem and [then] actually creating the graph is [much] less"*. Some people experienced issues with the lens view implementation. P8 thought the "*lens could be zoomed [more] in as it was a large screen"*. Some participants were happy that the interactions on a large screen felt "phone-like" to them. P4 said that it felt like "*I was using a phone scaled up"*. This indicates that the system is very learnable. VizInteract's System Usability Scale [9] score on the large display was 75.83, i.e., a highly usable system. Participants found the system very easy-to-use (μ= 4.1, sd=0.6) and agreed that it was easy-to-learn (μ=4.2, sd=0.97). P8 remarked that *"It's so easy to compose something here that making a mistake doesn't really feel risky"*.

6.4 Discussion

Our findings from this study characterize the exploration strategies used by people while using VizInteract on a large touch-enabled display. It shows participants were able to easily learn and use the multi-touch interactions for creating and editing multi-dimensional data visualizations (See Design Goal 3.2), even on a large display. Yet, the patterns observed on the large display in Study II reveal a distinct characteristic relative to Study I, as people used unique spatial arrangements for their visualizations. This answer our RQ for User Study II, i.e., that large displays elicit different usage patterns with VizInteract. We observed that people were 'staging' various visualizations in rows and picking and composing multi-dimensional visualizations using such staged attributes. This points to potential arrangement-related features, e.g., by enabling quick visualization of pair-wise combinations of all attributes placed on screen. We also observed that users used offscreen space for storing visualizations for quick reference. As our use case focuses on a single user comparing visualizations, without involving a collaborative setting, this behavior is fundamentally different from the territoriality observed in large tabletop configurations [50]. One implication of this finding is that touch-enabled large display VA tools should enable quick comparisons with already created multivariate visualizations to speed the referencing process. We also note that this observation aligns with our goal of rapidly composing and editing visualizations (See Design goal 3.1). The additional vertical space on the large display also afforded a unique arrangement of PCPs and SCPs: a PCP on top and a SCP at the bottom. Without prompting from the experimenter's side, many participants repeatedly and seemingly naturally created such arrangements. This arrangement supports correlation analysis in the PCP in combination with detailed analysis through the SCP. The possible implication for this behavior is to support an ad-hoc creation of SCPs, like an embedded SCP visualization, similar to previous work [27]. This behavior also in line with our goal to provide a flexible yet powerful interface (See Design goals 3.2).

6.5 Challenges

Confirming that there is always room for improvements, VizInteract faced some challenges on the large display. First, interaction with the lens view could be improved, e.g., by increasing the zoom factor, potentially through an associated user setting. To support the quick staging and arrangement of previously constructed visualizations, a fast interaction method could be introduced to enable saving and restoring of visualizations. Currently, displaying tens of thousands of data points simultaneously in VizInteract can cause visual clutter and too many data dimensions (multiple dozens) can cause performance issues on a tablet. However, large dataset strategies like sampling, aggregation, tuning/tweaking, and/or segmentation could be utilized to address this issue. A built-in short tutorial would also reduce the need for a training phase for VizInteract.

7 Conclusion and Future Work

Overall, we found that VizInteract's multi-touch interface affords the rapid construction and editing of multi-dimensional visualization. Both studies confirmed that users easily understood how to create visualizations through combination. Users were quickly able to complete realistic VA tasks and to derive valid insights from the data. As the basic interaction of combining attributes worked very well, we are planning to increase the scope of visualization options by implementing support for adding additional dimensions to SCPs and SPLOMs, through color or size encodings. Several users also requested trendlines and sorting of axes in VizInteract to facilitate identification of insights. Moreover, we are planning to explore the automatic display of associated SCPs for a PCP. Based on our findings, and instead of relying on simple visualizations, the next version of VizInteract could guide users to use filters on higher-order multi-dimensional visualizations. This might also point to a need for mechanisms to quickly generate alternate visualization of selected dimensions. Finally, we plan to explore how device displacement or changing the display orientation affects usage patterns.

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Appendix

A1. Tasks for Study II (Table 3)

Table 3. Tasks for Study II.

Question	Objective
Your video game archivist friend is in town, but she is only aware about indie game titles. She needs your suggestions about game trends and specific titles that are a little more mainstream. Show her some visualizations that can help her understand your choices for each of the below-mentioned tasks.	Introducing the scenarios
Q1: Your friend wants suggestions on high-selling and highly rated shooting and RPG games. Create a corresponding chart and record the names of 3 such games.	Explore how users create charts and use filter interactions
Q2: She wants to identify insights for mainstream popular North American titles. Specifically, what factors impact the North American game market?	Explore how users analyze dimensional relationships
Q3: She wants to know how European sales compare in the global market, especially for mainstream Co-op games?	Explore how users analyze dimensional relationships
Q4: A lot of popular publishers are still making games for slightly older consoles like Xbox 360 and PS3. Between Japan, Europe, and North America, she wants to know which gaming region has higher adoption for these games?	Explore how users utilize views to find high performing variables
Q5: Knowing about the recent rising popularity of Epic and Tencent Games, she is curious about the popular games from these companies in the North American market which are also highly rated by critics and are exclusively available on PC and PlayStation. Are there any options for her?	Check how users query for specific details and interact with numerical and categorical filters combined