Institute for Visualization and Interactive Systems (VIS)

Diploma Nr. 3577

Facilitating data exploration in casual mobile settings with multi-device interaction

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Course of Study:	Softwaretechnik
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Commenced:	November 1, 2013
Completed:	May 3, 2014
CR-Classification:	H.5.2

Abstract

Big data is the new buzzword of computer professionals. Governments and industry are increasingly looking to find benefits from exploring immense data sets using new powerful tools. Large amounts of data are generated through our daily activities: commuting, eating lunch, using mobile phones, and reading the bedtime story to the children. In a truly democratized society we should have access to the data we generate along with the tools needed to gain insight. Consequently, there is an emerging need for aggregating data from different sources and presenting it in forms that will make it accessible for different stakeholders within social entities pervasive computing systems will soon be required to provide opportunities for users to rapidly explore big data in ad-hoc casual settings.

This work focuses on how we can transform everyday spaces into data-rich environments where citizens can interactively explore data sets. Specifically, this work will investigate how we can transform table surfaces into interactive spaces by augmenting currently available mobile devices. Using multiple mobile devices for one and many users will be the focal theme and new interaction techniques are explored.

The project is build on past research from the t2i Interaction Laboratory and look for new sensing techniques, communication protocols and navigation patterns.

Keywords: mobile devices, mutual spatial awareness, interaction, casual, ubiquitous computing, evaluation, multi-surface, portable, motion tracking, data exploration

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Chapter 1

Introduction

A modern society needs modern approaches to everyday activities. A few years ago is was quite common to see people sitting in a café reading a newspaper. The newspaper will probably never completely vanish from this scene but today one can see a growing number of people using tablet computers or mobile phones. These mobile devices became an essential part of our everyday life and almost everybody knows how to use them. We check our email, read articles, take photos and share everything over the internet with our friends and colleagues. For some tasks we use our smartphone and for others we use the tablet as they both have their advantages. The tablet offers a bigger interaction space in terms of input and output which makes general interaction and reading more comfortable but the smartphone is more versatile. It fits nicely in our hands and can be operated using only one hand. For these reasons more an more people own both devices and carry them around. Unfortunately, in most cases, the devices are only loosely coupled, e.g. a shared cloud storage like Dropbox, or they are used separately and are not connected in any way. The core idea behind this work is to combine our already owned devices to a more sophisticated mobile desktop.

For centuries tables have been the central piece of furniture in our social environment. We gather around tables to meet, work, eat, celebrate and discuss everyday topics. We organize physical entities on tables to gain or share insights. So we decided to extend the interaction space to the whole table on which the mobile devices are placed and make them spatially aware of each other. By adding spatial awareness you can arrange the devices like pieces of paper or post its on a table which we all already do to communicate information to other people if we are sitting around a table. This leads to a stronger coupling of the devices which also enables a more sophisticated user interaction based on the relative positions. The devices can then be arranged in different ways to achieve a certain action and unlike traditional tabletops they are not bulky and can be used on any horizontal surface.

Smartphones and tablets are already fully integrated in our environment and using multiple devices in such a way could be seen as an embodiment of Mark Weisers vision ([1]). The devices are integrated more seamlessly into the world by breaking artificial boundaries between them and by emphasizing more convenient ways of interaction. Therefore every system doing so gets us closer to a world where "computers themselves vanish into the background" and people start using them without thinking. This is also strongly connected to the research trend called "Bring Your Own Device (BYOD)" as we allow users to bring their own devices and form an ad-hoc network between them [2].

The desire to provide easy access to data exploration in everyday spaces is the main motivation of this thesis. With datasets becoming more readily available, the future presents us with a number of data-related tasks such as providing community access to local government data, or analysing private tax or health records. Weise et al. argue for designing means for the general public to access and understand data [3]. New interactive technology is required to support societal activities by providing community-relevant data to individuals, businesses, and authorities whenever required. As indicated by Churchill the growing importance of big data and ubiquitous sensing generates a need for low-cost data exploration, to understand and properly analyse this data on a societal level [4]. Thus, human-computer interaction (HCI) should investigate new designs for systems that will empower users who lack data science knowledge to explore these datasets. Another question is where such an analysis would take place. We believe that familiar meeting places such as cafés could be suitable locations. We aim to design a system that would enable ad-hoc interactions with datasets using multiple mobile devices in everyday spaces.

Anticipated developments in mobile sensing technology are also a motivation factor. Several past research reports indicate that achieving portable mutual spatial awareness with mobile devices is a possibility. Low-cost ultrasonic Doppler sensing will soon be available and can be embedded in mobile devices [5]. Past research hints that positional awareness will soon be feasible by using triangulation approaches that rely on audible sound (BeepBeep [6]) or ultrasound (Relate [7]). We look forward to usage scenarios where mobile devices of varying form factors are handled and controlled in seamless orchestration, thereby enhancing the user experience. Because this thesis is based on research results and technology currently in development, we are not designing for an intangible near future (criticised by [8]), but rather are preparing for new capabilities in mobile devices that will be available very soon.

This work describes the design, implementation and evaluation of a system called *Thaddeus*, which can be used to collaboratively share information using everyday mobile devices. We named the system Thaddeus for “t(h)able-aware device dyad for ubiquitous sensemaking”. The devices in this system are strongly linked together from a content point of view as well as from an interaction point of view. This work focuses on the interaction in a casual setting with an extended interaction space to the whole table by making the devices spatially aware of each other. It is based on previous works such as DynamicDuo and MochaTop, which already show the core ideas, but is generalized here and brought to a more casual setting.

Chapter 2

Related Work

This chapter describes the related work to this thesis. There are several categories on which this thesis is built upon:

- Data exploration
- Interactive tabletop or public displays
- Spatial Tracking
- Spatial aware mobile devices
- Multi-surface environments
- Publication directly related to this work

2.1 Data exploration

Big Data is a modern keyword and mostly stands for huge amounts of data a company has acquired over years which now has to be analyzed while hoping to gain insights from it. However, raw data has no value in itself, but has to be processed to information before one can obtain any knowledge. An approach to master the vast amount of data is by using visual analytics tools. These tools combine multiple different visualizations, decision-making and human factors in data analysis [9]. Humans can perceive information visualizations better because forms and colors are more understandable than pure data [10]. Many visualizations techniques have been developed besides Node-Link-Diagrams, bar charts or scatter plots, which all serve a specific purpose. But there are additional challenges to master when you try to bring visualizations to mobile devices. The mobile context and technical limitations of the smaller devices make it nearly impossible to simply port existing visualizations ([11]) and visualizations developed for desktop computers do not scale well to mobile devices. Researchers are starting to address these challenges by either creating specialized visualizations for small screen spaces or enhancing the interaction with traditional visualizations. Han and Zhan describe a new visualization technique called Radial Edgeless Tree (RELT) for visualizing hierarchical data on palmsized devices [12]. The hierarchical information is visualized in a radial layout and instead of using space-consuming edges to explicitly make relationships, RELT uses adjacency and direction to represent relationships between nodes in order to save display space. Zhou et al. developed a framework for mobile volume visualizations for PDAs and mobile phones [13]. For a better performance they preprocess iso-surfaces on the server side which are then sent over the network to the devices. Sanfilippo et al. also brought visual analytics tools to mobile devices [14]. They try to extend the reach of the visual analytics technology beyond the traditional desktop by providing ubiquitous access to interactive visualization of information spaces. Shaer et al. indicated how horizontal surfaces can offer a variety of opportunities to explore massive data sets [15]. Examples like Phylo-Genie [16], Pathways [17] and WALDEN [18] also show that horizontal surfaces have a potential for communicating and manipulating data both for expert users and in everyday settings. In Thaddeus we offer several information visualizations to explore arbitrary data on multiple mobile devices which are placed on a regular table.

2.2 Interactive tabletops and public displays

Research and development in the field of interactive tabletops is done for almost 20 years by now. But still they are special and mostly seen on conventions or in labs as depicted by Müller-Tomfelde and Fjeld [19]. Several commercially available products shipped in the last years like the Reactable by Geiger et al. [20] or the Microsoft Pixelsense [21], but they did not have much of an impact. Microsoft also works on the third generation of their surface tables called Perceptive Pixel which are thinner, more responsive and easier to mount displays as the previous tables [22]. But the major drawback of an interactive table is that it is stationary and bound to a specific location (e.g. an office, meeting room, etc.). Yet, they slowly gain attention and are used more and more commercially or get integrated in multi-surface environments. Woźniak et al. built an application for tabletops, which is used to explore the potential of tabletops on maritime ship bridges [23]. They try to improve the handling of routine tasks which are not related to navigation like maintenance or route planning by adding a tabletop to the ships bridge.

Another research trend are public displays and how people can simultaneously interact with them. Alt et al. designed Digifieds, a system to run digital public bulletin boards [24]. Digifieds provided the possibility to use private smartphones to place information on a digital public notice board. The combination of private and public devices allows sharing some information with others without losing control of the entire dataset of a private phone. Those large screens also offer a great potential for gaining insights in complex data sets. Small details can be shown in high resolutions while still seeing the big picture. They also allow multiple users to look at the same data set and discuss about the same information. Therefor they are often integrated in multi-surface environments.

A significant amount of research on multi-surface environments is focused on combining multiple devices for professional analysis environments. VisPorter illustrated how multiple interactive surfaces can be used to construct a collaborative text foraging environment [25]. Danesh et al. presented the use of multiple handhelds for collaboration between school children where pupils could connect devices over a short distance [26]. The system enriches social interaction with playfulness and offers multiple pairing choices. This offers a new way of collaborating during school lessons. Furthermore, the system shows how multiple mobiles fit into a highly social environment. Thaddeus extends the above work by attempting to bring data analysis into everyday environments, using devices users already carry with them.

2.3 Spatial Tracking

It is crucial to have a reliable spatial tracking of objects when dealing with spatially aware tangible systems. When a larger display is used to show data to one or more people new interaction techniques like motion tracking are involved. Therefore various techniques have been developed and utilized in the past. Brandyopadhyay et al. used visual markers on objects and optical trackers in their Shader Lamp project to paint on objects [27]. Later infrared marker-based tracking was used in the PaperLens projects by Spindler et al. [28]. One of the more popular examples of a commercial motion tracking system is the Microsoft Kinect [29]. With a Kinect one can detect and track multiple persons at the same time and even finger tracking is possible with

3rd party software. With the spatial information of several bodyparts, gestures can be defined to interact with a system. Furthermore the distance sensor and camera of Kinect has been used to spatially track other objects or interaction. Wilson used the depth camera from the Kinect as a touch sensor by extracting touch events through a threshold operation on a known model [30]. For animation or industrial applications high quality motion trackers such as the Qualisys Motion Tracker are used [31]. The advantage of a higher quality motion capture system is the higher accuracy and faster response time for a large amount of tracking points.

2.4 Spatially aware mobile devices

The underlying concept of spatially aware mobile devices is the long before envisioned idea by Weiser [1], where digital and physical world should be merged. By giving the devices more information about their surroundings, they can behave accordingly. Early adopters of this idea were Ishii and Ulmers with Tangible Bits [32], where physical real-world objects were used to interact with digital information. With SifteoCubes Merrill et al. developed small touch-sensitive devices [33]. The cubes are interconnected through wireless and are aware of their mutual arrangement. The user interactions takes place by rearranging, tilting, touching and shifting the cubes. The aim is to reduce the cognitive workload of arranging digital objects by bringing them to the physical world.

Spatially aware mobile devices enable the extension of the interaction space beyond the regular display. In order to overcome the limitation of the small interaction space Chen presents a body-centric design space for mobile phones to extend a mobile device's interaction space from screen space to body space [34]. Because displays are too small for a proper user interaction Kratz et al. present HoverFlow with "around-device interaction" for wearable and mobile devices [35]. In HoverFlow they use IR-sensors to track hand gestures around a smartphone. By adding proximity sensors on the edges of a smartphone Butler et al. can track a finger next to the phone for interaction [36]. Hasan et al. present an interaction technique called "around-device binning" (AD-Binning) where the area around the phone is separated into different bins [37]. Hasan also assumes that finger tracking will becomes possible and uses the fingers to store and retrieve virtual information in bins around the phone. Lucero et al. illustrated how multi-device groups can be dynamically created for sharing multimedia content [38, 39]. Lissermann showed how spatially-aware paper-like devices can be used to organise video content [40]. In the research on MochaTop and DynamicDuo multiple mobile devices know the relative location of each other [23]. Both are inspired by the concept of having an interactive tablecloth to augment everyday surfaces to an interactive space [19]. DisplayStacks is a concept to organise digital documents in a physical way [41]. The authors connected three e-ink displays and added sensing technology to detect the position of the single display. The authors argue that the physicality—the tactile feedback—of the display stack supports work with digital documents. This work showed that placing digital content on physical surfaces improves the user experience. Instead of using custom technology, Thaddeus uses regular tablets and smartphones available on the market right now. In MochaTop the table surface is also divided into invisible interactive zones around a common central device [23]. Thaddeus extends this idea, but in contrast to AD-Binning we offer an additional screen for the zones as we use the smartphone as positioning device. Based on the positioning of the smartphone in those zones a certain interaction on both devices is achieved.

2.5 Multi-surface environments

Multi-surface environments typically consist of several digital displays such as a Powerwall, interactive tabletops and various mobile devices. They are used to display a large quantity of information or share the same information on multiple screens to enhance the collaboration between multiple users. When one is already using a tabletop in a system, it is only a small step to use additional devices which are then connected to the same tabletop. Beaudouin-Lafon describes the WILD room (Wall-sized Interaction with Large Datasets), which is an environment for exploring multi-surface interaction that includes a wall display, a tabletop and mobile devices [42]. They run several studies in collaboration with other laboratories in order to explore interaction in the WILD room and to determine whether generic techniques, such as drag-and-drop in a desktop environment, would emerge. With SkyHunter, Seyed et al. propose an application for a multi-surface environment to support oil and gas exploration [43]. They use a Microsoft Pixelsense tabletop and multiple tablets. A Microsoft Kinect provides the spatial tracking of the devices. Interaction with multi-surface environments is still an ongoing research and Wagner et al. described a body-centric design space called BodyScape for these environments [44]. With BodyScape they compared two free-hand techniques, on-body touch and mid-air pointing. There are already some interaction techniques for multi-device environments like flicking or picking [45, 46]. Nevertheless Santosa and Wigdor point out that the data management gets more difficult since the addition of extra devices fragments the information across them. They also identify a need for parallel cross-device interaction patterns. Furthermore they argue there is a specialized use of the devices based on the task type [47]. Also, the increased accessibility of computing devices and mobile data has led to a widespread adoption of multiple devices. Thus a vast number of people are already carrying a small personal multi-surface environment with them without noticing it. Normally they are not using them in a multi-surface-environment-way as those devices lack of the necessary interconnection. With Thaddeus we built a possible prototype for an interconnected usage of those devices and try to address the problems pointed out by Santosa and Wigdor. This prototype tries to overcome the fragmentation of information by using the tablet as a central hub to organize all the information. Furthermore it addresses the task specialization by having both devices used parallelly for which it defines new usage patterns.

2.6 Publication based on this work

A paper presenting the system described herein has been submitted to NordiCHI2014[1].

[1] http://nordichi2014.org/

Chapter 3

Design

Designing Thaddeus consisted of several ideation, refinement and testing phases. The initial concept was born through observing our campus environment and noticing more and more academics and students carried tablets to the university. Indeed, now more than 30% American households own a tablet [48]. These activities showed the multitude of possible combinations of devices and usage context they appear in. In order to aid the design process, a number of usage scenarios have been created for multi-device interaction in everyday settings. See Figure 3.1 for examples. Consequently, the most common of the devices – smartphones and tablets – became the focus of attention. We also aimed to investigate if we can bring new data exploration methods to everyday environment, motivated by the work cited in the previous section.

In order to develop a useable system, we decided to pursue an user centered design approach. Users were involved from the early stages of the design process. Most importantly, two studies have been performed in before that informed our design and shaped this final prototype.

3.1 MochaTop

MochaTop, the predecessor of Thaddeus, a low-fidelity horizontal prototype has been developed by Woźniak and Lischke [49]. This was a first working version of the system that used a simplified sensing technique. Phones and tablets were placed on an interactive table (Samsung SUR40) and tracked using tags on the back of the mobile devices. Four interaction techniques were intended: three zone-based

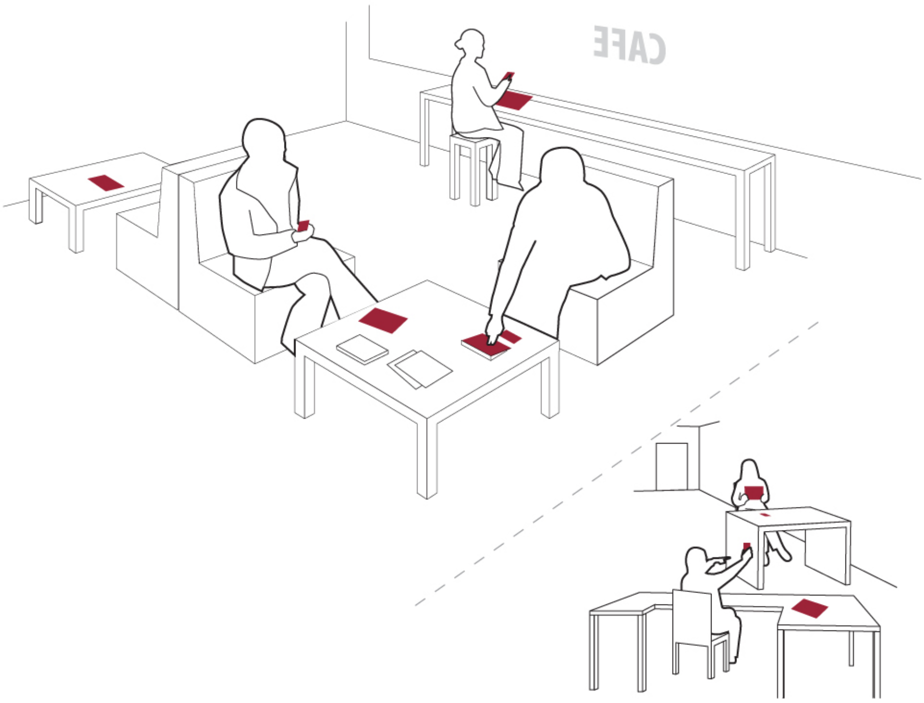


Figure 3.1: Examples of preliminary usage scenarios considered in our design process. We speculated how multi-device systems can complement meeting spaces such as cafes and workplaces.

visualization exploration patterns (See Figure 3.2 for details) and a distance-base technique for navigating within the application. Users could increase the distance between the two devices to go back to the main menu. This system was intended to explore facts and information about the distribution, consumption and price of fair trade coffee.

To validate the system a sandbox evaluation has been conducted with 23 participants (20 males, aged 22-31, mean age = 25.09, median = 25). The study consisted of an initial interview, 15 minutes of sandbox interaction with the prototype, a single task for the participants and an exit interview. The initial interview included questions on demographics. Afterwards, the participants were invited to explore the system in a semi-structured manner i.e. we provided encouragement for exploring all parts of the system only if required. By moving the smartphone the view on the tablet could be changed and information concerning the selected data point could be shown on

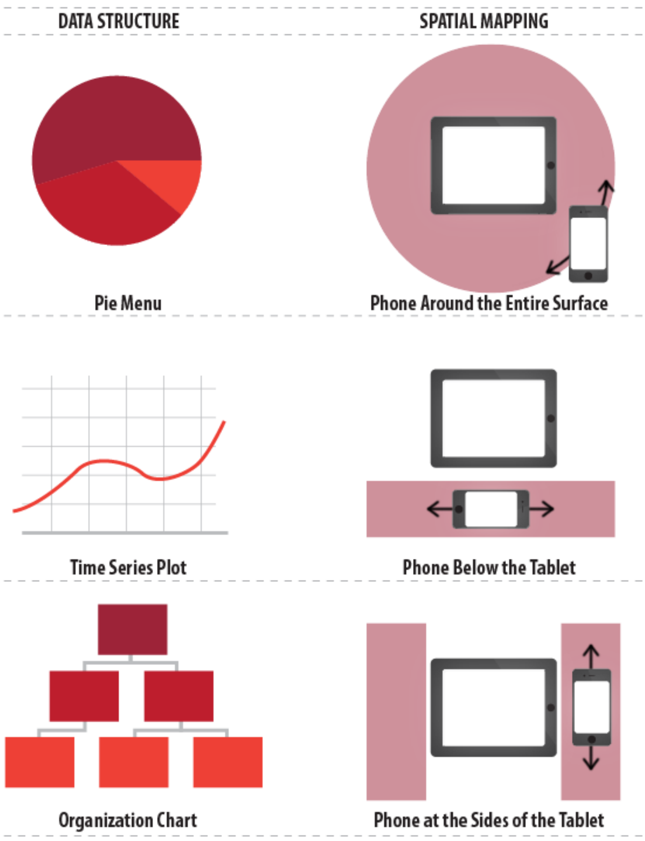


Figure 3.2: Information visualizations and corresponding spatial mappings used in the initial sandbox study.

the smaller device. Next, the participants were asked to use the system to extract numerical information from information visualizations. Lastly, a short interview was conducted in which the participants were asked for a qualitative account of the user experience. Throughout the entire session, video was recorded from two angles (directly above the table and facing the participants) and sound was captured.

3.2 Design Workshop

The first prototype was intended to give insight into a unknown topic using different visualizations. However, we noticed a few problems that called for redesigning parts of the system. Firstly, some users struggled with accessing the hierarchy chart. Secondly, the distance-based technique was still perceived as zone-based. All of the study participants immediately repositioned the phone to one of the table's corners

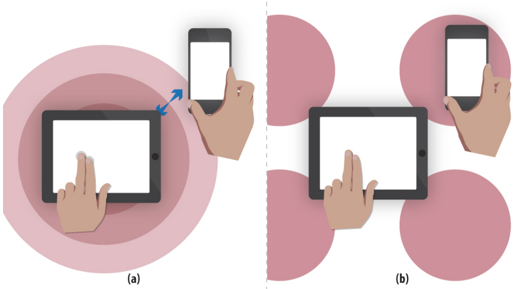


Figure 3.3: The rationale for zone-based input. Users were able to revert to the main menu by increasing the distance between the devices (a). However, all of the study participants immediately repositioned the phone to one of the table's corners as if the corners were active zones (b).

as if the corners were active zones instead of increasing the distance between the devices. 35% (n = 8) of the participants would simply lift the phone from its current position and put it back in one of the table's corners. Figure 3.3 illustrates the issue. This result prompted us to focus our investigation on mapping table zones. Because many of the users picked up the phone during the session, the spatial tracking was disabled for that moment since the devices had to lay down flat on the table for it to work.

So we organized a series design workshops with groups of users exploring ways to interact with different form of information representation using spatially aware mobile devices. Overall, 25 participants aged 22-32 (mean age = 24.64, median = 25, 18 males) participated in the study. The participants were remunerated with coffee and a sweet bun while having a short debriefing in a relaxed atmosphere. We used an array of paper prototypes (see figure 3.4) to validate our concepts and provoke users to share their ideas. In 12 sessions, each lasting about 25 minutes, pairs (and three participants in one of the session) explored paper prototypes looking for new interaction patterns for exploring data sets. We prepared printouts of some of the most popular information visualization artifacts (e.g. pie chart, time-series-graph, parallel coordinate plot, tag cloud). We attached the printouts to phones and tablets and asked participants how they would use both the devices to explore visualization effectively.

We slightly varied the order of the paper prototypes to compensate maturation, for instance, gaining experience from previous tasks. Nevertheless we had to maintain a coarse order as the tasks became more and more challenging. We started by showing

Figure 3.4: We used paper prototypes to find most common usage patterns.

them a pie chart on the tablet and asked them how they would select a slice on it. As we expected every group proposed touching the slice with the finger since they were dealing with a tablet. Then we asked them how to do the same thing without touch capabilities (e.g. tablet is too far away). Afterwards we introduced them to the concept of the spatial aware interaction by showing them the pie chart of the first prototype. We showed them that depending on the position of the smartphone around the tablet, a different slice of the pie chart is highlighted. After this short introduction, we continued with the paper prototypes for the rest of the visualizations. The following tasks were typically to find and select in a single value in a given information visualization. But we also had tasks for controlling a view parameter, rearranging objects or navigating through the shown visualization. All of the sessions were video recorded, yielding a total video time of 4 hrs 7 min, which was then carefully analyzed. The workshops have shown that users tend to map table surface to areas within the tablet screen (i.e. using zone-based input). All of the participants suggested using the phone as an aid in exploring the information presented on the tablet and none of them suggested the reverse solution. Many of the users suggested exploring the table space surrounding the device as an extension of the interaction space. They mentioned using the phone as an extra screen to present additional information and rearranging the devices to highlight different parts of the visualizations. By counting the number of proposed solutions (see below) we were able to identify clear interaction preferences for some of the visualizations. But for more difficult ones the participants proposed a wide range of solutions where

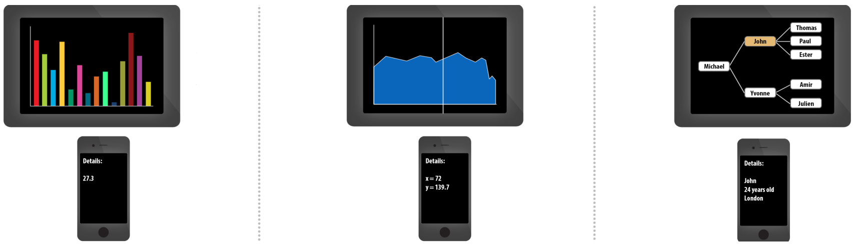


Figure 3.5: The three information visualisations in the final prototype. Users can explore the bar chart, the time series plot and the hierarchy diagram by repositioning the phone relative to the tablet.

no concrete recommendation is possible. The workshops led us to shortlist three information visualizations to be explored with zone-based input (see figure 3.5).

3.2.1 Tasks

The following is a list of the top three proposed solutions for each task and what percentage of groups proposed this solution. Note that the groups were able to give multiple solutions for the same task, but their first idea was tracked separately. The number of first ideas for a given solutions were used as a tie breaker if needed.

Time series plot

Browsing a time series plot and finding specific values.

1. Move through data points by moving the phone (portrait) horizontally below the tablet. (88%)
2. Tilt the phone to scroll through data points. (38%)
3. Hold phone over tablet to select a data point. (25%)

Hierarchy

Browsing through the nodes of a tree spanning from left to right and displaying information contained in the nodes.

1. Move phone horizontally below for column selection. (88%)
2. Move phone vertically below tablet to select a column entry. (38%)

3. Hold phone over tablet to select a node. (25%)

Parallel Coordinate Plot

Browse through the entries of a PCP and find a specific value.

1. Zoom/Filter first using phone. (88%)
2. Move phone horizontally below for column selection. (75%)
3. Move phone vertically on the side for value selection of a predefined column. (25%)

Tag cloud

Browse through the entries of a tag cloud and select a specific word.

1. Hold phone over tablet to select a word (fisheye lens). (50%)
2. Use phone like a computer mouse to move a cursor. (25%)
3. Use phones touch to navigate a cursor and control zoom. (25%)

Bubble graph

Gather bubbles of one color in a separate place (e.g. corner of screen, phone).

1. Select color on phone and drag the bubbles around with the phone acting as magnet. (63%)
2. Select color and put closest bubble of this color on the phone. (38%)
3. Hold phone over tablet to select a bubble (fisheye lens). (38%)

Node-Link diagram, Force directed layout

Manipulate a linear parameter [0..1] to control the bundling strength of an edge bundled graph.

1. Move phone horizontally below the tablet. (88%)
2. Move phone up/down next to the tablet. (50%)
3. Closeness of devices as indicator. (38%)

3D Visualization

Move, rotate and zoom in a 3D visualization of a medical image (foot).

1. Use phone as representation of the shown object to move and rotate in space. (63%)
2. Turn phone like a knob to zoom. (38%)
3. Use touch gestures on phone. (25%)

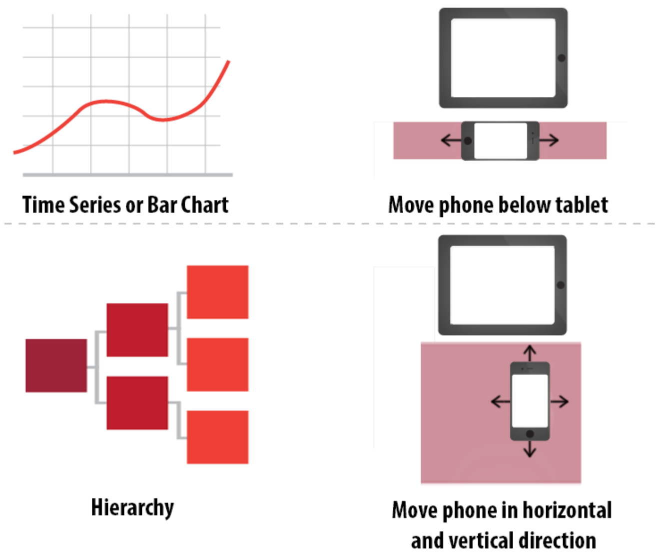


Figure 3.6: Information visualisations and corresponding spatial mappings used in the final prototype. Compare with Figure 3.2.

3.3 Final design

We evaluated the material gathered during the first and second user study. We analyzed the videos and concluded on final design choices. Zone-based input was still widely used and users reported that the new interaction patterns were beneficial:

I like the linear [below tablet] interaction, because I don't have to go around and cover the screen.

For our final inquiry, we designed a prototype that enabled users to interact with a data set on a regular office table. Three data representations can be accessed with Thaddeus (shown in Figure 3.6). The user can browse a bar chart and read exact values of the bars by placing the phone below a given bar. The phone shows then the value of the selected bar. Extracting additional data from a time series plot is possible by sliding the phone below or above the tablet to move a thin line. Corresponding values are displayed on the phone. Moving the phone below the tablet in up-down and right-left directions enables browsing a hierarchy diagram. Extra information about the elements of the diagram is presented on the phone.

Chapter 4

Implementation

In the first implementation for the sandbox study, fiducial markers were attached to the bottom of the devices to spatially track them on a Microsoft Pixelsense table. Therefore, the devices had to lay down flat on the table in order to be tracked. Each device stored the complete data set on itself. The spatial location and orientation was streamed from the table to both devices. Based on this information every device determined what content to display. The devices were coupled via UDP to send special events (e.g. a button press) to the partner device. While this implementation proved very useful to gather preliminary design insights, the interactive table was quite constraining.

The second-generation implementation used for our final system evaluation is a more sophisticated system. The setup supports extensive spatial tracking in six degrees of freedom. It is also scalable and can support an arbitrary number of devices. We tried to extend and advance the previous code from MochaTop but earlier architectural choices hindered further development. So we decided to reimplement the system from scratch with the gained knowledge and put effort into making the system more reuseable for future developments.

4.1 Mobile devices

In this second prototype we introduced the concept of central and satellite devices. Only the central device (usually the tablet as it has greater processing power) stores datasets and processes positional data. It also manages what is being displayed on the satellite devices. The central device can also enable a possibility to return a value, or enable touch sensitive areas on the satellite screens to extend user input. Currently, the central devices sends an image and a description string to the satellites. The additional string describes the location of touch sensitive areas on the image and actions to be taken when the areas are pressed. This way, a button can be drawn on the image which is later visible on the satellite. Each time such a button is pressed, the satellite sends a response back to the central device based on the previously received description string. The central device is responsible for generating information for the satellites, providing ways to return user input from a satellite and processing the returned input. It is also responsible for assuring that content presented on the satellite matches the spatial arrangement of the devices.

4.1.1 Implementation

We created for both, center and satellite devices, Android applications. We used Git and Gitorious as version control system to distribute and backup developed code. For development we used Eclipse with the Android Development Tools[1].

The satellite app *DDSatellite* is designed to solely display information sent by the center device and its implementation is therefore quite simple. It consists only of a *ViewerActivity* and uses a networking component. We implemented this networking component called *DDNetworking* as library which can be used in both Android applications for simple communication between the devices. The *ViewerActivity* also implements the *GestureListener* interface to react on user inputs. Those inputs are captured and sent over the network controller back to the center device.

The center application *DDCenter* also uses the the *DDNetworking* component to communicate with the satellites. In the center app we implemented several classes to hold different kinds of data (3D, hierarchical, time-series, etc.), a database containing all kinds of satellite views, a satellite view factory, the logic for the communication with QTM and the different visualizations.

The satellite views are dynamically constructed during runtime based on the current dataset. We use the term 'satellite view' to describe an image plus a describing string which can be sent to one or more of the satellite devices. Once a satellite view has been created it will be stored in the satellite view database for later usage. Since we use images which are sent over the network we want to avoid the rendering of the

[1] http://developer.android.com/tools/sdk/eclipse-adt.html

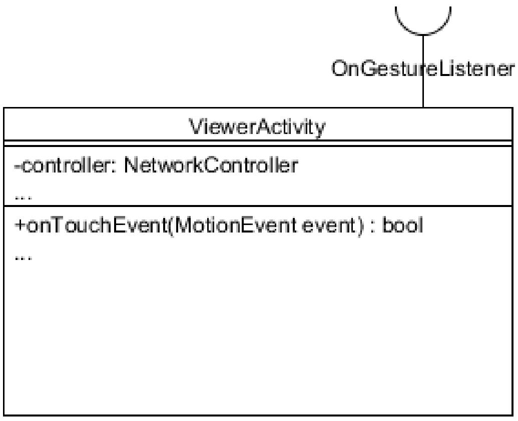


Figure 4.1: Simplified classdiagram of ViewerActivity of the satellite app.

same image twice, so we reuse satellite views from the database instead if needed. Below you see an example creation and storage of a satellite view:

```
sdb = SatelliteDatabase.getInstance();
SatelliteView mainSatellite = sdb.add("Main", 500, 600);
mainSatellite.addComponent(new Text(0.0f, 0.1f, "Main menu"));
mainSatellite.addComponent(new Button(0.0f, 0.4f, 1.0f, 0.1f,
     "Menu item 1", "CommandOpenM1", ButtonType.Click));
mainSatellite.addComponent(new Button(0.0f, 0.5f, 1.0f, 0.1f,
     "Menu item 2", "CommandOpenM2", ButtonType.Click));
```

The code above creates a new satellite view named "Main" in the database and defines the internal image width and height. Next a text and two buttons are added to the newly created satellite. Both *Text* and *Button* are custom component classes to facilitate creation of such satellite views. We also implemented an *Image* component to easily add images to a satellite view. Every component has x and y coordinates and buttons and images also have a width and height parameter. These parameters are relative coordinates to the final image itself and range from 0 to 1. This way we can scale up the images easily without having to adapt prior code. Besides the displayed button text a Button also has two additional parameters. The first defines a command which is executed when the button is pressed and the second defines the behavior of the button. Buttons can be clickable and also holdable. The command defined here is part of the describing string in the satellite view and gets sent back from the satellite when this button is actually pressed. To react on the button press the center now has to react on TCP responses containing this command. We also implemented the possibility to create arbitrary interactive zones anywhere on the final image. This way images and text can be interactive as well. In the prototype we used an image of arrows and made it holdable. By doing so we were able to implement the rotation of an object only when holding the arrow-button. Combining this with the spatial information one could image rotating a 3D image in the direction the phone is rotating.

For the communication with QTM we implemented a *QTMController* which contains the current location information of every device. Instead of letting QTM stream the positional information to the device we decided for a polling mechanism to deal with the lower processing power of today's tablets. The QTM component also contains classes to parse and convert the information QTM sends to our application. QTM comes with an communication specification containing every possible streaming format it currently supports. After implementing a parser for the streaming format we agreed on we received twice as much positional information from QTM as expected. We spent a long time analyzing network traffic using Wireshark[2] until we found out that the documentation is not correct and instead of floating point values with 4 bit length QTM sent double precision values with 8 bit length.

Finally the application for the center device contains all information visualizations and the information how to display additional information on the satellites. We implemented a bar chart, time-series plot, pie chart, hierarchy chart and a simple 3D cube. For the information visualizations we used zone-based interaction but for the bar chart we also implemented an interaction using the satellite device to point on a specific bar instead of having the zone based input. The 3D cube can be manipulated by rotating the satellite device in mid air while holding a button on the screen. Each visualization has a *VisualizationView* and *VisualizationActivity* class. The activity class prepares the dataset to be displayed, initializes the view class, creates satellite views based on the dataset and starts an update loop in which the visualization is updated with new positional information from the *QTMController*. Also response messages from the satellites are handled here. The view class draws a visualization based on a given dataset. It also provides an update method which updates the visualization based on newer positional information and gives feedback

[2] http://www.wireshark.org/

if something has changed and satellite views have to be updated. As normal for Android applications those two classes are tightly coupled.

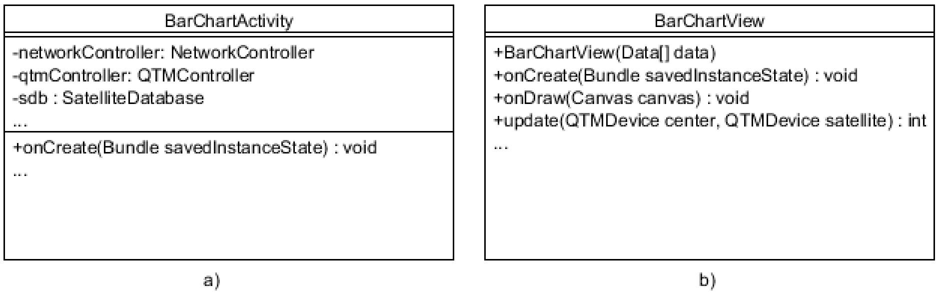


Figure 4.2: Two class diagrams depicting a visualization implementation with a) the activity class and b) the view class.

4.2 Tracking

By using more sophisticated spatial tracking Thaddeus can be used on any table, the devices can be picked up and used in midair. For acquiring the spatial information for each of the devices we used a commercially available Qualisys motion tracking system that used eight ceiling-mounted Qualisys Oqus cameras to provide high-fidelity high-framerate positional information. The surrounding eight-camera setup effectively eliminates occlusions that would generate tracking errors. In order to work properly the system has to be calibrated before usage every time. We used a T-shaped calibration wand and a L-shaped reference frame provided by Qualisys to calibrate the cameras properly. We attached several 4mm wide half-sphere passive reflective markers to each device which are for tracking purposes (Figure 4.3 shows how the devices were augmented). The markers are placed in the corner of the devices and are small enough to neither obstruct the screen of the devices nor hinder users handling the devices. For processing the camera data we used the Qualisys Track Manager (QTM) software. QTM offers the possibility the group several reflective markers together to form a body which is tracked as a whole which has its own coordinate system withing the space coordinate system. The software can compensate for lost markers as long as at least three of them are visible on a body. Figure 4.4 presents an overview of the prototype setup as deployed in our laboratory.

Figure 4.3: Reflective markers were placed on the devices.

4.3 Communication

We have set up a local wireless network to which every device and QTM is connected to. The devices generally communicate via TCP, which offers a more stable connection between them with no lost packets. But the satellite devices can register at a center device by sending an UDP broadcast over the wireless network. Once connected the devices communicate via TCP. There are basically two types of communication over the network. There are update messages sent from the center device to each satellite containing the new image to display and a describing string of that image. The other type of message are response messages from the satellites to the sender. Those response messages indicate whether an onscreen button is hold or tapped. Figure 4.5 provides an overview of the communication between the central device and the satellites.

The real time server (RT) from QTM sends the position and rotation matrix of each body via TCP to the central device. Table 4.1 shows a data packet composition sent by QTM for a 6DOF component. QTM offers the possibility to poll for several component types at the same time but note that this shows only the packet composition of a 6DOF component containing only one body. In our prototype we have defined two bodies – one tablet and one smartphone – for center and satellite device. Based on the number of components, component type and number of bodies

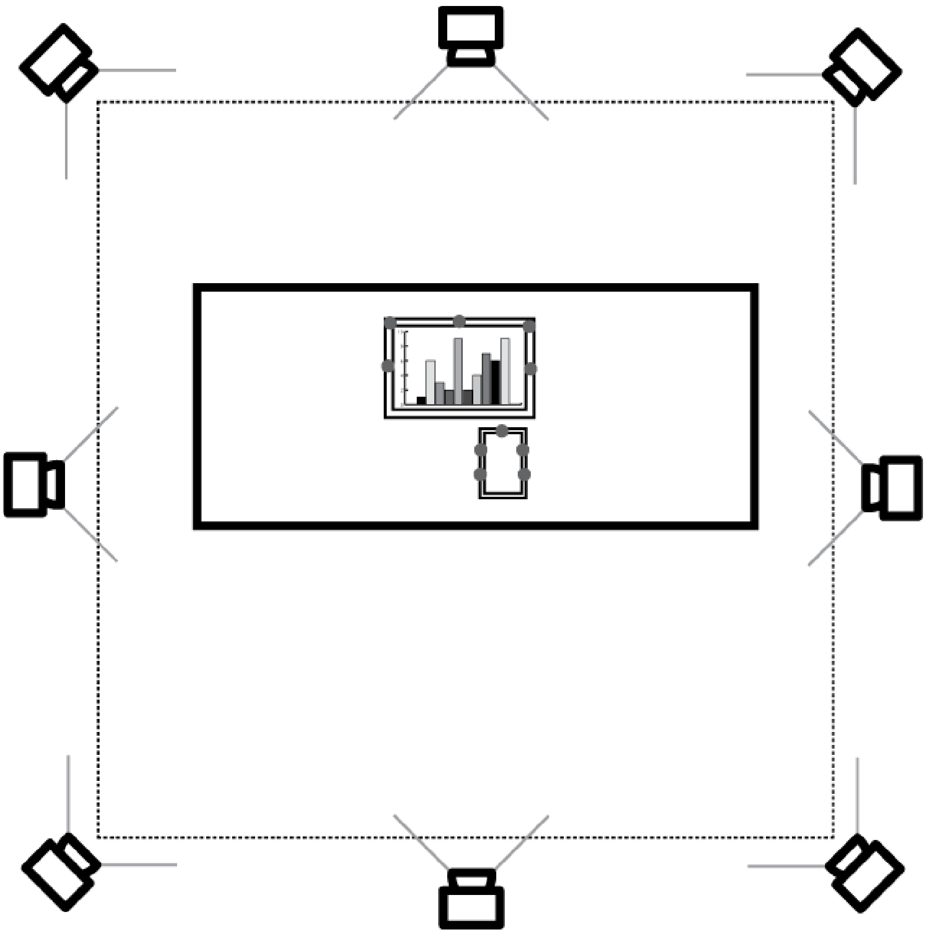


Figure 4.4: The motion tracking setup consists of eight ceiling-mounted Qualisys Oqus IR cameras and the mobile devices with passive reflective markers attached.

the packet composition can vary a lot. See QTM RT protocol documentation for further information.

We decided to use the 6DOF component since this gives us position an rotation of every object defined in QTM. The central device polls for the positional information whenever it has the capabilities. We decided for a polling mechanism to deal with the lower processing power of a tablet. The spatial information is buffered on the central device until newer information is fetched. In an update loop within the visualization activities the buffered information is constantly checked if an update of the satellites is necessary. Based on this information, the central device decides which devices need to be updated with what kind of information.

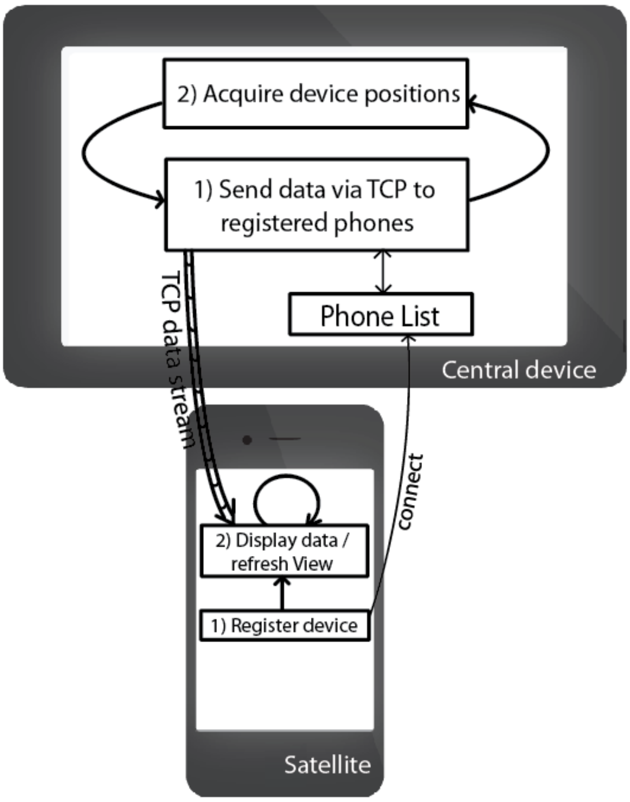


Figure 4.5: Interconnection between the central and possible multiple satellite devices.

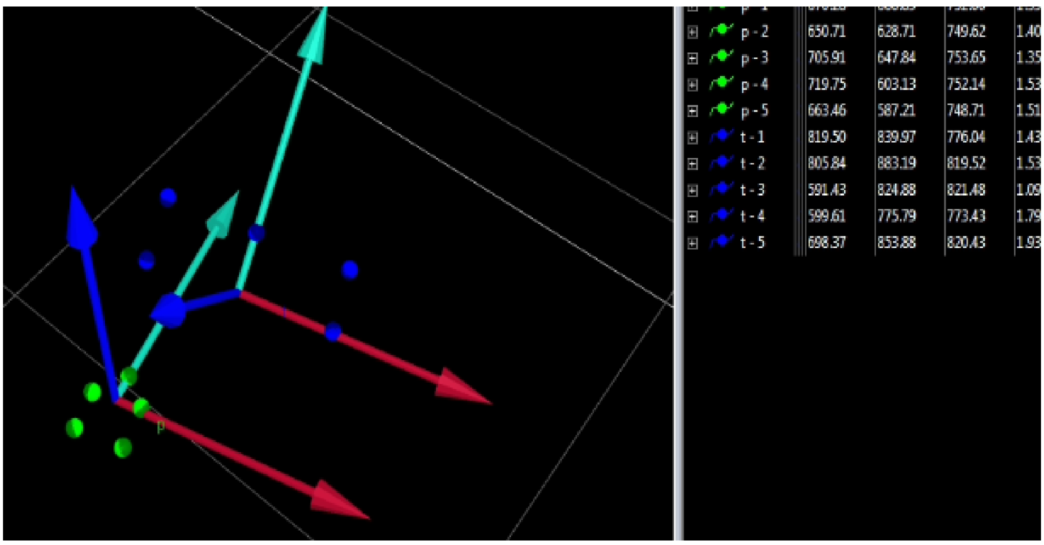


Figure 4.6: Tracking of two bodies in QTM.

Size in bytes	Name	Description
		Data packet header
4	Size	Size of the whole data packet
4	Type	Value = 3, which stands for data packet
8	Timestamp	Number of microseconds from start
4	Frame number	The number of the frame
4	Component count	The number of data components in the data packet
		Component header
4	Component Size	The size of the component including the header
4	Component Type	Value = 5, which stands for 6DOF
		Component data
4	Body count	The number of 6DOF bodies following this header
4	2D drop rate	Not used in our prototype
4	2D out of sync rate	Not used in our prototype
		Body data
8	X	X-coordinate of the body
8	Y	Y-coordinate of the body
8	Z	Z-coordinate of the body
9*8	Rotation	Rotation matrix of the body

Table 4.1: Data packet for a 6DOF component with one body sent by QTM.

Chapter 5

Evaluation

We conducted a user study to evaluate Thaddeus and assess the possible benefits of our new multi-device system over existing solutions. The study used a tablet-only touch-based system as a baseline. We did not consider a phone-only interface since both preliminary studies showed that users prefer exploring data on a larger screen. The baseline system overlays additional data on the visualizations when the user touches a given point by opening a closeable popup. This is the same data that is presented on the phone in Thaddeus. Our hypothesis was that while using Thaddeus may impact performance due to the novelty effect, users would appreciate the extended interaction capabilities of a dual-device system.

5.1 Study design

We evaluated Thaddeus in a controlled experiment. We recruited 18 participants (see Table 5.1 for demographics) through encouraging participation during courses and academic events. The participants were remunerated with a small gift consisting of a university-branded leather notebook and a pen. We used a Motorola XOOM tablet and an LG Nexus 4 smartphone as the central and satellite device in the study. These devices represent typical, mid-range appliances in order for the participants to be already acquainted with their form factors.

5.1.1 Tasks

Our study consisted of three experimental tasks, each addressing a different information visualization and consisting of several subtasks. We used a within-groups

18 Participants, age: 22-42 ($\mu = 26.61, \tilde{x} = 25$)	%	n
Male participants	72	13
Smartphone users	100	18
Tablet users	56	10

Table 5.1: Basic demographic and mobile device usage data for the study participants. Note that all of the participants were smartphone owners and the majority also owned a tablet.

repeated measures setup where users performed tasks both with Thaddeus and using the baseline system. The participants explored three different information visualizations. Table 5.2 provides a detailed description of the tasks.

Task	Subtask	Acronym	Count per task
Bar chart	Retrieve value at point	T1P	3
	Find maximum value	T1M	1
	Determine difference between values	T1D	1
	Compare two values	T1C	1
Time series plot	Retrieve value at point	T2P	3
	Find maximum value	T2M	1
	Determine difference between values	T2D	1
Hierarchy	Retrieve value at point	T3P	4
	Determine difference between values	T3D	1

Table 5.2: Task specification for the experiment. The tasks were performed by the participants in both conditions and task order was changed each time.

5.1.2 Procedure

The study began with an entry interview questionnaire that included questions on demographics and phone and tablet usage. This was followed by a short training session where the users explored the three information visualizations using both systems with a simplified dataset. We then proceeded to the three experimental tasks done in both systems resulting in a total of six tasks. After performing each task in both conditions the users were asked to indicate the preferred system and provide motivation for the decision. We used Latin squares to counterbalance order effects in the sample. We randomized the order of tasks as well as the order of conditions withing each task. The entire session was recorded on video with two cameras (one camera was facing the participant and a document camera recorder the tabletop). Finally, the participants were debriefed in a semi-structured interview where participants were asked to rate the system for fun ("Using Thaddeus is a fun experience.") and utility ("The system is easy to use") on a 7-point Likert scale (1 – fully disagree, 7-fully agree). The complete study design document including the questionnaires can be found in the appendix.

The collected data consists of video footage, task completion times, error data and qualitative feedback from the participants. During error analysis we distinguish between mistakes and slips [50]. We used ANVIL[1] to measure task completion times in the video footage and annotate errors. ANVIL offers the possibility to introduce custom keyboard shortcuts for annotating sections in videos which shortened the time needed for analyzing a video massively. Unfortunately ANVIL supports only a limited set of codecs and therefor we had to encode all of our video footage with the Cinepak codec to get it working.

5.2 Results

We evaluated Thaddeus through a mix of qualitative and quantitative methods to identify possible benefits of the new interface.

5.2.1 Task completion times

First, we investigate the impact of using Thaddeus on task completion times compared to the baseline system. We performed ANOVA for each task to determine if Thaddeus had a significant effect. Table 5.3 presents the results for every subtask.

The results show that Thaddeus did not produce a significant increase in task completion time in 8 out of 9 of the subtasks. High standard deviations are present in some of the subtasks, which probably indicate a need for further design efforts to make the task efficient for all users. As Thaddeus is a new interactive systems and all of the participants were experienced in using touch-based interfaces, we believe we can attribute the increased time to Thaddeus's relative novelty. However, the lack of significant effects shows that our new input method has potential to be at least equally fast as the touch-based method. The recorded error rates were low.

[1] http://www.anvil-software.org/

Subtask	n	$\mu_{Baseline}$	$\mu_{Thaddeus}$	$\rho_{Baseline}$	$\rho_{Thaddeus}$	F-value	p-value
T1P	108	2.83	3.49	0.74	1.25	3.675	> 0.01
T1D	36	5.82	11.18	1.22	6.17	9.259	0.006
T1M	36	3.81	4.58	1.37	1.48	1.845	> 0.05
T1C	36	7.01	12.71	1.54	8.24	14.34	> 0.01
T2P	108	3.41	7.13	1.95	2.11	3.675	> 0.05
T2M	36	6.85	6.85	3.48	2.97	0	> 0.1
T3P	144	4.43	4.93	1.85	3.23	1.094	> 0.05
T3D	36	8.45	7.87	3.85	3.17	0.206	> 0.05

Table 5.3: Task completion time means (in seconds), standard deviations (in seconds) and ANOVA results for each of the subtasks. Note that in most cases, Thaddeus did not produce a significant increase in task completion time.

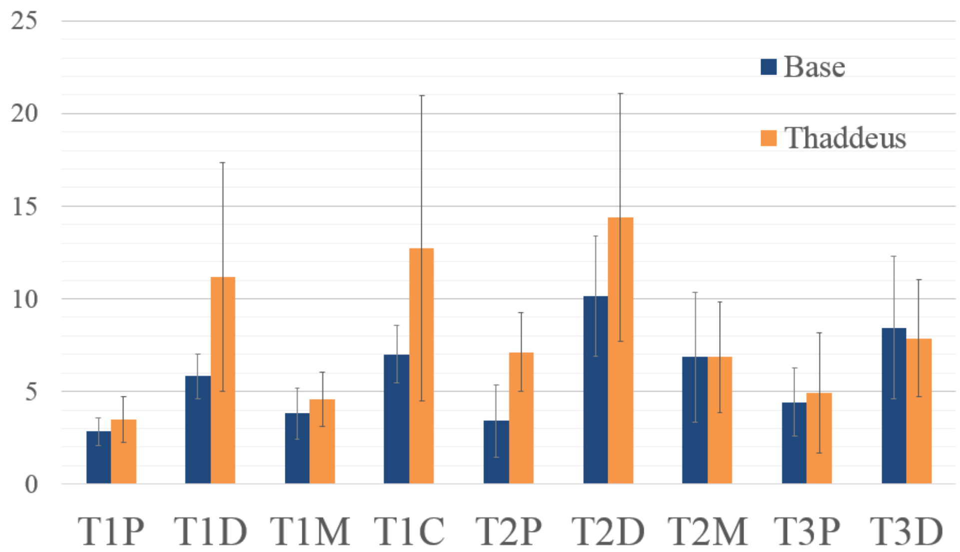


Figure 5.1: Task completion times split by subtask for Thaddeus and the baseline system.

The error rate for the base system was $\rho = 2.0\%$ and $\rho = 2.8\%$ for Thaddeus and no significant effect was observed. We can conclude that Thaddeus does not negatively affect task performance. Figure 5.1 presents a comparison of the task completion times for all of the subtasks.

5.2.2 User experience

Next, we investigated how users perceived interacting with Thaddeus and if it produced perceived benefits in user experience. We investigated system preference for each task as well as fun and utility ranked with a Likert scale. We hypothesized that since all of the participants already use a touch-base interface extensively, most of them would prefer the touch-based method as Thaddeus introduces a new learning curve. Figure 5.2 presents the system preference for each task.

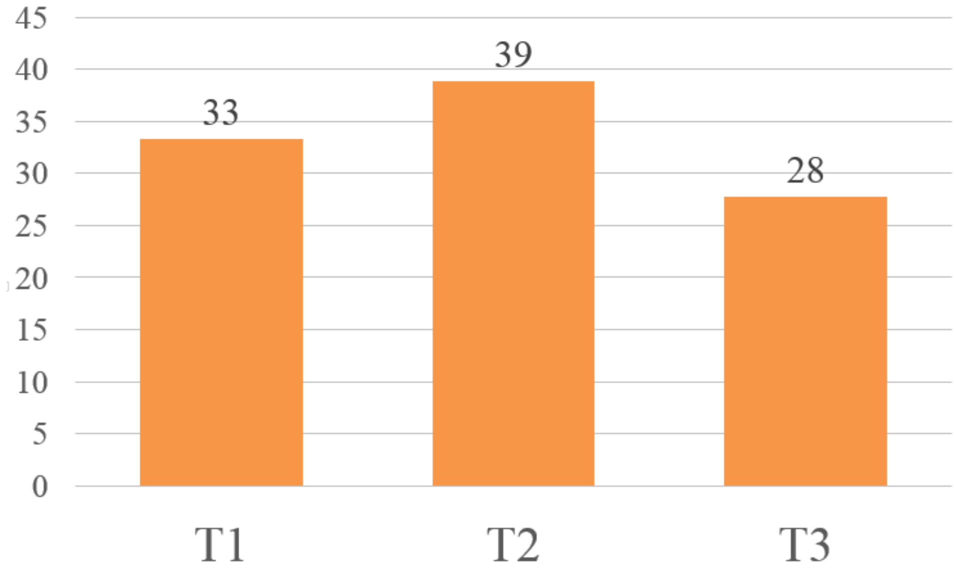


Figure 5.2: Percentage of users preferring Thaddeus to the baseline system for each of the study tasks. Note that users were experienced users of touch-based interfaces.

We can observe that approximately one third of the participants was willing to switch to using Thaddeus immediately following the study. We believe it is an acceptable result for a system that uses an input mode previously unknown by the users and given the positive performance assessment. Furthermore, the results indicate that the users perceived the performance in T2 (the time series plot) as most desirable. A recurring remark about T2 in the post study interviews was:

While I am more used to the touch interface, I feel that reading specific values is more effective with moving the phone.

Figure 5.3 shows the average scores for Thaddeus on the two Likert scales. We can observe that the users clearly perceived Thaddeus as a pleasurable experience

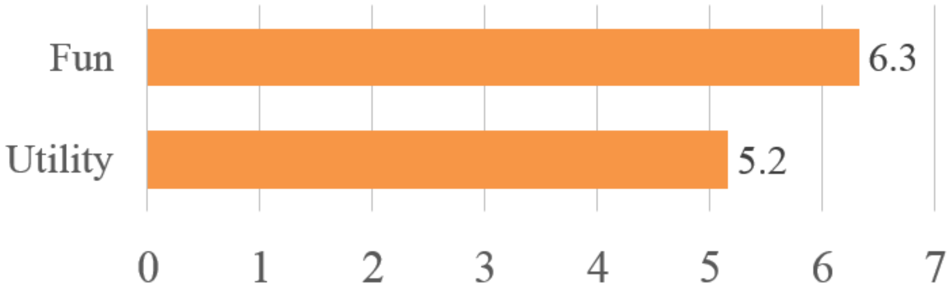


Figure 5.3: Average scores for fun and utility on a 7-step Likert scale for Thaddeus. The feedback was gathered during debriefing.

and most of them thought that the system was easy to use. Qualitative feedback gathered during semi-structured interviews provides more evidence. Participants remarked that using an additional device could be a solution when the amount of data is large:

When there is a lot of data it [Thaddeus] seems like a natural way to browse it.

I feel that the more data is presented the larger the benefits of the system.

Participants also commented that the system eliminates occlusion problems and, as a result, provides a better overview of the entire dataset:

It's good exploring and playing around graphs, best for scanning through several values.

Having an overview of the data without any overlays blocking the view is helpful.

Some of the users alluded to the possibility of using the system in a public setting.

I always carry a phone in my pocket. When a public tablet is provided, it would feel cleaner to use my own phone [to interact with the tablet].

This seems easy to learn. No need to touch at all! When it comes to a discussion within a meeting with several people it can be very helpful.

Others remarked that the possibility of using spatial awareness is useful, but the tasks to which it is applied must be carefully selected. Mutual spatial awareness must be a complementary input method for mobile devices rather than a replacement for touch and other input sources.

I would use it for specific tasks, but not for every task and every graph.

A key observation is that the short (usually less than 5 minute) learning session was enough for all of the participants to understand the principles behind Thaddeus. Even though participants were encouraged to ask questions and informed that they can terminate the experiment at any time, none of the users had doubts about how to access the information during performing the tasks. This shows that the feedback gathered during previous studies that hinted on the zone-based approach being an intuitive solution was a good design decision. Overall, the result of our mixed-methods study show that while Thaddeus had a highly limited impact on user performance, it was well received by the users. Both the results of the Likert questionnaire and interview data point to Thaddeus being a system providing a pleasurable experience and a gentle learning curve.

Chapter 6

Summary

In this thesis we introduced Thaddeus, a system that uses mutual spatial awareness as a new input source for a dual-device setup consisting of a phone and a tablet. Contrary to past work, which mainly focused on the collaborative context of multi-device usage and table-sized interactive surfaces, we investigated a single-user scenario that uses only mobile devices. A future scenario where users can explore various information visualizations on the go motivates our inquiry. We first analyzed a design study of MochaTop, a system developed earlier, which used a Samsung SUR40 interactive table with Microsoft Pixelsense for a rudimentary tracking of devices laying flat on it. In a second study we used paper prototypes to gain further insight into preferred interaction techniques for this kind of system. Those two preliminary design studies resulted in a final prototype that was evaluated in a formal experiment. The final prototype consisted of two Android applications running on either a phone or a tablet. For spatial tracking we used a motion tracking system from Qualisys, which uses eight ceiling-mounted infrared cameras to track passive reflective markers attached to the devices. The center device polls positional data from Qualisys Track Manager via wireless network which lastly enabled interaction based on spatial location of the devices. Afterwards we conducted another user study which showed that Thaddeus did not significantly decrease user performance compared to a traditional touch-based interface. Additionally many of the users perceived the system as fun and easy to use. Given that all users were proficient in using touch, the study confirms the feasibility of a system that employs spatial awareness as an input mode. Nevertheless, we managed to evaluate only three visualizations in our study. We also implemented interaction with the presented system by pointing with the smartphone on a given visualization, but we were not able to evaluate the user performance in this case. Further studies must be conducted in order to get a better understanding.

Chapter 7

Conclusion

Our inquiry shows that there is potential in systems similar to Thaddeus. We studied a specific use case where users explored information visualizations, but other usage contexts should be explored in the future. Our work provides only partial answers to how to design effective cross-device interaction techniques with spatial awareness and these patterns need to be refined. As new portable sensing technology is now emerging, we will soon be able to evaluate systems similar to Thaddeus in in-the-wild studies and see how they perform in real-life environments. We were thinking about possible future scenarios in different settings e.g. education, sports or tourism. We believe that long-term in-situ studies of how cross-device interaction techniques perform in work and leisure settings will result in a broader understanding of how the space around the devices can be used to benefit user interaction.

Appendix A

Appendix

- User study design document Thaddeus

User Study Design Document

Thaddeus

Date: 2014-03-28
Author: Benjamin Schmidt

1 TABLE OF CONTENTS

2 Document Overview

This document describes a test plan for conducting an evaluation for the prototype of Thaddeus. We want to gather a first feedback on the actual interaction process and find out if and where the prototype has to be adapted to improve the user's expectations.

3 Objectives

Can users operate the system without thinking after a short familiarization time? Do they have problems selecting the appropriate interaction movement? Are the users finding the invisible interaction zones?

4 Methodology

4.1 Equipment

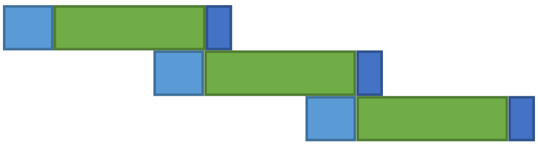
- Qualisys MotionTracker (8 camera setup)
- 8 passive reflective 4mm half sphere markers for the device tracking (4 for each device)
- Motorola XOOM MZ601 Tablet running the DDCenter software
- Google Nexus 4 Smartphone running the DDSatellite software
- Laptop running the Qualisys Qualitrack software for streaming live data over the network
- Camera for audio-video-recording
- Logging via the apps
- Questionnaires

4.2 Schedule

10. March	09:00 – 17:00	Testrun Visual Arena
24. March	09:00 – 12:00	Testrun Visual Arena
28. March	09:00 – 12:00	Testrun Visual Arena
31. March	09:00 – 17:00	Study Visual Arena
07. April	09:00 – 13:00	Study Visual Arena

On each day several sessions will be held with changing participants. Each sessions involves a participant exploring a dataset with Thaddeus. Every session is scheduled for 35 minutes. Starting with a 10 minute briefing and introduction, followed by 20 minutes system interaction, followed by a 5 minute debriefing. The system interaction is divided into 5minutes accommodation and 12 minutes of task completion time.

Sessions slightly overlap and briefing and debriefing take place parallel to the system interaction.



4.3 Participants

The participants' responsibilities will be to attempt to complete a set of representative task scenarios presented to them in as efficient and timely a manner as possible, and to provide feedback regarding the usability and acceptability of the user interface. The participants will be directed to provide honest opinions regarding the usability of the system, and to participate in post-session subjective questionnaires and debriefing.

We have ca. 20 student participants for this study with either design or engineering background. Participation at this user study is part of the lecture “Tabletop Computing” at Chalmers University of Technology, Sweden.

The participants will receive an overview of the usability test procedure, equipment and software.

4.4 Procedure

Participants will take part in the usability test at the Visual Arena in the Science Park in Lindholmen, Göteborg. The participant’s interaction with the system will be monitored by the facilitator seated in the same office. The test sessions will be videotaped.

The facilitator will brief the participants on the system and instruct the participants that they are evaluating the application, rather than the facilitator evaluating the participant. Participants will be informed that the participation is voluntary, that participation can cease at any time, and that the session will be videotaped but their privacy of identification will be safeguarded. The facilitator will ask the participant if they have any questions. The participants will also fill out a questionnaire.

After the introduction and the first questionnaire the participants will get 5minutes time to familiarize with the system by completing a few basic tasks for each visualization-modality-combination.

Afterwards the participants will complete the tasks as fast as possible while still trying to give the correct answer. After each visualization the system preference is noted by the facilitator.

The study will be concluded by giving the participants a debriefing and handing them a final questionnaire.

4.5 Tasks

Task #	Env.	Task description	Scheduled Time
1a	Base	Find 3 values in barchart.	2 min
1b	DD2	Find 3 values in barchart.	2 min
2a	Base	Find 3 values in linechart.	2 min
2b	DD2	Find 3 values in linechart.	2 min
3a	Base	Find age of 3 persons in hierarchy.	2 min
3b	DD2	Find age of 3 persons in hierarchy.	2 min
			= 12 min

There are two different environments defined – a base system and DD2. For comparison to regular tablet interaction we developed a base system which only uses the tablet to interact with the visualizations instead of using two devices. We compare both environments in terms of accuracy and performance time.

4.5.1 Task 1a: Base – Find values in barchart

The user has to find and tell the facilitator the values of the datapoints described below. In the base system they can set the cursorposition of the visualization by tapping the touchscreen of the tablet. An overlay with additional data is shown on the screen. By tapping on another column the overlay changes or closes if on no column is tapped.

We use a dataset containing 20 samples. With this amount of samples the bars have a width of 0.5 cm, which is still easily clickable by fingers.

Datapoint	**Reference Value**
Point Q	75
Point C	66
Point S	9
Highest value (B)	177
Difference between F and M	8
Values of the 3 lowest columns ?	5, 9, 10
Which column is higher? I or P ?	P (90 > 88)

4.5.2 Task 1b: DD2 – Find values in barchart

The user has to find and tell the facilitator the values of the datapoints described below. In DD2 they can set the cursorposition of the visualization by moving the phone below the tablet. The additional data is shown in the phone.

To compare DD2 to the base system we use a dataset with the same amount of samples with a similar distribution of values.

Datapoint	**Reference Value**
Point C	42
Point R	64
Point J	77
Highest Value (Q)	174
Difference between K and N	20
Values of the 3 lowest columns ?	7, 12, 13
Which column is higher? B or T ?	T (84 > 82)

4.5.3 Task 2a: Base – Find values in linechart

The user has to find and tell the facilitator the values of the datapoints described below. In the base system they can set the cursorposition of the visualization by tapping or swiping on the touchscreen of the tablet. An overlay with additional data is shown on the screen. By tapping on another area the overlay changes.

Datapoint	**Reference Value**
Value for x = 56	35
Value for x = 36	8
Value for x = 93	92
Highest value (85)	119
Difference between 40 and 70	30

4.5.4 Task 2b: DD2 – Find values in linechart

The user has to find and tell the facilitator the values of the datapoints described below. In DD2 they can set the cursorposition of the visualization by moving the phone below the tablet. The additional data is shown on the phone.

Datapoint	Reference Value
Value for x = 46	65
Value for x = 84	182
Value for x = 28	101
Highest value (87)	197
Difference between 20 and 50	40

4.5.5 Task 3a: Base – Find values in hierarchy

The user has to find and tell the facilitator the values of the datapoints described below. In the base system they can select an item of the visualization by tapping the touchscreen of the tablet. An overlay with additional data is shown on the screen. By tapping on another item the overlay changes.

Datapoint	Reference Value
Age of Lisa	28
Age of Adam	21
Birthplace of Paola	Paris
Job Title of Marge	Customer Support
Age difference between Josh and Adriano	6

4.5.6 Task 3b: DD2 – Find values in hierarchy

The user has to find and tell the facilitator the values of the datapoints described below. In DD2 they can select an item of the visualization by holding the phone over the tablet. The additional data is shown on the phone.

Datapoint	Reference Value
Point Bryan	26
Point Lesley	23
Birthplace of Amir	Kairo
Job Title of Bryan	Senior Manager
Age difference between Claude and Grace	7

4.6 Counterbalancing

To avoid the introduction of confounding variables the participants complete the four tasks in different order as depicted by the following table.

	First Task	Second Task	Third Task
User01	1ab	2ab	3ab
User02	1ab	3ab	2ab
User03	2ab	3ab	1ab
User04	2ab	1ab	3ab
User05	3ab	1ab	2ab
User06	3ab	2ab	1ab
User07	1ba	2ba	3ba
User08	1ba	3ba	2ba
User09	2ba	3ba	1ba
User10	2ba	1ba	3ba
User11	3ba	1ba	2ba
User12	3ba	2ba	1ba
User13	1ab	2ba	3ab
User14	2ab	3ba	1ab
User15	3ab	1ba	2ab
User16	1ab	2ba	3ba
User17	2ab	3ba	1ba
User18	3ab	1ba	2ba
User19	1ba	2ab	3ab
User20	1ba	2ba	3ab

4.7 Usability Metrics

Usability metrics refers to user performance measured against specific performance goals necessary to satisfy usability requirements.

4.7.1 Accuracy

By analyzing the recorded video information we identify and count errors in trying to complete the task or in the task results. We distinguish between mistakes and slips. Mistakes are errors in choosing an interaction and slips are errors carrying out an intended interaction.

Tracked Errors:

- Trying to interact in the wrong interaction zone
- Unintentional leaving of the interaction zone during interaction
- Giving the wrong answer

4.7.2 Time

By analyzing the recorded video information we measure the time taken to complete parts and the whole of a task. The time measured for each subtask is starting from the moment the question is given to the moment of correct response. The time for the complete task is taken from the first question given to the last correct response.

4.7.3 Preference

By handing the participants a post-session questionnaire we gather information about system preference for each task.

4.7.4 Fun

By handing the participants a post-session questionnaire we gather information about the user's enjoyment while using DD.

4.8 Questionnaire

In addition to the hands-on user study, the participants will receive a questionnaire before and after the study.

The pre-study questionnaire contains demographic questions and questions to gain insights in their usage of modern mobile devices. The focus is on how and if users interact with multiple mobile devices already.

The post-study questionnaire asks questions about their interaction preference during the study and the general enjoyment of such a system.

5 APPENDIX

- Pre-study questionnaire
- Post-study questionnaire

Questionnaire 1

In order to find out how you currently are using mobile devices in your everyday life we would appreciate if you complete the details below.

Age:	________	
Gender:	□ Male	□ Female
I own one or more smartphones:	□ Yes	□ No
I own one or more tablets:	□ Yes	□ No

Smartphone usage

During your week, how much time do you spend on the particular tasks defined below using your smartphone.

	Never	Very Rarely	Rarely	Occas-ionally	Frequent	Very Frequent
Phoning (Telephone or Skype)	□	□	□	□	□	□
Writing shot messages (SMS, WhatsApp, …)	□	□	□	□	□	□
Browsing the internet	□	□	□	□	□	□
Social media (FB, Twitter, Foursquare, …)	□	□	□	□	□	□
Taking photos	□	□	□	□	□	□
Showing photos to other people around you	□	□	□	□	□	□
Play audio (MP3-Player, radio, audiobook, …)	□	□	□	□	□	□
Navigation and travel planning (Maps, GPS, …)	□	□	□	□	□	□
Reading emails	□	□	□	□	□	□
Writing emails	□	□	□	□	□	□
Outdoor Activities (Hiking, Geocaching, ….)	□	□	□	□	□	□
Reading (books, recipes, digital print media, …)	□	□	□	□	□	□
Newsreader (News, weather, RSS, …)	□	□	□	□	□	□
Banking	□	□	□	□	□	□
Video Streaming (Youtube, …)	□	□	□	□	□	□
Calculator	□	□	□	□	□	□
Taking notes	□	□	□	□	□	□
Gaming	□	□	□	□	□	□
Alarm clock	□	□	□	□	□	□
Other applications	□	□	□	□	□	□

If other, please define:

Tablet usage

During your week, how much time do you spend on the particular tasks defined below using your tablet.

	Never	Very Rarely	Rarely	Occas-ionally	Frequent	Very Frequent
Phoning (Telephone or Skype)	☐	☐	☐	☐	☐	☐
Writing shot messages (SMS, WhatsApp, …)	☐	☐	☐	☐	☐	☐
Browsing the internet	☐	☐	☐	☐	☐	☐
Social media (FB, Twitter, Foursquare, …)	☐	☐	☐	☐	☐	☐
Taking photos	☐	☐	☐	☐	☐	☐
Showing photos to other people around you	☐	☐	☐	☐	☐	☐
Play audio (MP3-Player, radio, audiobook, …)	☐	☐	☐	☐	☐	☐
Navigation and travel planning (Maps, GPS, …)	☐	☐	☐	☐	☐	☐
Reading emails	☐	☐	☐	☐	☐	☐
Writing emails	☐	☐	☐	☐	☐	☐
Outdoor Activities (Hiking, Geocaching, ….)	☐	☐	☐	☐	☐	☐
Reading (books, recipes, digital print media, …)	☐	☐	☐	☐	☐	☐
Newsreader (News, weather, RSS, …)	☐	☐	☐	☐	☐	☐
Banking	☐	☐	☐	☐	☐	☐
Video Streaming (Youtube, …)	☐	☐	☐	☐	☐	☐
Calculator	☐	☐	☐	☐	☐	☐
Taking notes	☐	☐	☐	☐	☐	☐
Gaming	☐	☐	☐	☐	☐	☐
Alarm clock	☐	☐	☐	☐	☐	☐
Other applications	☐	☐	☐	☐	☐	☐

If other, please define:

If you own both, how do you synchronize your data and files?

If you own both, do you prefer the tablet over the smartphone for certain tasks? What tasks?

If you own both, do you prefer the smartphone over the tablet for certain tasks? What tasks?

Questionnaire 2

In order to gather additional information about the presented system please fill out the final questions below. Thank you very much.

What were your expectations when using multiple devices to browse data?

Would you use a system like Thaddeus to browse data when it would be seamlessly integrated in the devices architecture? Why? Why not?

	Fully disagree	Mostly disagree	Slightly disagree	Undecided	Slightly agree	Mostly agree	Fully agree
I would use Thaddeus	☐	☐	☐	☐	☐	☐	☐

Did you enjoy or had fun using Thaddeus? Why? Why not?

	Fully disagree	Mostly disagree	Slightly disagree	Undecided	Slightly agree	Mostly agree	Fully agree
I would use Thaddeus	☐	☐	☐	☐	☐	☐	☐

Preferation

	Thaddeus	Classic
Barchart	☐	☐
Linechart	☐	☐
Hierarchy	☐	☐

What are the reason for your preferation?

Barchart:

Linechart:

Hierarchy:

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All links were last followed on February 11, 2014.

Declaration

I hereby declare that the work presented in this thesis is entirely my own. I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

place, date, signature