Thaddeus: A Dual Device Interaction Space for Exploring Information Visualisation

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ABSTRACT
This paper introduces Thaddeus—a mobile phone-tablet system for mobile interaction with information visualisations. Our work is motivated by the roles smartphones and tablets play in everyday interactive spaces as well as anticipated developments in mobile sensing technology. We also aim to meet the social challenges of a data-driven society. We designed and implemented a system that uses mutual spatial awareness as an input mode, producing new interaction patterns for mobile settings. We gathered extensive user insight from two design studies and evaluated the system in a controlled experiment. We used qualitative and quantitative measures in the final evaluation. The results show that the system does not have a significant impact on performance, but users perceive it as pleasurable and easy to use. Thaddeus offers an enhanced user experience when exploring information on the go, and provides insights for future designs of mobile multi-device systems.

Author Keywords
Dual device; interactive visualization; multi surface environment; mobile interaction.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Nowadays, smartphones and tablets are increasingly permeating workplaces and homes [40]. We encounter mobile devices in different formats almost everywhere, from our local GP's office to the bus we take to work everyday. While tablets and phones often play precise roles, we rarely use the two device formats in combination. That thought led us to develop Thaddeus—a system that uses phones and tablets simultaneously in order to extend and enhance our everyday interaction space. Our work is motivated by the increasing importance of exploring datasets and how that could become a part of our future lives, bolstered by forthcoming developments in embedded mobile sensing technology.

Social challenges
The desire to provide easy access to data exploration in everyday spaces is the main motivation behind Thaddeus. 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. [36] argue for designing means for the general public to access and understand data. New interactive technology is required to support societal activities by providing community-relevant data to individuals, businesses, and authorities whenever required. The availability of big data must be complemented by methods to allow the individual to openly use it. As indicated by Churchill [8] 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. 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. With Thaddeus, we aimed to design a system that would enable ad-hoc interactions with datasets using multiple mobile devices in everyday spaces.

NordiCHI '14, October 26 - 30 2014, Helsinki, Finland

ACM 978-1-4503-2542-4/14/10…$15.00.
http://dx.doi.org/10.1145/2639189.2639237

Emerging enabling technologies

Thaddeus is also motivated by anticipated developments in mobile sensing technology. 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 [24]. Past research hints that positional awareness will soon be feasible by using triangulation approaches that rely on audible sound (BeepBeep [23]) or ultrasound (Relate [12]). 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 (See Figure 1 for examples). Because Thaddeus is based on research results and technology currently in development, we are not designing for an intangible near future (criticised by [5]), but rather are preparing for new capabilities in mobile devices that will be available very soon.

Furthermore, a study by Santosa and Wigdor [27] is one of the key motivations for Thaddeus. This study shows that users often carry phones and tablets simultaneously or multitask using those devices and there is thus a need for developing interaction techniques for single-user multi-device interactions. Santosa and Wigdor concluded that cross-device usage is largely limited in current interface designs. They also noted that users find the affordances of physical desks, and the placement of mobile devices on them, to be beneficial for work tasks. Several users were also observed using smartphones as secondary displays. Thaddeus aims to let users capitalise on the affordances offered by different devices.

In the remainder of this paper, we provide details on the design and implementation of Thaddeus through a detail account of inquiry into spatially aware mobile devices. We contribute: (1) the design of a dual-device system for interacting with information visualisations in a mobile setting; (2) insights into designing ubiquitous connected phone-tablet systems, based on two design studies; (3) experimental evaluation of the system.

RELATED WORK

The concept of Thaddeus departs from three accomplished research domains, tabletop interaction, multi-surface environments, and mobile, and goes further by demonstrating novel uses of ad-hoc interactive environments composed of mobile devices. We used the lessons learned from earlier research about designing multi-device systems and exploration of datasets on interactive surfaces.

Multi Device Interaction

Much research has been made into extending the interactive space by using more than one device. Past work was mainly motivated by the benefits expected from manipulating devices in physical space [25] as well as increasing potential for space multiplexing [16], possibly with multiple displays [13]. Hinckley et al. [14] suggested that proximate device coordination is one of the key goals for future interactive environments. Schmidt et al. [28] showed how mobile devices can create new interactions when combined with large horizontal surfaces. LensMouse [39] showed that simultaneous use of differently sized screens can improve task performance. Multi-device research is also relevant for the domain of public displays. Alt et al. designed Digifieds, a system to run digital public bulletin boards [1]. 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. These studies have shown that using multiple displays and devices can contribute to an enhanced user experience, and Thaddeus aims to explore this direction further. While we still address the domain of multiple-device interactions, we investigate displays with different screen sizes and focus on everyday interactions.

There exists studies on the use of multiple mobile devices for particular tasks. Tangible Views [34] extends an interactive table by using lightweight mobile displays around the table. These devices are used to overlay a view projected on the table and provide detailed information, showing the benefits of using more than one display at one point of time to make information understandable. Furthermore, Spindler et al. [33] addressed the space above the interactive table as a possible source of input. Lucero et al. [18,19] illustrated how multi-device groups can be dynamically created for sharing multimedia content. Similarly, Lissermann [17] showed how spatially-aware paper-like devices can be used to organise video content. Research in proxemic interaction [3] addressed mutual spatial awareness to provide context-aware content in smart environments—as opposed to how we use it, as an input method, in Thaddeus.

DisplayStacks [10] is a concept to organise digital documents in a physical way. 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.

Schwarz et al. built Phone as Pixel [31], a system to connect multiple devices to one larger display. With a regular camera they were able to build, in three to six seconds, one screen consisting of multiple devices of different form factors. We see a great opportunity in building systems using multiple devices together in spontaneous situations and different arrangements. In contrast to Phone as Pixel, Thaddeus uses the position changes of the devices as an additional input method. These works have shown that relative spatial placement can play an important role in user interaction, and Thaddeus explores that notion further.

Extending touch with around device Interaction

Using the space around a mobile device is an appealing solution when the space of the device's screen is limiting. SideSlide is a conceptual implementation of a system that avoids occlusion on mobile devices [6]. SideSlide uses a smartphone with IR proximity sensors on its long edges that detect fingers moving on the surface next to it. Gestures were designed and implemented to allow the user to scroll and zoom documents by moving one finger on each long side of the smartphone. Thaddeus extends that idea to the entire space around the mobile device. Thaddeus does not aim to enhance the interaction with users' fingers, and instead we extend the system with a second device. The idea to manipulate the content shown on small devices by moving the device was presented by Harrison and Hudson [11]. The authors use optical mouse technology to extend the screen of a small media player. By doing so, they are able to capture movements with high precision. This allows building "virtual windows," which place multiple functions or extended content on every surface. Instead of using relative movement, Thaddeus makes use of the relative position of two mobile devices. Similarly, Sahami et al. [26] proposed a login system for mobile devices by manipulating magnets around the device and sensing the movement using a built-in magnetometer. Hwang et al. [15] also explored magnets and designed tangible controllers, which can be placed around or on a mobile device to manipulate displayed content. These works warrant further exploration of using the space around a device as an input source. But, the interaction space can be extended not only around the device, but also above it (i.e. in midair), as shown by Grossman and Wigdor [21]. Soap [4] is an example of a device that provides effective interactions with a large vertical screen by manipulating a smaller object. In Thaddeus, we address horizontal screens where the smaller object has a display.

Data analysis on surfaces

A significant amount of research on multi-surface environments is focused on combining multiple devices for professional analysis environments. VisPorter [7] illustrated how multiple interactive surfaces can be used to construct a collaborative text foraging environment. Shaer et al. [32] indicated how horizontal surfaces can offer a variety of opportunities to explore massive data sets. Examples like Phylo-Genie [29], Pathways [38] and WALDEN [30] show that horizontal surfaces have a potential for communicating and manipulating data both for expert users and in everyday settings. Danesh et al. [9] presented the use of multiple handhelds for collaboration between school children where pupils could connect devices over a short distance. 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, in line with the Bring Your Own Device [2] trend and building on the affordances offered by manipulating physical, rather than virtual, objects [35].

Our work is strongly inspired by Weiser's vision [37] of a world consisting of three device classes—tabs, pads, and boards. While we believe that the board design space can be explored through yard-scale touch surfaces and large vertical displays, our investigation focuses on the digitally and physically combined use of multiple pads and tabs on a device-sensing horizontal surface. In line with Weiser's requirements, the devices are mutually aware of each other's presence both temporally and, most significant in our case, spatially. Contrary to commercially available systems like the Sifteo cubes [20], Thaddeus ensures that all devices have continuous access to relative positional information (i.e. distance and orientation).

DESIGN

Designing Thaddeus consisted of several ideation, refinement, and testing phases. The initial concept was born when observing our campus environment and noticing more and more academics and students carried tablets to the university. Indeed, now more than 30% of American households own a tablet [40]. A literature inquiry preceded our design activities. These activities showed us the multitude of possible combinations of devices and usage contexts. In order to aid the design process, we created a number of usage scenarios for multi-device interaction in everyday settings. See Figure 1 for examples. Consequently, we decided to focus on the most common of the devices—smartphones and tablets. We also aimed to investigate if we could bring new data exploration methods to everyday environments, motivated by the work cited in the previous section. Users were involved from the early stages of the design process. Most importantly, we performed two studies that informed our design and shaped our final prototype.

Initial study

In our first user inquiry, we conducted a series of design workshops with 25 participants (18 males, 7 females, aged 22–32, mean = 24.64, median = 24) recruited among novice students of the interaction design programme. In 12 sessions lasting about 25 minutes, pairs (and three participants in one of the sessions) explored paper prototypes looking for new interaction patterns that could be used for exploring datasets.

We prepared printouts of some of the most popular information visualisation artefacts (e.g. pie chart, time-series-graph, Parallel Coordinate Plots tag clouds). We attached the printouts to phones and tablets and asked participants how they would use both the devices to explore visualisation effectively. 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 to rearrange the devices to highlight different parts of the visualisations. The workshops led us to shortlist three information visualisations to explore using zone-based input. We also decided to implement a distance-based technique to investigate if it was indeed undesirable.

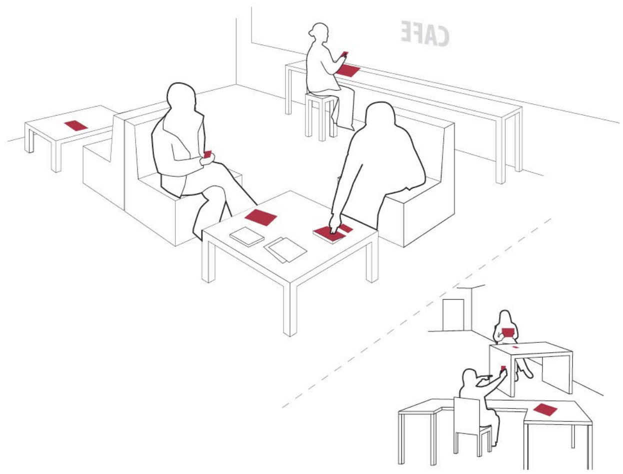

Figure 1. Examples of preliminary usage scenarios considered in our design process. We speculated how multi-device systems can complement meeting spaces such as cafes and workplaces.

Sandbox evaluation

Next, we developed a low-fidelity horizontal prototype — a preliminary working version of our system employing a simplified sensing technique. Phones and tablets were placed on an interactive table and tracked using tags on the back of the mobile devices. We designed four interaction techniques: three zone-based visualisation exploration patterns (See Figure 2 for details) and a distance-based technique for navigating within the application. Users could increase the distance between the two devices to go back to the main menu.

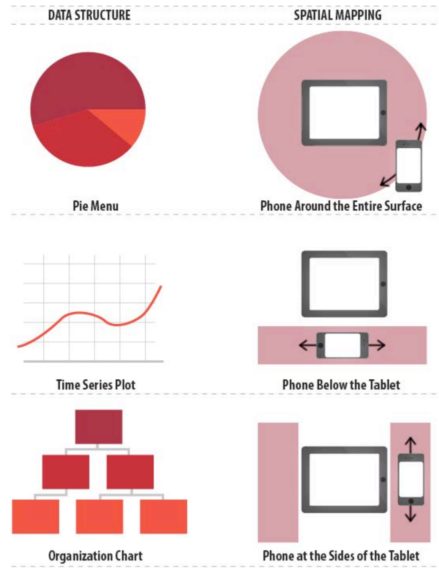

Figure 2. Information visualisations and corresponding spatial mappings used in the initial sandbox study.

We recruited 23 participants (20 males, 3 females, aged 22-31, mean age = 25.09, median = 25) through a campus-wide advertisement. Participants received a small gift as remuneration for the study. 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 but only if we needed to. In one example, we built an application to explore multi-dimensional datasets. We employed a set of alternative visualisation techniques, such as pie menus, time series plots, and process models, to provide an overview on the tablet. By moving the smartphone, the view on the tablet could be changed and information concerning the selected data point could be shown on the smaller device. Next, we asked participants to use the system to extract numerical information from information visualisations. Lastly, we conducted a short interview in which we 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.

Final design

We evaluated the material gathered during the second user study by analyzing both video angles together and the interviews, and decided on final design choices. Zone-based input was still popular with the participants, who 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.

However, we noticed one problem that called for a redesign of parts of the system. The distance-based function was perceived as being zone-based—all study participants immediately repositioned the phone to one of the table's corners, as if the corners were active zones. Instead of increasing the distance between the devices, 35% (n = 8) of participants would simply lift the phone from its current position and put it back in one of the table's corners. Figure 3 illustrates the issue. This result prompted us to focus our investigation on mapping table zones.

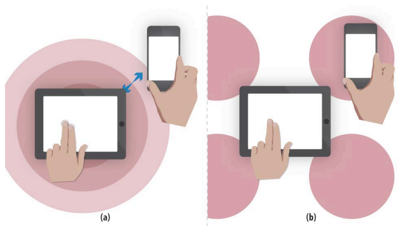

Figure 3. The rationale for zone-based input. Users were able to revert to the main menu by increasing the distance between the devices (a). However, all of the study participants immediately repositioned the phone to one of the table's corners as if the corners were active zones (b).

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 5 with spatial mappings shown in Figure 4). 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 the value of the 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. We named the system Thaddeus for "t(h)able-aware device dyad for ubiquitous sensemaking." Thaddeus is a novel contribution to the domain of multi-device environments as it: (1) focuses solely on a single user-multiple devices usage scenario (2) investigates mutual spatial positioning as an input source (3) uses only mobile devices with no stationary solutions e.g. projections or interactive tables and (4) anticipates upcoming mobile sensing technology.

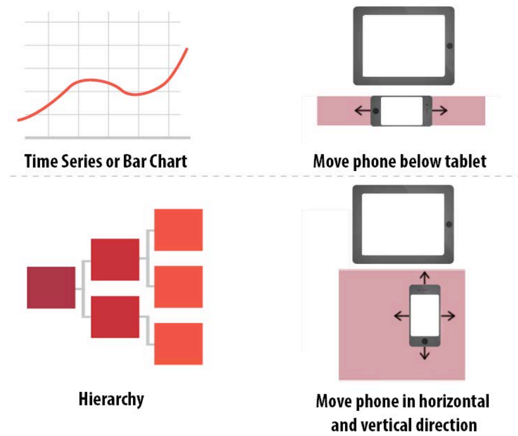

Figure 4. Information visualisations and corresponding spatial mappings used in the final prototype. Compare with Figure 2.

IMPLEMENTATION

In the first implementation used for the sandbox study, we used fiducial markers 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 content needed. The spatial location and orientation was streamed from the table to both devices. Based on this information, each 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 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. The devices communicate via TCP, which offers a more stable connection between them with no lost packets. By using more sophisticated spatial tracking, Thaddeus can be used on any table, and the devices can be picked up and used in midair.

In this second prototype we introduced the concept of central and satellite devices (or: proximate devices). Only the central device (usually the tablet as it has greater processing power) stores datasets and processes positional

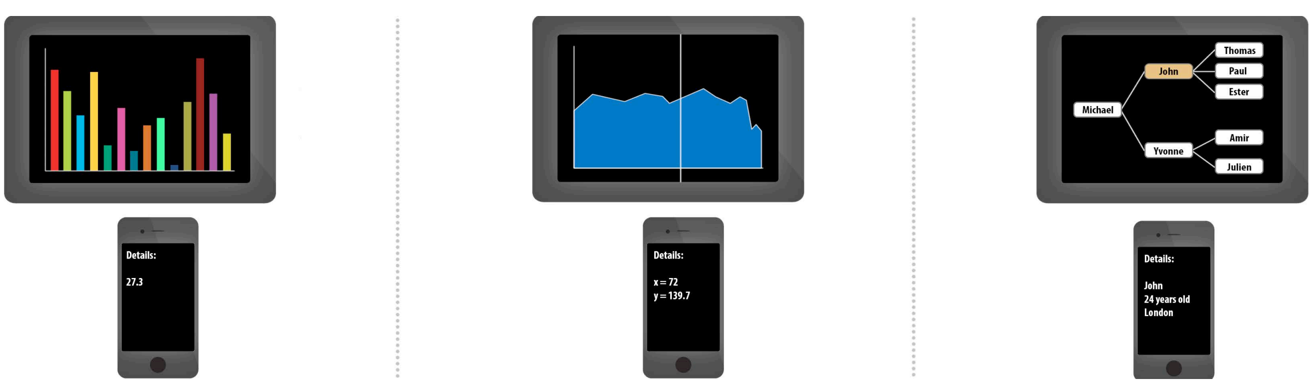

Figure 5. The three information visualisations in the final prototype. Users can explore the bar chart, the time series plot and the hierarchy diagram by repositioning the phone relative to the tablet.

data. It also manages what is displayed on the satellite devices. The central device also enable the possibility to return a value, or enable touch sensitive areas on the satellite screens to extend user input. Currently, the central devices send 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. Each time such a button is pressed, the satellite sends a response back to the central device based on the previously received description string. We also use TCP to communicate such a touch event from the satellite to the central device. 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. Figure 7 provides an overview of the communication between the central device and the satellites.

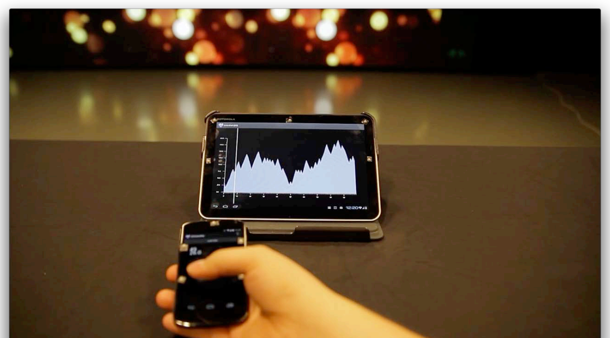

Figure 6. Reflective markers were placed on the devices.

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, thus accurately simulating a future system based on embedded mobile sensing. We attached several 4mm wide half-sphere passive reflective markers to each device, for tracking purposes (Figure 6 shows how the devices were augmented). The markers are placed in the corner of the devices and are small enough to not obstruct a device screens. We used Qualisys Track Manager (QTM) for processing the camera data that provides accuracy up to 3mm. The software can compensate for lost markers as long as at least three of them are visible on a device. QTM sends the position and rotation matrix of each object via TCP to the central device. Based on this information, the central device decides which satellite devices need to be updated with what kind of information. Figure 8 presents an overview of the prototype setup as deployed in our laboratory.

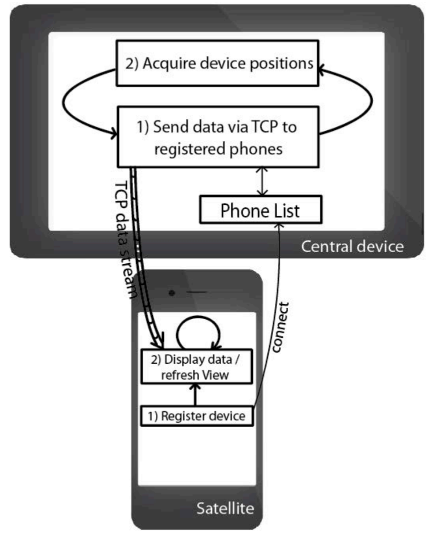

Figure 7. Connection between the central and satellite devices, which can be many.

EVALUATION

We conducted a user study to evaluate the robustness of the system as well as its user interface design and assess its potential relative benefit compared with 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 visualisations when the user touches a given point. For the time series plot, the user can slide their finger along the plot to reveal intermediate values. We chose to use a touch-based solution as it does not require any additional hardware and touch is often used in ad-hoc scenarios. 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.

Study design

We evaluated Thaddeus in a controlled experiment. We recruited 18 participants (see Table 1 for demographics) by soliciting 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 devices in the study. These devices represented typical, mid-range appliances, in order that participants be already acquainted with the form factors.

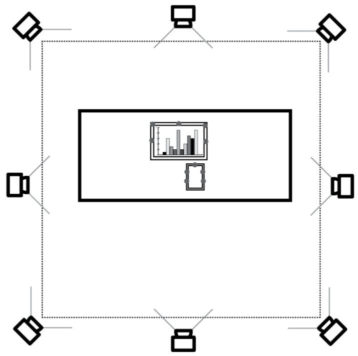

Figure 8. The motion tracking setup consists of eight ceiling-mounted Qualisys Oqus IR cameras and the mobile devices with attached passive reflective markers.

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 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.

Tasks

Our study consisted of three experimental tasks, each addressing a different information visualisation and consisting of several subtasks. We used a within-groups repeated measures setup where users performed tasks both with Thaddeus and using the baseline system. The participants explored three different information visualisations. Table 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
	Find difference	T1D	1
	Compare two values	T1C	1
Time series plot	Retrieve value at point	T2P	3
	Find maximum value	T2M	1
	Find difference	T2D	1
Hierarchy diagram	Retrieve value at point	T3P	4
	Find difference	T3D	1

Table 2. Task specification for the experiment. The tasks were performed by the participants in both conditions and task order was changed each time.

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 visualisations using both systems exploring a simplified dataset. We then proceeded to the six experimental tasks. After performing each task in two 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. The entire session was recorded on video with two cameras (one camera was facing the participant and a document camera recorded the tabletop). Finally, the participants were debriefed in a semi-structured interview where they were asked to rate the system's fun factor ("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 collected data consists of video footage, task completion times, error data, and qualitative feedback from the participants.

RESULTS AND DISCUSSION

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

Task completion times

First, we investigate the impact of using Thaddeus on task completion times as compared to the baseline system. We performed ANOVA for each task to determine if Thaddeus had a significant effect. Table 3 one presents the results for every subtask.

Sub-task	n	$\mu_{Baseline}$	$\mu_{Thaddeus}$	$\sigma_{Baseline}$	$\sigma_{Thaddeus}$	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
T2D	36	10,13	14,39	3,25	6,71	4,467	> 0.01
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 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.

The results show that Thaddeus did not produce a significant increase in task completion time in 8 out of 9 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 system 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. The error rate for the base system was ρ = 2.0% and ρ = 2.8% for Thaddeus and no significant effect was observed. We can conclude that Thaddeus does not negatively affect task performance. Figure 9 presents a comparison of the task completion times for all of the subtasks.

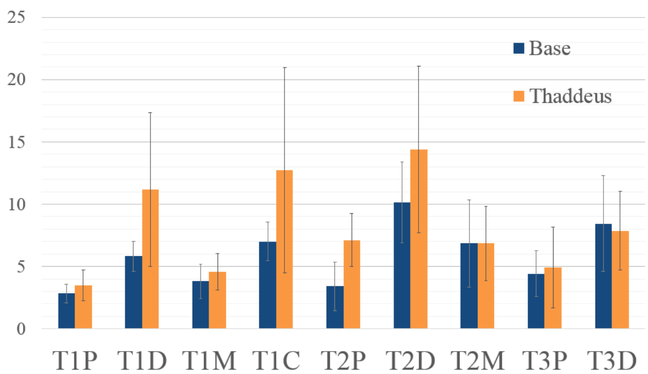

Figure 9. Task completion means by subtask for Thaddeus (light) and the baseline system (dark).

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 hypothesised 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 10 presents the system preference for each task.

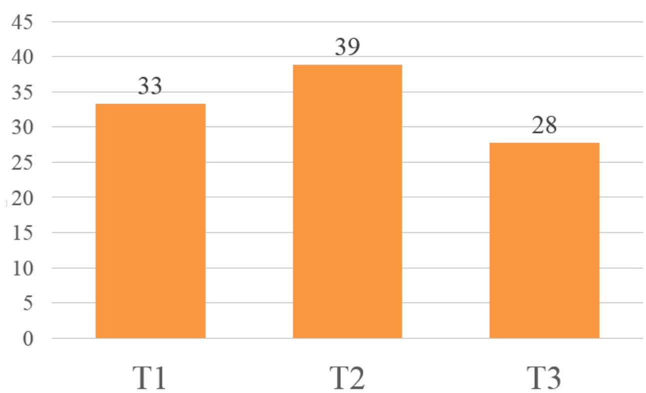

Figure 10. Relative percentage of users preferring Thaddeus to the baseline system for each of the study tasks. Note that users were experienced users of touch-based interfaces.

We can observe that approximately one third of the participants were 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 [22]. 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.

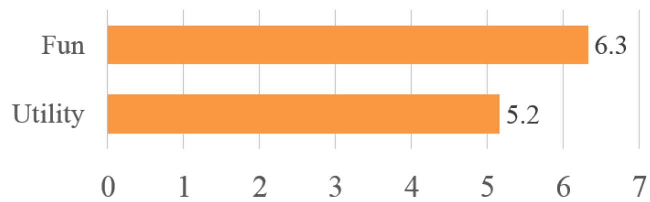

Figure 11. Fun and utility means on a 7-step Likert scale for Thaddeus. The feedback was gathered during debriefing.

Figure 11 shows the average scores for Thaddeus on the two Likert scales. We can observe that the users perceived Thaddeus as a pleasurable experience 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 could terminate the experiment at any time, none of the users had doubts about how to access the information while performing the tasks. This shows that the feedback gathered during previous studies, hinting the zone-based approach as an intuitive solution, led to a sound design decision. By analyzing the videos we observed that the form factor of the phone and the tablet permitted users to look at both devices simultaneously and no users reported a dual-screen setup as distracting.

Overall, the results of our mixed-methods study show that while Thaddeus had a limited impact on user performance, it was well received by the users. Both the interview results and the Likert questionnaire point to Thaddeus as being a system that could provide a pleasurable experience and a gentle learning curve. We can note that our users reported that using relative positioning as an input source can benefit interactions in some cases by limiting occlusions, increasing precision and facilitating browsing large data sets.

CONCLUSIONS AND FUTURE WORK

In this paper we introduced Thaddeus, a system using mutual spatial awareness as a new input source for a multi-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. Our work was motivated by potential future scenarios where users can explore data visualisations "on the go." We conducted two preliminary design studies that resulted in a final prototype that was evaluated in a formal experiment. The study showed that Thaddeus did not significantly decrease user performance compared to a traditional touch-based interface, and users perceived the system as fun and easy to use. Given that all users were proficient in using touch interfaces, the study confirms the feasibility of a system employing spatial awareness as an input mode as a complement to current technologies.

Our inquiry shows that there is potential in systems similar to Thaddeus. We studied a specific use case where users explored information visualisations, 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 with in-the-wild studies to see how they perform in real-life environments. Long-term, in-situ performance studies of cross-device interaction techniques 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. We also plan to investigate if switching between two co-located screens increases the user's cognitive load.

Acknowledgments

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement no. 290227. Thank you to Barrie Sutcliffe for his editorial work. Paweł Woźniak is an Early Stage Researcher in the DIVA Marie Skłodowska-Curie ITN. Paweł Woźniak and Morten Fjeld would like to thank the Swedish Foundation for International Cooperation in Research and Higher Education (STINT, grant 2013-019). This project was partly funded from the German Research Foundation within the Cluster of Excellence in Simulation Technology (EXC 310/2) at the University of Stuttgart.

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