Short-Contact Touch-Manipulation of Scatterplot Matrices on Wall Displays

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Abstract

This paper presents a short-contact multitouch vocabulary for interacting with scatterplot matrices (SPLOMs) on wall-sized displays. Fling-based gestures overcome central interaction challenges of such large displays by avoiding long swipes on the typically blunt surfaces, frequent physical navigation by walking for accessing screen areas beyond arm's reach in the horizontal direction and uncomfortable postures for accessing screen areas in the vertical direction. Furthermore, we make use of the display's high resolution and large size by supporting the efficient specification of two-tiered focus + context regions which are consistently propagated across the SPLOM. These techniques are complemented by axis-centered and lasso-based selection techniques for specifying subsets of the data. An expert review as well as a user study confirmed the potential and general usability of our seamlessly integrated multitouch interaction techniques for SPLOMs on large vertical displays.

CCS Concepts

• ***Human-centered computing*** → ***Visualization techniques; Information visualization; Visualization theory, concepts and paradigms;***

1. Introduction

Isenberg et al. [IIH*13] argued that the screen real-estate of large displays is an advantage to be exploited for better performance and user experience in visualization tasks. Large vertical displays are well suited for presenting and exploring detailed and large overviews. This is particularly true for scatterplot matrices (SPLOMs) when presenting a larger number of attribute combinations at once. Multitouch appears to be a natural choice for performing interactions with SPLOMs from up close, but presents a number of challenges, including the uncomfortable or even impossible access to plots beyond arm's reach [GCR14], and the fact that longer touch interactions on blunt surfaces can be truly unpleasant.

In order to overcome these challenges for SPLOM visualizations on very large multitouch displays ("walls") we developed a vocabulary of short-contact multitouch gestures for versatile view management and the selection of subsets of the data (see Figure 1). The paternoster navigation implements fling-based cyclic scrolling for easy access to matrix areas beyond arm's reach. Focus + context at the matrix level allows to resize individual plots which is consistently propagated across the affected rows and/or columns of the matrix to keep a consistent matrix layout. Focus + context at the scatterplot level provides local detail without changing the overall layout of the matrix and is also consistently propagated to the scatterplots in the respective columns or rows. All these techniques tie the fingers to the visualization displayed under the contact points and use fling gestures in combination with inertia to enforce the physicality of the interface. We performed an expert review and a user study to assess the usability of the interface, the comprehensibility of the visualization and the effectiveness of the system for analysis tasks.

SPLOMs are one of the most important multi-attribute visualization techniques which is why they are integrated in many visualization systems and should also be available in systems designed for display walls. However, simply showing SPLOMs on the large display and using standard multitouch gestures for panning and zooming would be very limiting since it would require keeping the fingers on the display for larger distances and quickly move parts of the SPLOM off the display. While remote interaction with the large display [KKTD17, HBED18, LKD19] avoids some of the issues, it seems unnecessarily indirect when being in arm's reach of the display surface. Furthermore, remote interaction requires additional devices and users need to shift attention between handheld or worn devices and the large display. This motivated us to seek for a short-contact multitouch interface for SPLOMs that enables the user to perform view management and interaction tasks in a comfortable way from up close. The main contributions of our work are:

Figure 1: *Touch-enabled visual analysis using SPLOMs on a large wall display (*$4.08 \times 2.31\,\text{m}$*). Our two-tiered Focus and Context (F+C) technique with an outer F+C at matrix level and an inner F+C within scatterplots improves the exploration process by giving access to detail even in dense areas (see Subsection 3.1).*

- A set of local short contact ("fling") gestures that enables SPLOM manipulation on the wall beyond the user's reach.
- A two-tiered F+C mechanism that combines matrix-level F+C with local plot-based F+C and propagates changes consistently across the SPLOM.
- A paternoster mechanism for cyclic horizontal and vertical scrolling of SPLOMs that complements physical navigation.

The participants of our user study who performed typical analysis tasks on the SPLOM judged our set of interaction techniques as well integrated and consistent but requiring learning.

2. Related Work

Previous studies have shown that working on large high-resolution displays can positively affect user performance for visualization tasks [AEYN11]. Liu et al. [LCB*14] examined the effect of display size in classification tasks and concluded that users perform difficult classification tasks significantly better on a wall display than on a desktop setup. Reda et al. [RJPL15] conducted a study on visual analysis and found that these displays can increase the amount of gained insights. Rajabiyazdi et al. [RWM*15] interviewed domain experts after they used a wall display and concluded that they mostly valued the possibility to study large views in detail and compare images at full scale. However, the size of such displays shifts the limitations from technological aspects to human perception [AEYN11]. As users stand close to the display, the extreme viewing angle leads them to misjudge angles and areas [BI12]. To minimize distortion we include interaction techniques to bring the area of interest closer to the user.

Some studies attribute better performance with wall displays to the use of *physical navigation* and its usage of embodied resources such as motor memory, peripheral vision, optical flow, focal attention and spatial memory [BN07, BNB07, AEYN11, EALN11]. Andrews et al. [AEYN11] argued that physical navigation can substitute or supplement techniques such as zooming and panning, overview and detail, focus + context, and semantic zooming. Users can focus on a region of interest by moving while retaining the context in peripheral vision and gaining the full overview by stepping back. Studies by Ball et al. [BN07, BNB07] indicate that users prefer physical over virtual navigation. However, user studies by Jakobsen et al. [JH15] cast some doubt on the extent of its advantages. They found neither performance improvements nor a preference of physical over virtual navigation when information spaces were too large for the display. Consequently, we provide the paternoster interaction technique that enables virtual navigation and can complement the physical one, to support both.

2.1. Interacting with Wall Displays

Serveral techniques for remote interaction with wall displays have been proposed. Von Zadow et al. [vZBLD14] designed *SleeD*, a sleeve multitouch display attached to the non-dominant arm as a private detail view. However, users reported it is hard to use for very high or low wall positions and it requires switching between displays. Dachselt and Buchholz [DB09] minimize such gaze shifts by using the built-in accelerometer of mobile devices to detect tilting gestures for zooming and panning. Nancel et al. [NWP*11] proposed mid-air gestures supported by a mobile device for the same interaction. However, mid-air gesture tracking takes a complex technical setup. Overall, these techniques extend the input possibilities but require the user to explicitly change the interaction mode or to shift their focus between devices. In contrast, we aim at keeping the interaction direct through touch, and at bringing remote content towards the user.

The issue of reachability is addressed by the *WallPad* of Gilliot et al. [GCR14] that provides a virtual pointer for accessing remote content. Similarly, Lischke et al. [LMH*17] proposed a technique called *Windows Spinning* that allows users to move the whole screen from left to right with the mouse and keyboard, inspired by the *Tablecloth* of Robertson et al. [RCB*05]. In comparison to other distortion-based techniques, participants considered *Windows Spinning* the most helpful to effectively manage application windows. Following the same principle, we propose the paternoster technique that additionally allows to move the screen vertically to bring the upper and lower areas into reach.

Albeit not our focus, the size of the display creates the opportunity to let multiple users interact simultaneously. Liu et al. [LCBL17] developed collaborative touch gestures for wall displays to support users working together but on different parts of the display. Von Zadow et al. [vZRB*16] created a low-cost system for user tracking called *YouTouch!* that uses an RGB + depth camera to associate person descriptors with detected touch events. Our work focuses on the interaction of a single user at a time and could be very well combined with the user identification of Zadow et al. but would require additional conflict resolution when two users interact with the same horizontal (or vertical) set of scatter plots.

2.2. Visualizations on Large Vertical Displays

Kister et al. [KKTD17] displayed standard graph visualizations on a wall display with interaction through spatially-aware mobile devices as personal views. The large display gives an overview and the mobile devices provide detail views. Prouzeau et al. [PBC17] studied selection techniques for graph exploration with pairs of users and proposed a technique to propagate selections in the graph to help them solving a task collaboratively. While these examples mainly support overview and detail to navigate, we explore how to make use of focus + context techniques.

Langner et al. [LKD19] focused on different visualizations in coordinated views. Mobile devices and direct touch gestures support visual exploration. As both display types provide touch input, they developed a consistent interaction vocabulary with a small set of gestures for direct and remote interaction. In our work, we similarly use well-known gestures for common tasks such as selection but extend these with the ability to navigate globally while being close to the display. Horak et al. [HBED18] utilized smartwatches to support remote visual analysis on the wall in a similar fashion. These are non-intrusive and leverage proprioception for eyes-free interaction. The system uses the accelerometer of the smartwatch for coarse remote control of a virtual pointer on the wall display. The combination of our direct multitouch gestures with interaction through such devices would extend our work to support remote interaction as well as direct interaction in a promising way.

2.3. Multi-touch Interaction with Information Visualizations

A few commercial visualization systems already present mobile applications but these seem not to be designed truly for touch since they just replace mouse clicks with taps. One exception is Vizable by Tableau [Tab]. Also, few visualization techniques have been addressed within academic research. Baur et al. [BLC12] designed *TouchWave*, a multitouch version of stacked graphs that tackles the main limitations of these graphs such as legibility, comparing values, and scalability. Similar to their approach, we use the pinch gesture to activate focus + context. For bar charts, Drucker et al. [DFS*13] designed a WIMP-style interface and a gesture-centric direct-touch interface to interact on tablet devices. They compared them in a user study and most participants preferred and performed significantly better with the gesture-centric interface, arguing that the interface better matched their problem-solving approach and felt more natural. We designed a gesture-centric interface as well, particularly adapted to wall displays. *Touch the Time* [RROF18] presented multitouch interactions for focus + context in Horizon Graphs. Horizontal pinch gestures enlarge a time range over all time series and vertical pinches enlarge the height of individual time series while compressing all others to the remaining space. The number of foldings for each Horizon Graph adapts dynamically to the respective height.

2.4. Scatterplots and Scatterplot Matrices with Touch

For scatterplots, there have been different approaches on how to leverage multitouch interaction. *Kinetica* [RK14] is a proof of concept application for tablets that employs physical metaphors to create a natural user interface [JGH*08] to explore multivariate data with a combination of scatterplots, histograms, and pie charts. Also for tablets, Sadana and Stasko [SS14] explored the design space of multitouch gestures to design and implement interaction techniques for data exploration with scatterplots. Later they extended their system by combining scatterplots with bar charts, line charts and parallel coordinates in multiple coordinated views [SS16]. They used a combination of UI elements and gestures, since, as they argued, using too many gestures would require a bigger effort for the user to discover and remember them. They also relied on known gestures such as pinching or double-tapping for zooming. However, one of the main challenges was to choose gestures that could be used consistently in all visualizations for the same task, even when there was another gesture that would fit that task in a particular visualization better. In a study [SAS18] users preferred this system over Tableau's Vizable. Inspired by their work, we incorporated the tap, lasso, and swipe gestures for the selection of data items on the wall.

In *ScatterTouch* [HHDR10] a single scatterplot is shown on a tabletop display and users can apply focus + context with fisheye distortion to create multiple focus regions. This technique was introduced by Furnas [Fur86] and similarly used with scatterplots by Büring et al. [BGR06]. They compared it to a ZUI-like (zoomable user interface) technique and users preferred focus + context, although task completion times were similar. Content-aware extensions of this technique such as the *JellyLens* [PPCP12] adapt to the shape of the region of interest to make better use of empty space. Since the scatterplots in a SPLOM share their axes, we activate focus + context inside the scatterplot with a pinch gesture similar to ScatterTouch, and then extend it to the whole matrix by propagating the effect along the complete row or column.

Recently, Chegini et al. [CLL*17] experimented with scatterplots and scatterplot matrices on a large vertical display, porting *ScatterDice* of Elmqvist et al. [EDF08] to a touch interface. Applying the concept of overview and detail, the matrix is used as the overview, while any scatterplot inside the matrix can be selected as a detail view to interact with. In contrast, we do not split into different views but rather enable two-tiered focus + context, and address the reachability issue [CSAS] by providing an interaction technique for virtual navigation.

3. Visual and Interaction Design

The research of Sadana and Stasko [SS14] on multitouch for working with single scatterplots on tablets inspired our work even though they were designing for an entirely different form factor. They derived a list of standard tasks such as select, zoom, and filter for scatterplots and designed a multitouch vocabulary for these. The approach of Chegini et al. [CLL*17] for interacting with a SPLOM on a vertical 83-inch display relies on having all interface elements as well as the entire SPLOM within arm's reach. However, with our approach we wanted to support SPLOMs displayed on the entire surface area of a much larger wall display.

Our iterative design process was based on rapid prototyping on our display with a size of 4.08×2.31 m allowing us to simulate particular interactions by actually performing them and imagining the visual responses. We started by displaying full-screen SPLOMs of sample datasets (iris [DG], cars [DG], and movies [The]). That led to the discovery of multiple issues, some obvious, such as the limited access to the upper and lower display areas, as well as less obvious ones, such as the blunt surface which made it quite unpleasant to slide the fingers over a long distance. In our particular setup, we also had to take into account a certain unreliability due to the limitations of the infrared multitouch recognition (IR) technology. For instance, our IR-based setup recognizes fingertips already some millimeters above the screen before actually touching it, and sometimes touch points might not be reported during long-range touch interactions.

Hence, we aimed at designing multitouch gestures that had to be short, robust and locally applicable to overcome reachability issues as well as limitations related to the multitouch technology and the large size of the display. We derived the following design rules to achieve consistency across the individual techniques and to smoothly integrate them with one another.

- All long-range movements, swipes or drags on the display that would extend beyond arm's reach should be replaced by short-contact fling (also known as flick) gestures to deal with reachability, unpleasantness and to mitigate fatigue issues.
- Simple local interaction techniques such as selection and filtering should use only one finger.
- Complex interactions applied within a limited range should be done with gestures of two fingers, either of one hand or—in most cases—one finger per hand.

Using these design rules, we developed virtual navigation techniques to complement physical walking and to avoid uncomfortable postures when interacting with lower and upper display areas. We also wanted to provide access to more detailed information on demand by using a focus + context approach. This was motivated by the observation that the large viewing angle of our wall display provided a natural focus of a SPLOM within arm's reach and perspectively compressed the context beyond (see Figure 1). Thus, we expected that a further interactive focus + context approach applied in the vicinity of the user would blend well with the natural focus + context of the display.

Our resulting design can be grouped into multitouch gestures applied locally (scatterplot-centered) for tasks such as focusing, selecting and filtering, and global (matrix-wide) gestures for tasks such as plot and screen management as well as for navigation of the matrix. In the following subsections we also report on some of our intermediate designs that led us towards our multitouch interaction vocabulary as shown in Figure 2. We decided to keep the interaction touch-based and close-range, and to aim for direct interaction without needing additional devices. We know that wall interaction can benefit from tracked mobile devices (e.g. Langner et al. [LKD19]) and we see potential in combining it with our approach, but that requires additional hardware, switching focus between displays, and appropriate transitions between using the mobile devices and the direct touch interaction on the wall. In addition, we wanted to enforce the physicality of the interface by simulating inertia for the items affected by fling gestures.

The appearance of the matrix itself is designed with respect to the wall's specific properties. Dark colors are used for the backgrounds in order to reduce eye strain. In contrast, the data points

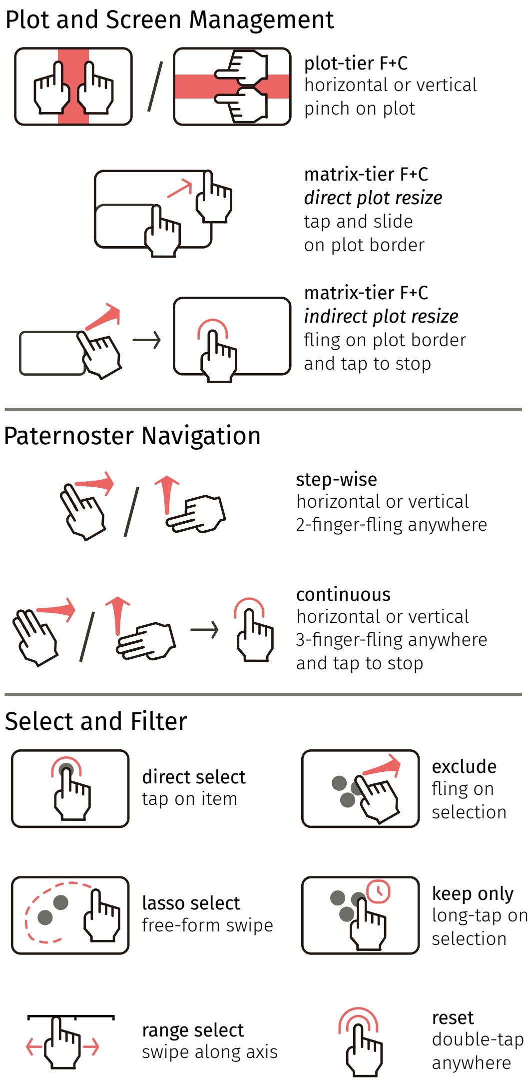

Figure 2: *Overview of our multitouch interaction vocabulary and how, where, and by how many fingers the gestures are triggered. Fling gestures (⟶) replace long range movements and enable SPLOM manipulation and navigation beyond the user's reach. Continuous movements (⟶) are intended for local changes and selections (albeit they could have matrix-wide effect). The exclude filter is an exception from our rules but was kept due to its natural metaphor of throwing things away.*

are drawn in bright colors with slight alpha blending. The borders between the plots are wide enough to enable touch interaction. The value labels, tick marks, and plots' background grids are computed by the extension of *Wilkinson's algorithm* by Talbot et al. [TLH10], an optimization algorithm to find the best start and end values, the step size for a given variable range, and the number of ticks.

3.1. Two-Tiered Focus + Context

For effectively exploring the dataset on the wall we propose a two-tiered focus + context (F+C embedded F+C) that works at the ma-

(a) (b) (c) (d)

Figure 3: *Global F+C by resizing a plot with a fling gesture. A fling is applied on the corner (subfigure a and b). The plot expands with a constant speed (subfigure c) until it is stopped by a single tap (subfigure d). The matrix-wide effects can be seen in Figure 5.*

Figure 4: *Global F+C by directly resizing a plot. (top) The user long-taps on the corner of the plot to initiate a horizontal and vertical resize. (bottom) The plot corner moves along with the finger and therefore the plot expands. The plots to the right and top shrink accordingly.*

trix level (outer F+C) as well as at the scatterplot level (inner F+C). Both tiers can be applied on their own but are more effective when combined. This way, the user can focus on scatterplots of interest by giving them more space during analysis as a first step but further emphasize relevant regions or value ranges inside the already enlarged plots as a second step. Both tiers help to explore large datasets with many dimensions. When data items of interest are in small or dense regions, and the user wants to see more details or to resolve overplotted regions, they are especially useful in combination. Both variants work not only horizontally or vertically, but also combined as a two-dimensional technique.

Matrix-wide F+C Manipulation

As mentioned above, at the matrix level, F+C can be applied by dynamically modifying the size of a scatterplot that then becomes a focus area inside the matrix. Since plot sizes can vary depending on the number of attributes or the interactions one has performed before, a pinch even with two hands at the borders of the plot may not be possible on large scatterplots. Thus, we offer different methods to resize plots. The user can resize the plot by dragging a corner or border of a particular plot towards the intended size and release it. This direct plot resize is intended for small changes of size (see Figure 4) since it is limited by the user's reach.

In order to exceed this limit and to realize larger size changes we propose a short-contact fling-based solution, that also avoids long unpleasant dragging on the blunt screen surface. Performing a fling outwards or inwards at the corner or the border of the plot triggers a continuous increase or decrease of the plot size at a constant velocity until the user taps on the screen to halt at the current size (see Figure 3). Along with the ongoing resize of the scatterplot, the entire matrix is being transformed by consistently adjusting all other plots. Every plot in the column and in the row of the changed scatterplot is respectively adjusted to the width or height of the changed attribute axes. All changes are propagated along the row and the column, which results in a kind of cross-haired focus with the initially changed plot at its center (see Figure 5). Plots that do not belong to the cross-hair (and thus belong to one of the context-regions) are decreased uniformly according to the remaining space in their very context region.

Our approach is not limited to a single focus region: Multiple focus regions can be defined easily (see Figure 5). Propagating the size change of attribute axes of two or more plots results in increasing the axes of those attributes where these dimensions also cross in the matrix. Multiple focus regions allow the user to choose more than two attributes of interest.

Resizing of the scatter plots changes the aspect ratio which in-

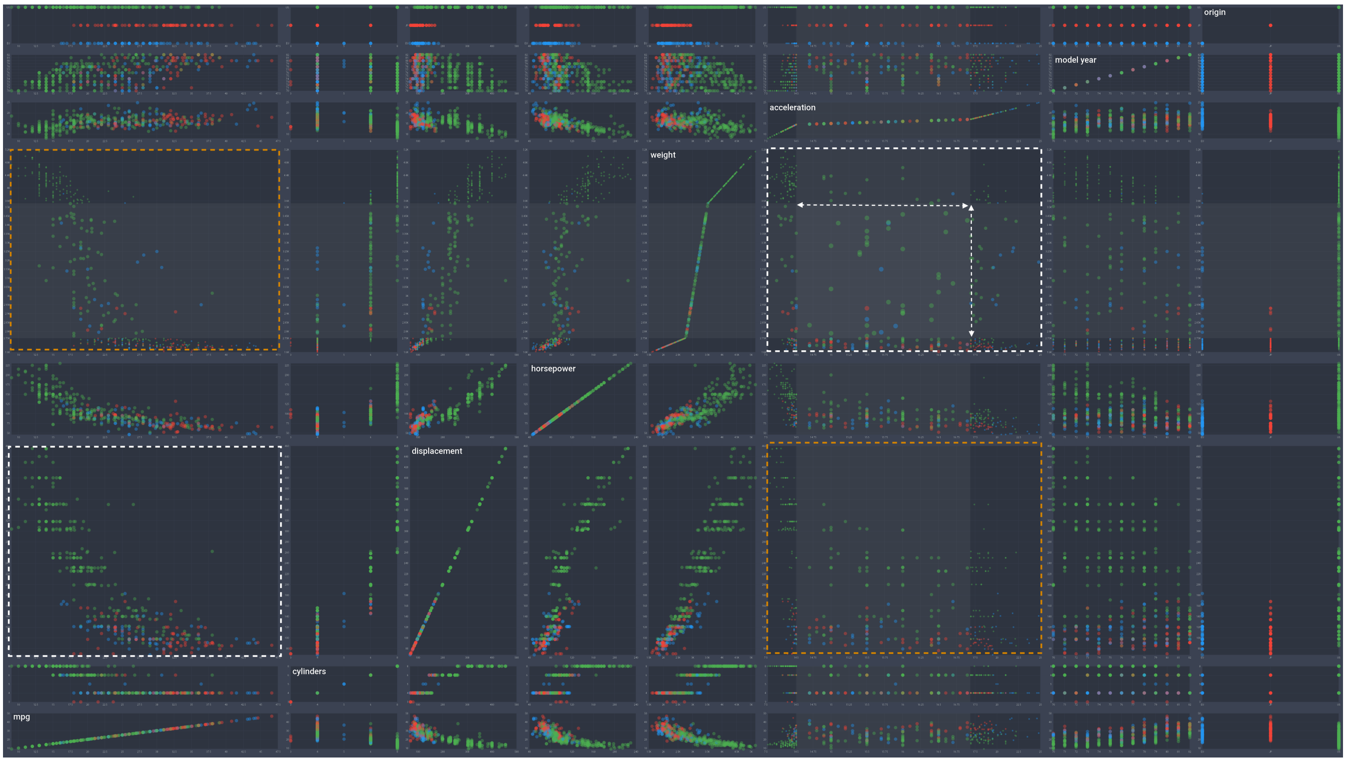

Figure 5: ***Two-tiered focus + context. Matrix-tier.*** *Consistent matrix with multiple focus regions. Initially, the axes of the attributes* displacement *and* mpg *were enlarged in one plot (lower-left white rectangle) as well as the axes of* acceleration *and* weight *in another (upper-right). Increasing these attributes entails row-wise and column-wise propagation, which results in two additional focus regions (orange rectangles), where the enlarged attribute axes also meet;* mpg *and* weight *(upper-left orange rectangle) and* acceleration *and* displacement *(lower-right orange rectangle).* ***Second tier. Plot-tier focus + context.*** *Focusing on a value range in* acceleration *and in* weight *(white lines) has created a two-dimensional focus region inside the plot. The focus on those ranges is also propagated through the* weight *row and the* acceleration *column as second tier. Applying plot-tier F+C is possible in plots of any size.*

fluences the perceived patterns to a certain extent. However, the x/y ratio of a scatterplot is in most cases arbitrary - often 16:9 since that is the aspect ratio of the display. However, the range on each axis is typically different and even the units are often different, e.g. cylinders vs. horsepower. Furthermore, users intentionally change the aspect ratio of a plot and therefore are able to observe the changes of the aspect ratio and the influence on the patterns. Thus, changing the ratio might actually help to detect different patterns.

Plot-wide F+C

Focus + context inside a scatterplot is activated by a pinch gesture. Depending on the angle between the two fingers, F+C is applied on the x or on the y-axis. As long as the pinch is ongoing, this focus region is linearly scaled to fill the area between both fingers. The context areas to either side of the focus region are linearly scaled down respectively to fit the remaining space. The focus region is highlighted by a slightly brighter background color and larger data points, whereas the context remains in the previous plot color. The ticks and labels of the focus range as well as the context ranges on the respective axes adapt to the updated space (see Figure 6).

Consecutively, focus + context can also be applied in both dimensions for two attributes (see Figure 6). Here, a similar pattern as with the global variant appears locally. There is a center region where both focus regions cross, four one-dimensional focus areas (for only one attribute), and four remaining context areas. The background colors and the size of the data points vary to represent these different levels accordingly. In contrast to ScatterTouch [HHDR10] that only deals with a single scatterplot, our solution maintains coherence across all plots when activating a local focus region since the F+C is propagated along the column and row of the plot inside every single plot the row or column contains. Otherwise, visual breaks between adjacent plots would occur. As mentioned, both F+C variants can be combined in order to emphasize a particular region inside a focus plot further (see Figure 5).

A zooming and panning approach was initially supported alongside focus + context, including a user interface button to switch between both. Since both techniques can be used to enlarge a region of interest, zooming and panning were eventually discarded in favor of F+C because the latter keeps all scatterplots in view and is akin to the familiar resizing of cells in a table or matrix.

Figure 6: *Plot-tier focus + context creation (top) for one attribute, here* displacement*, and combined in two dimensions for two attributes, additionally with* horsepower *(bottom).*

3.2. Fling-based Paternoster Navigation

Given the size of wall displays, it can be physically challenging to reach every area on the screen. The upper part is often too high for most people to reach comfortably, and reaching the bottom area requires to crouch if the bottom of the display is close to the floor. Furthermore, according to the results of the user studies conducted by Bezerianos and Isenberg on perception on tiled-display walls, perception accuracy is impacted by the horizontal and vertical placement of visual elements on the wall, and the lower positions should not be used to show task-relevant data representations [BI12]. Thus, we propose a consistent cyclic scrolling of the entire scatterplot matrix. Since it imitates the behavior of the old type of elevator that moves continuously in a loop, we call it paternoster. The approach works horizontally as well as vertically. If the movement is in the horizontal direction, entire columns move, disappear beyond the screen border, and then reappear on the opposite side. In vertical direction the rows move, disappear and reappear at the top or at the bottom of the screen respectively. When the transition ends, the rows (respectively columns) snap full into place without being cut off. For better keeping track, the technique is constrained to only one direction at a time. In initial tests, diagonal movements of the entire SPLOM were hard to follow by users.

Prior work only used horizontal cyclic scrolling for arranging windows in a large desktop environment spanned across multiple horizontally arranged displays with the mouse (see Lischke et al. [LMH*17] and Robertson et al. [RCB*05] in section 2). These solutions were neither designed towards the specifics of SPLOMs nor touch-enabled larger walls that are operated while standing.

For this setup, we provide two different variants of the technique, a step-wise and a continuous one. A horizontal or vertical two-finger fling gesture triggers the step-wise paternoster in the respective direction (not depicted, please see supplementary video). The fling's maximum velocity determines the distance that should be moved which is then mapped to the number of rows or columns to scroll, since plots should not be split. The actual scrolling of the paternoster is then animated with a slow-in/slow-out transition which makes the movement easier to follow.

Although the step-wise variant worked well for columns and rows in the proximity of the user, the fling had to be applied multiple times for distant columns. This is why we developed an additional variant with a continuous movement that works alongside the step-wise variant. A three-finger fling triggers the continuous paternoster (see Figure 7). The matrix scrolls continuously in the direction of the fling at a constant speed until the user stops it explicitly with a tap anywhere on the screen. This is similar to the continuous resize interaction for individual plots. When the user taps to stop the paternoster, the plots snap back or forward to the next grid position. This snapping is animated with a bouncing animation. The snapping and the size of the individual scatterplots make it easy to stop the movement at the right time but if a mistake occurs it can be typically corrected by using the step-wise scrolling once. In a first implementation, the step-wise variant was triggered by a single finger which interfered with invoking gestures on the individual plots. Thus, we opted for a two-finger fling and used the three-finger fling for the continuous variant.

With the proposed paternoster technique any plot can be easily brought within arm's reach by a simple fling. As mentioned in section 2, previous research showed that users may prefer physical over virtual navigation [BN07]. More recent research by Jakobsen [JH15] contradicts that finding. Either way, with the paternoster technique users have both options available at any time, for instance, a user might walk horizontally in front of the display and uses the paternoster vertically. Observing people using our system, they often simply step aside to focus on the next plot, but for looking at a plot near the other border, about 4 meters away, they tend to use the paternoster horizontally.

3.3. Selection and Filtering of Data Points

The premise for the local interactions with the data points was to employ familiar metaphors and extend them as intuitively as possible with standard touch gestures, based on reflections of Drucker et al. [DFS*13], and of Sadana and Stasko [SS16]. Three ways of selection are provided in our system: tapping on a single item, lasso selection and axis-based selection (see supplementary video). Tapping and lasso are common for selecting one or multiple items. Axis-based selection was inspired by the work of Sadana and Stasko [SS14] on scatterplots to select items in a certain value range. Selection provides visual feedback by changing the appearance of the data items. Selected points are highlighted by adding a bright visual outline and by showing their labels, if possible, without overlap. Unselected ones become more transparent and thus blend with the background. The system propagates selection across all views according as with brushing and linking.

Filtering is coupled with selection. The user has the option to

(a) (b) (c)

Figure 7: *A continuous vertical paternoster is triggered by a three-finger-fling downwards (a). The matrix is moving at a constant speed in (b) until it is stopped by a tap in the desired location (c). The orange arrow shows the already traveled distance in (b) and (c) respectively. Due to the cyclic scrolling of the matrix the rows that were pushed out at the bottom of the display re-appear at the top.*

Figure 8: *A long-tap gesture on selected items filters out the non-selected ones. The user initiates filtering by tapping the currently selected items (left). After a fixed duration, a long tap is detected. The filtering takes place and all other items disappear (right).*

Figure 9: *Users can exclude selected items with a fling gesture. The user starts a fling gesture on the currently selected items (left). The selected items are filtered out. Since all selected items vanished, no selection is active anymore and all elements are displayed with the usual transparency again (right).*

filter by excluding the currently selected items or by keeping only those and thereby excluding all other items. Although the possibility of employing user interface buttons for each action was discussed and prototyped, eventually, we opted for employing gestures for either filter operation to provide a purely gesture-driven interface. For keeping only the current selection, a long tap is used (see Figure 8). For excluding the selected items, a fling gesture is used that constitutes a throw-away metaphor (see Figure 9).

4. Evaluation and Discussion

For evaluation, we had three central research questions: (1) Usability of the interface: Are users able to perform and learn the touch gestures? (2) Comprehensibility of the visualization: Are the two-tiered focus + context areas and the selection mechanisms used and understood by users? (3) Effectiveness of the system: Are users able to solve complex tasks as they are typical for analytics scenarios?

4.1. Hardware Setup

We tested the visualization system for a tiled-wall (4.08 m wide and 2.31 m high) of 16 displays arranged in a 4×4 matrix with a total resolution of 7680×4320 pixels. It supports multitouch using a custom built PQLabs G4 overlay, which uses IR emitter/receiver pairs integrated into the bezel slightly above the surface. Thus, the system recognizes fingers already some millimeters above the screen. However, some touch points are not reported during long range touch interactions. Four NVIDIA Quadro M6000 graphics cards (in one machine) provide the entire resolution; each a quadrant of the whole wall. The PQLabs Linux driver [PQL] is used via TUIO 1.1 [TUI]. For gesture recognition we created our own C++ library for processing the TUIO stream, where a set of gesture recognizers watches the touch points for patterns and triggers a gesture once one of the described patterns emerge.

4.2. Expert Review

We conducted a preliminary expert review to discover issues before a controlled user study. We therefore asked an academic researcher with 10+ years of experience on large-scale touchscreens and gestural interaction to review our system by answering test questions on the cars dataset. Despite never having used the system before, the expert was able to solve all tasks without assistance after a brief tutorial. Two notable findings from the expert review on our initial prototype were the following: (a) The originally planned gesture for reset (a 5-finger "wipe") was unintuitive and hard to trigger. Generally, the expert tried to use a double-tap instead. (b) A dedicated button for switching between the F+C mode and the previously existing zoom/pan mode would likely confuse users. Consequently, we removed zoom/pan entirely and modified the gesture set to the final state shown in Figure 2, which was also used in our user study.

4.3. User Study

Our user study focused on assessing how the techniques support the users in given tasks and to obtain their feedback on the multitouch gestures. Following Wongsuphasawat and Shneiderman [WS09], the study had the following structure:

1. Introduction to the visualization and description of the dataset.
2. Tutorial of the system, followed by a free exploration phase.
3. Observation of the participant solving a set of 3 defined tasks.
4. SUS questionnaire and interview about the user experience.

The user study was conducted with 11 participants (9 male, 2 female) with a median age of 24. Most participants were undergraduate students (9) and had a background in computer science (9). The SPLOM was used with a movie dataset that contains 12 attributes on 2702 records. In contrast to the cars dataset that was used earlier in the expert review, this dataset is more challenging and interesting considering the participants' age. Our participants were familiar with the concept of SPLOMs and could therefore focus on our proposed gestures and techniques but had never used our system before.

The initial introduction, a tutorial including training tasks and a free exploration phase ensured that the participants were familiar with all interaction possibilities. In the main part of the study, participants were asked to solve three complex tasks consisting of several subtasks, e.g. "Find the movie with the highest budget for each year of the 80s. Which two movies of these are the longest?".

4.4. Results

All participants were able to solve all the tasks with our techniques. The answers to the SUS questionnaire (see Figure 10) [Bro96] and the interview showed that the participants liked and understood the gestures and comprehended the system and the integration of the visual techniques such as the two-tiered F+C. The overall average SUS score for our system is 71.4, with a standard deviation of 12.3. Given the unavoidable hardware limitations of our IR-touch recognition setup including too early touch recognition as well as losing touch points during prolonged touch interactions, this is a promising result which gives us confidence that our approach provides a valuable foundation for future work. Especially, none of our participants made negative remarks on the visualization techniques and gestures in principle, and assessed it as *well integrated* (3.2 of [0;4] for question 5 in SUS "I found the various functions in this system were well integrated") and *consistent* (3.55 of [0;4] for question 6 "I thought there was not too much inconsistency in the system"). Question 10 yielded the lowest average score (1.91 of [0;4]) for "I did not need to learn a lot of things before I could get going with this system". This was an expected result since the participants had to memorize the entire gesture vocabulary (see Figure 2).

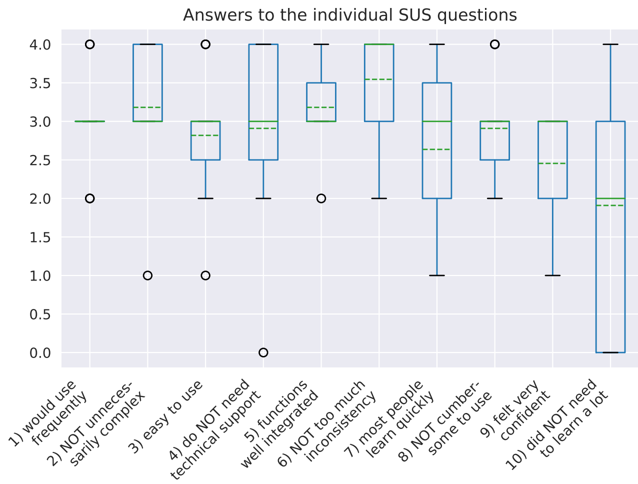

Figure 10: *Detailed breakdown of SUS answers (higher is better). Questions 2, 4, 6, 8, and 10 are inverse in the questionnaire (negative wording). They were transposed to the positive side for calculating the score (as described in the original SUS paper [Bro96]) and for the chart (see the additional NOT marks). Dashed green lines represent means and solid green lines show medians.*

Participants expressed in the interviews that they especially liked the local focus + context (55%) and the paternoster navigation (45%). Four participants remarked on the usefulness of the two-tiered F+C. The observation and post-study interviews showed that users prefer different techniques according to their specific interaction style and analysis strategy. The participants were asked about their preference regarding the two variants of resizing plots and the paternoster technique. 45% of the users preferred the step-wise paternoster, especially its higher precision for smaller distances, even if they had to employ it multiple times to navigate further. On the other hand, 27% favored the fling-initiated continuous variant as it allowed them to easily access more distant plots. In contrast to the step-wise variant, the amount of scrolling is directly visible. Participants that mixed both variants pointed out that the step-wise paternoster is more suited for smaller distances while the continuous variant allows to reach plots further away.

Similarly, there was no obvious preference for one of the resize variants. 36% relied entirely on the direct resize as it seems more familiar and offers a more precise control. Three users specifically used it to align the current plot of interest with the display to keep the bezels from overlapping with the area inside the scatterplot. Again, some participants preferred to mix both variants depending on whether precision or access beyond arm's reach was required.

Interestingly, almost half of the participants avoided the range selection entirely by replacing it with the plot-wide focus + context followed by one of the other selection variants. They consecutively created focus areas until the desired range could be trivially selected with the lasso or the direct data point selection. The other half, however, made extensive use of range selection and 36% even mentioned it as a feature they especially liked. One participant criticized that ranges are not directly selected on the data but on the axis and suggested to employ a two-finger pinch for range selection and a four-finger pinch for the plot-wide focus + context.

None of the participants reported arm fatigue during the study, what might indicate that our short-contact gestures mitigate this effect which is important for the usability during extended analysis sessions at large high-resolution displays [AEYN11, WJ16].

4.5. Limitations

Munzner [Mun14] reported a scalability of desktop-based SPLOM visualizations of up to 12×12 matrices, which seems much without any view management such as focus + context techniques. In our experience, matrices larger than 16×16 make individual plots quite small even on the wall display. Also, the interaction pattern changes as the number of attributes grows: The use of focus + context interaction at the matrix-level becomes necessary and is used more often. From close up, resolution and overlapping can become an issue for large datasets even though our wall has already 33 megapixels. In performance tests, we could still render and smoothly interact with the wines dataset [DG] at 60 Hz, which has 12 attributes, 6497 records and therefore requires to draw 935 568 data points in total. Even though this dataset does not seem to be really large, significant over-plotting already occurs in some regions due to the distribution of the data values but also due to the size of the scatter points which should also be recognizable from a distance. To alleviate the problem, we use alpha-blending to provide an impression of the local point density. However, for further scalability data preprocessing as well as visual and semantic aggregation techniques need to be integrated into our system. Furthermore, it is obvious that SPLOMs are only one tool of many in a visual analytics system for the analysis of real-world datasets.

Even though our gesture recognition focuses on a single user interacting with one or both hands, we observed a casual collaboration of users who took turns interacting on the screen and showing each other different aspects of the data using our techniques. This seemed to happen naturally, as if one took turns in speaking. To take this further, interaction through complementary tools should enable users to help each other instead of competing. Phases of close and loose collaboration among users could be supported through territoriality [SCI04] using separate areas on the large screen as suggested by Liu et al. [LCBL17] or mobile devices. While our visualization and interaction with SPLOMs already allows multiple focus areas (see Figure 5), for supporting multiple users we would have to add user identification by e.g. using the approach of Zadow et al. [vZRB*16] and additional conflict resolution mechanisms when two users interact with the same horizontal (or vertical) set of scatter plots.

5. Conclusion and Future Work

We designed, implemented, and evaluated short-contact multitouch gestures and corresponding interaction techniques for SPLOMs displayed on wall displays. The fling-based paternoster allows virtual navigation by employing cyclic scrolling of the SPLOM which complements physical navigation and moves plots into arm's reach for further interaction. Our two-tiered F+C technique works on the matrix and on the scatterplot level. Changes are consistently propagated vertically and horizontally along the rows and columns of the SPLOM. Moreover, the two-tiered F+C and its consistent propagation is not limited to a multitouch interface but could also extend the scalability of SPLOM-based analysis on the desktop. Brushing and linking works consistently with the two-tiered F+C approach.

Overall the expert review and the user study confirmed the utility of the interaction and visual design. It was interesting to observe that users selected different variants of the proposed interaction techniques depending on their individual analysis strategies. However, learnability is still an issue. Users felt that they need to learn a lot in order to use the system to its full extent, which fits the reflections of Drucker et al. [DFS*13] on the challenges of making the gestures of a touch interface easy to discover and memorize. Touch precision and gesture detection stability are still an issue that affects the use of the interaction techniques. Most participants quickly learned to overcome these issues and to employ the various interaction techniques during their tasks. The user study highlights the need for precision as well as range for interaction techniques that provide access to data beyond arm's reach. The presented interaction design provides solutions for both of these aspects.

There are many possibilities to extend the SPLOM visualization and the interaction repertoire; for instance, provide the possibility of changing the column or row order to arrange relevant attributes next to each other. Data analysis is an iterative process and thus users also need to undo and redo actions. Currently, we only support undoing the last filter operation. Also, users need to be able to store subsets of the data records after filtering and recall them for comparison. In the expert review, our participant suggested leaving breadcrumbs or visual cues on the already visited plots to support a user's mental map better—especially for large SPLOMs.

The successful interaction with SPLOMs on the large display motivated us to think about how other standard visualization techniques can be adapted for large displays following our short-contact multitouch approach. The main challenge here is to find a common subset of multitouch gestures that works well across all visualizations but to provide a consistent set of gestures for visualization-specific interactions as well. Our multitouch approach could be very well combined with remote interaction techniques involving handheld or in particular worn devices to allow for interactions from a distance as well as from close up. It is our goal to integrate several visualization techniques and the corresponding remote and multitouch interaction techniques into a coordinated multi-view framework to allow users to select and combine the best tools for the job. The findings of Langner et al. [LKD19] provide initial guidelines towards this goal.

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