# GRASP: Combining Spatially-aware Mobile Devices and a Display Wall for Graph Visualization and Interaction

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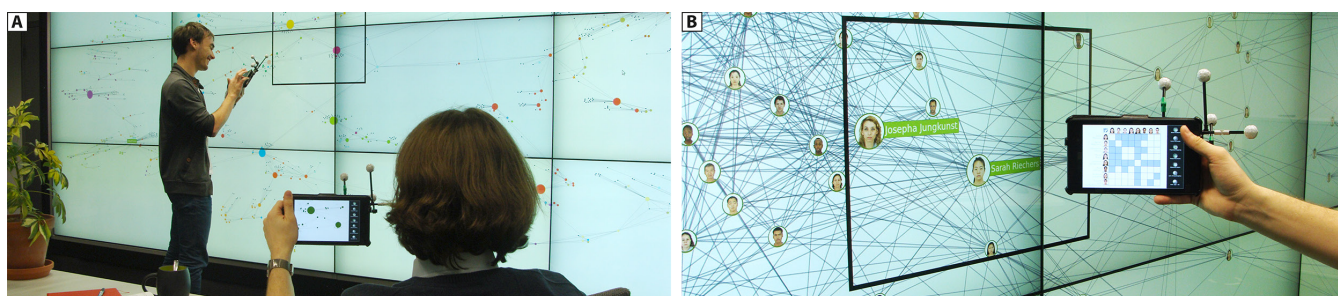[2]Institute for Computer Science, University of Rostock, Germany

**Figure 1:** *Mobile devices support graph visualization and interaction on wall-sized displays close to the display wall and further away (A). The* GRASP *system provides a mobile toolbox with selections, alternative representations, lenses, and filtering close to the user (B).*

**Abstract**

*Going beyond established desktop interfaces, researchers have begun re-thinking visualization approaches to make use of alternative display environments and more natural interaction modalities. In this paper, we investigate how spatially-aware mobile displays and a large display wall can be coupled to support graph visualization and interaction. For that purpose, we distribute typical visualization views of classic node-link and matrix representations between displays. The focus of our work lies in novel interaction techniques that enable users to work with personal mobile devices in combination with the wall. We devised and implemented a comprehensive interaction repertoire that supports basic and advanced graph exploration and manipulation tasks, including selection, details-on-demand, focus transitions, interactive lenses, and data editing. A qualitative study has been conducted to identify strengths and weaknesses of our techniques. Feedback showed that combining mobile devices and a wall-sized display is useful for diverse graph-related tasks. We also gained valuable insights regarding the distribution of visualization views and interactive tools among the combined displays.*

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Information Interfaces and Presentation]: User Interfaces—Interaction styles

## 1. Introduction

Graph visualization and interaction typically takes place in traditional desktop workplaces. Many solutions exist that support visualization on regular displays with mouse and keyboard interaction. A limitation of the classic environment though is that it is stationary and offers only indirect input. On the other hand, devices like tablets and smartphones let visualization applications become mobile, and visual data exploration can take advantage of their direct input capabilities via touch or movement of the device [BLC12, DFS*13, SSMD14]. However, mobile devices are usually limited in terms of display size, which restricts the amount of information that can be shown [Chi06].

This is where large display walls excel. Megapixel displays offer much space for visualizing much information. Previous studies describe the advantages and capabilities of large display spaces in terms of visualization, interaction, and sense-making [AEN10, BI12,JSHKH13,JH15]. Yet, the traditional ways of visualizing data and interacting with them can hardly be applied to large displays simply due to their increased physical size and the need for alternative input capabilities beyond mouse and keyboard.

Therefore, we investigate new ways of combining the advantages of mobile devices and large displays. Our goal is to create a visualization environment that utilizes the enormous space of large displays and adds to this the flexibility, display capabilities, and interaction modalities of mobile devices. First research in this di-

rection has examined the use of mobile displays in combination with tabletops for information visualization, utilizing the spatial relation between mobile and larger display [VTS*09, STSD10]. Our work addresses the use of mobile devices as personal visualization and interaction tools extending the capabilities of a large, wall-sized display. We specifically focus on graph exploration and manipulation and on how graph-specific tasks can be supported with a combination of mobiles and wall. Having single-user and multi-user scenarios in mind, we need to support both, personal retreat for in-depth investigation and public exchange for collaborative sense-making. The goal is to have the appropriate visualization and interaction available when and where it is needed by the user. To achieve this, we designed a set of techniques called GRASP ("Graphs in Space") for graph visualization and interaction. We combine spatially-aware mobile interactions (i.e., tracking location and orientation of mobile devices in space) with wall-centered and body-relative movements as well as touch input on both display types.

From a visualization perspective, we use different visual representations (i.e., node-link diagrams and matrices) that are distributed among displays depending on the task at hand. In terms of interaction, we utilize the advantages of natural user interaction close to the wall display and remotely from a distance. Instead of enforcing particular input styles (e.g., spatial movement or touch on the display wall), our solution has been designed so as to support flexible user positions in front of a large display. The goal is to adapt the interaction facilities to the users' workflow, not the other way around. This way, we can support real-world scenarios such as meetings and discussions of data analysis, and permit individual user behaviors including the possibility of interacting while moving, standing, or sitting.

In summary, this paper contributes a repertoire of direct and remote interaction techniques that utilize the advantages of physical navigation, spatial interaction, and physical metaphors to support diverse graph exploration and manipulation tasks on wall-sized displays using mobile devices. To evaluate the developed techniques and investigate their combination in workflows, we conducted a qualitative user study. We report on user feedback and corresponding observations. Based on that, we discuss the potential and the challenges of combining mobile devices and a wall-sized display for graph visualization and interaction.

Before going into details on our solution, we will first review previous related research and then introduce two scenarios based on which we identify relevant interaction tasks to support.

## 2. Related Work

Our research is related to data exploration on wall-sized displays, to mobile devices and spatial interaction, and to interactive graph exploration and manipulation. Relevant previous work is reviewed in the following.

### 2.1. Interactive wall-sized displays for data exploration

Diverse aspects of large wall-sized displays have been addressed in visualization-related research. Andrews et al. [AEN10] study

how the spatial organization on large displays can support recall and organization when working on sensemaking tasks. Endert et al. [EALN11] investigate how visual encodings are influenced by the size and diversity of data on large displays. Bezerianos and Isenberg [BI12] specifically look at the perception of visual variables when users move in front of wall-sized displays. Taking this further, Isenberg et al. [IDW*13] propose hybrid-image visualizations that contain both details (visible at close range) and overview (visible from afar) in one image.

Interaction with visual representations presented on large screens depends largely on the input capabilities of the display (e.g., touch or pen). Because of the physical size of large displays it is often helpful to employ sensors that detect movements in front of the display. Jakobsen et al. [JSHKH13] suggest applying the users' physical distance to the wall for specific explorations of the visualization. Jakobson and Hornbæk investigated physical and virtual navigation in a comparative study [JH15] and found benefits of physical movement dependent on the use case. In our previous work [KRMD15], we use body movements in combination with touch and mid-air gestures to position and parametrize magic lenses for visual graph exploration on a large display wall. These works all apply the body's physical movement and proxemic dimensions [GMB*11] for the exploration of information spaces at large displays. Furthermore, body-centric interactions have been used to trigger tools and adjust parameters [STKB10, KRMD15]. Building on these principles, we consider physical navigation [BNB07], spatial movement, and body-relative layers as interaction styles within our multi-device scenario. However, we argue for flexible movement, instead of triggering manipulations through implicit actions and behavior.

### 2.2. Mobile devices and spatial interaction

Visualization on mobile devices comes with its own advantages and also challenges [Chi06, EWE09, BLEJ*13]. An obvious challenge is to cope with limited resources (display space, computing power, memory). At the same time, first touch-enabled visualizations [DFS*13, SS14] present the advantages of directly exploring and manipulating visualizations. Further, a new range of applications becomes possible with spatially-aware mobile devices. These are devices whose position in space can be tracked and hence different views can be shown according to this position. This spatial movement of a mobile device has proven to be faster for navigation tasks (zoom and pan) than standard touch interactions [SSMD14].

In combination with large displays, mobile devices lend themselves to present detailed information or selected parts of the data at high-resolution [VTS*09, vZBLD14]. However, the connection and transfer of content between devices requires additional software solutions (e.g., [BFE15]). In this setup, the role of a device is often dependent on its distance to the large display. Schmidt et al. [SCRG10] use mobile devices in direct contact with a large display's surface for pointing purposes. To synchronize content and control the view of a large display or projection during multi-disciplinary team discussions, Olwal et al. [OFGM11] used tablets allowing shared pointing, navigation, and annotation possibilities. Mobile devices can further be used as a directional pointer towards the large display, as investigated in PointerPhone [SBR13]. This can be used to select and navigate con-

tent at different scales [PNB09] or transfer and arrange information and data objects from a distance [CNS*14, LvZH*16]. User interface items on the mobile device may further be used to manipulate content and set parameters [vZBLD14]. These elements can be sketched [TBJ15] or applied as tangible objects [JDF12] that even allow eyes-free control of the view on the wall-sized display. Baur et al. [BBF12] use the whole mobile device as a direct controller and manipulator of the content on the large display using the position and orientation of the device when interacting at a distance.

In general, tracking the position and optionally the orientation of mobile devices allows for diverse spatial interactions, not just pointing. Spindler et al. [STSD10] define an interaction vocabulary for spatial interactions with tablet-sized displays on top and over a large tabletop device for the infovis domain. In our work, we add to this line of research by studying the use of mobile devices and large displays. We apply and adapt their vocabulary to the actual application context and workflows for graph data analysis and extend the work towards vertical displays where issues of focus changes and stronger separation between devices need to be considered.

## 2.3. Interactive graph exploration and manipulation

There is a vast amount of research on the visualization of graphs [vLKS*11, KPW14, HSS15]. In this work, we focus on *interaction* for the exploration and manipulation of multivariate graphs. McGuffin and Jurisica [MJ09] discuss the need for dedicated techniques for graph interaction and propose several solutions for selection and layout manipulation. Tominski et al. [TAS09] present a variety of interactive graph exploration techniques, including graph lenses and navigation tools. For novel interaction modalities, pen and touch gestures have been extracted from a user-elicited study by Frisch et al. [FHD10] for the creation and manipulation of graphs. Further, Riche et al. [RDLC12] use touch-enabled tools to de-clutter edge congestions, and graph-related magic lenses [TAvHS06] have been applied on touch surfaces [KRD16].

For physical navigation, graph interaction on large displays has been studied by Lehmann et al. [LSST11]. They track the user's position and head orientation to visualize a graph at different levels of detail. The movement of multiple users in collaborative scenarios has been studied by Prouzeau et al. [PBC16] for the specific task of selection on large displays. Adding mobile devices, Spindler et al. [STSD10] combine a mobile display with a tabletop for the purpose of semantic zooming in a hierarchical graph structure. Roberts et al. [RAMH12] investigate the use of mobile devices for reading textual information associated with a 3D graph structure. Finally, Cheng et al. [CLMT12] discuss presenting different overview and detail views on mobile devices in conjunction with a large vertical display where multiple users can look at individual parts of a graph visualization.

In summary, we see several previous works that address visualization of and interaction with graphs, and works that consider the specifics of large displays and mobile devices. Yet, there is no previous research that solved the specific requirements and tasks of graph visualizations with the help of this novel combination of a large display and mobile devices. With our work, we aim to narrow this gap. We apply the advantages of both device classes to support a diverse range of tasks which we discuss in the next section.

## 3. Scenarios and Tasks

The GRASP techniques are clearly motivated by the new possibilities of modern display environments and interaction modalities. Our goal was to design techniques that demonstrably benefit from the new technology. Yet at the same time, the techniques should be generalizable and practically relevant. To obtain generalizable techniques, we consider accepted task taxonomies and frameworks. For the general interaction tasks (*I*) we refer to Yi et al. [YKSJ07], refining them where appropriate with graph-specific tasks (*G*) from the taxonomy of Lee et al. [LPP*06]. For manipulative editing tasks on graphs (*E*) we use the overview of Gladisch et al. [GKT*15].

To achieve practical relevance and gain an understanding of possible workflows, we consider two concrete application scenarios. Both scenarios were devised, discussed, and iterated under consideration of existing work on visualization and interaction tasks for graphs [PPS14, WEF*14]. We opted for devised scenarios, because they allow us to achieve a better coverage of relevant tasks and a more comprehensive use of the visualization environment.

Next, we describe the two scenarios and the involved tasks in detail. Later in Section 4, we refer to these scenarios' task to systematically develop a corresponding interaction repertoire.

### 3.1. Scenario I: Disease co-occurrences

The first scenario focuses on finding cancer relations through common appearances of diseases using a graph data set of disease occurrences. Nodes represent diseases and genes, whereas edges present the disease co-occurrence or a disease's relation to a gene.

We assume a group of biologists meet to discuss the research topic of colon cancer. They sit together jointly discussing possibly interesting aspects in the data while also looking for detailed information individually. In a first phase of hypothesis generation, the biologists examine if colon cancer occurs in relation with other forms of cancer or generally with diseases of indigestion. In a hypothesis verification phase, the biologists want to study in more detail the symptoms and diagnoses of diseases that are connected to colon cancer. Experienced participants of the group add and update the graph with data from a recent publication. This scenario incorporates the following tasks:

- Find and select the cluster of cancer diseases
  I [SELECT/EXPLORE]; G [OVERVIEW]
- Find and select all neighbors of colon cancer
  I [CONNECT]; G [ADJACENCY]
- Filter neighbors by type of disease
  I [FILTER]; G [ATTRIBUTE-BASED]
- Compare the number of diseases per type
  I [EXPLORE]; G [ATTRIBUTE-BASED]
- Identify important nodes connected to colon cancer
  I [CONNECT]; G [ATTRIBUTE-BASED]
- Access details such as symptoms and diagnoses
  I [ABSTRACT&ELABORATE]; G [ATTRIBUTE-BASED]
- Add and update a disease, relations, and attributes
  E [ADD NODES]; E [ADD/REMOVE EDGES];
  E [ADD/UPDATE ATTRIBUTES]

## 3.2. Scenario II: Advertisement in a social network

In our second scenario, a social network is investigated to find people with wide-spread influence in order to use them for product endorsement and to send them advertisements for a specific new product. There are two different types of nodes: people and product/fan pages. Edges exist between friends as well as between people and certain products or fan pages they liked. In this scenario, an advertisement consultant first identifies cliques of certain size and appropriate target age and gender. She then explores these groups in more detail finding the ones with a sufficient number of neighbors and an active engagement with product pages before finally adding a connection from the most-likely candidates to the product. This process includes the following tasks:

- Filter people by age and gender to see target group
  I [FILTER]; G [ATTRIBUTE-BASED]
- Identify cliques of people by size and product engagement
  G [CONNECTIVITY]; G [ATTRIBUTE-BASED]
- Separate products and people
  I [FILTER]; G [ATTRIBUTE-BASED]
- Analyze common friends
  G [COMMON CONNECTIONS]
- Examine specific attributes of candidates
  I [ABSTRACT&ELABORATE]; G [ATTRIBUTE-BASED]
- Add edge from selected candidates to new product
  E [ADD EDGES]

These devised scenarios enable an understanding of application-specific processes close to the real world. The association with task taxonomies is useful for generalizing concepts and easily applying them to different application contexts. Based on the two scenarios and the identified tasks, we will now introduce the GRASP visualization and interaction repertoire.

## 4. GRASP: Interactive Techniques for Graph Visualizations

The core of our approach is to take advantage of the space on and in front of wall-sized displays. The wall-sized display presents the main visualization as an overview of the information space. We assume the large display to be touch-enabled, but also consider the option of a non-interactive wall-sized display. Mobile devices are used as personal displays, their position, orientation, and movement (and thereby an estimate of the user's position) is tracked in the space in front of the wall-sized display so that individual interactions with the mobile devices can be linked and related to specific objects on the display wall. However, to support real-world behavior we do not want to enforce a restrictive movement of users to stay in contact with the wall-sized display or require physical navigation, i.e., the body movement to control the view within the information space [BNB07]. As part of our design goals, we aim to support flexible movements and remote interactions, i.e., interactions when being far from the display wall either during movement or from a standing or sitting position. Hence, interactions should not be restricted to a specific distance from the wall-sized display.

While the wall-sized display may support interactive exploration and manipulation of the main visualization, our focus lies on combining mobile devices in this setup and providing a rich set of individual local interactions on each user's personal mobile device.

The mobiles are meant to bridge the gap between display wall and user by presenting a rich set of views onto the data, including

- a close-up excerpt from the data on the wall,
- the visualized data with adjusted level of detail,
- alternative representations of the data in focus, or
- User Interface widgets and setting dialogs.

Therefore, we introduce an interaction repertoire of techniques called GRASP, which stands for "Graphs in Space" and incorporates the graspable capabilities of the mobile device as a personal toolbox. Applying research on proxemic interaction [GMB*11, JSHKH13], we use the distance and orientation of the user's device to trigger minor adjustments of detail level, focus views, and tool size. However, as a design principle we define the need for *explicit interactions* for major manipulations, such as view changes. As a result, to switch between these views and the diverse features of the mobile toolbox, we suggest the use of an explicit tool menu on the mobile display where users can select the appropriate view.

In the following, we focus on covering the tasks identified in the previous section including exploration and selection, details on demand, connectivity and adjacency tasks through alternative representations and lenses, as well as diverse filtering techniques. Table 1 provides a brief overview of these solutions. All techniques have been implemented and their seamless combination can be seen in our accompanying video (https://imld.de/grasp).

| Tasks | GRASP techniques |
|---|---|
| I [EXPLORE], G [OVERVIEW] | • physical navigation<br>• mobile focus view selection (4.1.1) |
| I [SELECT] | • individual data and group selection (4.1.2)<br>– on display wall<br>– on mobile device<br>– using pointing selection |
| I [ABSTRACT & ELABORATE] | • labeling technique on movement (4.1.2)<br>• details on demand after selection (4.2) |
| E [ADD/ UPDATE NODE ATTRIBUTES] | • manipulating attributes in detail view (4.2) |
| I [CONNECT], G [ADJACENCY, CONNECTIVITY] | • adjacency matrix as alternative representation (4.3)<br>• tangible Bring Neighbors Lens (4.4) |
| E [ADD/REMOVE EDGES] | • tap on cells in adjacency matrix (4.3) |
| I [FILTER], G [ATTRIBUTE-BASED] | • tangible Attribute Filter Lens (4.5.1)<br>• body-relative range filtering (4.5.2)<br>• distribution overview with sieve filter tool (4.5.3) |

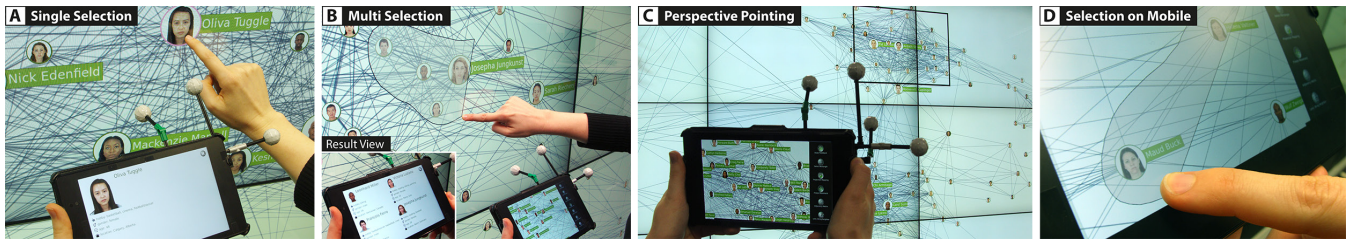**Table 1:** *Tasks and respective* GRASP *techniques*

**Figure 2:** *Selection Techniques & Details on Demand: Tapping a node opens associated details on the mobile (**A**). Encircling multiples nodes enables group selections (**B**). Remote pointing provides a focus view on the mobile (**C**), which can be used for remote selection using either tap or encircling (**D**).*

### 4.1. Exploration and selection

The basic interaction step in both of our scenarios is the exploration and navigation within the data space to select interesting content. While the wall-sized display presents the main visualization and thereby the context for all other interactions, users have to select the current focus view for their personal mobile device. We will first present the possible alternatives to define this focus view, before discussing how to actively select data either directly at the display wall or through this mobile focus view.

#### 4.1.1. Mobile focus view selection

When working with a mobile device, the user first has to determine on which part of the data to focus (I [EXPLORE], G [OVERVIEW]) and hence what part to show on the mobile display. For that, the mobile device's absolute position in space and its orientation can be used to allow pointing towards the content to select a rectangular focus region of the data for visualization on the mobile. Visual feedback on the wall display indicates the current region of interest which is transfered to the mobile display (see Figure 2C). The feedback is designed to be minimalistic and unobtrusive to reduce interruptions of other users.

When pointing at the large visualization, alternative mappings are possible: orthogonal and perspective pointing (or their combination [LvZH*16]). For orthogonal pointing, only the position of the device and its orthogonal projection to the wall display are used. While this requires body movement in front of the display, it allows a flexible hold of the device and thereby precise, more stable selection on the display wall. In perspective mode, the orientation of the device is used to point at the display. However, we correct the rectangular focus to avoid distortions. As a result, the perspective mapping allows a farther reach of elements on the wall using only a tilt of the mobile device, even when sitting at a distance to the display (remote interaction). A button press can switch between the perspective and orthogonal pointing techniques to adapt to the user's current goals. Similarly, pointing can also be frozen to focus and fixate a region of interest (similar to [STSD10]), so that users can focus on the lens content and may relax their posture. The amount of visible content on the mobile depends on the zoom factor set on the device. It can be adjusted through a slider, a pinch gesture on the display, or using the measured distance from the mobile to the wall (similar to previous work on proxemics without additional devices [JSHKH13]). We implemented all of these mappings and features to care for the diverse tasks and scenarios. We believe that

especially the perspective pointing allows for very flexible reach of elements independent from the current position of the user.

#### 4.1.2. Data selection

As the user moves in front of the wall-sized display to explore the data space, different techniques are required to support selection of visualized graph data (I [SELECT]) both in close proximity and farther from the display wall. We therefore propose a number of **selection techniques** directly on the display wall, directly on the mobile device, or triggered from the device through pointing. To find a starting point on where to select and explore the data, the user requires some basic information to identify interesting structures or read individual labels. We recommend a smart labeling technique that shows nodes at different levels of detail (incl. labels, images, basic attribute data) on the wall-sized display depending on their distance to the user. This is accomplished using a level of detail value which triggers different visual representations of the nodes. It is set to higher values for nodes close to a user depending on their euclidean distance and their degree relative to the graph's maximum degree. When multiple users influence the same node, i.e., users are in close proximity, the higher value is used. When near the wall, users can tap to select individual elements on the display, e.g., a disease node or person (see Figure 2A). Furthermore, users can select multiple nodes by encircling them (see Figure 2B). Selections are managed on a per-user basis. When performed on the wall, they are associated with the device closest to the location where selection took place.

To examine the entire information space or select larger parts of it, the user may step back and move in front of the display wall or casually sit at a distance to discuss the data with colleagues. As a result, contact with the display is not always possible or wanted. Users can apply different selection techniques for remote interactions and during physical navigation in accordance with our design principles, keeping the interaction consistent with the techniques on the wall-sized display as an essential interaction guideline: It is possible to tap elements on the mobile to select individual nodes or encircle a group of elements to select them (see Figure 2D). Beside these tap and lasso selections, a rectangle selection of all elements currently visible on the mobile can be triggered. This is especially useful for selecting clusters, e.g., a cluster of cancer diseases. Afterwards, individual elements of the selection can again be de-selected using tap on the mobile device. Elements currently selected on the mobile are highlighted through color on the wall-sized display to ease rediscovery of the focus when looking at the display wall.

## 4.2. Details on demand

As the user aims to get more information on the content after selection, the role of the mobile device immediately changes to a second screen for additional visual output. While the wall display presents an overview of the nodes and edges, the mobile device may display a **detail view** with more information associated with selected content (I [ABSTRACT&ELABORATE]). When a single node is selected, detailed information of the object are shown by presenting an organized table of the multi-variate data attributes. In the disease scenario, the biologists see textual details such as information on the category of the disease, its short description, symptoms, and the known number of occurrences. In the social network example, demographic information, such as gender, age, and location, as well as interests, group association, and page likes are presented (see Figure 2A). For a group of nodes in the social network example, we currently provide individual information on all selected nodes in a grid overview (see Figure 2B). As the nodes in the disease scenario contain more numerical data, aggregated visualizations of information on graph attributes may be shown and could be extended to other alternative representations for comparison (e.g., star plots or parallel coordinate plots) or the specific node-link relations within the selected group (different layouts of sub-graphs, etc.).

In addition, the second screen can be more than just an output device. A characteristic of mobile devices is their suitability for personal input, including the advantage of providing a familiar personal keyboard. They can hence be used for manipulating data, e.g., to edit data values and enter new data within the detail view (E [ADD/UPDATE ATTRIBUTES]).

## 4.3. Encode and manipulate in alternative representation

Alternative representations and different encodings of the graph data can help identify connections or patterns in the topology. By providing those representations on the additional mobile display, they can become movable in space and hence can be flexibly arranged to investigate the coupling with the original representation. Seeing both adjacency matrix and node-link representation simultaneously can support different tasks [GFC05]. As part of GRASP, we visualize the adjacency matrix for parts of the data similar to NodeTrix [HFM07], but in a physically decoupled way to show both representations at the same time creating a **movable adjacency matrix** (see Figure 3A). Either by pointing at and freezing a region of interest or while continuously pointing, we present the adjacency matrix (I [ENCODE], G [CONNECTIVITY]) for the nodes in focus. Absolute movement in space or perspective pointing determines the selection of the relevant focus. The adjacency matrix fills the mobile display, while feedback on the wall-sized display shows which nodes are currently included in the matrix visualization. In the social network scenario, the user looks at the inter-connections between people of a possibly interesting target group that relates to specific product pages. The adjacency matrix on the mobile device allows a direct overview of connected elements by looking at rows or columns of the matrix instead of following individual edges in the node-link representation.

While relations are presented as an overview, our scenarios also suggest the need to manipulate and configure edges in the visualization (E [ADD/REMOVE EDGES]). When aiming to create an edge on
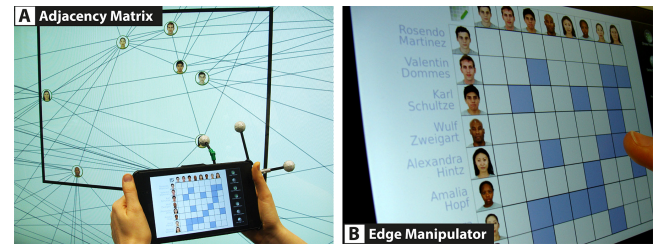


**Figure 3:** *The Adjacency Matrix as an alternative representation can be extracted to the device and moved freely in space (A). It also provides remote edge manipulation (B).*

the display wall by connecting two nodes through dragging (e.g., as suggested by users in [FHD10]), moving along a wall-sized display might be tiresome or impossible when other users are occluding parts of the display wall. The decoupled view on the mobile display and the alternative representation allow remote addition and removal of edges in an elegant way (see Figure 3B). After unlocking the edit mode, the user can simply tap on a cell of the adjacency matrix to create an edge between nodes [GSLT15]. The creation is then animated on the wall-sized display and the matrix is adapted to reflect the change. Similarly, an edge can be removed by tapping on the according cell. Dragging on multiple cells within a row or column, or even diagonally when selecting blocks of cells, can manipulate multiple edges at once, allowing quick creation of clusters.

## 4.4. Connect and adjacency – Bring Neighbors Lens

To support connectivity and adjacency tasks focusing on the relation between nodes beside the adjacency matrix, we implemented a variation of the Bring Neighbors Lens [TAvHS06]. Magic lenses are established interactive tools in visualization supporting diverse tasks [TGK*16]. They allow a transient change of a visualization in a locally restricted focus area by adding, enriching, or removing content. In our set of techniques, we decouple the focus and context view by presenting the focus view on the mobile device. As the mobile moves within the space in front of the wall-sized visualization, we use it as a novel perspective **tangible graph lens**. By pulling in the adjacent nodes of all nodes in focus, the Bring Neighbors Lens highlights their inherent connections (I [CONNECT]; G [ADJACENCY]). For the disease scenario, this specifically supports the user in getting an overview of diseases and genes connected to colon cancer. In the social network, friends of the nodes in focus are moved in and create a local friendship overview (see Figure 4A).

Bring Neighbor as the lens function, i.e., the effect that defines how the visualization is modified, is applied to a selected region of interest. One essential part when working with lenses is the manipulation of the properties that define that region of interest (shape, size, position, orientation). To fit a typical tablet, we restrict the lens to be of rectangular shape. The position and size of the lens are defined by the mobile's focus view consistent with our previously described techniques (c.f. 4.1.1) for pointing and size manipulation using a slider on the mobile, pinching on the display, or the user's distance from the display wall. This again allows both
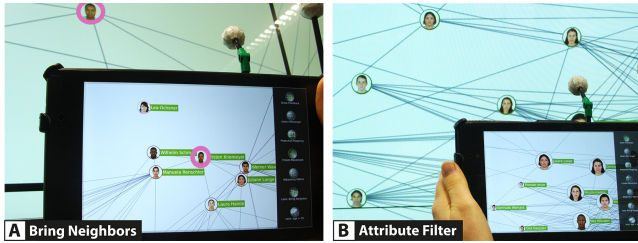
**Figure 4:** *Tangible Graph Lenses: Bring Neighbors pulls in adjacent nodes of nodes in focus (here: highlighted in pink) (A) and Attribute Filter enlarges nodes with specific attribute values (B).*



**Figure 5:** *Body-relative attribute filtering: Left-right movement supports selection of individual attribute ranges (B), a down movement then brings the selected range into focus (C).*

physical navigation as well as remote interaction from a casual position. It can be used to actively move around and explore the data set identifying regions of interest or can be frozen and decoupled from the device's pointing position.

### 4.5. Attribute-based data filtering

An important requirement of our previously introduced scenarios is the support of overview & filter tasks in versatile ways. In the most basic form, this can be the access and further analysis of individual target groups by reducing the visual elements through filtering of attribute values, for example, seeing only women for certain product endorsements. For further analysis of the data set, users may want to explore the separate layers and understand the distribution of data points along specific data attributes and dimensions. For our disease scenarios, this relates to separating the types of diseases a cluster consists of and investigating these separated groups.

#### 4.5.1. Local highlighting – Attribute Filter Lens

To address the filtering of content by attribute value, we added to the tangible lens character of the mobile by integrating a configurable Attribute Filter Lens which allows highlighting of nodes with certain attribute values or within a specified value range (I [FILTER], G [ATTRIBUTE-BASED]) locally on the device. To accomplish a configuration that fits the user's need, the lens requires parametrization of the specific lens function. For filtering this includes mainly the selection of appropriate attribute values or value ranges. For other lens functions this could similarly be a zoom factor for magnification or selecting a layout of how neighbors are presented (see 4.4). This is done by setting individual parameter values in a user interface on the mobile display using widgets (similar to Figure 6A).

For our social network scenario, Figure 4B shows an example lens configuration for highlighting all people older than 35 as a possible target group for advertisement. Note that in contrast to the following techniques, the focus of the attribute filter lens lies on the definition of criteria to create a single set of resulting nodes. However, criteria can be a set of parameters from different attribute types defining this result (e.g., females from Wales older than 35).

#### 4.5.2. Body-relative range filtering

For analysis purposes, the spatial separation of nodes with different attribute values can support more thorough investigations of different groups and their relations. For the marketing analyst in our
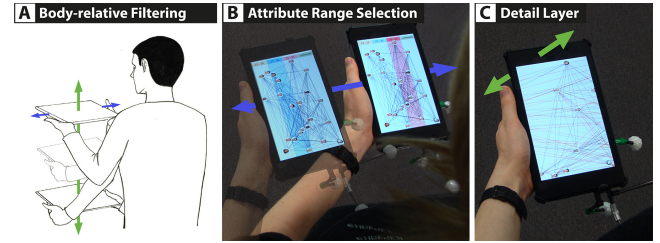
scenario, it is interesting to analyze the age distribution as an additional criterion (I [FILTER]) to gain a better understanding how the people are interconnected and divided among their ages within a selected target group (e.g., men with at least 15 friends). Here, the user wants to separate the nodes according to their age, but also see the relations within an age group and among age groups.

As we have seen in previous techniques, spatial tracking of mobile devices can be used directly related to a wall-sized display in various ways. While our wall-centric approaches (cf. tangible graph lenses) refer to the whole context visualization and are characterized by a direct spatial coupling and physical navigation to identify regions of interest, users are also interested in exploring or filtering further details of a previous selection in a separate, decoupled view. In order to support this tasks (G [OVERVIEW]; I [FILTER]), we propose the seamless integration of body-relative layers which enable decoupled, personal interactions by parameterizing the interaction space around the user (see Figure 5A). Holding a clutch button on the mobile and simultaneously moving the device relative to the previous position creates a spatial degree of freedom which can be used to browse through layered ranges of the attribute distribution. All possible ranges are laid out in the horizontal dimension, providing a **body-relative range filter**. Using the vertical movement, the user can then activate a range to expand it and see a more detailed view (see Figure 5C). In both cases, the body awareness can help support this browsing of graph subsets (I [EXPLORE], G [OVERVIEW]) and filtering of attribute ranges (I [FILTER]). In addition, we argue that the spatial parameterization facilitates the ability to store and retrieve items based on physical mnemonics and human proprioception (cf. [MBS97]).

#### 4.5.3. Distribution overview – Sieve filter tool

The previous technique focused on the exploration of separated attribute ranges. Another essential task is providing visualizations that enable understanding of the distribution of nodes within an attribute dimension, e.g., the distribution of disease types in a cluster around colon cancer. In order to avoid creating multiple instances of attribute filter lenses and switching between them, we propose using naive physics [JGH*08] to advance understanding of data. This GRASP technique simulates pouring graph nodes through a filter, applying the metaphor of a sieve tool with differently grained holes as representatives of different filter criteria (cf. [RK14]).

As introduced before, for our social network scenario it is relevant to look at the age distribution within an interesting cluster. The
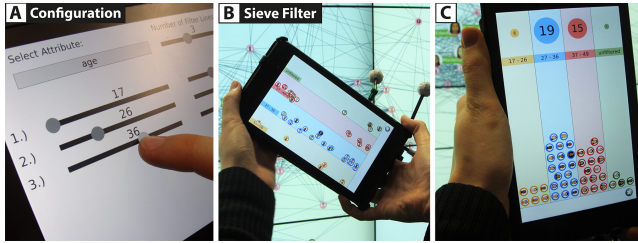
**Figure 6:** *Sieve Filter Tool: After configuring the filter criteria (**A**), nodes are spatially separated using physics (**B**). When rotated, they will fall to create a comparative view (**C**).*

**sieve filter tool** supports this kind of filter tasks by simply selecting an attribute on the mobile, defining separated age ranges with sliders (e.g., 12–20; 21–30) and starting the tool (see Figure 6A). The sieve filter tool visualizes every selected node as a physical object. A shake gesture allows the user to virtually throw all elements through the previously defined filter barriers. Conforming to the expectations of our metaphor of a sieve tool all nodes are filtered by their attribute and are spatially separated in their visual position (see Figure 6B). This allows a fast recognition of the different age groups, and the change of layout can be followed easily by seeing generally-known physical behaviors. In addition, the user can rotate the mobile device and all filtered data items fall to the ground within their valid attribute boundaries. This enables a comparative view (similar to [HVF13]) showing the distributions of the previously defined attribute regions by the total amount (absolute height) and with additional labels that highlight the amount of nodes inside each range (see Figure 6C).

## 5. Implementation & Setup

Our prototype was developed using Python with libavg (http://libavg.de) as basis for the user interface, as well as pymunk (http://pymunk.org/) for physics. We used the NetworkX library (https://networkx.github.io) to handle graph data and integrate graph algorithms. For the social network data set (218 nodes and 1530 edges), we used an anonymized export of a facebook account, which we linked with face images from the Chicago Face Database [MCW15] (see Figure 1B). The data for the human disease network (1419 nodes and 2738 edges) were provided by Goh et al. [GCV*07] and can be seen in Figure 1A. All data were processed in the GraphML format.

The technical setup consists of a large, touch-enabled display wall of 4.86 m in width and 2.06 m in height (frame height at 2.3 m), with a resolution of 7680 × 3240 pixels. We used Google Nexus 7 tablets with attached IR markers as mobile devices which are spatially tracked by the 3D tracking system Opti-Track (http://optitrack.com). In the future, these could be replaced by mobile devices with on-board tracking, such as Google Tango tablets. All application content is processed on a 2-core Intel Xeon processor, clocked at 3.3GHz and with two AMD HD 7970 graphics cards. Graphics are streamed to the mobile devices. Input is gathered on the wall display, mobile devices, and tracking machine and then transmitted to our central wall computer.

## 6. User Feedback

To gain a better understanding of the GRASP repertoire and the users' workflow as well as evaluate the cooperation of our techniques, we conducted a qualitative user study to get hands-on feedback with our system. We recruited 9 participants (3 female, 6 male) between the age of 22 and 35 (avg.: 26) through mailing lists including students and post-doctoral personnel with background in visualization, but not necessarily graphs, to explore the social network data set. While they were not part of our research group, the students had previously attended courses at our institute. They used the setup as described in the implementation section. All participants use mobile touch-enabled devices daily, but have little experience with larger wall-sized displays. Two worked with graph data frequently, while three used node-link diagrams only occasionally.

The sessions took approximately 45 min per participant and were divided into two sections: In the first section (S1), the experimenter would describe a possible task and ask the participant to suggest how they would accomplish a solution. Afterwards, the experimenter explained the individual features including the possible alternatives within the system while the participant interacted. This process was repeated for every feature to make the participant familiar with the application. The second section (S2) addresses our main research question of how and if the techniques are used in sequence and combination and how they fit within a user's workflow. This section consisted of five larger exploration tasks that incorporated a sequence of two to three sub-tasks. Participants were asked to accomplish these tasks without help from the experimenter who stayed at a neutral position away from any interaction to not interfere with movement and behavior. Participants were encouraged to describe and comment on all their actions. The sessions were videotaped and a second experimenter was present to record comments and actions along a semi-structured protocol. Finally, participants filled out a post-study questionnaire with seven questions relating to the assessment of our techniques and additional open questions.

Phase S2 incorporated tasks that were organized to form logical interaction steps. Tasks generally belonged to one of three task types: As an example of the first type, users had to investigate the neighbors of a specific node which were difficult to identify as they were part of different clusters and hence distant from each other. They had to compare their attributes and elaborate on their details (representing tasks: *select, connect/reconfigure, abstract&elaborate*). For the second type, users had to focus on smaller groups, such as family connections, where in one case they had to identify the older generation and add edges from the son's new fiancée to the graph (*encode/connect, filter, select from group, manipulate*). Finally tasks of the third type were of a more explorative nature focusing on larger clusters. In one example, the users had to discuss and explore the age distribution and patterns within a specified group of friends (*overview, explore/connect, filter*).

Two of the researchers separately went through protocoled data to summarize and categorize behavior. The videos were used for confirmation where protocols were insufficient. As a result of the protocol analysis, videos were examined specifically to code participants' movement (type and amount) and observe their focus switches between devices. From the protocols, the video data, and the questionnaires, we extracted interesting observations including

minor user interface improvements and possible alternative interactions. In the following, we discuss selected insights focusing specifically on items concerning 1) the participants' distribution of focus between the individual displays, 2) the participants' workflow and sequence of actions, as well as 3) the individual techniques.

### 6.1. Distribution of focus

Our study started with the *details on demand* technique that provides further information on the mobile when selecting a node on the wall. We observed that there was an initial phase where users had to comprehend the decoupled input and output possibilities of the device combination. However, it took only a short time for them to understand the mobile's role as a personal visualization and interaction tool that extends the capabilities of the large context display.

Beside the wall selection, during our studies we learned that all participants liked the spatial pointing as an alternative selection technique. We observed very different styles of user movements, distances to the wall, and levels of focus and awareness concerning the mobile and large display. Based on our interviews, observations, and video recordings, we identify two groups (G1 and G2) which were equally represented in our study and which are also reflected in their choice of selection technique. Some participants strongly focused on the combination between the wall and mobile and thereby switched their gaze and physical position frequently. This group (G1, $n = 4$) used both interactive displays equivalently and thereby seemed to have a strong overall awareness of the whole content at any time. They brought the mobile selection, detail view, or tool view into line with the large context visualization as they switched their focus and used the display wall for selection as well. Within G1, one participant (P1) showed unusual behavior in that he picked up content from the wall-sized display using touch and then often turned away from the display wall, temporarily focusing completely on the mobile display, but all in all switching his attention frequently between devices. In contrast, several other participants (G2, $n = 5$) were very focused on the mobile device. They used the large context visualization mainly as an overview from which they picked regions of interest. For selection they preferred pointing techniques and worked with content on their mobile in a more exclusive way while only sometimes looking up at the display wall for orientation and overview. We see that these participants typically interacted far away (2–3 m) and used the perspective pointing and mobile interactions more prominently (e.g., pointing, freezing, encircle selection on the mobile) instead of actively using physical navigation in front of the wall.

### 6.2. Workflow and sequence of actions

Participants were very successful in solving the given tasks and found diverse solutions and workflows. They often started out by selecting a region of interest (ROI), followed by further refinement and application of a tool or lens. Specifically, participants from G1 frequently used touch on the wall for data collection (tap or lasso), while participants from G2 primarily used pointing and optionally froze the movement before using either the rectangle selection or a tap or lasso selection on the mobile device. Freezing was very important to participants and was used constantly after pointing, likely

to relax the posture and focus on the selected ROI. However, not all participants clearly separated freeze from rectangle selection. Except for the detail view and sieve filter tool, all other techniques can be applied continuously without prior content selection. We observed that for at least two participants this separation seemed to be a challenge and might have caused minor issues in the deactivation of tools. For instance, it seemed that after unfreezing when moving along to other regions, they were surprised by the Bring Neighbor lens still being active.

Participants resided at very different distances to the wall-sized display (with some relation to their association to G1 or G2) and hence moved very differently during the study. At the extremes, a participant (P8) from G2 was consistently at a distance of approx. 3 m central to the display wall and rarely moved from that position, using perspective pointing for all her interactions with the wall-sized display. On the other hand, two participants (P1, P9) were very active using criss-cross movements within the complete space in front of the display wall. However, the majority of our participants ($n = 6$) naturally positioned themselves at their individual neutral distance (approx. 1–2 m from the display wall, P7 at 3 m) which seemed to be their personal comfort position. They all moved strongly parallel to the wall at this personal distance, with participants from G1, who used touch on the wall most, returning to this distance before moving sideways again. To access content at the top of the display, all but one participant (P4, height: 1.88 m) switched to perspective pointing, instead of lifting their arms using orthogonal pointing. To summarize, the tool seemed to be flexible and could be used by all participants independent from position and movement in front of the display wall. We observed that it was very helpful to combine the different tools and techniques for solving tasks. This was done frequently and naturally by all participants and was not even mentioned as a feature.

### 6.3. Observations concerning GraSp techniques

Offloading the *adjacency matrix* onto the mobile display to simultaneously show both visual representations physically decoupled was well-accepted by all participants. Participants used the adjacency matrix frequently to identify connections and patterns while referring back to the node-link representation on the wall-sized display specifically when editing the selected sub-graph. There was some disagreement on whether the unlock button for edit operations was necessary. While some explicitly found it to be an unnecessary interaction step (P6) as they were holding the mobile with both hands while reading the matrix, others (P5, P8) used their forefinger strongly to follow rows and columns and hence found an unlock operation essential to prevent unintended manipulations.

The *tangible graph lenses* proved to be very flexible tools that were frequently combined with other techniques for solving tasks. A typical interaction flow often consisted of pointing towards a ROI, freezing the content, applying a lens function, and finally selecting identified content using a lasso to gain further details. Surprisingly, this also meant that lenses were rarely used as active tools to be moved continuously around the data set to gain insights, but were rather used on already explicitly chosen areas using the freeze operation. Even in explorative tasks, participants often worked with samples from selected clusters instead of moving about the whole

node-link representation. However, this may change with experience or may also be a result of the specific set of tasks used in this study and will have to be investigated further in future work.

With the *sieve filter tool* we aimed at observing the use of physical metaphors for data analysis tasks. While it was obvious that time efficiency was not improved by the animation of physics, we saw a variety of enjoyment in all participants from actively smiling to comments of "This is like playing" (P7). One participant (P8) specifically addressed that "Most people want more fun during work". As a result, participants seemed very engaged with the tool. However, while the animation initially actively helped participants understand the process of categorizing and filtering the nodes (P9), for solving the tasks some discussed the need for a quick and direct presentation of the results (P5, P9) without the additional interactions of shaking or turning the device.

## 7. Discussion

We identified challenges and advantages of the combination of mobile devices and a large display. It is a general limitation of visual data analysis that it is only feasible for a limited number of nodes, i.e., for larger graphs an initial query or filtering step is necessary before reasonable use in a visual exploration setup. The large display and multi-device setup can help distribute this content and organize data at different levels of detail. However, as a certain limitation this also requires more cognitive effort for the user in managing content on the different devices. The study has reinforced that with multiple displays there is the need of additional focus and attention switches which may lead to additional interaction efforts and increased cognitive load, e.g., for tracking changes on the wall. Clear visual indications of focus regions and selected objects on both devices and consistent feedback can reduce these efforts. In addition, we have also seen several advantages of this device combination as each user worked with the mobile as their own tangible personal tool, and seamlessly accessed content even from afar.

Because of our design, all interactions were feasible and executable on the mobile display while using the wall-sized display mainly for overview tasks. We specifically focused on this setup to support the use in multi-user scenarios. Taking our techniques as the basis, further investigations could enrich this scenario by allowing more diverse views and changes on the display wall. Our techniques utilize the mobile as a personal toolbox for graphs and thereby allow independent parallel work on the same context visualization without disturbing other collaborating users. After initial registration of devices, all mobile interactions are possible, and touch selections on the wall are automatically send to the closest device. However, the current prototype is focused on parallel, individual work and does not prevent editing conflicts so that extension is required for actual application to multi-user and collaborative scenarios.

In our use of physical metaphors, e.g., for perspective pointing and the sieve tool, we saw evidence of participants enjoying the use of physics for visual data analysis. However, this needs to be differentiated for beginners and experts. While slow animations and additional interactions help to develop a clear understanding of the principles and steps needed, we found the lack of efficiency in the

sieve tool too severe for repeated use in professional contexts. Consequently, shortcuts, ways of personal configuration, or automated adaption to the user's experience level should be included in a future iteration of the system.

As the number of participants in our user study was small, no significant quantitative statements can be made. However, with our qualitative measures and observations we aimed to present tendencies and rise questions for future research studies and application designs. Even within our small group of participants, we saw that there is not just one single style of interaction. This confirms related work (e.g., [TBJ15]) where diverse exploration strategies for selected tasks have been observed. While we identified two general groups of focus behavior, even within these groups there were variations in terms of workflow and sequences of action (see 6.2). The GRASP techniques were flexible enough to allow for these variations including the different patterns of movement for navigation within the data space. However, more adaptations to the individual usage should be considered and could further personalize the system (e.g., unlock button for manipulation). All in all, we see the advantage and strength of productive solutions in the versatility and composition of tools and techniques to fit individual strategies and user preferences.

## 8. Conclusion and Future Work

In this paper, we presented the GRASP system, a set of interactive techniques that combine a wall-sized display and mobile devices tracked in space for graph visualization and interaction. Our techniques support individual local interaction on each user's personal mobile device, which serves both as an additional, tangible visualization view that can be manipulated as well as a pointing device to interact with and coupled to the display wall. Therefore, the contributed techniques are designed to allow interacting in close proximity to the display wall as well as remotely from afar.

The GRASP techniques form a toolbox that addresses a large range of diverse graph visualization tasks from basic selections and details on demand to alternative representations, manipulations, tangible graph lenses, and diverse filtering techniques. Therein, we investigated physical metaphors as well as spatially-aware and body-relative interactions for selecting and filtering multivariate data items. In a qualitative study, we found workflows to be very diverse and our system well suited to handle a wide range of interaction sequences and combined techniques.

In the future, we plan to apply this promising combination of devices to other data types and fields of visualization including extensions with multiple coordinated views or dynamic graphs. Furthermore, we aim to intensify our discussion of multi-user scenarios by adding collaborative techniques using several mobile devices and large displays in synergy within multi-display environments.

## 9. Acknowledgement

## References

[AEN10] ANDREWS C., ENDERT A., NORTH C.: Space to think: Large high-resolution displays for sensemaking. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2010), CHI '10, ACM, pp. 55–64. doi:10.1145/1753326.1753336. 1, 2

[BBF12] BAUR D., BORING S., FEINER S.: Virtual projection: Exploring optical projection as a metaphor for multi-device interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2012), CHI '12, ACM, pp. 1693–1702. doi:10.1145/2207676.2208297. 3

[BFE15] BADAM S. K., FISCHER E., ELMQVIST N.: Munin: A peer-to-peer middleware for ubiquitous analytics and visualization spaces. *IEEE Transactions on Visualization & Computer Graphics 21*, 2 (2015), 215–228. doi:10.1109/TVCG.2014.2337337. 2

[BI12] BEZERIANOS A., ISENBERG P.: Perception of visual variables on tiled wall-sized displays for information visualization applications. *IEEE Transactions on Visualization and Computer Graphics 18*, 12 (Dec. 2012), 2516–2525. doi:10.1109/TVCG.2012.251. 1, 2

[BLC12] BAUR D., LEE B., CARPENDALE S.: Touchwave: Kinetic multi-touch manipulation for hierarchical stacked graphs. In *Proceedings of the 2012 ACM International Conference on Interactive Tabletops and Surfaces* (2012), ITS '12, ACM, pp. 255–264. doi:10.1145/2396636.2396675. 1

[BLEJ*13] BERGSTROM-LEHTOVIRTA J., EKLUND T., JYLHÄ A., KUIKKANIEMI K., AN C., JACUCCI G.: Bubblesdial: Exploring large display content graphs on small devices. In *Proceedings of the International Conference on Mobile and Ubiquitous Multimedia* (2013), MUM '13, ACM, pp. 1:1–1:10. doi:10.1145/2541831.2541845. 2

[BNB07] BALL R., NORTH C., BOWMAN D. A.: Move to improve: Promoting physical navigation to increase user performance with large displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2007), CHI '07, ACM, pp. 191–200. doi:10.1145/1240624.1240656. 2, 4

[Chi06] CHITTARO L.: Visualizing information on mobile devices. *Computer 39*, 3 (2006), 40–45. doi:10.1109/MC.2006.109. 1, 2

[CLMT12] CHENG K., LI J., MÜLLER-TOMFELDE C.: Supporting interaction and collaboration on large displays using tablet devices. In *Proceedings of the International Working Conference on Advanced Visual Interfaces* (2012), AVI '12, ACM, pp. 774–775. doi:10.1145/2254556.2254708. 3

[CNS*14] CHUNG H., NORTH C., SELF J. Z., CHU S., QUEK F.: Visporter: Facilitating information sharing for collaborative sensemaking on multiple displays. *Personal Ubiquitous Comput. 18*, 5 (June 2014), 1169–1186. doi:10.1007/s00779-013-0727-2. 3

[DFS*13] DRUCKER S. M., FISHER D., SADANA R., HERRON J., SCHRAEFEL M.: Touchviz: A case study comparing two interfaces for data analytics on tablets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2013), CHI '13, ACM, pp. 2301–2310. doi:10.1145/2470654.2481318. 1, 2

[EALN11] ENDERT A., ANDREWS C., LEE Y. H., NORTH C.: Visual encodings that support physical navigation on large displays. In *Proceedings of Graphics Interface 2011* (Waterloo, Ontario, Canada, 2011), GI '11, Canadian Human-Computer Communications Society, pp. 103–110. URL: http://dl.acm.org/citation.cfm?id=1992917.1992935. 2

[EWE09] EISSELE M., WEISKOPF D., ERTL T.: *Interactive Context-Aware Visualization for Mobile Devices*. Springer Berlin Heidelberg, 2009, pp. 167–178. doi:10.1007/978-3-642-02115-2_14. 2

[FHD10] FRISCH M., HEYDEKORN J., DACHSELT R.: Diagram editing on interactive displays using multi-touch and pen gestures. In *Proceedings of the International Conference on Diagrammatic Representation and Inference* (Aug. 2010), Diagrams '10, Springer, pp. 182–196. URL: http://portal.acm.org/citation.cfm?id=1884734.1884759. 3, 6

[GCV*07] GOH K.-I., CUSICK M. E., VALLE D., CHILDS B., VIDAL M., BARABÁSI A.-L.: The human disease network. *Proceedings of the National Academy of Sciences 104*, 21 (2007), 8685–8690. doi:10.1073/pnas.0701361104. 8

[GFC05] GHONIEM M., FEKETE J.-D., CASTAGLIOLA P.: On the readability of graphs using node-link and matrix-based representations: A controlled experiment and statistical analysis. *Information Visualization 4*, 2 (July 2005), 114–135. doi:10.1057/palgrave.ivs.9500092. 6

[GKT*15] GLADISCH S., KISTER U., TOMINSKI C., DACHSELT R., SCHUMANN H.: Mapping tasks to interactions for graph exploration and editing. In *Poster at IEEE Conference on Information Visualization (InfoVis)* (10 2015), IEEE. 3

[GMB*11] GREENBERG S., MARQUARDT N., BALLENDAT T., DIAZ-MARINO R., WANG M.: Proxemic interactions: The new ubicomp? *interactions 18*, 1 (Jan. 2011), 42–50. doi:10.1145/1897239.1897250. 2, 4

[GSLT15] GLADISCH S., SCHUMANN H., LOBOSCHIK M., TOMINSKI C.: Toward using matrix visualizations for graph editing. In *Poster at IEEE Conference on Information Visualization (InfoVis)* (10 2015), InfoVis'15, IEEE. 6

[HFM07] HENRY N., FEKETE J.-D., MCGUFFIN M. J.: Nodetrix: a hybrid visualization of social networks. *IEEE Transactions on Visualization and Computer Graphics 13*, 6 (Nov. 2007), 1302–1309. doi:10.1109/TVCG.2007.70582. 6

[HSS15] HADLAK S., SCHUMANN H., SCHULZ H.-J.: A survey of multi-faceted graph visualization. In *EuroVis - STARs* (2015), The Eurographics Association. 3

[HVF13] HURON S., VUILLEMOT R., FEKETE J.-D.: Visual Sedimentation. *IEEE Transactions on Visualization and Computer Graphics* (Nov. 2013). doi:10.1109/TVCG.2013.227. 8

[IDW*13] ISENBERG P., DRAGICEVIC P., WILLETT W., BEZERIANOS A., FEKETE J. D.: Hybrid-image visualization for large viewing environments. *IEEE Transactions on Visualization and Computer Graphics 19*, 12 (Dec 2013), 2346–2355. doi:10.1109/TVCG.2013.163. 2

[JDF12] JANSEN Y., DRAGICEVIC P., FEKETE J.-D.: Tangible remote controllers for wall-size displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2012), CHI '12, ACM, pp. 2865–2874. doi:10.1145/2207676.2208691. 3

[JGH*08] JACOB R. J., GIROUARD A., HIRSHFIELD L. M., HORN M. S., SHAER O., SOLOVEY E. T., ZIGELBAUM J.: Reality-based interaction: A framework for post-wimp interfaces. In *Proc. of the SIGCHI Conference on Human Factors in Computing Systems* (2008), CHI '08, ACM, pp. 201–210. doi:10.1145/1357054.1357089. 7

[JH15] JAKOBSEN M. R., HORNBÆK K.: Is moving improving?: Some effects of locomotion in wall-display interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2015), CHI '15, ACM, pp. 4169–4178. doi:10.1145/2702123.2702312. 1, 2

[JSHKH13] JAKOBSEN M. R., SAHLEMARIAM HAILE Y., KNUDSEN S., HORNBÆK K.: Information visualization and proxemics: Design opportunities and empirical findings. *IEEE Transactions on Visualization and Computer Graphics 19*, 12 (Dec. 2013), 2386–2395. doi:10.1109/TVCG.2013.166. 1, 2, 4, 5

[KPW14] KERREN A., PURCHASE H. C., WARD M. O. (Eds.): *Multivariate Network Visualization*, vol. 8380 of *Lecture Notes in Computer Science*. Springer, 2014. doi:10.1007/978-3-319-06793-3. 3

[KRD16] KISTER U., REIPSCHLÄGER P., DACHSELT R.: Multilens: Fluent interaction with multi-functional multi-touch lenses for information visualization. In *Proceedings of the 2016 ACM International Conference on Interactive Surfaces and Spaces* (11 2016), ACM. doi:10.1145/2992154.2992168. 3

[KRMD15] KISTER U., REIPSCHLÄGER P., MATULIC F., DACHSELT R.: Bodylenses: Embodied magic lenses and personal territories for wall

displays. In *Proceedings of the International Conference on Interactive Tabletops & Surfaces* (2015), ITS '15, ACM, pp. 117–126. doi:10.1145/2817721.2817726. 2

[LPP*06] LEE B., PLAISANT C., PARR C. S., FEKETE J.-D., HENRY N.: Task taxonomy for graph visualization. In *Proceedings of the 2006 AVI Workshop on BEyond Time and Errors: Novel Evaluation Methods for Information Visualization* (2006), BELIV '06, ACM, pp. 1–5. doi:10.1145/1168149.1168168. 3

[LSST11] LEHMANN A., SCHUMANN H., STAADT O., TOMINSKI C.: *Physical Navigation to Support Graph Exploration on a Large High-Resolution Display*. Springer, Berlin, Heidelberg, 2011, pp. 496–507. doi:10.1007/978-3-642-24028-7_46. 3

[LvZH*16] LANGNER R., VON ZADOW U., HORAK T., MITSCHICK A., DACHSELT R.: *Content Sharing Between Spatially-Aware Mobile Phones and Large Vertical Displays Supporting Collaborative Work*. Springer International Publishing, 12 2016, pp. 75–96. doi:10.1007/978-3-319-45853-3_5. 3, 5

[MBS97] MINE M. R., BROOKS JR. F. P., SEQUIN C. H.: Moving objects in space: Exploiting proprioception in virtual-environment interaction. In *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques* (1997), SIGGRAPH '97, ACM Press/Addison-Wesley Publishing Co., pp. 19–26. doi:10.1145/258734.258747. 7

[MCW15] MA D. S., CORRELL J., WITTENBRINK B.: The chicago face database: A free stimulus set of faces and norming data. *Behavior Research Methods 47*, 4 (2015), 1122–1135. doi:10.3758/s13428-014-0532-5. 8

[MJ09] MCGUFFIN M. J., JURISICA I.: Interaction Techniques for Selecting and Manipulating Subgraphs in Network Visualizations. *IEEE Transactions on Visualization and Computer Graphics 15*, 6 (2009), 937–944. doi:10.1109/TVCG.2009.151. 3

[OFGM11] OLWAL A., FRYKHOLM O., GROTH K., MOLL J.: *Design and Evaluation of Interaction Technology for Medical Team Meetings*. Springer Berlin Heidelberg, Berlin, Heidelberg, 2011, pp. 505–522. doi:10.1007/978-3-642-23774-4_42. 2

[PBC16] PROUZEAU A., BEZERIANOS A., CHAPUIS O.: Evaluating multi-user selection for exploring graph topology on wall-displays. *IEEE Transactions on Visualization and Computer Graphics PP*, 99 (2016), 1–1. doi:10.1109/TVCG.2016.2592906. 3

[PNB09] PECK S. M., NORTH C., BOWMAN D.: A multiscale interaction technique for large, high-resolution displays. In *2009 IEEE Symposium on 3D User Interfaces* (March 2009), pp. 31–38. doi:10.1109/3DUI.2009.4811202. 3

[PPS14] PRETORIUS J., PURCHASE H. C., STASKO J. T.: Tasks for multivariate network analysis. In *Multivariate Network Visualization: Dagstuhl Seminar #13201, Dagstuhl Castle, Germany, May 12-17, 2013, Revised Discussions*. Springer International Publishing, Cham, 2014, pp. 77–95. doi:10.1007/978-3-319-06793-3_5. 3

[RAMH12] ROBERTS C., ALPER B., MORIN J. K., HÖLLERER T.: Augmented textual data viewing in 3d visualizations using tablets. In *IEEE Symposium on 3D User Interfaces (3DUI)* (March 2012), pp. 101–104. doi:10.1109/3DUI.2012.6184192. 3

[RDLC12] RICHE N. H., DWYER T., LEE B., CARPENDALE S.: Exploring the design space of interactive link curvature in network diagrams. In *Proceedings of the International Working Conference on Advanced Visual Interfaces* (2012), AVI '12, ACM, pp. 506–513. doi:10.1145/2254556.2254652. 3

[RK14] RZESZOTARSKI J. M., KITTUR A.: Kinetica: Naturalistic multi-touch data visualization. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2014), CHI '14, ACM, pp. 897–906. doi:10.1145/2556288.2557231. 7

[SBR13] SEIFERT J., BAYER A., RUKZIO E.: *PointerPhone: Using Mobile Phones for Direct Pointing Interactions with Remote Displays*. Springer, Berlin, Heidelberg, 2013, pp. 18–35. doi:10.1007/978-3-642-40477-1_2. 2

[SCRG10] SCHMIDT D., CHEHIMI F., RUKZIO E., GELLERSEN H.: Phonetouch: A technique for direct phone interaction on surfaces. In *Proceedings of the ACM Symposium on User Interface Software and Technology* (2010), UIST '10, ACM, pp. 13–16. doi:10.1145/1866029.1866034. 2

[SS14] SADANA R., STASKO J.: Designing and implementing an interactive scatterplot visualization for a tablet computer. In *Proceedings of the International Working Conference on Advanced Visual Interfaces* (2014), AVI '14, ACM, pp. 265–272. doi:10.1145/2598153.2598163. 2

[SSMD14] SPINDLER M., SCHUESSLER M., MARTSCH M., DACHSELT R.: Pinch-drag-flick vs. spatial input: Rethinking zoom & pan on mobile displays. In *Proceedings of the Conference on Human Factors in Computing Systems* (4 2014), CHI '14, ACM, pp. 1113–1122. doi:10.1145/2556288.2557028. 1, 2

[STKB10] SHOEMAKER G., TSUKITANI T., KITAMURA Y., BOOTH K. S.: Body-centric interaction techniques for very large wall displays. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction* (2010), NordiCHI '10, ACM, pp. 463–472. doi:10.1145/1868914.1868967. 2

[STSD10] SPINDLER M., TOMINSKI C., SCHUMANN H., DACHSELT R.: Tangible views for information visualization. In *ACM International Conference on Interactive Tabletops and Surfaces* (2010), ITS '10, ACM, pp. 157–166. doi:10.1145/1936652.1936684. 2, 3, 5

[TAS09] TOMINSKI C., ABELLO J., SCHUMANN H.: CGV – an interactive graph visualization system. *Computers & Graphics 33*, 6 (2009), 660 – 678. doi:10.1016/j.cag.2009.06.002. 3

[TAvHS06] TOMINSKI C., ABELLO J., VAN HAM F., SCHUMANN H.: Fisheye tree views and lenses for graph visualization. In *Proceedings of the Conference on Information Visualization* (Washington, DC, USA, 2006), IV '06, IEEE Computer Society, pp. 17–24. doi:10.1109/IV.2006.54. 3, 6

[TBJ15] TSANDILAS T., BEZERIANOS A., JACOB T.: Sketchsliders: Sketching widgets for visual exploration on wall displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (2015), CHI '15, ACM, pp. 3255–3264. doi:10.1145/2702123.2702129. 3, 10

[TGK*16] TOMINSKI C., GLADISCH S., KISTER U., DACHSELT R., SCHUMANN H.: Interactive lenses for visualization:an extended survey. *Computer Graphics Forum* (2016). doi:10.1111/cgf.12871. 6

[vLKS*11] VON LANDESBERGER T., KUIJPER A., SCHRECK T., KOHLHAMMER J., VAN WIJK J. J., FEKETE J., FELLNER D. W.: Visual analysis of large graphs: State-of-the-art and future research challenges. *Computer Graphics Forum 30*, 6 (2011), 1719–1749. doi:10.1111/j.1467-8659.2011.01898.x. 3

[VTS*09] VOIDA S., TOBIASZ M., STROMER J., ISENBERG P., CARPENDALE S.: Getting practical with interactive tabletop displays: Designing for dense data, "fat fingers," diverse interactions, and face-to-face collaboration. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces* (2009), ITS '09, ACM, pp. 109–116. doi:10.1145/1731903.1731926. 2

[vZBLD14] VON ZADOW U., BÜSCHEL W., LANGNER R., DACHSELT R.: Sleed: Using a sleeve display to interact with touch-sensitive display walls. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces* (2014), ITS '14, ACM, pp. 129–138. doi:10.1145/2669485.2669507. 2, 3

[WEF*14] WYBROW M., ELMQVIST N., FEKETE J.-D., VON LANDESBERGER T., VAN WIJK J. J., ZIMMER B.: Interaction in the visualization of multivariate networks. In *Multivariate Network Visualization: Dagstuhl Seminar #13201, Dagstuhl Castle, Germany, May 12-17, 2013, Revised Discussions*. Springer International Publishing, Cham, 2014, pp. 97–125. doi:10.1007/978-3-319-06793-3_6. 3

[YKSJ07] YI J. S., KANG Y. A., STASKO J., JACKO J.: Toward a deeper understanding of the role of interaction in information visualization. *IEEE Transactions on Visualization and Computer Graphics 13*, 6 (Nov. 2007), 1224–1231. doi:10.1109/TVCG.2007.70515. 3