Exploring Tangible and Direct Touch Interfaces for Manipulating 2D and 3D Information on a Digital Table

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ABSTRACT

On traditional tables, people often manipulate a variety of physical objects, both 2D in nature (e.g., paper) and 3D in nature (e.g., books, pens, models, etc.). Current advances in hardware technology for tabletop displays introduce the possibility of mimicking these physical interactions through *direct-touch* or *tangible* user interfaces. While both promise intuitive physical interaction, they are rarely discussed in combination in the literature. In this paper, we present a study that explores the advantages and disadvantages of tangible and touch interfaces, specifically in relation to one another. We discuss our results in terms of how effective each technique was for accomplishing both a 3D object manipulation task and a 2D information visualization exploration task. Results suggest that people can more quickly move and rotate objects in 2D with our touch interaction, but more effectively navigate the visualization using tangible interaction. We discuss how our results can be used to inform future designs of tangible and touch interaction.

INTRODUCTION

Tabletop displays offer great potential for bridging the gap between the digital and physical world through use of *touch* and *tangible* interaction. Both approaches offer many advantages over traditional computing; while we have become relatively accepting of the limitations imposed in the digital interaction space by one-point interaction, this style of interaction appears awkward and constrained when contrasted with the physical world, where we are accustomed to using as many fingers as required for our current task. In the physical world, we also regularly manipulate a variety of physical objects. Digital tables offer a convenient supporting surface on which people can both place and interact with tangible input devices and use multi-touch, multi-finger interaction.

The variety and type of multi-touch-enabled surfaces [3, 9, 13, 17, 31] is expanding rapidly. As these inventions evolve, it appears that some qualities of multi-touch interaction are similar to qualities generally accredited to tangible user interfaces (TUIs). Both promise a natural interaction experience, both are easy to learn, and both offer support for co-located collaborative work. Our research focuses on the less-investigated integration of touch and tangible interaction; we study the interplay between these two modalities to gain a better understanding of the characteristics of touch and tangible interaction on tabletops in order to allow us to benefit from the combined interaction design space.

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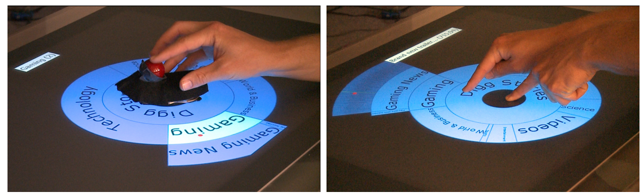

Figure 1: Using tangible (left) and touch (right) input to control a 2D information visualization.

We contribute to the exploration of this rich interaction design space by investigating whether we can characterize touch and tangible input methods as a step toward understanding how to best use them. We present touch and tangible designs (Figure 1) that each can be used to accomplish the same tasks. We compare these techniques to improve our understanding of the relative advantages and disadvantages of touch and tangible interaction. In particular, we compare the two techniques with respect to (a) the presentation of visual information (2D or 3D) and (b) the task being performed (precise or exploratory). Our *two-touch* interaction technique uses one touch for direct input and the second touch for relative input. Our *tangible* interaction technique uses an embedded trackball in a base that is designed to glide over the surface of the table and whose exact position and orientation can be sensed.

RELATED WORK

2D & 3D Multi-Touch Interfaces. While research into multi-touch enabled surfaces started over two decades ago [20], recent hardware advances [3,9,13,17,31] have sparked a new surge of interest surrounding hardware and software for large surface, multi-touch interaction [12, 22]. While hardware options are still in flux, they currently offer a variety of possibilities including recognition of multiple touches [9], recognition of identifiable touches [3], and recognition of objects simultaneously with but distinct from multiple touches [13, 17, 31].

Most state of the art interaction techniques however, are typically limited to 2D movements and rotations within the surface plane. Both single-user [30] and multi-user [23] scenarios have been investigated on interactive tabletops with one or several discrete input points from each person, typically simulating pointing with mice. Others have explored using multiple contact points together (multiple fingers or both hands) to enrich interaction, such as scaling and rotating objects [19, 24], or enabling precise selection [1]. Researchers have also explored gesture-based interaction on direct-touch surfaces, interpreting the shape or dynamics of human hands as abstract commands [32].

3D visuals on large surfaces and input to such renderings have been explored in a variety of research fields. Grossman and Wigdor [7] provide a broad review of input and output technologies that extend the interaction space from 2D to 3D. Here we note projects that have specifically used 3D in tabletop interfaces. Ståhl et al. [27] describe a tabletop interface where multiple users can form search queries using RFID tags and interact with objects using single touch gestures. Objects float to the surface when accessed and sink back into the background when no longer used. Hancock et al. [10] presented and studied a set of multi-touch interaction techniques for the manipulation of virtual objects with 3D visuals and six degrees of freedom (DOF) interaction on a digital tabletop. We build on this research both through extending one of the presented multi-touch techniques in our two-touch interaction and through use of the 3D docking task as one of the tasks in our study.

Tangible User Interfaces. Tangible user interfaces (TUIs), inspired by the seminal work of Fitzmaurice et al. [6], expand the interaction vocabulary by exploiting the fine-grained human ability to manipulate tangible objects. The main benefits claimed in this area of research are intuitiveness [16], motor memory [18], learnability [26] and the possibilities of conveying the rich meanings in social settings [14]. Some TUI examples are literal instantiations of metaphors [28, 29] where the physical and the digital are tightly coupled. Other variations allow for more generic mixed physical and graphical interaction [25]. Often uses of the tangible paradigm are motivated by the goal to support co-located collaboration (e.g., TViews [21] and Urp [29]).

Several hardware advances have made TUIs possible on tabletop displays. Wilson [31] demonstrates a vision-based system capable of tracking physical objects through visual barcodes, hands and sheets of paper using IR illumination and an off-axis camera equipped with an IR cutoff filter. A similar technique is used in the reacTable [17] to track objects that serve as input to a virtual musical instrument.

Even though tangible input happens in 3D, the interface visuals often remain 2D [5]. Photohelix [11], an application tailored for co-located browsing and sharing of digital photo collections, represents an exploration into hybrid applications where a physical handle is used to manipulate complex data sets in combination with direct touch elements. We extend the basic ideas in Photohelix by incorporating a trackball into the tangible input thus expanding Photohelix's 3DOF input to our TableBall's 5DOF input.

There are some exceptions to the use of 2D visuals. IlluminatingClay and Sandscape [15] allow people to interact with real clay (or sand) whose shape is tracked and used to form virtual 3D imagery. The ActiveDesk [6] allows designers to work with 3D virtual data like on a traditional drafting table using tangible guides, rulers, and a stylus.

DESIGN CONSIDERATIONS

We often interact with objects that are predominately 2D, such as paper, but perform many 3D operations such as folding, turning, flipping, and stacking. Both touch and tangible input are promising interaction techniques that may allow similar operations for both 2D and 3D *virtual* objects on an interactive table. In this section, we attempt to highlight some of the advantages, disadvantages, and differences between touch and tangible interaction that are important to consider in the design of techniques that attempt to support this physicality. Table 1 summarizes these differences.

Direct Connection to Visuals. When manipulating objects in the real world our actions are directly coupled—cause and effect become visible in the same place. More precisely we usually have to touch objects to move or manipulate them, for example, when folding a sheet of paper. Direct-touch interfaces make it possible to design similar digital interfaces. This ability to directly touch digital information is one of the appealing characteristics of digital tabletop interaction. Isomorphic visual feedback of action is accredited with reducing cognitive disconnect and hence improving continuity of action [2]. A direct spatial mapping also aids in non-verbal communication through natural hand gestures and body language [8, 19]. It can help collaborators to understand which parts of the information are presently being inspected (e.g., "look at this"). Interaction with the digital through the use of physical objects warrants a similar experience, in fact the

	Touch	**Tangible**
2D	Familiar mouse interactions can often be transferred to touch interactions	3D object-manipulation must be mapped to control 2D virtual objects—there may not be a clear mental model of how this should be done
3D	Limited to surface interactions (may not be suitable for necessary indirect control above/below surface)	Can detect movement separately from the surface (either above or outside display region)
Both	Direct connection to visual information	Indirect connection to visual information (via tangible device)
	Precision limited to finger	Higher precision possible (e.g., pen, trackball)

Table 1: Comparison of touch and tangible interaction for 2D and 3D interfaces.

direct integration of input and output stands at the core of the tangible interaction paradigm.

This direct coupling may be the most essential aspect of both touch and tangible interaction for providing physicality, but it also serves to highlight a subtle difference between the two. Touch interaction provides a direct connection between a person's hand or finger and the virtual objects that they manipulate. On the other hand, tangible devices provide a direct connection between the person and the device itself, and therefore an indirect connection between them and the information being provided. It may be that people can become embodied with tangible devices and act as though they are a part of themselves [4], but there is still a qualitative difference of directness between touch and tangible.

A final differentiation to take into account is the space above the surface. Direct-touch interfaces provide direct coupling as long as the user's hands are in contact with the screen but it is broken as soon as the touching fingers leave the surface. Due to their 3D nature tangible interface elements can help in providing a more holistic interaction vocabulary including the space above a digital table.

Supplementary Indirect Control. While it is important to provide tightly coupled visual feedback sometimes it is necessary and can be beneficial if an interaction has an *additional* indirect component. A person can still maintain direct contact by touching or placing a physical device on a virtual object, but then simultaneously control some aspect of that virtual object indirectly. For example, in the same way that one might first select a window in a typical GUI before scrolling within that window, a person could place and hold one finger on a list on a digital table and then scroll through its contents using an easier-to-control scroll wheel.

Both tangible and touch interaction are capable of providing this indirect component. A tangible device can be augmented with an additional degree of freedom or another tangible object to provide this indirect control, and direct-touch interaction can be augmented with indirect second or third touches. It is not immediately clear if one of these approaches is superior to the other, but providing indirect control through multiple touches may break a person's mental model, since it would require performing that manipulation *somewhere* on the display. That is, the display would no longer be dedicated to only information display and manipulation, but also would become a more abstract input device. Tangible devices would not impose this limitation.

Precision. Complex tasks often require different phases of interaction and different granularities of motor control, for example, a ballistic movement (e.g., reaching out for the stereo) and a fine-grained manipulation (e.g., adjusting the volume). In addition to absolute motion control, interaction techniques can be designed so that fine-grained control for precise interaction is supported—possibly through an additional, relative element in the interaction mapping [1].

Tangible and touch interactions differ greatly in terms of their support for precise control. Touch interaction is limited to the physical constraints of the human hand. In order to achieve higher precision than the size of one's finger, it is necessary to use either a physical device (e.g., a pen) or some form of relative (indirect) control. On the other hand, tangible devices are limited only by what is physically possible to manufacture. For example, a knob or trackball can provide a high degree of precision and is physically easy to manipulate.

Mappings. Tangible and touch input can be mapped in different ways to varying functionality. In this paper, we present only two of countless possibilities: 3D manipulation and 2D information exploration. Many other design possibilities are conceivable and some are discussed later.

Because we are using tangible input devices (physical objects and touch surfaces) to manipulate virtual things, people bring with them many experiences from the physical world. Due to the almost unconstrained freedom of interaction we have in the real world, it is easy to frustrate or confuse people through a disparity of performed action and system response. To clarify, one could imagine the possible applications of a screwdriver in the real world of which only a few include the tool's original purpose. For example, we can repurpose the screwdriver as a weapon or simply as a toy to fiddle with. When using tangibles as input devices, it is practically impossible to anticipate all possible expected uses of the device. Consequently, it is easy to generate an unexpected or confusing system response. It is necessary to consider these physical experiences and to try and match the effect of a person's actions with their expectations.

For example, it might be a bad idea to design an interface that contains virtual objects that do not remain underneath the user's finger while being dragged across the screen. This is due the expectation that objects react directly to the application of force and do not magically "jump" to a new location in the real world. However, there are several examples that break with what is physically possible and are still readily accepted. Consider scaling of onscreen objects in multi-touch applications. This is often implemented mapping the distance of two touch points to the scale factor of the object in a uniform manner. In reality objects would not behave like that, at best they would deform elastically in the areas subject to applied force.

Additionally, people generally have experience with more traditional GUIs (i.e., the WIMP interface). Effects not possible in the physical world, such as hiding or zooming a window, may still be familiar to many people. Tangible and touch input also differ in the possibilities they allow for mapping familiar actions to the control of virtual objects. On the one hand, touch interfaces provide similar interactions to a mouse (e.g., pressing buttons) and on the other, tangible interfaces provide physical interactions that mimic actions like picking up or flipping over objects. Both techniques can thus leverage familiar interactions, but in different ways.

INTERACTION TECHNIQUES

We provided one touch and one tangible technique, created with the specific purpose of comparison. They both provide

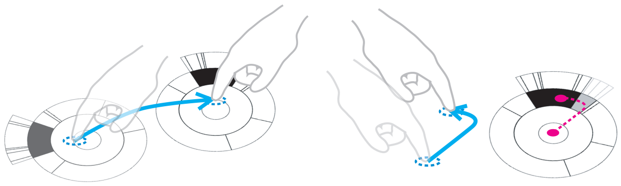

Figure 2: DTRT: (left) direct touch causes rotation and translation in 2D; and (right) a relative second touch is used for navigation.

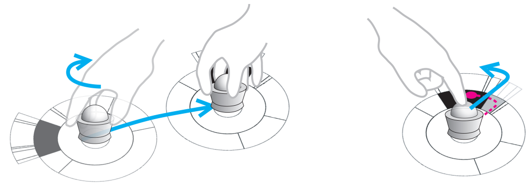

Figure 3: Tangible technique: (left) moving and twisting the physical device causes 2D rotation and translation; (right) trackball rotation is used for navigation.

5DOF: (a) 3 direct DOF for rotation and position along the table's surface in 2D, and (b) 2 relative control DOF for precise manipulations. We provide two applications of the additional DOF: to rotate a 3D pyramid and to navigate within a radial space-filling (RSF) tree visualization.

Touch

We use the two-touch technique described in Hancock et al. [10] to manipulate 3D objects and extend the use of the second touch for navigation of the RSF tree (Figure 2). We chose the two-touch technique for two reasons: (1) that technique was shown to be superior to a single touch technique and suitably comparable to the three-touch technique and (2) our choice of hardware (a SMART Board) limited our choice to a maximum of two touches.

Direct Control, First Touch

The first touch selects the digital item and provides direct control using an interaction known as rotate n' translate (RNT) [19]. When the touch point in contact with the digital item is moved, the 2DOF of the single touch are combined with a virtual force opposing the direction of movement to create 3DOF output: x, y, and angle of rotation. A special area in the item's centre is reserved for translation only. The direct touch provides identical interaction whatever the digital item is; what works with the RSF tree, works with the 3D pyramids. The first touch selects a pyramid and moving it moves and rotates the virtual object in 2D. Therefore rotation is parallel to the plane of the table.

Relative Control, Second Touch

The second touch provides an additional cursor to make precise selections on the RSF tree. The touch that controls this relative interaction does not have to be on the RSF tree. It can instead be beside so that the visual manipulation of the cursor is easy to see. Also the relative interaction allows for more precise selection of small areas. With the 3D pyramids, the second touch provides for the two additional rotations necessary to position an object precisely in 3D. The direct touch provides object rotation about the z-axis (yaw). The relative touch movement in x and y provide object rotation about the x-axis (pitch) and about the y-axis (roll).

Tangible

Extending the basic concept in Photohelix [11], we developed TableBall (Figure 3), a trackball and tangible input device that is capable of sensing 5DOF. We track the absolute position and rotation on the surface of the table for 3DOF and the trackball provides an additional 2DOF.

Direct Control, Position & Rotation

The TableBall's position selects the digital item touched and provides direct control. The position on the table, both x, y location and the entire device's rotation, is sensed by the external tracking system. Placing the TableBall on a digital item selects it. Moving the TableBall in contact with the selected item provides integrated rotation and translation. TableBall's x and y location directly sets the item's 2D position and its rotation directly sets the selected item's rotation. The position and rotation interaction is identical whether the digital item is a RSF tree or a 3D pyramid.

Although our tracking system supports computation of the values for roll and pitch directly from the position of TableBall in space, we decided to use the tangible object only on the table's surface to prevent users from having to operate the device in mid air for three reasons. First, lifting the device up from the table would break visual feedback with the digital item, possibly increasing the cognitive load for the user. Second, operation in mid-air lacks the physical support of the table and consequently reduces precision of the control. Third, operating a physical device in mid-air can be tiresome and result in fatigue effects and unnecessary discomfort for the user.

Relative Control, Trackball

The movement of the trackball is interpreted as indirect x and y movement on the tabletop display surface. The indirect trackball interaction offers precise selection on the RSF representation and with the 3D pyramids, it provides for the two additional rotations necessary to position an object precisely in 3D. The trackball control provides object rotation about the x-axis (pitch) and about the y-axis (roll).

USER STUDY

We performed a user study to help further explore the design space of touch and tangible interaction. We first compared the techniques using tasks from prior work to evaluate their efficacy for 3D object manipulation. We then explored how people can use these techniques to control a 2D information visualization. We chose these two tasks because they cover a broad spectrum of interaction possibilities. Namely, they span across 2D and 3D and contain elements that require both precise action and exploration.

Participants

Ten people, predominately students and staff from a local university, participated in our study (5 male, 5 female). Ages ranged from 23 to 36 ($M = 29.1$, $SD = 4.0$). Six participants reported playing 3D games at least once a year, and the remaining four played seldom or never. Five had previously seen or used a tabletop display, likely at a demo or previous study in our lab.

Apparatus

Participants stood at a rear-projected 2800 × 2100 pixel tabletop display with a 146 cm × 110 cm display area (19 pixels / cm). The display surface was 90 cm above the floor. Two-touch input was provided through a SMART Board DViT[1]. The TableBall was implemented using optical tracking from a Vicon[2] system for 2D position and rotation (x, y, and azimuth) and an upside-down wireless optical mouse mounted with a disassembled trackball to provide the other two degrees of freedom. An orthogonal 3D projection was used to render the 3D visuals and no z-movement was provided (as in Hancock et al. [10]).

Procedure and Design

Participants performed two tasks for each technique (touch and tangible) in the same order. The order of techniques was counterbalanced. Participants completed a questionnaire after completing the tasks for each technique and were interviewed at the end of the experiment.

Task 1: Docking Pyramids

The first task was the same task used in Hancock et al. [10], which itself is an adaptation of the task from Zhai and Milgram [33] used to compare 6DOF techniques.

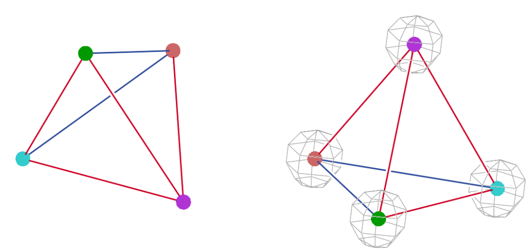

Figure 4: Participants were asked to dock a pyramid (left) inside a target pyramid (right).

Participants were asked to dock one pyramid inside another of equal size (Figure 4). The corners and edges were coloured to help participants correctly orient the pyramids, and halos were used to provide depth cues. The source pyramid was considered successfully docked when all four vertices were within 126 pixels (6 cm) of the corresponding vertices on the target. Unlike the task in [10], only one (large) tolerance level was used, as we did not expect the tolerance level to interact with technique. We did, however, vary the level of rotation required to complete the task. In the planar-only condition, the task could be completed by using only 2D translation and rotation (i.e., movement in x & y and rotations about z). In the full-rotation condition, the task required both movement in 2D and rotation about some axis other than z to complete the task. Data from the docking task were analyzed using a two-way within-participants analysis of variance using the factors technique (touch or TableBall) and rotation (planar only or full rotation).

[1]SMART Technologies DViT. http://smarttech.com/dvit

[2]Vicon Motion Tracking. http://www.vicon.com

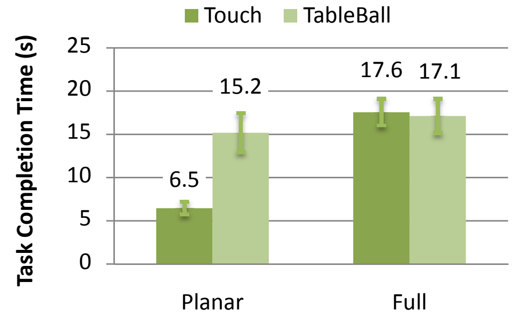

Figure 5: There was a significant interaction between device and type of rotation.

For each technique, participants completed 12 practice trials followed by 16 actual trials (8 repetitions of each rotation) for a total of 56 trials. Task completion times and all input from the table and TableBall were logged.

Task 2: Exploring Data

For the second task, participants were asked to explore first a small and then a large data set, represented as RSF trees. Participants were asked five questions about each data set and asked to answer out loud after exploring the data using one of the two techniques. The two small data sets (one per technique) contained information about cheese (19 rows of data) and coffee (21 rows). The two large data sets contained information about salaries of University of Michigan professors (105 rows) and articles posted to the website http://digg.com (1001 rows).

To familiarize participants with RSF trees, a tutorial was given on the connection between a node-link and space-filling representation of a book and its chapters and sections. To verify understanding, participants were asked to label a space-filling tree based on those from a node-link tree. All participants successfully labelled the second tree.

For this part of the experiment, the data collected were primarily observational. For the small dataset, participants were not given explicit instructions on how the input techniques they used in Task 1 would map to the information visualization provided. They were, however, told that the representation was interactive and that they could “open up” any of the nodes in the tree using a red cursor. For the large data set, the mapping was explicitly described.

Results

Task Completion Times

Participants completed task 1 marginally faster ($F_{1,9} = 4.7$, $p = .06$) using touch ($M = 12.0s$, $SE = 1.0s$) than TableBall ($M = 16.2s$, $SE = 1.9s$). Participants also performed planar rotations significantly faster than full rotations ($F_{1,9} = 35.6$, $p < .001$) and there was a significant interaction between technique and rotation ($F_{1,9} = 14.3$, $p < .01$). Pairwise comparisons (Figure 5) also showed that touch was significantly faster for docking tasks that required only planar rotation ($p < .01$), but not for tasks that required full spatial rotation ($p = .84$).

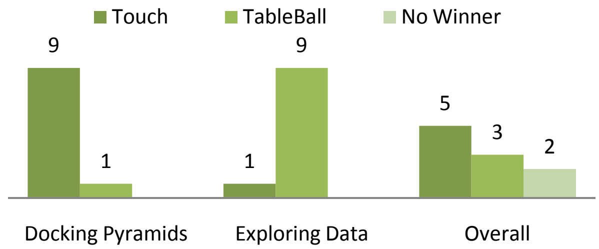

Figure 6: Participant preference data.

Questionnaire Data
Participants were asked questions on a 7-point Likert scale. We performed Wilcoxon Signed-Ranks tests to compare participant responses for each technique. For the docking-pyramids task, participants rated touch as easier to use ($z = -2.0$, $p = .046$) and less difficult for turning objects in the plane ($z = -2.5$, $p = .01$). They also felt that with touch, objects reacted as expected ($z = -2.0$, $p = .048$) and that they could easily move an object where they wanted ($z = -2.2$, $p = .03$). For the exploring task, participants rated the TableBall as easier to use ($z = -2.6$, $p = .01$) and less difficult to control ($z = -2.7$, $p < .01$). They also found it easier to navigate data ($z = -2.0$, $p = .04$) and to share data with others ($z = -2.2$, $p = .03$). Participants preferred touch for docking pyramids and TableBall for exploring data. There was no clear overall winner, but only two people were indifferent about their choice (Figure 6).

Discussion

Direct Connection to Visuals
For the touch technique, the benefit of superimposing the control space and display space is made apparent by the improved speed for 2D manipulations of the pyramid. People's comments did not directly mention this mapping, but their language indicated that there was some cognitive benefit. People would describe this technique as "hands-on" or say that they could "get their hands dirty". These words indicate that their mental model is that they are directly touching the virtual objects on the screen.

For the tangible technique, there was some concern expressed over the fact that the TableBall occluded some of the tree visualization and made it hard to read without turning and clutching the device. This problem could potentially be alleviated by reducing the size of the entire device to be not much larger than the ball itself, and to fit inside the centre of the tree (i.e., at its root). While this may improve the situation there is no clear way to completely eliminate this particular concern.

The participants concerns and preference for the touch technique for 2D manipulations of pyramids indicate that the necessity of this indirectness may be an important distinguishing factor between TUIs and touch interfaces.

Supplementary Indirect Control
Our results indicate the usefulness of indirect manipulation. In particular, full rotation in 3D requires an indirect interaction, because it is not physically possible to reach inside the display. Navigation to small nodes in the tree visualization also required some level of indirection. Participants were able to complete all trials in both tasks, without significant difficulty. They also commented that the tangible technique made it easier to "navigate to the smaller nodes" for the data-exploration task and some commented that it made it "easier to rotate in 3D" for the pyramid task.

This preference for the tangible technique for 3D rotations and information navigation suggests a superiority of the tangible technique with regard to the support of indirect control. That is, participants did not seem to appreciate having the touch input multi-purposed for both direct and indirect control. On the other hand, this did not seem to be an issue for the tangible condition.

Precision
Our study provides significant evidence suggesting people's desire to have precise control. In particular, most complained about the lack of support for precise control in the data exploration task with the touch technique and praised the ability of the tangible technique to "fine-tune" their selections. The results thus provide support for our claim that tangible devices can better support precise actions on a table.

In the pyramid task, we also observed a need for this fine-grained control. A typical strategy was to first orient the source pyramid to resemble the target pyramid separately (i.e., not in-place). Once an approximately correct orientation was achieved, the participant would then move the pyramid within bounds of the target. The participant would then fine-tune the orientation once it was in-bounds. The separation of this task into stages, together with claims made about the superiority of the tangible device for fine control highlights the differences between our tangible and touch techniques in their support of these different stages. That is, tangible interaction was better for fine-control of rotations in 3D, whereas touch interaction was better for less-precise 2D movements.

Mappings
Participants provided significant evidence that consistent logical mappings were an essential component of a good design. They frequently complained that the mapping of touch to control the tree visualization was not what they had expected. In particular, they expected that touching any part of the visualization with their second finger would activate that node of the tree. One participant described the disadvantage as follows: "the time it takes for the mind to react is quicker than the touch [interaction]." This particular expectation likely comes from the participants' familiarity with mouse interactions, as direct selection with a mouse is likely how one would interact with a RSF tree implemented on a traditional computer.

Our results also suggest that both tangible and touch interfaces can support familiar actions from the physical world. Participants described several benefits of both techniques in terms of appropriate mapping. One participant said that with touch, you could "just drag it over and it worked", for the pyramid task. Another suggested that the TableBall was "easy to move and rotate at the same time".

ALTERNATIVE DESIGNS

The purpose of our study was not to eliminate one or the other technique, but rather to understand the relative advantages and disadvantages of touch and tangible interaction and to inform further iterations of the design. What follows are examples of how our findings can be used to improve such designs.

Participants performed and rated touch input as better than tangible for most 2D translation and rotation tasks, yet seemed to prefer tangible for fine control and rotation of 3D objects. An alternate method for manipulating 3D objects would be to combine the best aspects of both techniques. That is, direct touch can be used to control 2D translation and rotation (i.e., about z) and the trackball can be used to control 3D rotation (i.e., about x and y). In this case, the physical connection is still maintained by the touch, but rotations can be effected indirectly with more precision using the alternate hand.

Participants often complained that they would prefer to be able to touch a particular part of the tree directly. We initially felt it necessary to provide indirect controls to navigate the tree so that smaller nodes (those too difficult to select with one's finger) could still be acquired. To achieve both goals, an improved technique could cause the cursor to move directly to where the second finger is touched, and then provide the ability to refine the selection by "scrubbing" (i.e., so that a large movement of the finger will result in a small movement of the cursor).

CONCLUSION

In summary, the results of our study highlight several advantages and disadvantages of both touch and tangible user interfaces. In particular, touch interfaces were shown to provide a more direct connection between the person touching the display and the information presented. Touch interfaces were also shown to leverage many of the interactions familiar from traditional use of a mouse on the computer. On the other hand, TableBall provided superior indirect control when necessary. In particular, this indirect control was found to be more precise than touch interaction. Both techniques were found to leverage our natural abilities to manipulate objects in the physical world.

In the future, we intend to investigate how our findings might best be integrated into existing tangible user interface frameworks. Our intention is to demonstrate that many of the benefits accredited to tangible devices can be shown to exist for touch-based interaction on a tabletop display and that the relative benefits of each can be better used to create an environment that makes effective use of both techniques.

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