Accepted to IEEE InfoVis 2018

Multiple Coordinated Views at Large Displays for Multiple Users: Empirical Findings on User Behavior, Movements, and Distances

Ricardo Langner, Ulrike Kister, Raimund Dachselt

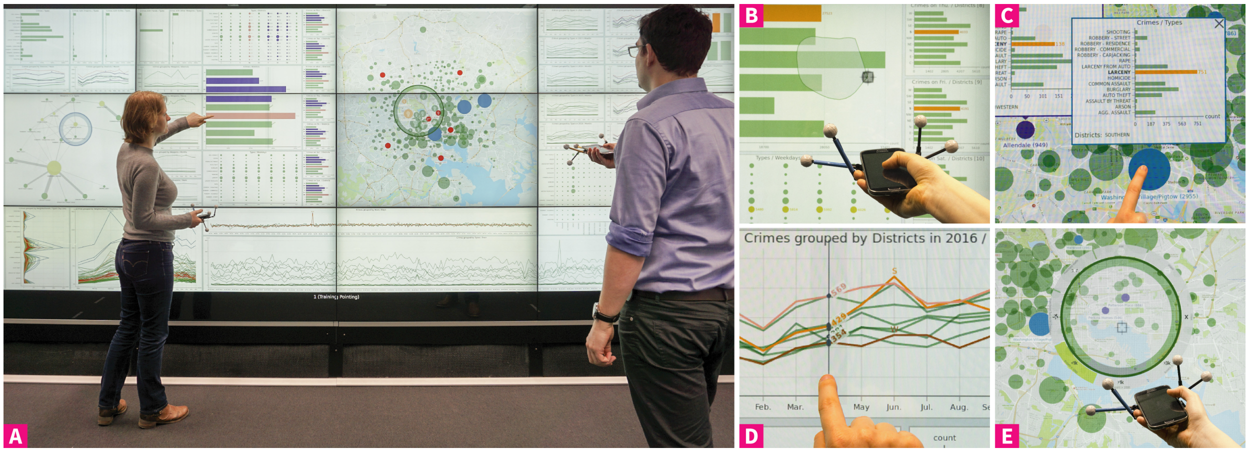


Fig. 1. **Multi-user MCV application on an interactive wall-sized display:** (a) Interaction from close (touch) and a distance (mobile device); (b) 'Lasso' selection tool; (c) Details on demand; (d) Interactive ruler for value comparison; and (e) Magic lens with menu.

Abstract—Interactive wall-sized displays benefit data visualization. Due to their sheer display size, they make it possible to show large amounts of data in multiple coordinated views (MCV) and facilitate collaborative data analysis. In this work, we propose a set of important design considerations and contribute a fundamental input vocabulary and interaction mapping for MCV functionality. We also developed a fully functional application with more than 45 coordinated views visualizing a real-world, multivariate data set of crime activities, which we used in a comprehensive qualitative user study investigating how pairs of users behave. Most importantly, we found that flexible movement is essential and—depending on user goals—is connected to collaboration, perception, and interaction. Therefore, we argue that for future systems interaction from the distance is required and needs good support. We show that our consistent design for both direct touch at the large display and distant interaction using mobile phones enables the seamless exploration of large-scale MCV at wall-sized displays. Our MCV application builds on design aspects such as simplicity, flexibility, and visual consistency and, therefore, supports realistic workflows. We believe that in the future, many visual data analysis scenarios will benefit from wall-sized displays presenting numerous coordinated visualizations, for which our findings provide a valuable foundation.

Index Terms—Multiple coordinated views, wall-sized displays, mobile devices, distant interaction, physical navigation, user behavior, user movements, multi-user, collaborative data analysis.

1 Introduction

Interactive wall-sized displays (referred throughout the paper as large or wall-sized displays) have immense potential for information visualization (InfoVis) and visual data analysis. In particular, the combination of extensive size—up to several meters—plus high resolution enables the presentation of large amounts of data and a multitude of visualization views, so it can also trigger increased quantity and quality of insights [52]. At the same time, those displays require user input beyond mouse and keyboard, typically interaction that apply principles of natural user interfaces (NUI) for InfoVis [40, 56]. A common way of making large displays interactive is the use of direct touch interaction. Furthermore, it has been shown that users naturally move in front of large displays in form of *physical navigation* [7, 52] and that they expect to get system reactions from afar [47], which is why we argue to seriously consider interactions at varying distances. Besides users' perception [10], previous research on data visualization for large displays mainly focused on different input modalities, such as touch interaction [49], mid-air gestures [4], body movements [4, 30, 35, 41], or mobile device interactions [24, 34]. While each modality has both advantages and drawbacks, only a few works [4, 34] made use of more than one input modality. This is especially critical as it is a reasonable way to address the previously mentioned need for interactions at varying distances. As a result, we yet have little or no knowledge of how users behave and move in front of wall-sized displays while exploring large amounts of data or views, when or from which position they want to interact, and how user tasks or goals relate to such user movement. Also, in many cases, the large display only shows a moderate number of views, which is surprising considering the extensive display size.

Another benefit of wall-sized displays is their suitability for collaborative data analysis as multiple users can access and interact with the display at the same time. Until now, collaboration with large displays often focuses on other application areas (e.g., [23, 27, 39, 43, 62]), while collaboration for InfoVis has mostly been investigated on and around interactive tabletop surfaces (e.g., [26, 67, 68]). Depending on current goals, tasks, and strategies, users collaborate in various styles of interaction [26], which can generally be categorized into closely coupled or loosely coupled collaboration (i.e., working closely together or parallel

• *Ricardo Langner, Ulrike Kister, and Raimund Dachselt are with the Interactive Media Lab at the Technische Universität Dresden, Germany. E-mail: {langner, kister, dachselt}@acm.org.*

This is the accepted version of the article. The definitive version of record is published in *IEEE Transactions on Visualization and Computer Graphics*, Volume 25, Issue 1. doi:10.1109/TVCG.2018.2865235.

work). However, it is yet unclear how multiple users proceed to explore several visualization views on large displays as well as how a team of analysts behaves and moves in front of the display, especially when considering the flexibility and freedom to decide from which position or distance they want to interact.

The concept of *multiple coordinated views* (MCV) is an essential tool for visualizing and analyzing multivariate data, and we argue it would particularly benefit from the increased screen real estate. We therefore specifically selected this concept and investigate how multiple users interact with MCV on interactive wall-sized displays. We envision that in the future many visual data analysis scenarios will take advantage of large displays: (i) to present large amounts of information and dozens of visualization views and (ii) to allow teams of analysts to freely move and walk around as well as explore data from varying distances via both touching the display directly and interacting from a distance. To realize distant interaction, we suggest using mobile devices such as smartphones as they are widely used, easily available, have great wireless connectivity, sensors provide information about surroundings, and most importantly they support the same type of input modality (touch input). We imagine that analysts bring their own smartphone to working sessions, point it towards the large display and interact from a distance by performing touch gestures on their hand-held device. As a step towards this idea and to explore basic user behavior and movement as well as the demands regarding distant interaction for InfoVis-related tasks, we address three essential components: a design, an application, and a user study. Consequently, our primary contributions are:

- **Design:** We first highlight and discuss important design considerations when bringing MCV to large displays including aspects of visual and interaction consistency, use of visual variables, and multi-user requirements. We then propose an interaction concept for working with MCV from varying positions and distances. We carefully construct a consistent set of interaction techniques for direct touch and distant device interaction using mobile devices. This design focuses on interactions with components that are essential for data analysis, such as data items, analysis tools, and views.
- **Application:** We present a fully functional MCV application with a large number of coordinated views (>45) visualizing a real-world, multivariate data set of crime activities. This prototype implementation demonstrates the applicability of the design considerations to an application case. It enables the study of user behavior and movement in a setting with realistic workflows and data analysis processes.
- **User Study:** Finally, we report on observations and results of an empirical investigation with pairs of users working together to explore a multivariate data set. We discuss aspects of behavior including movement, strategies, and communication as well as observations regarding the use of direct touch and distant interaction for InfoVis-specific tasks and actions.

2 Background

By building on research at the intersection of information visualization and natural user interfaces, we review prior work with a focus on (i) large vertical displays and (ii) collaboration at interactive displays.

2.1 Information Visualization on Large Vertical Displays

There is ample evidence of the potential of large vertical displays for visualization: Many recent works have asserted the positive impact of display size for sensemaking [1], immersive observation and comparison of data [52], as well as exploratory visual analysis [53], with increasing effect for complex tasks [44]. One important reason is the use of *physical navigation* and the resulting performance improvements including advantages for spatial memory [6, 7, 28]. Especially due to this movement, however, bringing InfoVis to wall-sized displays requires rethinking of visualization design, perception, and interaction techniques [2]. Main issues regard the perception of visual variables and visual encoding that are very dependent on distance and viewing angle [10, 19]. As a result, the spatial grouping has to be especially considered for scaling data visualization to large displays [79].

Furthermore, applications for novel display environments also benefit from natural user interfaces (NUI) and interactions beyond the desktop [31,40,56]. These interfaces have a range of advantages, make interactions with data and tools more direct and thereby allow for reducing the use of complex interface components such as menus [18]. The most predominant novel input modality is *touch interaction* and a number of interactive wall-sized displays rely on touch for main interaction (e.g., [13,24,27,43,49]). Especially visualization on tablets was shown to benefit from this type of interaction [9,18,58,59], while it was also combined with other modalities such as pen [77] or speech [64].

User Movements and Proxemics: Due to the impact and natural use of physical navigation, research has also focused on understanding and interpreting *proxemics*. While this term has originally be defined for user-user distances [21], it has also been applied to user-display proximity and interpretation of movement for interaction [20,47]. For InfoVis specifically, the users' physical distance to a large display can be used to, for example, increase level of detail when stepping closer [13,30]. Beside basic body movement, mid-air gestures can be used from the distance. However, it has been shown that users only rely on them when interaction cost is high (long movement or standing up to touch the display) [29]. Novel systems have started to build on body movement for exploring information spaces, for instance, to select visualizations on a slice of the wall-sized display [17], control a magic lens using mid-air gestures and body movement [35], or move individual views in an MCV using explicit hand gestures and collaboration concepts [4]. However, these solutions are very exploratory and less likely to be used in practical InfoVis applications soon.

Additional Mobile Devices and Cross-Device Interaction: An alternative way of addressing physical navigation and the resulting challenge of distant interaction is the use of additional mobile devices, creating multi-device environments. While these mobile devices can be used in combination with each other [22,38], their addition to large displays is especially beneficial as they provide a hand-held interface component at any position in front of the display. The connection between the devices can be initiated by direct contact with the large display [60], by coupling the device through the user, e.g., using the connection of the touching hand [24, 74], or by pointing at the display [33, 39, 63]. In this setup, a device can play different roles. In a strong connection, it can be used to enter input [45] and control parameters [74]. Instead of touch, additional tangibles on the mobile screen [32] or body-worn remote controllers [36] can enable 'eyes-free' parametrization. Furthermore, transferring content can also be accomplished through the mobile device [16]. This may also include flexible arrangement and control of an item or cursor through the device's movement [8,39] or by using the device as a trackpad [12,63]. Building specifically on movement, selections at different scales can be made depending on user's distance to the display—'linking the scale of perception with that of interaction' [48]. Most related work aimed to use the display of the mobile device for *separate content visualization* including detailed information or selected parts of the data at high-resolution [24, 34, 73, 74]. The large display presents a context visualization giving an overview, while mobile devices are used to show excerpts (details) [14], adapted views with additional content [5], or views resulting from analysis tools [34].

2.2 Collaboration at Interactive Displays

It has been shown that collaboration for data analysis has great benefit and increases the number and quality of insights [15, 26]. When collaborating, users have been noticed to separate the space on a table into varying territories [61], which was similarly observed for collaboration at vertical displays [3]. However, these territories are transient as people move around [27]. Different coupling styles have been found for collaborative data analysis with the main category describing whether users work closely together or separate from each another for parallel work, refined as closely and loosely coupled collaboration [26, 67], respectively. It has further been shown that distance between users has an impact on effectiveness of collaboration [23], specifically closely coupled collaboration improves when being physically close. This closeness has been observed to be naturally adopted by collaborating users [76]. Additionally, when working together and exchanging information, users naturally position themselves in so called f-formations [46], which can be evaluated to identify users' intentions. When working in parallel, challenges regarding territoriality [27] arise, as well as additional coordination costs especially for interactions with large 'visual footprint' [49].

While in the context of collaborative data analysis (e.g., [68]) many solutions focused on tabletop setups, recent systems also address collaboration at wall-sized displays and present tools to support collaboration (e.g., [13, 35, 43]). For visualization, this setup was applied to investigate selections by multiple users in node-link diagrams [49], which resulted in positive effects as users could discuss each others work after loosely coupled and parallel interactions. When comparing a large display with multiple desktop interfaces for path-finding tasks with pairs of users [50], the quality of insights was very high from the start when using the large display, but efficiency decreased due to required communication and coordination. However, users generally consider collaboration and communication to be worthwhile [42], as collaborative gestures can enhance interactions even though they may require additional coordination effort (e.g., [43]).

3 Bringing Large-Scale MCV to Wall-Sized Displays

Multiple coordinated views (MCV) are an important solution to exploratory visualization [55]: Operations and interactions are synchronized across a number of visualization views by using mechanisms such as linked brushing. Interactive wall-sized displays provide several meters of display space, making it possible to present plenty of those views and support collaborative data analysis. When bringing such large-scale MCV to large displays, there are, however, specific aspects and challenges to consider, which we will discuss briefly. These aspects (A1-A5) form design considerations and goals that our system—and most likely any similar system—needs to address.

(A1) **Visual Simplicity and Layout** A large number of views can quickly increase visual complexity of interfaces. As a result, systematic grouping and layout of views becomes important, especially since not all views can be perceived at the same time. An initial grouping can easily be realized using semantic view information, such as visualization technique, view title, or shown data attribute. However, since views rarely contain only one attribute, grouping can be ambiguous. Consistency between views also reduces complexity [51], which includes adapting scales and color schemes to ease transition and comparison between views. *We propose that MCV applications should provide initial view layouts that are tailored to specific use cases and, if reasonable, allow manipulations such as swap positions or resize afterwards.*

(A2) **Movement and Flexible Distance** As one of the most important aspects of our work, this results from an interplay of 'good perception' and 'good interaction'. We argue that it is almost impossible, but certainly uncomfortable, to stay in close proximity or touch distance all the time because of the extensive display size and a person's field of view. Users move and adapt positions according to their needs, for instance, to read details or get an overview. For interaction, this user movement as well as reachability issues of large displays at corners or borders are major challenges, as it is difficult to support these aspects by direct touch interaction alone. Therefore, we should aim to provide good interaction from any position in order to avoid frustration. *More specifically, we suggest applications that enable flexibility and freedom in a way that users can individually decide from which position and distance they want to interact with the visualizations.*

(A3) **Simplicity in Interaction** While visualizations can become complex, interaction should be as easy as possible by, for example, building on established methods and gestures. This also entails consistency for solutions with traditional interfaces and, in particular, interaction mappings using multiple input modalities. Besides simplicity and following consistent metaphors or mental models, redundancy can aid the adaptation to diverse user preferences. *We thus suggest avoiding the use of complex or movement-intensive gestures in favor of a very basic interaction vocabulary and consider the general principle of mapping simple interactions to functions that are most frequently used.*

(A4) **Influence of Visual Variables** While the number of presentable views is an advantage of large displays, it is also a challenge regarding the need to guide users towards content and make connections visible. This is especially relevant when close to the display, as more content lies beyond the user's field of view, but also when being further from the display where changes have to be perceivable from afar. At the same time, the selection of visual variables and visual encodings needs to consider issues of perceptual scalability, which result from distance and the variety of viewing angles [10, 19]. *We think that color could be a prominent variable, independent from distance to the display, to guide attention and show links between visualizations, which then would not really be available for encoding data.*

(A5) **Support for Multiple Users** To enable collaboration at wall-sized displays, phases of varying collaboration styles have to be considered [26, 67]. Therefore, interaction with MCV also needs to support parallel work, especially when designing for multiple selections. This entails to rethink linked brushing in order to enable different selection sets. For example, Isenberg and Fisher [25] introduce user-specific color schemes for selections to support the understanding and awareness of collaborative interaction. Furthermore, all otherwise global interactions may require local solutions, for instance, regional undo and redo operations [62]. *In connection with A3, we suggest basic MCV functionalities such as linked brushing need to be compatible with varying collaboration styles using simple means, before introducing additional, specialized collaboration tools.*

4 Interaction Design for Large-Scale MCV

After presenting important design considerations when bringing MCV to large displays, we now contribute a concrete interaction design that builds upon these considerations. For this design, we envision an interactive wall-sized display showing plenty of multiple coordinated views arranged over the entire screen space and allowing interaction from varying distances. For this, we combine two input modalities in a seamless way: *direct touch* on the large display (TOUCH) and *distant interaction* using mobile devices (DISTANT). With this design we also:

- Describe a new InfoVis interface for large-scale MCV on large displays. Although individual aspects build on prior work, we carefully selected and combined different approaches.
- Explore possibilities of an intentionally small and basic interaction vocabulary (A3) that nevertheless enables both interactions close to the display and farther away (A2).
- Present a specific but exemplary mapping of touch input to MCV functionalities, which serves as a basis for a functional and practical application enabling realistic data analysis workflows.

We generally aim to only use established or classic touch gestures (A3), such as Tap, Hold, Drag, or Pinch, no matter from where users interact (TOUCH or DISTANT). Fig. 2 illustrates the interaction vocabulary for both input modalities and gives an overview of deployed gestures. We address user movement and flexible distances (A2) by suggesting both a TOUCH and a DISTANT gesture for each application function.

4.1 Interaction Style and Vocabulary

As a supplement to direct touch at the large display (TOUCH), the basic idea of how users interact with MCV from varying distances is to understand the use of a smartphone as an extension of an arm's reach. Similar to laser pointers, users point the mobile device towards the wall-sized display and trigger actions by touching its screen. We wanted to enable a casual and loose interaction style [39]: Hold the mobile device in one hand and in a relaxed way (close to the body, at hip height or in front of the body). Since gaze switches between devices are time-consuming [66], we suggest touch gestures on phones are 'eyes-free' (e.g., [45, 65]), i.e., users can perform input such as Tap, Hold, or Swipe anywhere on the smartphone without looking down at its screen. Relating to the design aspects A2 and A3, our goal was to develop a consistent interaction mapping for TOUCH and DISTANT. Once users know and understand how to interact with one of the modalities, they should be able to easily perform the same actions with the other one. To further consider simplicity (A3), we make use of an intentionally small and basic interaction vocabulary (Fig. 2 top) for both TOUCH and DISTANT. We selected the following individual distant interactions as functional equivalents for common direct touch interaction.

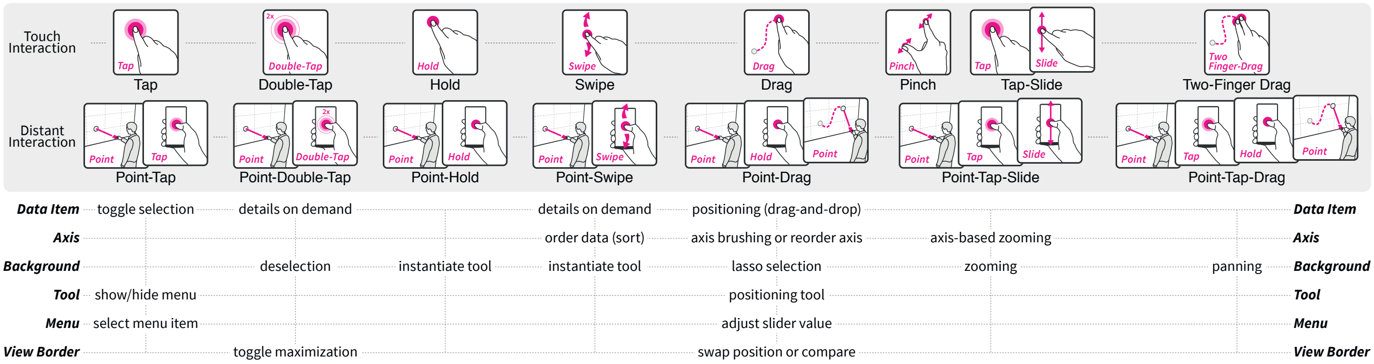


Fig. 2. **Interaction design*** **for MCV on wall-sized displays:** *(top)* The basic interaction vocabulary for direct touch interaction (TOUCH) and distant interaction (DISTANT), alignment indicates functional equality; *(bottom)* Mapping of interactions to specific functionalities of the application based on the visual context (interface element). * *Please also refer to the accompanying video.*

Point-Tap & Point-Double-Tap: Distant interactions for triggering a discrete tap gesture. Users point towards a target and then tap once or twice on the mobile device.

Point-Hold: The hold gesture is recognized as a discrete event at a specific position. Users point towards a target, then touch the screen of the mobile device for a certain duration.

Point-Swipe: Again, this is used for discrete interactions. Users point towards a target, touch the mobile's screen, and quickly swipe upwards or downwards on the mobile device.

Point-Drag: This continuous interaction uses Point-Hold and enables drag-and-drop functionality by moving the mobile device. Users point toward a target and perform a hold on the device, then the pointing cursor can be moved onto another position on the wall-sized display.

Point-Tap-Slide: The identical touch gesture (Tap-Slide) of this continuous interaction is used in the popular mobile app 'Google Maps' as well as other research prototypes (e.g., [58]), primarily designed as an alternative to the pinch gesture allowing zooming with a single finger. Users point towards a target, tap once on the mobile devices and then continuously slide a finger up and downwards on the device.

Point-Tap-Drag: In contrast to Point-Tap-Slide, the final movement or drag of this continuous interaction is performed by moving the device. Users point towards a target, tap once on the mobile devices, then perform a hold on the device, and finally move the cursor to another position on the large display by pointing.

4.2 Interaction with Visual Elements of Views

Interaction with visual elements of visualizations is essential for InfoVis. Drucker et al. [18] show that direct interaction on such elements is a valuable alternative to the use of menus, dialogs, or other WIMP-style components. This usually includes data items, labels, axes, or backgrounds of visualizations. Fig. 2 illustrates our mapping of interactions (top) to MCV functionalities (bottom).

Data Items: Interaction on data items allows selection and details on demand; in case of network visualizations or node-link diagrams also repositioning. As with most of today's applications, direct Tap or Point-Tap on items toggles a selection state (cf. selection operations [78]). A Double-Tap or Point-Double-Tap is used to access details on demand. Since DISTANT allows for alternative gestures at pointed locations, a Point-Swipe upwards also triggers details on demand, while a Point-Swipe downwards hides such extra information. Finally, if supported by a chart, a Drag or Point-Drag of a data item is used to manipulate its position (e.g., exploring a network visualization).

Axes: As proposed by Sadana and Stasko [58, 59], axes of plots can be used for selection and zooming. A Drag or Point-Drag along an axis selects multiple items (axis brushing, e.g., [59]). A Swipe or Point-Swipe along an axis orders data items. In charts such as parallel coordinate plots, axes can be reordered by an orthogonal Drag or Point-Drag. For TOUCH, axis-based zooming can be applied with a Pinch [58] gesture. However, since for DISTANT a Pinch would enforce two-handed interaction and restrict users freedom (A3), we additionally propose using a Tap-Slide or Point-Tap-Slide.

Canvas Background: Interaction on view backgrounds typically affects multiple items at once. For instance, a simple Drag or Point-Drag on the background can enable a 'lasso' selection tool: Users draw a shape onto the plot (encircle); when finished, items within or crossing the shape are selected. In addition, items can be deselected using a Double-Tap or Point-Double-Tap on the background. Furthermore, since the 'lasso' selection uses Drag or Point-Drag, an alternative for panning zoomable visualizations is needed. Many current touch-enabled web applications already pursue the strategy of using one-finger gestures for page navigation (Drag) and two-finger gestures zoom-and-pan (Pinch and two-finger Drag). Thus for TOUCH, we suggest using Pinch and two-finger Drag for zoom-and-pan, while for DISTANT Point-Tap-Slide can be used for zooming and Point-Tap-Drag for panning.

4.3 Control of Analysis Tools

The canvas background is also an appropriate interface element to instantiate interactive analysis tools (e.g., [54, 57, 71, 72]) functioning on visualizations. We selected interactive rulers and magic lenses (Fig. 1d+e) as representatives to describe how such analysis tools can be operated, because they require typical actions such as tool positioning and configuration. Interactive rulers are movable lines used to, for example, access values of data points (line charts) or colorize items below or above a certain threshold (bar charts).

Instantiation, Positioning, and Removal: Generally, a Hold or Point-Hold can be used to instantiate tools, which can then be positioned by drag-and-drop (Drag or Point-Drag). Distant interaction again allows for alternatives: A Point-Swipe upwards also opens a tool—in the sense of pushing a tool towards the large displays. Depending on the tool itself, other approaches can be useful. For instance, standard graphics design software allows to create guides by dragging them out of a ruler border region, which can be applied for interactive rulers in a similar way: A Hold or Point-Hold on an axis seamlessly followed by a Drag or Point-Drag creates and moves a ruler into the plot. An easy way for TOUCH and DISTANT to remove tools from visualizations is to simply drag them outside the plot, or in the case of DISTANT, a Point-Swipe downwards can be used alternatively.

Configuration: Tools typically allow users to configure parameters. Traditionally, this involves a menu with several entries allowing to activate or deactivate functions, select values from lists, or set numeric values, which we hence also incorporate in this design. For magic lenses, a configuration menu lets users activate lens functions and adjust specific parameters [71], such as zoom factor for fisheye lenses, attribute values for filter lenses, or opacity for local edge lenses [69]. A menu for interactive rulers could allow, for example, selecting the color for items below or above the ruler or whether to show values for intersected data items. Once a tool is instantiated, a Tap or Point-Tap on the tool toggles the visibility of the corresponding configuration menu. Again, an alternative for this is to perform a Point-Swipe upwards (show) or downwards (hide) on the tool. A simple Tap or Point-Tap allows interacting with menu items in order to access submenus, toggle buttons, or

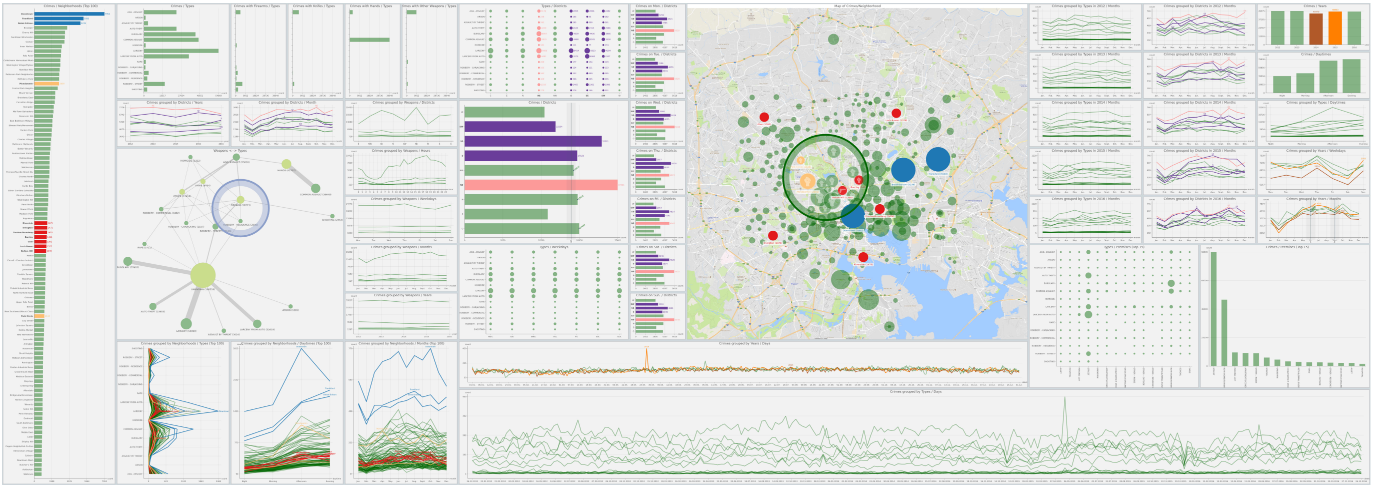


Fig. 3. **Complete screenshot of the implemented prototype**: All views are linked by default, green is used a base color for visualizations, while other colors highlight selected data items. A magic lens on the map augments neighborhoods (circles) with icons for the highest weapon type.

select list items. Sliders for the manipulation of numeric values can be controlled using a Drag or Point-Drag gesture.

4.4 Interaction with Visualization Views

As mentioned (A1), some use cases certainly benefit from the possibility to rearrange views as part of the exploration process. While view management is not the focus of this work, we present a few examples to illustrate the usefulness of our basic vocabulary. For interaction with views, we generally suggest using the border region of visualizations (i.e., padding or whitespace) as a handle. The most common way to arrange MCV is a grid layout. A basic operation on grids is to swap positions of two views, where we suggest to simply Drag (or Point-Drag) a view and finish the gesture on top of another (drag-and-drop). Dropping the view on a cell border instead allows to choose between view settings for visual comparison such as side-by-side, shine-through, or folding [70]. A temporary maximization of a view (fullscreen) can be achieved with a Double-Tap or Point-Double-Tap, which is applied similar to windows on classic desktop systems.

5 Data Set and Prototype Implementation

So far, we presented a seamless interaction concept for large-scale MCV on wall-sized displays. Now, we briefly describe our fully functional application, which demonstrates how our concept can be realized. Our high-fidelity prototype shows a real-world, multivariate data collection of crime activities in 47 coordinated views and implements essential MCV functionality that enables realistic and practical use (see Fig. 3).

As **data**, we use a real-world victim-based crime data set[1]. In a preparation step, we cleaned up data and excluded crimes from the incomplete year 2017. As a result, the data set consists of approximately 242k individual crimes (data items) between the years 2012 and 2016 as well as 15 dimensions, such as date, time, location, crime type (code), weapon, district, and neighborhood. Visualizations of this data set can be used by very different people and for diverse purposes, including but not limited to planning of police activities and crime prevention, governmental administration regarding prognosis of financing, as well as citizens concerned with quality of life or safety in neighborhoods. In particular, we think that both the subject and complexity of the data make this collection very appropriate for a mainstream audience.

For the fully functional **prototype**, we use Python and the open source high-level development platform libavg[2], which offers great support for touch input and graphics-intensive applications. We also scripted a basic grid system dividing the screen into 24×12 cells and realized five different types of visualizations: Bar chart (vertically and horizontally), line chart, scatterplot, map visualization, and node-link diagram. All charts are synchronized and linked with each other, dynamically scale according to assigned display space, as well as allow the configuration of the data mapping (e.g., scales, input and output range, clamping, ticks, sorting) and visual appearance (e.g., location of axes, colors, spacing, thickness, shape). We actively designed all visualizations to be homogeneous in terms of mapping and appearance (A1). By using green as a base color, we specifically ensure that the visual variable color is free to emphasize connections through linked brushing (A4). To enable parallel data selection, we created a basic multi-selection tool that allows for several selection sets of data items over the entire MCV. Sets are shared among users—they are not assigned to individuals. While selections triggered by Tap or Point-Tap within a 3.5 s interval add or remove items to/from a current set, taps inside other views or 'lasso' selections (Fig. 1b) always create new selections. Each set is highlighted using a predefined list of colors.

Furthermore, positions of items in a node-link diagram can be manipulated and zooming and panning works on maps, which use background images from Google Maps. Our application handles all input gestures and functionalities mapped to interactions with data items, background, tool, and menu (see Fig. 2). Interactions on axes allow the creation of interactive rulers (Drag or Point-Drag from an axis into the plot); sort, axis brush, or axis-based zoom are not implemented yet. Rulers (Fig. 1d) work on bar charts, line charts, and scatterplots; magic lenses (Fig. 1e) and details on demand (Fig. 1c) are available on maps.

While the application also supports platforms such as desktop computers, we principally developed it for our large, touch-enabled display wall, which consists of twelve 55" displays (Fig. 1a). It has a size of $4.9\,\text{m} \times 2.0\,\text{m}$ with a resolution of 7680×3240 pixels and is driven by a workstation PC running Ubuntu. We also used different Android smartphones with simple mobile apps displaying blank screens and directly sending touch input to the PC. To enable pointing from a distance, we tracked phone locations using a motion capture system[3]. Although this required instrumenting phones with reflective markers (e.g., Fig. 1b+e), it provided absolute, high-precision positions without drift or offset over time. However, sensor technology continuously develops and Google's project Tango or Microsoft's HoloLens demonstrate that for future applications external tracking will no longer be necessary.

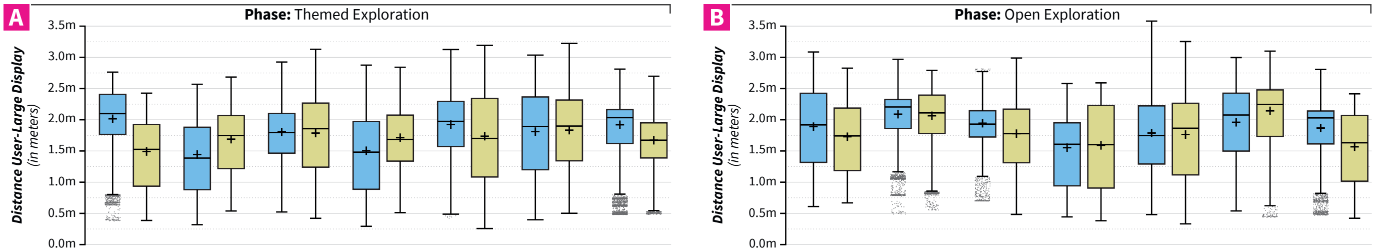
6 User Study: Goals and Methodology

We conducted a qualitative user study to learn how people use a visualization interface that specifically allows interactions from close proximity as well as overview distances. In particular, we were interested in how users behave and interact while exploring data on a

[1]Victim Based Crime Data by Baltimore Police Department (08/25/17), licensed under CC BY 3.0, source https://data.baltimorecity.gov/

[2]Development platform libavg: http://libavg.de/

[3]Motion capture system (http://www.optitrack.com/) with 12 infrared cameras mounted to the ceiling



A — Phase: Themed Exploration

Participant	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
TOUCH (in %)	34.3	92.6	93.4	63.9	25.0	66.9	81.2	50.3	80.0	88.2	75.5	60.7	9.4	51.0
DISTANT (in %)	65.7	7.4	6.6	36.1	75.0	33.1	18.8	49.7	20.0	11.8	24.5	39.3	90.6	49.0
# touch downs	70	149	122	108	192	130	117	173	50	170	94	163	234	98
walked (in m)	136	145	188	195	204	287	259	217	208	373	269	257	168	232
Duration	20 min.		21 min.		30 min.		28 min.		25 min.		28 min.		37 min.	

B — Phase: Open Exploration

Participant	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
TOUCH (in %)	62.0	83.3	23.5	4.9	10.3	52.4	100.0	79.6	84.8	95.5	94.8	71.4	22.2	85.4
DISTANT (in %)	38.0	16.7	76.5	95.1	89.7	47.6	0.0	20.4	15.2	4.5.0	5.2	28.6	77.8	14.6
# touch downs	50	48	17	41	29	63	14	54	46	66	58	7	45	48
walked (in m)	89	84	39	38	73	106	70	69	84	139	120	77	50	88
Duration	13 min.		7 min.		12 min.		8 min.		10 min.		11 min.		10 min.	

Fig. 4. **Data analysis** for phases (a) *themed exploration* and (b) *open exploration*. Box plots with Tukey-style whiskers ($1.5 \times$ IQR) show the distance in meters between participants (P1-14) and the large display. The table shows for each participant the proportion of direct touch (TOUCH) and distant interactions (DISTANT), total number of performed input gestures (e.g., tap, drag), approximated walking distance in meters, and duration per team.

wall-sized display. The following questions motivated our study: How much/often do users move? In which direction do they move? Do they work from varying distances? Which tasks or actions are carried out from a distance? When is pointing from afar preferred over direct touch at the display? How do multiple users explore data collaboratively? How do they stand or move together? Do they interact simultaneously?

Thus, we decided to observe pairs of users exploring data collaboratively. Teams of two already allow observing typical collaboration behavior, while not entailing more diverse coupling styles or complex formations. We also wanted to ensure that all users interact with the system actively and avoid pure observers. Finally, we wanted to reduce confounding variables and keep analysis manageable. As a result, we focused on different behavioral aspects, such as *user positions and movements* (spatial relations user-display and user-user), *collaboration styles* (close or loose), *interaction styles* (casual or focused), and *interaction modality* (TOUCH or DISTANT).

We conducted four pilot study runs. In a first run we assessed the overall procedure and duration, after which we decided to skip zoom and pan tasks to reduce training time. The next two runs were used to test various mappings for the pointing position including distance-dependent pointing [39]. We finally selected plain perspective pointing with smoothed data using a 1€ filter [11], since it was much more self-explanatory (A3) and better fits the design idea of extending the arm's reach. The last run was then used to validate that all interactions were feasible using distant interaction only. It showed that participants could easily achieve all interactions within an average time.

6.1 Participants

In addition to the 8 participants from the pilot study, 14 students (3 female, 11 male) from four different departments of the local university (6 psychology, 5 computer science, 2 mechanical engineering, 1 civil engineering) volunteered in the user study. They were generally interested in the topic of information visualization and human-computer interaction, were recruited via mailing lists and social media channels, and did not receive any payment. The average age of our 14 main participants was 24 years ($M = 23.57$, $SD = 1.55$), the self-reported height ranged from 164 cm to 198 cm ($M = 181.64$, $SD = 8.29$), and one participant was left-handed. Five participants were familiar with a wide range of visualization techniques, another five had intermediate InfoVis knowledge, while four had little to no experience with visual data analysis. All participants had normal or corrected-to-normal vision and none reported other physical impairments, such as hand jitter. We ensured that members of each team knew each other, so they were either friends or had worked together in the past.

6.2 Apparatus

The study was conducted in a quiet lab environment, where we used the technical setup, prototype, and data set as described above. Both mobile devices (identical 5" Samsung Galaxy S4, 130 g, $137 \times 70 \times 7.9$ mm) were connected with the application PC via WLAN. The lower display border was at a height of 0.39 m and the upper at 2.45 m. Duplicated task descriptions were presented on the top and bottom (at height of approx. 0.52 m and 2.4 m) of the wall-sized display using white text color and a font size of 15 mm (x-height). The smallest text within visualizations had a font size of 9.5 mm (x-height). In addition to the motion capture system, which covered a space of approximately 5.3×3.5 m in front of the large display, a Kinect sensor tracked participants from behind (centered, 4.8 m from large display, 1.5 m above ground). Furthermore, two ordinary desktop computers in the corners of the room were used for electronic questionnaires and a table for two experimenters was located beside participants' interaction space.

6.3 Procedure and Tasks

Sessions took on average 85 min and began with a general explanation of the data, its dimensions, and the basic view layout. This was the only time that the experimenter was within the participants' interaction space. After that, both experimenters (one recording observations) were sitting at a table placed aside to avoid any influence on participants' movements. The following procedure was divided into three interaction phases: Training, themed exploration, and open exploration.

Training: This phase (avg. 28 min) contained training of TOUCH and DISTANT interaction separately. The order of these modalities was counterbalanced between sessions. Initial explanations and calls to action were read by the experimenter. Participants could ask questions and individually retry each interaction until they felt they had understood the action. Finally, each training ended with a set of tasks per participant where each of them was asked to perform four actions, e.g., "Select the neighborhood with the highest sum of crimes in Octobers.". These tasks were also used to validate that participants had understood the general layout of the views and could find the mentioned data items.

Themed Exploration: This phase (avg. 27 min) included six question blocks (order randomized over sessions) with each three to five questions forming a logical workflow, for example: (1) "How many crimes were committed with each of the given weapons?", (2) "Did the number of crimes with firearms increase over time?", (3) "Which crime types are committed using firearms?", and (4) "How do crimes of these crime types differ in terms of time of day?" Participants were instructed to clearly declare when they could answer a question and pronounce the result. That is, answers were not registered according to specific interactions but could be discussed among the participants until they were sure to have found the result.

Open Exploration: This phase (avg. 10 min) consisted of four hypotheses, which were randomized over sessions and presented to the participants one by one, for example, "A snow storm in January 2016 lead to a decrease of criminal activity." Users were encouraged to explore data to find evidence on whether to confirm or reject a hypothesis. To validate theses, participants often had to regard different views and connect information, or make assumptions and find supporting facts.

All tasks within the study phases were presented both at the top and bottom of the large display for comfortable reading. After an initial survey concerning demographics and experience, participants filled out questionnaires after each modality training to rate the interaction mapping and perceived comfort of interactions. A final questionnaire after the open exploration phase allowed to assess physical and mental demand and ease of use (Raw NASA TLX), evaluate their preference between TOUCH and DISTANT, as well as rate the general system.

6.4 Collected and Derived Data

Each session was video and audio recorded. Collected raw data consists of both user positions in front of the large display (all body joints as recorded by Kinect sensor) and spatial device positions (6DOF) with a sampling rate of 12 Hz. Additionally, detailed descriptions of higher level application events (e.g., data item selected, ruler created) as well as touch input events (e.g., 2D position, type such as tap, hold or swipe) for the large display and both mobile devices were logged. While each session was accompanied by two to three researchers, at least one exclusively observed behaviors of participants and took notes in a semi-structured protocol. Based on this collected data, we derived statistical values per participant and team including event-based information such as number of selections/deselections or completion times for individual study phases, distances relating to display-user, display-device, and user-user, and interaction phases (counts and time span) of using either TOUCH or DISTANT interaction.

7 Results: User Behavior and Usage Patterns

7.1 Data Analysis Method

The following analysis of study data was conducted on the basis of protocol notes, questionnaire answers, collected and derived data from tracking users and devices, and video data. We sorted and categorized the protocol notes of the experiments according to four main categories regarding (i) collaborative behavior or position, (ii) the users' workflows and strategies, (iii) comments focusing on interaction modality, and (iv) individual system functionalities. Each of these categories was divided into multiple sub-categories that evolved during grouping. To prepare for video coding, the recorded video data and collected tracking data were integrated into the open-source group analysis toolkit GIAnT [75], which we adapted and extended by various additional views allowing us to visualize correlation within the data and identify especially relevant or interesting time spans. In particular, the extended GIAnT[4] allowed us to see top views of left-right and distance movements as well as user-specific movement paths, a timeline of logged application events, TOUCH and DISTANT interactions per user on timeline and in display coordinates, heat maps of touches on the mobile device per user, and general statistic values per selected time span. Two experimenters then defined codes based on the grouped protocol notes and did an initial joint open coding run using GIAnT to iterate these codes and ensure consensus. This was followed by a closed coding phase, in which we analyzed exploration phases with a focus on reasons for both varying distances to the display and changes in user-user distances. Further aspects were hand postures and situations where users switched hands, joint and crossing movements of team members, as well as how participants solved issues of reachability at the large display.

7.2 Analysis of User Behavior and Movement

Movement and Physical Demand: On average, participants walked a distance of 438 m (SD=105 m) during the entire study session. Nevertheless, no participant complained about any fatigue or issues with standing or walking even when being asked explicitly during the debriefing. The questionnaire showed that participants generally found that they "moved a lot to answer the questions" ($M = 4.93$, $SD = 1.03$, scale 1-7). However, this was positively commented on: "It was very exciting, moving around was kind of activating to me" (P7) and "It was great that I could move around" (P12) who also highlighted the importance of movement for thinking. This is also confirmed as physical demand was rated low ($M = 3.36$, $SD = 1.44$, scale 1-10), while mental demand was at $M = 6.5$ ($SD = 1.76$). Tasks often included searching for and moving towards specific views. This implied more effort and movement, but orientation improved a lot over time and participants remembered relevant charts, e.g., "That's over there" (P8).

Distance Between Large Display and Users: The distance between users and large display varied (Fig. 4), but generally all teams preferred an 'overview distance' and stood quite far away from the display (*themed:* $M = 1.71$ m, $SD = 0.16$ m; *open:* $M = 1.81$ m, $SD = 0.18$ m). Independent of the used interaction modality, participants did not remain close to the display but mostly moved back and forth. This was especially the case at the start of a new tasks where people often stepped back. It is unclear if this occurred for reading or orientation reasons. Some participants specifically commented on losing an overview when standing in close proximity (P11: "Changes are not easily comprehensible when I am close to the large display"). This resulted in almost equally high values when users rated whether they often spent time 'close to the display' ($M = 4.29$, $SD = 0.96$, scale 1-7) or 'far from the display' ($M = 4.62$, $SD = 1.08$). Most participants indeed used physical navigation and approached the display especially to read and discern details, although text labels (x-height ≥ 9.5 mm) were designed to be readable from a distance of 3 m. We also observed people leaning forward (P4,7,10,12-14) or kneeling down (P2,11,12) to read details. In some cases it even seemed that people preferred to lean forward instead of taking another step towards the large display (P4).

Postures and Device Handling: Participants handled the mobile device in many different ways. During the themed exploration phase, eight of 14 participants used DISTANT for more than 30% of their interactions (Fig. 4a). For these, we observed four people loosely holding the device in one hand and sometimes even keeping the other hand in the pocket (P1,4,5,13), two operating the device with both hands (P6,12), and two frequently mixing between the styles (P8,14). We also saw a participant putting the hand with the device on the other forearm for stabilization and support (P11). When not interacting with it, many participants let the mobile hang down (P5-9,11,14) or held it behind their back (P9,11). Interestingly, even though the device pointer could be used, participants often pointed towards the large display with their hands/finger to draw attention to specific locations (P4,7-12).

7.3 Analysis of Collaboration Aspects

Team Work and Verbal Communication: Participants spent the majority of time in closely coupled collaboration. Teamwork was considered helpful for answering the questions ($M = 6.29$, $SD = 0.96$, scale 1-7) and team members strongly agreed that collaboration felt comfortable ($M = 6.86$, $SD = 0.35$). Besides common verbal communication, we noticed that people regularly gave instructions and direct commands to each other (P8: "Go over there and take a look", P11: "Could you please create a ruler", P14: "Could you please select [this]"). In fact, for two of the teams (P5+6,13+14) we observed situations where one member clearly led the exploration process by giving orders or instructions from the back, while the other team member performed the actions.

Distance and Formation of Team Members: Participants spent a lot of time in close proximity: Mean distance between users was on average 1.1 m ($SD = 0.14$ m). They principally remained together and often moved in parallel (Fig. 5b), even interacted simultaneously with the same chart (Fig. 6a). We also observed situations where one member controls a chart from a distance and the partner observes the

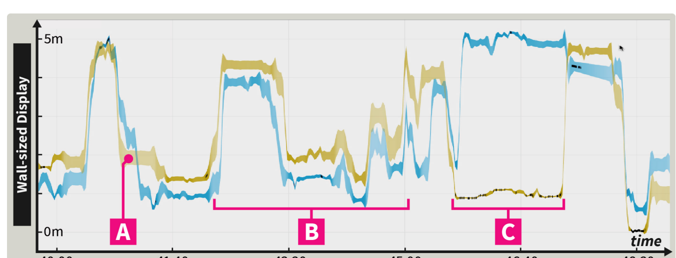


Fig. 5. **Left-right (LR) movement:** GIAnT view [75] shows users' (P7+8) movement over time, line width encodes distance to the display. (a) Crossing walking paths; (b) Moving in parallel; and (c) LR separation.

[4]Extended GIAnT: Detailed images can be found in the supplementary material; sources are available at https://github.com/imldresden/GIAnT

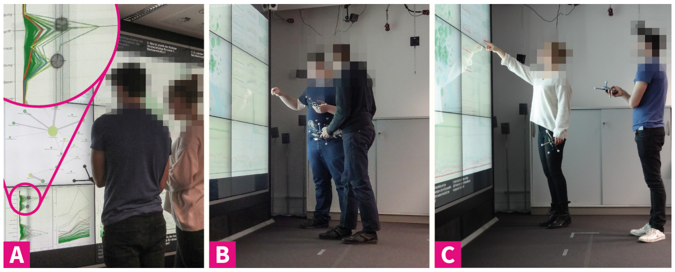


Fig. 6. **Typical study scenes:** (a) Simultaneous interaction on the same chart (see cursors); (b and c) Generally close collaboration, but with differences in group formation and used modality.

chart in close proximity and reads details (P11+12). Interestingly, this behavior was also frequently seen for interaction with lenses: one participant moved the lens with DISTANT interaction, while the other stood close to identify and select results (P1+2,5+6,13+14). Furthermore, sometimes teams started a task by standing far apart from each other identifying relevant charts. They, however, quickly switched to a closer work style as this seemed more efficient for them. We also observed 'presentation situations', where one team member was close to the large display and helped or explained details to the partner, who stood farther back (P3+4,5+6,13+14). In general, team members only rarely and very shortly separated from each other. These separations were sometimes triggered by (i) searching for appropriate views to answer the question or more often (ii) using a separate view for selection of aspects by one team member while the other identified different aspects in another chart (Fig. 5c). The latter describes situations where participants worked especially close together, despite the spatial distance (P3+4,5+6,7+8,11+12). In contrast to the definition of *same problem different areas* by Tang et al. [67], we observed lively conversations in such cases. For instance, one member selected crime types with firearms in the node-link diagram, while the partner compared highlighted crime types regarding time of day in another line chart.

Crossing Walking Paths: While participants generally moved together, active team members often advanced towards the chart first, making the partner follow. This often resulted in crossing of paths (Fig. 5a), which occurred independent of loose or close collaboration phases. Only two teams (P5+6,13+14) actively avoided crossing in front of their partner and therefore willingly put up with additional movement to walk around their back. The majority of participants had no problem crossing in front of their team member including repeatedly stepping into their line of sight when working together closely (P3+4,7+8,11+12). Crossing of paths also occurred in parallel work and could be seen especially when teams searched for a specific views or information. Even when using DISTANT interaction, participants passed their partner to achieve an orthogonal position towards the large display. However, we observed little to no conflicts between users resulting from movement.

Interaction Conflicts: A consequence of concurrent user actions is the risk of interaction conflicts. For one of the teams (P13+14), we observed problems in identifying the individual cursors and issues when both wanted to select data items simultaneously (e.g., one used touch and the other interacted from a distance). Despite these issues, we altogether saw fewer conflicts than originally expected. Basic social protocols and verbal coordinations served as effective, already existing mechanisms to prevent real conflicts. In a working team, people communicate and thus share possible action plans and ideas about start points for a data exploration. They also identify conflicts quickly and work around such issues, for instance, by organizing themselves between active (e.g., create and move a lens) and passive (read off information) interactions (P11+12).

Degree of Participation and Team Influence: While participants generally considered the work of the team 'balanced' (M = 5.93, SD = 0.88, scale 1-7), we noticed the actual number of interactions was uneven for some teams (P1+2,9+10,11+12,13+14, see Fig. 4a). However, we also observed that these team members were clearly engaged in the task and sometimes stood back for overview positions while the partner interacted. We further noticed that team members influence each other regarding interaction modality and distance to the wall-sized display. For instance, P13 was very quick and sure of his actions and strongly preferred DISTANT from afar, which resulted in P14 initially moving back with him using DISTANT until she was much more sure of her own actions and switched to TOUCH at the large display.

7.4 Analysis of Application Usage

Performance: All teams successfully answered the questions in approximately 40 min (M = 37.3 min, SD = 5.7 min) for both exploration phases. Teams often differed in the extent of how they justified their reasoning and how much they discussed their results among the team before answering. Overall, participants rated their own performance highly (M = 8.14, SD = 0.91, scale 1-10) and considered their work as requiring intermediate effort (M = 6.0, SD = 1.36).

Preferred Interaction Modality: In the exploration phases, nine participants preferred TOUCH (P2,3,7-12,14), as each initiated at least 70% of their interactions directly on the large display (see Fig. 4 for individual exploration phases). However, there were very diverse answers on whether 'TOUCH was used more than DISTANT' (M = 5.36, SD = 1.72, scale 1-7). Noteworthy, one team (P3+P4) completely switched their style of interaction from TOUCH to DISTANT between the themed and open exploration phase. When asked about individual application functionalities TOUCH was generally preferred for single selection (TOUCH: 10, DISTANT: 4) and ruler (TOUCH: 11, DISTANT: 3), while this was balanced for multi-selection (TOUCH: 8, DISTANT: 6) and lens interactions (TOUCH: 6, DISTANT: 7, abstention: 1). While TOUCH ratings were very consistent among participants, DISTANT ratings varied much more. Many participants had trouble selecting small items with DISTANT (M = 3.29, SD = 1.58, scale 1-7), but found larger, continuous interactions such as lens movement very easy (M = 6.31, SD = 0.72).

Selection of Data Items: Regarding the selection of data items, we noticed that both techniques, i.e., tapping items one by one or encircling multiple items with a 'lasso', were equally accepted. While some participants (P6) even used a lasso for single data items, others (P11) selected multiple nearby items by tapping each item successively. Since selections were synchronized between all appropriate views, we also observed that the selection of items and more importantly the resulting colored highlight was used to identify other task-relevant views (P1+2,5+6,11+12). Participants also utilized the feature of multiple but differently colored selections to compare data. In some situations, teams even renewed selections in a way that, for example, items are colored as different as possible (P11+12) or a group of items absolutely need to be highlighted identically (P11+12). However, in case of a visual overload because of to many selections, participants easily 'cleared up the interface' and thus reduced visual clutter by explicitly deselecting unnecessary or irrelevant data items.

Interactive Rulers and Magic Lenses: In context of analysis tools, interactive rulers were often used to identify items with specific properties (e.g., items above a value; P11+12), to easily compare items, or to read precise values of items. While rulers were predominantly created using TOUCH on the large display, magic lenses were created interchangeably with either modality. Interestingly, we sometimes observed people approaching the large display in order to create or configure a tool (ruler: P13; lenses: P5) and then immediately stepping away to move the tool around. Participants that would usually prefer TOUCH (P2,10,11) actively commented on their preference of DISTANT for tool movement. In some of these cases, people actively collaborated, i.e., one person used TOUCH on the large display and configured the tool or selected results, while the partner then continued and controlled the tool using DISTANT (P1+2,5+6,13+14).

8 Discussion and Future Work

Our work explored basic user behavior and movement focusing on multiple users exploring multiple coordinated views on an interactive wall-sized display. We provided users with the flexibility to freely choose from which position or distance they interact with the system (A2).

Movement Based on our observations and user feedback, standing and walking in front of the large display was not as demanding and frustrating as expected, even though study sessions took quite long.

A possible reason is that participants were very interested in the data and worked in a very focused and concentrated way to complete the tasks. We also assume that working together rather than alone helped to 'forget' about the effort of walking back and forth. Even more, they clearly wanted to stand and walk close to each other most of the time (A5), which may be why movement was associated positively (A2). Finally, it is well-known that physical activities can help and support thinking, which was also mentioned by some participants.

Setup In our study, we used an external system to locate mobile devices within a tracking volume (coverage indicated by markings on the floor). While this allowed for absolute and precise device tacking, the additional markers and markings might have influenced the handling of devices or user behavior, which could be addressed by using other more lightweight localization approaches (e.g., [46]) or nothing but advanced internal sensors. To support the variety of collaborative data analysis scenarios, we also suggest to expand on other possible setups, such as different display sizes and resolutions, for future work. In addition, a table in front the large display could allow analysts to sit down for longer working sessions, take notes, or place additional materials and even other mobile devices such as tablets. It would be interesting to learn how users' physical activity would be affected. Beside the technical setup, our study was limited to pairs of users and tasks fostering closely coupled collaboration. Setting involving larger teams or tasks that trigger more loosely coupled collaboration are likely to show different workflows, other degrees of participation, or additional interaction conflicts (e.g., caused by linked brushing). However, we believe that many of our findings and observations, such as typical distances for reading or overview, will persist.

Distance Despite the fact that participants who use pointing a lot tend to remain at a larger average distance than those preferring TOUCH, we could not find a clear connection between the overall walking distance and people's preferred input modality. This may be because even people preferring DISTANT stepped towards the large display to view details and they often moved in parallel to the display in order to avoid pointing from large viewing angles. However, one of the participants (P10) spent much time far off the large display, but also preferred TOUCH. As a result, this participant covered long distances (roughly twice as much as others), while still rating physical demand low. As a limitation of our study, our application implements a specific view layout with a reasonable number and size of views and labels (readability, visual clutter, grouping), which may have affected user movements. Thus, it would be interesting to further explore the effect of their number and size on user distances and selected input modality.

Interaction Modality Although our study showed that most participants used both TOUCH and DISTANT, they clearly made use of TOUCH more. Among other possible reasons, we think that one factor is the legacy bias for direct touch: Touch-enabled devices and displays are all around us—people's first action when seeing a 'bright shiny display' is to touch it. Conversely, it is clear that precise pointing from a distance takes practice and people need do deal with handling and precision issues (size and weight of the device, attached markers, hand jitter). Furthermore, since movement was positive to participants, they quickly accepted the extra steps needed to touch the wall-sized display. In long-term usage, people's individual understanding of when DISTANT would be beneficial might develop, which would be interesting to follow up.

Device Usage Our concept of interacting with a mobile device in a relaxed and eyes-free way seems to have worked very well: Participants' attention was on the large display—they interacted from a distance without looking down to the mobile device. Of course, data analysis can also benefit from using modern mobile devices as additional screens to, for example, manage selection sets [24] or display alternative representations [34]. Compared to our approach, however, users then often switch their attention between the displays, which can be time-consuming [66]. Although both variants–with or without display use–have advantages, we think that application designs need to carefully consider when display use would be beneficial, and when hindering. It requires further investigations to better understand which InfoVis-specific tasks, actions, or use cases would benefit from using an additional mobile display.

MCV Aspects By developing a large-scale MCV application for a wall-sized display, we showed that specific design considerations (A1-A5) should be taken into account. View grouping (A1) and a modest use of color (A4) can help to address issues of visual complexity. We also learned that even for showing numerous views, support for concurrent interactions of multiple users on single views is needed (A5). The large display size can also lead to situations where users initially interact at different locations, but then want to coordinate their actions to, for example, compare selected data items (A5). While we investigated a basic variant of MCV, other important aspects remain open for future work. First, as mentioned in 4.4, *layout manipulation or view rearrangement* (A1) will allow users to adapt the interface situationally. It seems interesting to also look at both size and number of views as well as at flexible positioning of views within a zoomable information space [70]. Second, while we use the entire display space from the very beginning, working sessions involving the *creation of views* are also realistic and highly relevant. The user behavior and way of collaboration can be different to a predefined layout. Finally, in reflection of design choices we made, it is not self-evident to *link all the views* of a large-scale MCV by default. While we choose a standard behavior and linked all views, more manual approaches such as MyBrush [37] can have large effects on the way of using MCV on large displays.

Overall, we think it is important to give users the flexibility and freedom to move in front of a large display. We observed lots of natural movement and hence argue that besides simple hand or arm gestures, users should not be forced by a system to, for example, walk or move in specific ways. The repertoire of movements naturally performed by people can be manifold, so selecting certain movements or changes in distances to be interpreted for explicit input (e.g., [30, 35]) remains problematic. Agreeing with Jakobsen et al. [30], we believe distance should only be used to amplify natural actions of user movement, for instance, adjusting orientation cues such as titles or labels when stepping back or showing more data details when stepping close.

9 Conclusion

In this work, we investigate the use of multiple coordinated views (MCV) on interactive wall-sized displays. We discuss important design considerations and develop an interaction concept and fully functional application for working with MCV from varying positions and distances. In particular, our application builds on design aspects such as *simplicity*, *flexibility*, and visual *consistency*. It also supports data analysis in a large number of coordinated views by multiple users (*collaboration*). To improve our understanding regarding the implication and implementation of discussed aspects such as user movement and flexible distances, simple and consistent interactions, or multi-user support, we also conducted a qualitative user study on the behavior of teams of two using our application. Among others, findings indicate that users associate movement positively and thus often move and vary their distance to the display, stand and walk close to each other most of the time, also use natural and non-digital interaction such as pointing with fingers, or often prefer direct touch interaction but also learn when distant interaction can be beneficial. While we looked at a basic variant of MCV on wall-sized displays, we think this setting offers an only partly realized potential, which can be further explored by investigating aspects such as layout manipulation, dynamic view creation, or manual control of linked brushing. We believe many visual data analysis scenarios could benefit from such novel InfoVis interfaces and we hope our interaction design, application, and study findings lay the foundation for interesting future work in this area.

Acknowledgments

The authors wish to thank: Marc Satkowski for his enormous work on the prototype implementation; Marie Grimmelsmann for her help during the study; and the anonymous reviewers for their thorough comments and suggestions to improve the paper. This work was supported in part by DFG grant CollabWall (DA 1319/11-1).

References

[1] C. Andrews, A. Endert, and C. North. Space to think: Large high-resolution displays for sensemaking. In *Proc. CHI '10*, pp. 55–64. ACM, 2010. doi: 10.1145/1753326.1753336

[2] C. Andrews, A. Endert, B. Yost, and C. North. Information visualization on large, high-resolution displays: Issues, challenges, and opportunities. *Information Visualization*, 10(4):341–355, Oct. 2011. doi: 10.1177/1473871611415997

[3] A. Azad, J. Ruiz, D. Vogel, M. Hancock, and E. Lank. Territoriality and behaviour on and around large vertical publicly-shared displays. In *Proc. DIS '12*, pp. 468–477. ACM, 2012. doi: 10.1145/2317956.2318025

[4] S. K. Badam, F. Amini, N. Elmqvist, and P. Irani. Supporting visual exploration for multiple users in large display environments. In *2016 IEEE Conference on Visual Analytics Science and Technology (VAST)*, pp. 1–10, Oct 2016. doi: 10.1109/VAST.2016.7883506

[5] S. K. Badam and N. Elmqvist. Visfer: Camera-based visual data transfer for cross-device visualization. *Information Visualization*, 2017. doi: 10.1177/1473871617725907

[6] R. Ball and C. North. Visual analytics: Realizing embodied interaction for visual analytics through large displays. *Computers & Graphics*, 31(3):380–400, June 2007. doi: 10.1016/j.cag.2007.01.029

[7] R. Ball, C. North, and D. A. Bowman. Move to improve: Promoting physical navigation to increase user performance with large displays. In *Proc. CHI '07*, pp. 191–200. ACM, 2007. doi: 10.1145/1240624.1240656

[8] D. Baur, S. Boring, and S. Feiner. Virtual projection: Exploring optical projection as a metaphor for multi-device interaction. In *Proc. CHI '12*, pp. 1693–1702. ACM, 2012. doi: 10.1145/2207676.2208297

[9] D. Baur, B. Lee, and S. Carpendale. Touchwave: Kinetic multi-touch manipulation for hierarchical stacked graphs. In *Proc. ITS '12*, pp. 255–264. ACM, 2012. doi: 10.1145/2396636.2396675

[10] A. Bezerianos and P. Isenberg. Perception of visual variables on tiled wall-sized displays for information visualization applications. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2516–2525, Dec. 2012. doi: 10.1109/TVCG.2012.251

[11] G. Casiez, N. Roussel, and D. Vogel. 1 € filter: A simple speed-based low-pass filter for noisy input in interactive systems. In *Proc. CHI '12*, pp. 2527–2530. ACM, 2012. doi: 10.1145/2207676.2208639

[12] O. Chapuis, A. Bezerianos, and S. Frantzeskakis. Smarties: An input system for wall display development. In *Proc. CHI '14*, pp. 2763–2772. ACM, 2014. doi: 10.1145/2556288.2556956

[13] M. Chegini, L. Shao, D. J. Lehmann, K. Andrews, and T. Schreck. Interaction concepts for collaborative visual analysis of scatterplots on large vertically-mounted high-resolution multi-touch displays. In *Proc. Forum Media Technology & All Around Audio Symposium*, pp. 90–96, 2017.

[14] K. Cheng, J. Li, and C. Müller-Tomfelde. Supporting interaction and collaboration on large displays using tablet devices. In *Proc. AVI '12*, pp. 774–775. ACM, 2012. doi: 10.1145/2254556.2254708

[15] G. Chin, Jr., O. A. Kuchar, and K. E. Wolf. Exploring the analytical processes of intelligence analysts. In *Proc. CHI '09*, pp. 11–20. ACM, 2009. doi: 10.1145/1518701.1518704

[16] H. Chung, C. North, J. Z. Self, S. Chu, and F. Quek. Visporter: Facilitating information sharing for collaborative sensemaking on multiple displays. *Personal Ubiquitous Computing*, 18(5):1169–1186, June 2014. doi: 10.1007/s00779-013-0727-2

[17] J. Dostal, U. Hinrichs, P. O. Kristensson, and A. Quigley. Spidereyes: Designing attention- and proximity-aware collaborative interfaces for wall-sized displays. In *Proc. IUI '14*, pp. 143–152. ACM, 2014. doi: 10.1145/2557500.2557541

[18] S. M. Drucker, D. Fisher, R. Sadana, J. Herron, and m. schraefel. Touchviz: A case study comparing two interfaces for data analytics on tablets. In *Proc. CHI '13*, pp. 2301–2310. ACM, 2013. doi: 10.1145/2470654.2481318

[19] A. Endert, C. Andrews, Y. H. Lee, and C. North. Visual encodings that support physical navigation on large displays. In *Proc GI '11*, pp. 103–110. Canadian Human-Computer Communications Society, Waterloo, Ontario, Canada, 2011.

[20] S. Greenberg, N. Marquardt, T. Ballendat, R. Diaz-Marino, and M. Wang. Proxemic interactions: the new ubicomp? *interactions*, 18(1):42–50, Jan. 2011. doi: 10.1145/1897239.1897250

[21] E. T. Hall. *The Hidden Dimension*. A Doubleday anchor book. Anchor Books, 1990.

[22] P. Hamilton and D. J. Wigdor. Conductor: Enabling and understanding cross-device interaction. In *Proc. CHI '14*, pp. 2773–2782. ACM, 2014. doi: 10.1145/2556288.2557170

[23] K. Hawkey, M. Kellar, D. Reilly, T. Whalen, and K. M. Inkpen. The proximity factor: Impact of distance on co-located collaboration. In *Proc. GROUP '05*, pp. 31–40. ACM, 2005. doi: 10.1145/1099203.1099209

[24] T. Horak, S. K. Badam, N. Elmqvist, and R. Dachselt. When david meets goliath: Combining smartwatches with a large vertical display for visual data exploration. In *Proc. CHI '18*, pp. 19:1–19:13. ACM, 4 2018. doi: 10.1145/3173574.3173593

[25] P. Isenberg and D. Fisher. Collaborative brushing and linking for co-located visual analytics of document collections. *Computer Graphics Forum*, 28(3):1031–1038, 2009. doi: 10.1111/j.1467-8659.2009.01444.x

[26] P. Isenberg, D. Fisher, M. R. Morris, K. Inkpen, and M. Czerwinski. An exploratory study of co-located collaborative visual analytics around a tabletop display. In *2010 IEEE Symposium on Visual Analytics Science and Technology*, pp. 179–186. IEEE, Oct 2010. doi: 10.1109/VAST.2010.5652880

[27] M. R. Jakobsen and K. Hornbæk. Up close and personal: Collaborative work on a high-resolution multitouch wall display. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 21(2):11:1–11:34, 2014. doi: 10.1145/2576099

[28] M. R. Jakobsen and K. Hornbæk. Is moving improving?: Some effects of locomotion in wall-display interaction. In *Proc. CHI '15*, pp. 4169–4178. ACM, 2015. doi: 10.1145/2702123.2702312

[29] M. R. Jakobsen, Y. Jansen, S. Boring, and K. Hornbæk. Should i stay or should i go? selecting between touch and mid-air gestures for large-display interaction. In J. Abascal, S. Barbosa, M. Fetter, T. Gross, P. Palanque, and M. Winckler, eds., *Human-Computer Interaction – INTERACT 2015*, pp. 455–473. Springer International Publishing, Cham, 2015.

[30] M. R. Jakobsen, Y. Sahlemariam Haile, S. Knudsen, and K. Hornbæk. Information visualization and proxemics: Design opportunities and empirical findings. *IEEE Transactions on Visualization and Computer Graphics*, 19(12):2386–2395, 2013. doi: 10.1109/TVCG.2013.166

[31] Y. Jansen and P. Dragicevic. An interaction model for visualizations beyond the desktop. *IEEE Transactions on Visualization and Computer Graphics*, 19(12):2396–2405, Dec. 2013. doi: 10.1109/TVCG.2013.134

[32] Y. Jansen, P. Dragicevic, and J.-D. Fekete. Tangible remote controllers for wall-size displays. In *Proc. CHI '12*, pp. 2865–2874. ACM, 2012. doi: 10.1145/2207676.2208691

[33] R. Jota, M. A. Nacenta, J. A. Jorge, S. Carpendale, and S. Greenberg. A comparison of ray pointing techniques for very large displays. In *Proc. GI '10*, pp. 269–276. Canadian Information Processing Society, Toronto, Ont., Canada, Canada, 2010.

[34] U. Kister, K. Klamka, C. Tominski, and R. Dachselt. Grasp: Combining spatially-aware mobile devices and a display wall for graph visualization and interaction. *Computer Graphics Forum*, 36(3):503–514, 2017. doi: 10.1111/cgf.13206

[35] U. Kister, P. Reipschläger, F. Matulic, and R. Dachselt. Bodylenses: Embodied magic lenses and personal territories for wall displays. In *Proc. ITS '15*, pp. 117–126. ACM, 2015. doi: 10.1145/2817721.2817726

[36] K. Klamka and R. Dachselt. Elasticcon: Elastic controllers for casual interaction. In *Proc. MobileHCI '15*, pp. 410–419. ACM, 2015. doi: 10.1145/2785830.2785849

[37] P. Koytek, C. Perin, J. Vermeulen, E. André, and S. Carpendale. My-brush: Brushing and linking with personal agency. *IEEE Transactions on Visualization and Computer Graphics*, 24(1):605–615, 2018. doi: 10.1109/TVCG.2017.2743859

[38] R. Langner, T. Horak, and R. Dachselt. Vistiles: Coordinating and combining co-located mobile devices for visual data exploration. *IEEE Transactions on Visualization and Computer Graphics*, 24(1):626–636, Jan 2018. doi: 10.1109/TVCG.2017.2744019

[39] R. Langner, U. von Zadow, T. Horak, A. Mitschick, and R. Dachselt. *Content Sharing Between Spatially-Aware Mobile Phones and Large Vertical Displays Supporting Collaborative Work*, pp. 75–96. Springer International Publishing, 2016. doi: 10.1007/978-3-319-45853-3_5

[40] B. Lee, P. Isenberg, N. H. Riche, and S. Carpendale. Beyond mouse and keyboard: Expanding design considerations for information visualization interactions. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2689–2698, Dec. 2012. doi: 10.1109/TVCG.2012.204

[41] A. Lehmann, H. Schumann, O. Staadt, and C. Tominski. *Physical Navigation to Support Graph Exploration on a Large High-Resolution Display*, pp. 496–507. Springer Berlin Heidelberg, 2011. doi: 10.1007/978-3-642-24028-7_46

[42] C. Liu, O. Chapuis, M. Beaudouin-Lafon, and E. Lecolinet. Shared

interaction on a wall-sized display in a data manipulation task. In *Proc. CHI '16*, pp. 2075–2086. ACM, 2016. doi: 10.1145/2858036.2858039

[43] C. Liu, O. Chapuis, M. Beaudouin-Lafon, and E. Lecolinet. Coreach: Cooperative gestures for data manipulation on wall-sized displays. In *Proc. CHI '17*, pp. 6730–6741. ACM, 2017. doi: 10.1145/3025453.3025594

[44] C. Liu, O. Chapuis, M. Beaudouin-Lafon, E. Lecolinet, and W. E. Mackay. Effects of display size and navigation type on a classification task. In *Proc. CHI '14*, pp. 4147–4156. ACM, 2014. doi: 10.1145/2556288.2557020

[45] H. Lü, M. Negulescu, and Y. Li. Gesturemote: Interacting with remote displays through touch gestures. In *Proc. AVI '14*, pp. 325–328. ACM, 2014. doi: 10.1145/2598153.2598195

[46] N. Marquardt, K. Hinckley, and S. Greenberg. Cross-device interaction via micro-mobility and f-formations. In *Proc. UIST '12*, pp. 13–22. ACM, 2012. doi: 10.1145/2380116.2380121

[47] C. L. Paul and L. Bradel. Size matters: The effects of interactive display size on interaction zone expectations. In *Proc. AVI '18*, pp. 41:1–41:5. ACM, 2018. doi: 10.1145/3206505.3206506

[48] S. M. Peck, C. North, and D. Bowman. A multiscale interaction technique for large, high-resolution displays. In *Proc. 3DUI '09*, 3DUI '09, pp. 31–38. IEEE Computer Society, Washington, DC, USA, 2009. doi: 10.1109/3DUI.2009.4811202

[49] A. Prouzeau, A. Bezerianos, and O. Chapuis. Evaluating multi-user selection for exploring graph topology on wall-displays. *IEEE Transactions on Visualization and Computer Graphics*, 23(8):1936–1951, Aug 2017. doi: 10.1109/TVCG.2016.2592906

[50] A. Prouzeau, A. Bezerianos, and O. Chapuis. Trade-offs between a vertical shared display and two desktops in a collaborative path-finding task. In *Proc. GI '17*. CHCCS, May 2017.

[51] Z. Qu and J. Hullman. Keeping multiple views consistent: Constraints, validations, and exceptions in visualization authoring. *IEEE Transactions on Visualization and Computer Graphics*, 24(1):468–477, Jan 2018. doi: 10.1109/TVCG.2017.2744198

[52] F. Rajabiyazdi, J. Walny, C. Mah, J. Brosz, and S. Carpendale. Understanding researchers' use of a large, high-resolution display across disciplines. In *Proc. ITS '15*, pp. 107–116. ACM, 2015. doi: 10.1145/2817721.2817735

[53] K. Reda, A. E. Johnson, M. E. Papka, and J. Leigh. Effects of display size and resolution on user behavior and insight acquisition in visual exploration. In *Proc. CHI '15*, CHI '15, pp. 2759–2768. ACM, 2015. doi: 10.1145/2702123.2702406

[54] N. H. Riche, T. Dwyer, B. Lee, and S. Carpendale. Exploring the design space of interactive link curvature in network diagrams. In *Proc. AVI '12*, pp. 506–513. ACM, 2012. doi: 10.1145/2254556.2254652

[55] J. C. Roberts. State of the art: Coordinated & multiple views in exploratory visualization. In *Proc. CMV '07*, pp. 61–71. IEEE Computer Society, 2007. doi: 10.1109/CMV.2007.20

[56] J. C. Roberts, P. D. Ritsos, S. K. Badam, D. Brodbeck, J. Kennedy, and N. Elmqvist. Visualization beyond the desktop–the next big thing. *IEEE Computer Graphics and Applications*, 34(6):26–34, Nov.-Dec. 2014. doi: 10.1109/MCG.2014.82

[57] J. M. Rzeszotarski and A. Kittur. Kinetica: Naturalistic multi-touch data visualization. In *Proc. CHI '14*, pp. 897–906. ACM, 2014. doi: 10.1145/2556288.2557231

[58] R. Sadana and J. Stasko. Designing and implementing an interactive scatterplot visualization for a tablet computer. In *Proc. AVI '14*, pp. 265–272. ACM, 2014. doi: 10.1145/2598153.2598163

[59] R. Sadana and J. Stasko. Expanding selection for information visualization systems on tablet devices. In *Proc. ISS '16*, ISS '16, pp. 149–158. ACM, 2016. doi: 10.1145/2992154.2992157

[60] D. Schmidt, F. Chehimi, E. Rukzio, and H. Gellersen. Phonetouch: A technique for direct phone interaction on surfaces. In *Proc. UIST '10*, pp. 13–16. ACM, 2010. doi: 10.1145/1866029.1866034

[61] S. D. Scott, M. S. T. Carpendale, and K. M. Inkpen. Territoriality in collaborative tabletop workspaces. In *Proc. CSCW '04*, pp. 294–303. ACM, 2004. doi: 10.1145/1031607.1031655

[62] T. Seifried, C. Rendl, M. Haller, and S. Scott. Regional undo/redo techniques for large interactive surfaces. In *Proc. CHI '12*, pp. 2855–2864. ACM, 2012. doi: 10.1145/2207676.2208690

[63] S. Siddhpuria, S. Malacria, M. Nancel, and E. Lank. Pointing at a distance with everyday smart devices. In *Proc. CHI '18*, pp. 173:1–173:11. ACM, 2018. doi: 10.1145/3173574.3173747

[64] A. Srinivasan and J. Stasko. Orko: Facilitating multimodal interaction for visual exploration and analysis of networks. *IEEE Transactions on Visualization and Computer Graphics*, 24(1):511–521, Jan 2018. doi: 10.1109/TVCG.2017.2745219

[65] S. Stellmach and R. Dachselt. Still looking: Investigating seamless gaze-supported selection, positioning, and manipulation of distant targets. In *Proc. CHI '13*, pp. 285–294. ACM, 2013. doi: 10.1145/2470654.2470695

[66] D. S. Tan and M. Czerwinski. Effects of visual separation and physical discontinuities when distributing information across multiple displays. In *Proc. OZCHI' 03*, pp. 184–191, 11 2003.

[67] A. Tang, M. Tory, B. Po, P. Neumann, and S. Carpendale. Collaborative coupling over tabletop displays. In *Proc. CHI '06*, pp. 1181–1190. ACM, 2006. doi: 10.1145/1124772.1124950

[68] M. Tobiasz, P. Isenberg, and S. Carpendale. Lark: Coordinating co-located collaboration with information visualization. *IEEE Transactions on Visualization and Computer Graphics*, 15(6):1065–1072, Nov 2009. doi: 10.1109/TVCG.2009.162

[69] C. Tominski, J. Abello, F. van Ham, and H. Schumann. Fisheye tree views and lenses for graph visualization. In *Proc. IV '06*, pp. 17–24. IEEE Computer Society, Washington, DC, USA, 2006. doi: 10.1109/IV.2006.54

[70] C. Tominski, C. Forsell, and J. Johansson. Interaction support for visual comparison inspired by natural behavior. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2719–2728, Dec 2012. doi: 10.1109/TVCG.2012.237

[71] C. Tominski, S. Gladisch, U. Kister, R. Dachselt, and H. Schumann. Interactive lenses for visualization: An extended survey. *Computer Graphics Forum*, 36(6):173–200, 2017. doi: 10.1111/cgf.12871

[72] L. Vlaming, C. Collins, M. Hancock, M. Nacenta, T. Isenberg, and S. Carpendale. Integrating 2d mouse emulation with 3d manipulation for visualizations on a multi-touch table. In *Proc. ITS '10*, pp. 221–230. ACM, 2010. doi: 10.1145/1936652.1936693

[73] S. Voida, M. Tobiasz, J. Stromer, P. Isenberg, and S. Carpendale. Getting practical with interactive tabletop displays: Designing for dense data, "fat fingers," diverse interactions, and face-to-face collaboration. In *Proc. ITS '09*, pp. 109–116. ACM, 2009. doi: 10.1145/1731903.1731926

[74] U. von Zadow, W. Büschel, R. Langner, and R. Dachselt. Sleed: Using a sleeve display to interact with touch-sensitive display walls. In *Proc. ITS '14*, pp. 129–138. ACM, 2014. doi: 10.1145/2669485.2669507

[75] U. von Zadow and R. Dachselt. Giant: Visualizing group interaction at large wall displays. In *Proc. CHI '17*, pp. 2639–2647. ACM, 2017. doi: 10.1145/3025453.3026006

[76] J. R. Wallace, N. Iskander, and E. Lank. Creating your bubble: Personal space on and around large public displays. In *Proc CHI '16*, pp. 2087–2092. ACM, 2016. doi: 10.1145/2858036.2858118

[77] J. Walny, B. Lee, P. Johns, N. H. Riche, and S. Carpendale. Understanding pen and touch interaction for data exploration on interactive whiteboards. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2779–2788, Dec 2012. doi: 10.1109/TVCG.2012.275

[78] G. J. Wills. Selection: 524,288 ways to say "this is interesting". In *Proc. IV '96*, pp. 54–60, 120, Oct 1996. doi: 10.1109/INFVIS.1996.559216

[79] B. Yost and C. North. The perceptual scalability of visualization. *IEEE Transactions on Visualization and Computer Graphics*, 12(5):837–844, Sept. 2006. doi: 10.1109/TVCG.2006.184