Investigating the Use of Spatial Interaction for 3D Data Visualization on Mobile Devices

Wolfgang Büschel, Patrick Reipschläger, Ricardo Langner, Raimund Dachselt
Interactive Media Lab Dresden
Technische Universität Dresden, Germany
{firstname}.{lastname}@tu-dresden.de

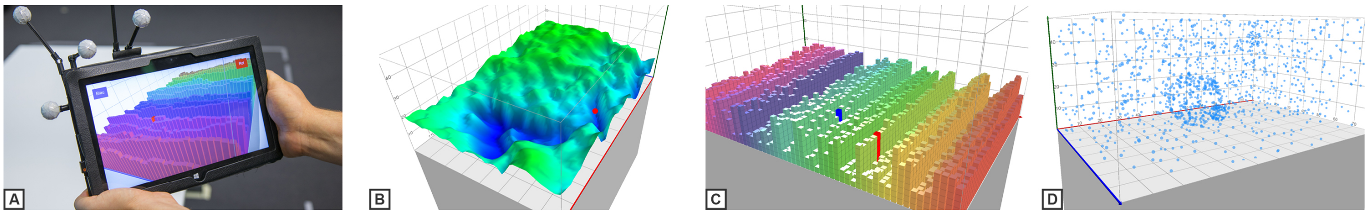

Figure 1. Using mobile devices for in-place 3D data visualization: *(a)* Our prototype running on a tracked tablet that we used for the study. We investigated three different 3D visualizations in our study: *(b)* Height map used in the navigation task (NT), *(c)* Bar chart used for the comparison task (CT), *(d)* Scatterplot used in the structural understanding task (ST).

ABSTRACT
Three-dimensional visualizations employing traditional input and output technologies have well-known limitations. Immersive technologies, natural interaction techniques, and recent developments in data physicalization may help to overcome these issues. In this context, we are specifically interested in the usage of spatial interaction with mobile devices for improved 3D visualizations. To contribute to a better understanding of this interaction style, we implemented example visualizations on a spatially-tracked tablet and investigated their usage and potential. In this paper, we report on a qualitative study comparing spatial interaction with in-place 3D visualizations to classic touch interaction regarding typical visualization tasks: navigation of unknown datasets, comparison of individual data objects, and the understanding and memorization of structures in the data. We identify several distinct usage patterns and derive recommendations for using spatial interaction in 3D data visualization.

Author Keywords
3D Data Visualization; Immersive Visualization; Mobile Devices; Spatial Input; Tangible Displays

ACM Classification Keywords
H.5.2 User Interfaces: Input devices and strategies, Interaction styles

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INTRODUCTION
3D visualizations are extensively used for data of a physical nature, e.g., in fluid dynamics visualization [6] or medical visualization [35]. The third dimension has also been used in various examples of information visualization, e.g., [3, 16, 38, 44]. However, even though the additional dimension can be beneficial, the utility of 3D visualizations is limited by problems such as occlusion, misleading perspective, and poor readability [9]. Effective interaction techniques can help to overcome these issues, making interaction a particularly important aspect of 3D visualization. Especially with the advent of *Immersive Analytics* [2, 12], 3D visualizations are brought into the focus again, and advanced interaction techniques are being developed. We see this as one example of the general trend to apply natural interaction techniques to visualization and making interactive data visualization more tangible and engaging.

Mobile devices with their multi-touch input have become an increasingly important platform for such novel visualizations [26, 39]. Not surprisingly, touch is one of the most investigated novel interaction styles. Yet, while there has been research on data visualization on mobile devices in general, e.g., [10, 22, 43, 45], there is much less work specifically on interaction for *mobile 3D visualizations*. In addition to touch, *spatial interaction* is an interesting alternative for mobile input that may help to lift visualizations from surfaces into interactive spaces. This approach uses the movement of handheld, spatially-aware mobile devices to interact with data virtually residing in physical space [6, 46], i.e, *in-place visualizations*. This promising interaction paradigm has even been shown to outperform the well-known touch gestures drag and pinch-to-zoom for 2D navigation tasks on mobile devices [47] but has rarely been investigated for the class of 3D visualizations.

In this paper, we contribute to a better understanding of this interaction paradigm by presenting and discussing the results of a user study in which we examined *spatial device input* in comparison to *direct touch input*. Of particular importance to us were the potential benefits of spatial input for typical tasks, how physical space is used during the exploration of data, and the limitations of spatial input. To this end, we designed and implemented several typical 3D visualizations of abstract data: 3D height maps, 3D bar charts, and 3D scatterplots. In contrast to related works, instead of examining specialized tools for specific 3D visualizations, we first focused on general aspects of visual exploration that all involve *navigation* (i.e., viewport manipulation), as they are among the most essential tasks necessary for every visualization and most likely to benefit from spatial interaction. Thus, we selected three typical visualization tasks for our study: (a) navigating between a set of unknown data points, (b) comparing individual data objects in varying distances, and (c) understanding and memorizing structures in the data. Our results show a general preference of spatial interaction. We also designed *3D trajectory visualizations* and used them to explore the logged tracking data of our study (for both touch and spatial input) with the help of spatial interaction. In doing so, we were able to identify distinct usage patterns of both touch and spatial interaction, like users trying to employ a bird's eye view above the visualization, reducing its complexity or taking fixed positions along the main axes of a visualization.

To summarize, the contributions of this paper consist of (i) our report on a user study comparing spatial interaction and touch input for 3D data visualization, (ii) the identification and analysis of interaction patterns with the help of 3D trajectory visualizations, and (iii) insights into and recommendations for the design of in-place 3D visualizations.

RELATED WORK

In recent years, there has been a lot of research on novel techniques for *interaction in 3D environments*, with one focus being on touch interaction (e.g., [14, 18, 24, 42, 49, 50, 52]). A report on the current state of the art was presented in 2015 by Jankowski & Hachet [21].

Regarding *3D visualization* specifically, examples include the work by Yu et al. [54], who presented a technique for touch-based interaction with 3D data using the border of the visualization, or the work by Coffey et al. [13] proposing techniques to explore volume datasets in a multi-surface environment. Klein et al. [25] developed a set of touch interaction techniques and widgets for the exploration of 3D flow visualizations. However, although such individual techniques have been developed, no clear standard for touch interaction for 3D visualization has emerged yet. Furthermore, often tabletops are used. Thus, many of the proposed techniques cannot be applied to mobile devices since, for example, they involve larger scale bimanual interactions.

Spatial Interaction for 3D Visualization

Handheld mobile devices such as smartphones and tablets have been used as tangible peephole windows into mostly 2D information spaces [31, 32, 40, 53]. For example, Spindler et al. [48] explored the use of handheld, tangible magic lenses for (2D) information visualization. Also, 3D (information) visualization has already been proposed as a use case in Fitzmaurice's work on situated information spaces [17]. Furthermore, in the last years, mobile devices have been used for spatial interaction in 3D environments: For example, Pietroszek et al. [34] used a smartphone as a tangible input device to rotate a plane in 3D space. The output, however, was decoupled from the input and shown on a separate display. More generally and not specific for 3D visualization, Medeiros et al. [29] used a tablet as a universal controller for virtual environments. Bergé et al. [5] proposed the use of smartphones as personal detail views for publicly displayed 3D content. Spindler et al. [46] explored the use of tangible magic lenses for the exploration of 3D scenes, making use of head-coupled perspective (HCP) to provide a pseudo-stereoscopic view to the user. Thomason & Wang [51] presented ScatterDice Mobile, a gyroscope-based, mobile version of the ScatterDice [16] technique, that uses animated 3D rotations to improve exploration of multidimensional scatterplots. Recently, Besançon et al. [6] proposed a combination of touch and spatial interaction with a tablet computer for the exploration of 3D visualizations. They used spatial input to directly control the position and orientation of 3D datasets as well as of cutting planes in the visualization. Büschel et al. [11] presented prototypes using spatial interaction for 3D visualization, also in combination with head-coupled perspective. Examples like these show the great potential of spatial interaction for 3D data visualization.

Some work also exists regarding immersive and mixed reality visualizations. For example, Drochtert & Geiger [15] developed a collaborative mixed reality graph visualization for mobile devices. Meiguins et al. [30] showed an AR prototype for the visualization of 3D scatterplots that allowed interaction by moving AR markers in the front of the camera. Systems that involve larger, stationary setups include, e.g., [8, 38, 41, 55].

While some of the research on spatial interaction for 3D visualization includes some form of evaluation, much of the work focuses on the validation of very specialized techniques or tools (e.g., [6, 34, 51]). In contrast, we believe that there is still a lack of general knowledge of how spatial interaction with mobile devices differs in relation to touch and how it can be used to improve interfaces for 3D data visualization.

Studies on Spatial Interaction

In the following, we will examine studies on spatial interaction that are closely related to our research. For 2D information spaces, spatial interaction was investigated, among others, by Kaufmann et al. [23] and Spindler et al. [47], who found advantages of spatial input compared to classic touch input. Besançon et al. [6] compared touch and spatial interaction for 3D data exploration and found that users, when given the choice, spent most of their time with the spatial interaction modality and usually preferred a hybrid approach. While this is interesting for our work, the scope of their study was limited to their specific interaction techniques. Also, their system included a large secondary monitor, while we focus specifically on the mobile device for both input and visualization.

Recently, Besançon et al. [7] published a comparative study of mouse, touch, and tangible input for 3D docking tasks. With similar levels of accuracy, users were much faster with tangible input. Again, input and output space of the tangible condition were separated as they used a tracked prop and a conventional display. Thus, applicability to our use case is limited.

Marzo et al. [28] studied input modalities for object manipulation (rotation, translation) in Mobile Augmented Reality. They compared touch, spatial interaction and a combination of both. Interestingly, they found that overall the best results were achieved by combining touch and spatial interaction, with spatial interaction only performing worse on large rotations. However, they did not specifically examine interaction for data visualization. Hürst & Bilyalov [19] studied the performance of spatial versus touch-based peephole navigation for VR panoramas. They reported that spatial interaction was significantly faster and also preferred by most users but also had limitations, e.g., when users were sitting. Similarly, Arvola & Holm [1] found that using the device orientation for panning was more engaging for users than touch interaction for exploring panoramas on mobile devices.

Qi et al. [36] compared HMDs, Fishtank VR, and Fishtank VR combined with an additional haptic input device for the analysis of volume visualizations. HMDs performed significantly slower and were perceived as being inside the data compared to looking from the outside like the other modalities. The author's recommendation was to use such "outside-in" systems for better overview and context. We believe this indicates that a smaller visualization scale, e.g., table-sized instead of room-sized, may be advantageous, something that we considered in our study design.

The benefits of physical navigation, both for immersive virtual environments and large display walls, have been examined by various researchers and with different results. Many found that physical navigation improves task performance, e.g., [4, 27]. Rädle et al. [37] also studied the effect of touch versus spatial/physical navigation in zoomable user interfaces on large display walls and found that both navigation performance and long-term spatial memory benefit from spatial interaction. On the other hand, Jakobsen & Hornbæk [20] only found advantages for physical navigation when virtual navigation was not possible. It is an open research question whether these findings hold for mobile spatial interaction with in-place 3D visualizations.

While these studies examine aspects of spatial interaction related to our use case, we think that there is still a lack of studies specifically examining the fundamentals of spatial interaction for mobile 3D data visualization.

STUDYING SPATIAL INTERACTION FOR 3D VISUALIZATION

Our main interaction concept is to explore 3D visualizations situated at a fixed position by physically moving a mobile device through space, which presents a view into the data. Specifically, the location and orientation of the mobile is mapped to a virtual camera (Figure 2). For such systems, we would envision the users to employ physical navigation to get an overview and navigate between subsets of the data, as well as smaller scale spatial interaction supported by touch input to precisely investigate structures or specific data items. Users would freely move the handheld device to explore the visualization, to easily compare values at different viewpoints, and to filter or select specific data points with subsidiary touch interaction techniques.

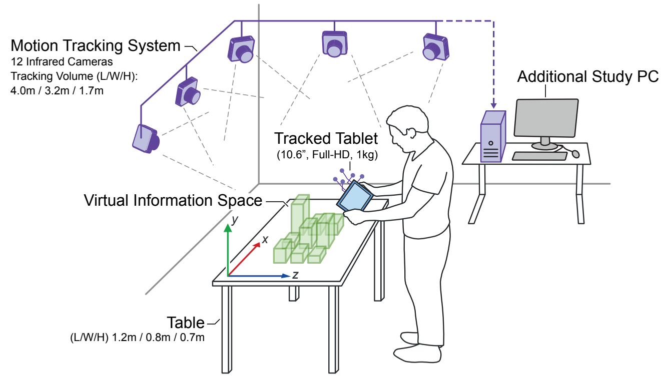

Figure 2. Basic technical setup of the study: A motion tracking system tracks the position and orientation of the mobile device (tablet). The visualization is fixed in space on top of a table.

With our investigations we aim to explore how spatial input can help to address limitations of 3D data visualizations in regard to how users navigate, explore, and understand data. We want to understand the implications of using spatial input for basic exploration tasks: Which tasks can benefit from spatial input? How is the physical space used during exploration tasks? What are the limitations of spatial input? To investigate these questions, we continuously refined and practically tested our interaction principle using different prototype implementations. As part of this process, we conducted a user study and report on its results and findings. We chose a within-subject design with two independent variables (3×2 factorial design). Our main focus was on the comparison of user behaviors in three different *tasks* (**NT** navigation task, **CT** comparison task, and **ST** structural understanding task). For each of these three tasks we used a different visualization technique. The second independent variable was the *input modality* (touch or spatial). Users had to fill out questionnaires and were closely observed and videotaped during the study.

Participants

18 unpaid participants (3 female, 15 male) from the local university's computer science and math departments volunteered for the study. Their age ranged from 22 to 32 years. When assessed about their prior experience, almost all participants reported heavy use of touch-enabled mobile devices such as smartphones or tablets. Many of them declared to be reasonably experienced in the field of information visualization based on courses they attended. Furthermore, most participants reported experiences with traditional 3D computer graphics, as they often play computer games or use 3D modeling software.

Apparatus and Implementation

All tasks were performed with our prototype, based on the *MonoGame* 3D engine and written in C#. A schematic depiction of the setup and technical details can be seen in Figure 2. We attached IR reflecting markers to the Microsoft SurfacePro 2 tablet (10.6", Full-HD, 1 kg) used in our study and tracked its position with an OptiTrack system. A table, serving as an orientation guide, was placed in the center of the tracking volume. All visualizations were scaled to the width and length of the table and were virtually located on top of it.

We implemented the two input modalities for our prototype as follows: Spatial input directly mapped the device's position and orientation to the virtual 3D camera. The scene was fixed in place and could not be repositioned. For the touch condition, we used an orbit camera model, which was selected based on our review of the literature and own experiences. Input mapping was comparable to the one employed by Besançon et al. [7]: Users could rotate the camera on the sphere horizontally and vertically by using one-finger drag gestures. The distance to the focus point could be manipulated by a pinch gesture, resulting in a zoom. Finally, the position of the focus point on the ground plane of the visualization was manipulated by using a two-finger drag gesture.

Tasks

To structure our study, we devised three tasks for testing different important aspects of 3D information visualization: navigation in unknown datasets, comparison of individual data objects, and the understanding and memorization of structures in the data. We selected these tasks because they are among the essential tasks of visual data exploration and all of them include view manipulation. Every *type of visualization* has its own characteristics (e.g., how to explore or manipulate the visualization). Therefore, we selected three different, common 3D visualization techniques suitable for studying the chosen tasks.

Navigation Task (NT)

This task focused on *finding* and *navigating to specific points* within a visualization. Twelve spheres representing potentially interesting points were consecutively placed on a 3D height map (Figure 1b). Users had to find the current sphere within the visualization and center the view on it. After briefly remaining in this position, the target was confirmed, and the next sphere appeared.

Comparison Task (CT)

In this task the participants had to *estimate the relative size of data objects*. We used a 3D bar chart with 40×60 bars and clearly highlighted two of the bars (Figure 1c). Participants had to decide which bar was higher and press the accordingly labeled button on top of the screen. To this end, they had to *navigate* the visualization to get a better understanding for the bars' actual heights. Participants had to solve six of these trials in total.

Structural Understanding Task (ST)

The goal of this task was to explore how users gain a *structural understanding* of a visualization with spatial navigation in comparison to touch. Participants had to explore 3D scatterplots with clearly visible clusters of points (Figure 1d). After participants felt confident in their understanding of the data, they switched to a neighboring PC where they had to pick from four pictures of similar plots, selecting the one picture showing the data they explored before. Like in CT, users had to complete six trials per modality.

As the last two tasks also include a navigation component, we explicitly analyzed the basic navigation within a 3D information space in the first task and did not vary the order of the tasks between the participants.

Procedure and Measurements

After obtaining informed consent, each participant was first asked to fill out an entry questionnaire, asking for demographic details and prior experiences. Participants could familiarize themselves with the prototype and the current modality using a training phase at the start of each modality and task. To counterbalance learning effects, every odd user started with spatial interaction and every even one started by using touch. Participants were asked to complete a questionnaire on the current task/modality after every task, six in total. This questionnaire was based on the NASA-TLX, asking how demanding a task felt for the user. Additionally, we asked the participants about their perceived level of control and precision of the camera. All questionnaires used a 7-point scale, with 1 always being the positive answer (e.g., not demanding, always in control). Participants had to stand while using touch input and had to hold the tablet in hand. They were also offered a pause between tasks to rest their hands after holding the tablet, but none of the participants took this opportunity. The study concluded with a final questionnaire, where users were asked to state their preferred interaction modality, both in general and by task, and to give some textual feedback. The overall duration of the study for each participant was 45 to 60 minutes, depending on individual performance. Each participant was observed and filmed during the study. Additionally, tracking data and events were logged. We also measured task completion times and errors rates, however the main focus of this paper are the qualitative results.

Data Collection and Method of Data Analysis

Each participant was recorded from a fixed position with a full view of the tracking volume. In addition, for some participants, video was also taken with a secondary, mobile camera to capture details and for documentation. Filming was done from some distance and great care was taken that the participants were not disturbed in their tasks. Two experimenters were observing the study at all times. One observer was taking handwritten notes in real-time during the whole study, the other conducted the study and was responsible for the video recording. We also digitally logged the camera position and orientation (i.e., the viewing direction) with 60Hz during both the spatial and touch condition. In an event log, all task-related events, such as completion of (sub-)tasks, target acquisition in NT, and the selected answers in CT and ST, were automatically recorded.

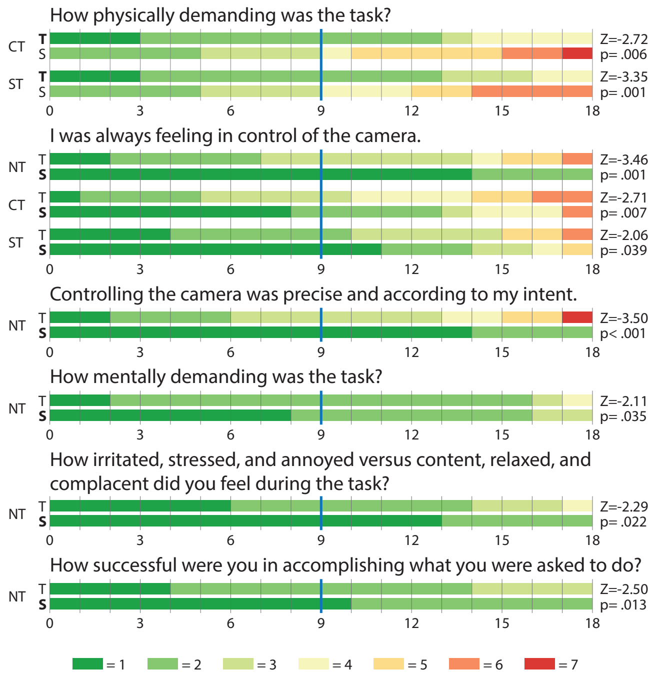

Figure 3. Subset of the questionnaire results. Only the results that showed a significant difference between spatial interaction (S) and touch (T) are listed. In all questions, 1 (dark green) always denotes the most positive answer (e.g., not demanding, always in control).

We statistically analyzed the answers to the questionnaires, the task completion times in all three tasks, and the error rates in CT and ST. The questionnaires also included free text questions on what the participants liked or disliked and space for additional comments. These answers were transcribed and higher level themes (e.g., on physical demand) were identified and cross-checked with the experimenter's notes. Our observations during the study indicated that participants followed certain strategies or patterns during the task. Based on the extensive notes taken during the study and the video recordings, we identified a preliminary list of patterns for further inspection. We then visualized the logged camera position data individually for each user and task. In this way, we were able to specifically determine which strategies were employed by which user and for which task. This allowed us to quantify the number of occurrences and thus refine the list.

RESULTS & DISCUSSION

In this section we will discuss our findings in relation to our research questions, give an analysis of the questionnaires, report on spatial exploration patterns that we observed, and derive preliminary design recommendations for in-place 3D visualizations. We also discuss limitations of our study.

Analysis of Task Load and User Preferences

The analysis of the intermediate questionnaires (Figure 3) using Wilcoxon signed-rank tests showed a clear difference between spatial interaction and touch[1]: Participants perceived a higher physical demand for using spatial interaction ($M_T = 2.20, M_S = 3.41$), while also perceiving a better control of the camera ($M_T = 3.00, M_S = 1.72$). For the *navigation task*, participants also found the camera to be more precise when using spatial interaction ($M_T = 3.11, M_S = 1.22$). They also reported lower mental demand ($M_T = 2.06, M_S = 1.67$), a lower stress level ($M_T = 1.94, M_S = 1.28$), and a higher perceived success rate ($M_T = 2.00, M_S = 1.50$) for this task. The final questionnaire showed spatial interaction to be perceived as more supportive for all tasks. Overall, 15 of the participants would prefer spatial interaction (2 touch, 1 undecided). Additionally spatial interaction was perceived as more comfortable to use by 14 of the participants (3 touch, 1 undecided). Overall, spatial interaction was described as fast and simple by three participants and "more memorable" and "more interesting and engaging" by other participants. Two users criticized the weight of the device and three mentioned tracking jitter as problematic. Furthermore, nearly all participants kneeled down during the comparison task (CT) while using spatial interaction to explore the scene from a lower point of view. Three users explicitly found this stressful and annoying.

[1] M_T: Average score for touch, M_S: average score for spatial. Lower values are always better. To achieve this, data was recoded when necessary.

Analysis of Completions Times and Success Rates

While the focus of our study was on the feedback of the questionnaires and our observations, we also analyzed the recorded completion times for each task as well as the success rates for CT and ST. Shapiro-Wilk tests showed that none of the data was normally distributed. Therefore we analyzed the results by using Wilcoxon signed-rank tests. We found no significant differences in completions times or error rates for CT and ST. However, we did find a significant difference in completion time between spacial interaction ($M = 89.82s, SD = 22.61s$) and touch ($M = 67.54s, SD = 9.16$) for NT ($Z = 3.506, p < 0.001$) with a large effect size (Pearsons correlation, $r = 0.8264$).

Analysis of Spatial Exploration Patterns

During the study we observed different participant behaviors. To further analyze these, we visualized and inspected the camera position data for each user and task. To this end, we developed a custom analysis tool that visualizes the camera movement as trajectories around the virtual table representation (Figure 4 and Figure 5). We also experimented with including camera orientation data but opted against this because of visual clutter. Relative camera movement speed is color coded from red (slow) to green (fast), and filtering allows us to inspect both individual as well as aggregated data. Besides inspection on a desktop PC, we also used our spatial interaction prototype to explore the camera trajectories in place, which helped us to get a better understanding of the spatial relations, e.g., the typical camera distances from the visualization.

This analysis for the different tasks and both modalities showed some interesting, task- and modality-dependent behavior patterns, which represent user strategies. They help us to understand user preferences and may be used to inform the design of future interfaces for 3D visualizations.

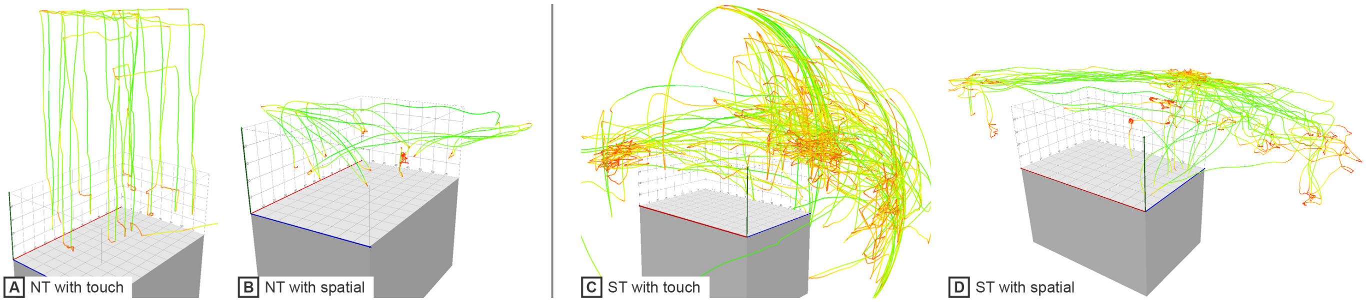

Figure 4. Visualization of selected camera trajectories of individual participants as line stripes. Color resembles movement speed (red = slow, green = fast). *(a)* NT with touch, using bird's eye strategy, *(b)* a comparable strategy when using spatial interaction for the same task, *(c)* ST with touch, showing both the typical spherical patterns of the orbit camera model and the principal viewpoints selected by the participant, *(d)* similar patterns can be detected for spatial interaction.

Reduction of Dimensions

One general behavior that we observed for all tasks and modalities was to reduce the tasks to a 2D problem: For the navigation tasks (NT) with touch interaction, most participants placed the camera in a bird's eye view above the visualization. This effectively reduced the 3D navigation task to a 2D one, with only pinch-to-zoom and drag-to-pan being required (Figure 4a). While this exact strategy is not possible for spatial interaction, many participants employed a similar way of assuming an overview position and shortly moving in on the targets (Figure 4b).

When comparing objects (CT), nine participants only explored the visualization from afar, viewing it from the three principal directions but never choosing a viewpoint where only one of the highlighted bars was visible. The other nine participants examined the bars at close distance, comparing them to the surrounding ones and then made their decision. We observed these two different strategies regardless of the used interaction modality. It should be noted that attempts to align the two bars for comparison caused problems due to the perspective and the results were not better than those of users who tried to measure the height less rigidly.

For the structural understanding task (ST), 13 participants primarily rotated the camera to explore the scene, which resulted in sphere-like movement around the visualization due to the used orbit camera, which can be seen in Figure 4c. While these sphere-like patterns themselves are highly dependent on the camera model, we observed reduction strategies like in CT for both spatial interaction and touch. It consisted of exploring the scene mainly from the front, sides, and the top of the visualization and frequently switching between those positions. This results in the characteristic patterns seen in Figure 4c and d, with the red clusters indicating the main points of view and the green lines showing the movements between them.

Movement around the Table

Regarding movement around the table during spatial interaction, we found that for NT, some participants frequently moved around the table to reach newly appearing targets. However, as mentioned above, many participants remained mostly stationary. Ten participants frequently walked around the table during CT and eight during ST, while the others mostly stood in place and tried to reach views with minimal movement. We did not observe any problems with the table blocking access to the visualizations. Furthermore, four users explicitly mentioned that the table helped them to orientate themselves.

Speed and Rate Changes

Especially for the Navigation Task (NT), we observed that touch movement was more uniform than spatial interaction, with less rapid speed changes. Spatial movement, on the other hand, was more dynamic, with rapid movement between the target positions. Interestingly, despite the speed with which the users moved the tablet, we found very little over- and undershooting (which would have been logged as losing the acquired target). For the other tasks, the differences between the modalities were less discernible, indicating that navigation was of lesser importance in these tasks.

Limitations

Each task was only studied with one visualization, mainly to keep the duration for each participant tolerable. However, by only studying each of the tasks with only one of the three visualizations, we cannot rule out that our findings do not transfer to other visualizations. Clearly, at least some of the observations, such as the bird's eye strategy, are depending on the type of visualization.

There is no generally accepted set of state-of-the-art input techniques for 3D navigation using touch on mobile devices. We decided for a specific camera model and a specific touch mapping. No alternative mappings were examined in the main study. Thus, while we took great care in our touch implementation, it is unclear whether a different mapping would lead to different results.

The technical setup of our study allowed us to use a large tracking volume of approx. $4.0\,\mathrm{m} \times 3.2\,\mathrm{m} \times 1.7\,\mathrm{m}$. Since we observed participants who made full use of this volume, it is possible that they would behave differently in both a larger volume or a much smaller interaction volume. Furthermore, as our study took place in a laboratory setting (computer science lab) it would be interesting whether the quite expressive type of interaction (user walks and moves the device) would be acceptable to the users in other, e.g., business or collaborative, settings.

INSIGHTS & RECOMMENDATIONS

The findings of our study lead us to report insights and suggest several recommendations for the envisioned concept of spatial interaction with in-place 3D visualizations.

Connecting the Physical and the Virtual

How to *position* or anchor virtual information in physical space is a complex topic and can be addressed by two fundamentally different strategies. The approach that we used in our prototype is to absolutely fix the virtual information in physical space. We believe that this provides users with a very good spatial understanding of the data and helps to build a clear mental model of the visualization. However, it also creates a mismatch between the potentially unlimited virtual space and the limitations of the physical environment. The other approach is to fix the data on the device and use spatial interaction in the form of device gestures or touch input to move, rotate, or zoom the data. This eliminates the constraints of the physical environment, but could have a negative effect on the user's mental model. Interaction techniques like *clutching and freezing* (e.g., [47, 48]) might be used to combine these two approaches, where the data is fixed in the physical world, but can be transformed at will, e.g., moved to a more comfortable position or reduced in size to get a better overview of the data.

We also propose to use physical landmarks, like the table in our study setup, to provide a general frame of reference to the users (similar to the virtual ones proposed by Müller et al. [33]). These landmarks can be used to guide the user's process of positioning (location and size) virtual 3D visualizations in relation to to the real, physical environment. While this might lead to sometimes uncomfortable positions such as kneeling, our observations and remarks by some participants show that the physical table in our study setup did not restrict the users but was considered helpful for orientation. We therefore believe this to be a promising technique to strengthen the bound between the virtual and physical world. Making use of (video-based) *Augmented Reality* is another, related approach that should be investigated but goes beyond the scope of this paper. Furthermore, we also propose to use the aforementioned *clutching and freezing* techniques to reduce the physical demand on the user that might arise from this technique.

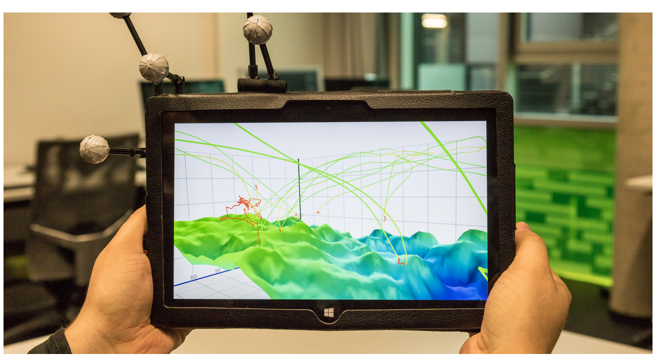

Figure 5. Visualization of selected camera trajectories of individual participants as line stripes. Color resembles movement speed (red = slow, green = fast).

As an advanced technique, *smart snapping mechanisms and predefined perspectives* can be used, especially in combination with physical landmarks. For example, when using a table, rotating a visualization might snap to 90° angles to keep it aligned with the table borders. This directly addresses our observation that several participants moved between a limited number of main points of view (Figure 4c and d).

Guidance & Learnability

Both our observations and the participants' assessment confirm that spatial interaction is *intuitive* and *easily discovered* (learnability). Thus, we believe that spatial interaction is suitable for pickup-and-use scenarios with very limited training time. In contrast, the discoverability of specific input mappings for touch in 3D is more problematic and users generally needed a brief introduction.

We also observed that users develop and employ different interaction strategies to more efficiently solve a task and that some seem to be "ideal" or "perfect" for specific visualizations or tasks. For example, for our navigation task viewing the visualization directly from above is optimal in terms of occlusion. However, several participants did not or not immediately find these strategies. We suggest that for each visualization where such a *default strategy* can be identified, it should be initially presented to novice users of the system. We believe that visualizations like the trace visualization that we developed to analyze our study data can help designers to detect such strategies.

Tool Assistance & Task Complexity

Despite the suitability of spatial interaction for simple tasks, *specialized tools*, i.e., to support selection or prevent occlusion, are essential for more complex tasks and warrant further study. This is emphasized by difficulties that our participants had at completing the comparison task as well as from the feedback we received. This is in line with our expectations and we suggest to develop and evaluate such tools, such as the clipping plane presented in [6], specifically for different types of visualization. Thus, we informally tested a spatially controlled clipping tool with our prototype. Perhaps unsurprisingly, we found that in our setup, where the camera is generally controlled by device movement, also using the device as a spatial controller for the clipping tool does confuse users. This is a clear difference to systems that use an additional (fixed) display (e.g., [6, 34]) where the mental model of the user is not that of a lens into an information space.

In general, our analysis of the completion times and error rates indicate that the influence of the modality is weaker for more complex tasks. Both the comparison and the structural understanding task show less differences between modalities, with very similar strategies for touch and spatial interaction. We believe that for more complicated tasks the input modality plays a subordinate role behind the user's focus on solving the task itself.

CONCLUSION & FUTURE WORK

In this paper we investigated the basic usage of spatial interaction with mobile devices for the use case of 3D data visualizations. In the context of visual data exploration, we wanted to learn more about how users interact with this type of input, its benefits, and its limitations. As of yet, there is a lack of studies comparing touch and spatial interaction for mobile 3D visualization that focus on the essentials of spatial interaction, instead of investigating specific techniques like, e.g., slicing. Therefore, we designed and conducted a user study in which participants explored visualizations by physically moving a mobile device and, in comparison, using touch input. Our study involved three basic but common visualization tasks: *navigation*, *comparison*, and *structural understanding*.

Users perceived spatial interaction as more supportive, comfortable and overall preferable to touch input. Furthermore, we found different spatial exploration patterns (i.e., strategies) for users exploring the data. These patterns show both similarities and distinctive differences of how users explore datasets when using touch or spatial interaction. We think that there is value in examining these strategies further, learning how different types of visualizations influence them and how immersive 3D visualizations in interactive spaces have to be designed to better support exploration and analytics.

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