The Impact of Tangible Interaction Techniques on Higher Cognitive Processes

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I hereby declare that I have created this work completely on my own and used no other sources or tools than the ones listed, and that I have marked any citations accordingly.

Hiermit versichere ich, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie Zitate kenntlich gemacht habe.

Aachen, November 2021
CHRISTIAN CHEREK

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Abstract

Multitouch interaction brought incredible advancements to our everyday life. The success of smartphones is unprecedented in modern history for a good reason. On multitouch displays, input and output are collocated at the tip of our fingers. This enables immediate feedback, highly flexible utilization of the available space, updatability of interfaces, and new accessibility features. However, a touchscreen's flat surface lacks haptic features, neglecting a big part of our sensory capabilities. This thesis integrates itself into the tangible research community by presenting novel ways to create tangibles for capacitive screens and presenting a software framework to develop tangible applications with Apple's native APIs. We developed the Design Space of Tangible Interaction, a taxonomy to help researchers and designers comparing tangible designs and finding new ways to interact with tangibles. In this spirit, we evaluated tangibles in novel ways beyond their well-established usability benefits. We found them to contribute to users' way of thinking, awareness for collaborators, and intuitiveness of highly complex input tasks.

Überblick

Multitouch Interaktion hat unser Leben auf viele Arten bereichert. Das erkennt man nicht zuletzt an dem besipiellosen Erfolg den Smartphones und Tablets seit der Präsentation des iPhones haben. Ein wichtiger Grund hierfür ist die räumliche Nähe von Eingabe und Ausgabe. Touch-Eingaben auf dem Display ermöglichen direktes Feedback, eine hohe Flexibilität für die Anzeige, Anpassbarkeit der Interaktion und sogar Zugänglichkeitsfunktionen für körperlich und geistig beeinträchtigte Menschen. Gleichzeitig fehlen der glatten Glasoberfläche eines Touchdisplays jedoch jegliche haptischen Eigenschaften, die es ermöglichen würden unseren haptischen Sinn für die Orientierung auf dem Display einzusetzen. Die Tangible Forschung hat es sich zum Ziel gesetzt, diese Haptik wieder auf Touchdisplays verfügbar zu machen. Diese Arbeit integriert sich in die Tangible Forschung indem sie eine neue Art Tangibles zu bauen für kapazitive Displays präsentiert. Außerdem präsentiert sie ein Software-Framework mit dem Tangible Anwendungen für macOS mit Apples nativen APIs entwickelt werden können. Wir präsentieren den Design Space of Tangible Interaction, eine Taxonomie mit der Tangibles miteinander in ihren Eigenschaften verglichen und neue Interaktionsdesigns gefunden werden können. Aufbauend auf die existierende Tangible Forschung zur Nutzbarkeit von Tangibles, präsentieren wir mehrere Studien, die zeigen, dass Tangibles auch für komplexe Eingaben eine intuitive Eingabeschnittstelle sind, sie Menschen helfen eine höhere Aufmerksamkeit für die Eingaben anderer aufzubringen und sie sogar unser abstraktes Denken beeinflussen können.

Acknowledgements

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Thanks to my family, who supported me during my studies and after, your understanding and guidance helped immensely, especially in difficult times.

Thanks to all my thesis students and student assistants, I enjoyed working with all of you!

I also want to thank all of our participants and volunteers who helped with this research. This includes participants for the studies, helping hands when some small device just did not want to work, and my colleagues who always helped if something needed an additional hand.

And most important, thank you, Lara! Your support, guidance, protection, and love mean the world to me.
Without you, none of this would have happened.

Conventions

Throughout this thesis, we use the following conventions.

We use the plural “we” in the entire thesis instead of “I” even if the author solely did the work.

Some of the materials, studies, and contributions to creating tangible applications in this thesis have been published previously. We state this at the beginning of every chapter and cite the publications accordingly.

Source code and implementation symbols are written in typewriter-style text. `myClass`

The whole thesis is written in American English.

If we refer to a person in the singular, we use “they \them” pronouns to emphasize that we do not refer to a specific gender.

Chapter 1

Introduction

> *"Channeling all interaction through a single finger is like restricting all literature to Dr Seuss's vocabulary."*
>
> *—Bret Victor 2011*

Tangibles are physical tokens that are in some way or another tracked by a digital system. This definition includes standard physical controllers like mouse and keyboard, but also other physical buttons and knobs, for example, volume and airflow controls in a car.

Additionally, tangibles can represent specific objects in an application's domain, for example, physical meeples in a digital board game. In this case, a tangible is a physical representation of an object that otherwise only exists in its virtual world. The tangible is directly coupled to the corresponding virtual object; for example, if a user moves the tangible meeple, its virtual counterpart moves along. Such a close connection between tangibles and their virtual representation is often applied to interactive tabletops. The tangibles represent domain objects of the application that runs on the tabletop's display.

Tangibles are physical objects that are detected by a digital system.

More recently, tangibles are also applied to Augmented and Virtual Reality (AR and VR) applications, as controllers and as domain objects, e.g., in VR building applications. Fig-

Figure 1.1: Examples for tangible interaction: A learning application where tangibles represent nodes in a graph, tangible meeples in a tabletop game representing space ships, tangibles to control lightsabers in a VR application, and a tangible pen to create 3D designs in augmented reality by Wacker et al., 2019 (top left to bottom right).

Tangibles can be physical controllers for a digital system or a graspable representation of a digital object.

ure 1.1 shows a collection of examples for tangible interaction. Examples for tangibles as controllers are the ARPen, presented by Wacker et al., 2019, users can use a physical pen to create 3D shapes and draw in Augmented Reality. In Beat Saber, a Virtual Reality application by Beat Games[1], players use their controllers as lightsabers. As domain objects, tangibles can represent many different objects. Top right in Figure 1.1 tangibles are used as physical space ships for a virtual tabletop game. Top-left the tangibles represent graph nodes in a computer science teaching application.

Fitzmaurice et al., were the first to introduce physical controllers for on-screen operations.

Fitzmaurice et al., 1995 were the first to present the idea of tangible interaction. They described ”Bricks”, tangible tokens that can be used to, for example, draw on an interactive tabletop. As shown in Figure 1.2, they did not use their ”Bricks” as domain objects but instead as physical tokens for on-screen controls to resize or bend shapes in a drawing application. Users can “grab” a shape with two Bricks and then manipulate it by moving the tangible controllers across the screen.

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[1] https://beatsaber.com

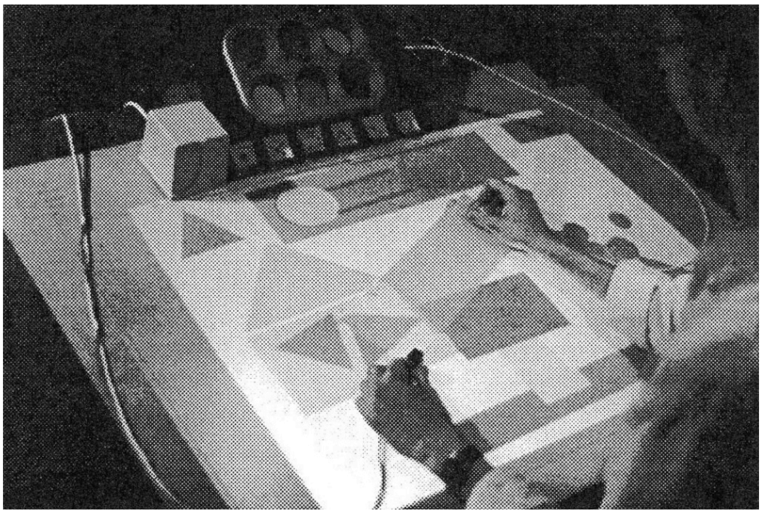

Figure 1.2: Bricks, as presented by Fitzmaurice et al., 1995. The tangible tokens represent corner boxes of a resize operator in a drawing application.

Underkoffler, Ishii, 1999 created the first representation of tangibles as domain objects. They presented URP, an urban planning shadow simulation. In their simulation, users place buildings that are represented by tangible objects on a tabletop display. The system detects the positions of all buildings and displays the shadows these buildings cast during the day. Figure 1.3 shows a picture of their application with tangible buildings and their virtual shadows. Since a projector displays the shadows above the screen, the tangible buildings cast a solid virtual shadow and a real wireframe shadow.

Underkoffler and Ishii were the first to create domain-specific tangibles for an urban shadow simulation.

Tangible interaction quickly showed many advantages over pure multitouch interaction. Fitzmaurice, W. Buxton, 1997 were the first to show that tangible interaction can outperform mouse and keyboard in time and error rates.

Tangibles' speed and accuracy outperform time-multiplexed interaction like mouse-desktop systems.

To discuss why researchers had the idea to bring physical controls to multitouch, we first have to look at the success of multitouch interaction in commercial applications.

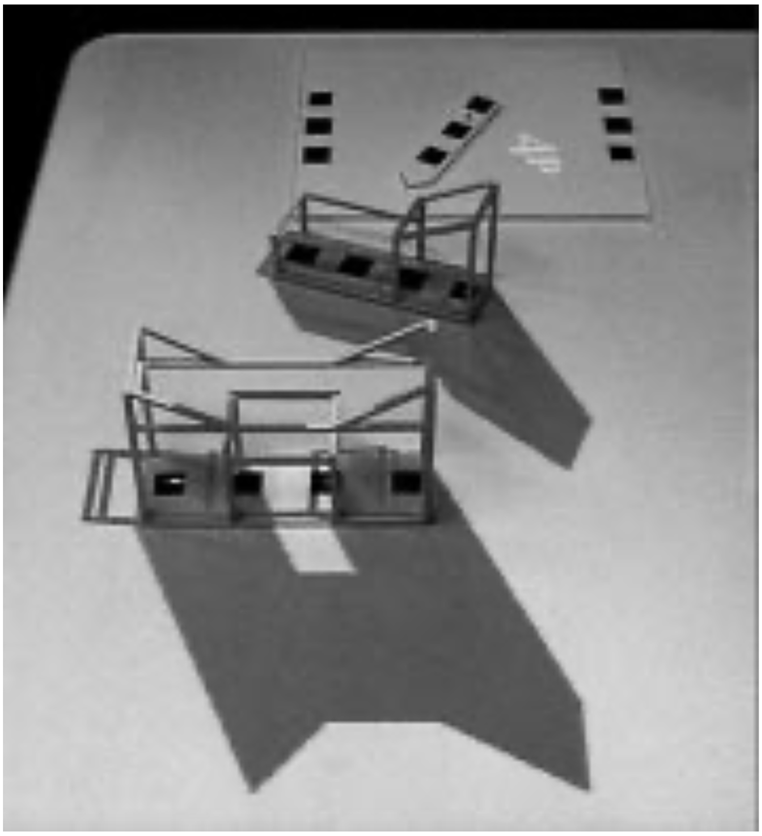

Figure 1.3: URP as presented by Underkoffler, Ishii, 1999. The physical representations of buildings cast a virtual shadow on the display. In this picture, the time is set to the late afternoon.

1.1 The Success of Multitouch Interaction

Early multitouch sensing technologies were bulky hard to use but also showed to be promising due to the directness of the interaction.

Touch-sensitive input showed to be a promising technology, already when most sensors were only able to detect single touchpoints. W. Buxton et al., 1985 described the benefits of touch tablets over mice and motivated future development of the technology. They used a resistive sensing technology for this work. As described, e.g., by Hillis, 1982, these sensors detect touch via physical deformation of a resistor. This way, they can even detect multiple pressure levels. However, since all sensors need to be connected to the system with their individual wires, these sensors are limited to a relatively low resolution. Despite these limitations, these sensors were already very successful among commercially available devices, such as personal digital assistants (PDAs).

The first to present a low-cost and scalable technique to detect a potentially unlimited amount of touchpoints on a surface were Han, 2005. They presented a visual tracking system that uses Frustrated Total Internal Reflection (FTIR) as initially described by Wyman, 1965. Many researchers adopted their concept, combined with a Diffuse Illumination (DI) system, as described by Matsushita, Rekimoto, 1997, this tracking mechanism even can detect a hover state of the finger. Visual tracking sensors have also been applied in commercial touch-sensitive tables, for example, in Samsung's SMART Signage SUR40 with Microsoft® PixelSense™[2].

FTIR allows the creation of low-cost multitouch tables with top or bottom projectors.

These early touch systems, however, still had difficulties due to their detection mechanisms. Visual tracking systems need a camera to look at the scene, which requires a certain distance for the lens to catch every input. Many implementations also utilize a projector to display digital content. Thus, tabletops that use cameras and projectors tend to be bulky. Therefore, visual tracking systems can inherently not be mobile. Additionally, FTIR and DI use infrared reflections to detect touch points. However, utilizing infrared light makes them prone to disturbances from common light sources like the sun or bright lightbulbs. Therefore, visual-based tracking requires a very controlled environment, which makes them less useful in everyday applications.

However, since FTIR uses infrared reflections to detect touch, it is susceptible to strong light sources like the sun.

Resistive sensors like Hillis, 1982 need a certain pressure applied by their user to detect a touch. W. Buxton et al., 1985 already noted that this creates friction, which is unpleasant if used for a long time. It also makes gesture interaction more difficult since pressing and moving the finger even increases the friction and thus creates heat, which is unpleasant for the user. Therefore, most PDAs were shipped with a pen included to press and draw on the device. Nevertheless, displays with resistive touch detection

Other sensing technologies like, e.g., resistive touch, have a bad user experience due to the required force when touching.

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[2] https://www.samsung.com/de/support/model/LH40SFWTGC/EN/

found fairly wide commercial success, for example, in cash registers.

Capacitive sensing of the fingertips helped touch interaction to achieve today's success.

In late 2006 LG Electronics announced the first mobile phone that included a capacitive touch detection LG Electronics Inc., 2006. Shortly after, Apple announced the first iPhone, the first widely successful mobile phone with a capacitive multitouch screen Apple Inc., 2007. Since then, virtually every successful mobile device has a multitouch screen included and only very few or even no physical buttons at all. The technology is so successful that developers implement it in many other devices that used to be controlled with physical controllers. Figure 1.4 shows a collection of devices that include touchscreens:

Beyond smartphones, many devices that used to be controlled by buttons now include a touch screen.

- A washing machine by SAMSUNG, 2020 where physical controls for the program and temperature are omitted in favor of a touch screen.
- A vacuum cleaner by Yanko Design, 2016 that is controlled by touch and allows users to look at the picture of a camera located at the nozzle.
- A stove by SEG Hausgeräte GmbH, 2020 that shows menus and submenus on a touchscreen
- And a Kickstarter financed drill by Robbox Inc., 2020 that includes a touchscreen to set the desired depth of a drilled hole.

These are only some examples of many devices that now include a screen and touch instead of physical buttons, sliders, or knobs.

Our hands contain some of the densest areas of afferences in the body and are a rich source of tactile feedback.

While sometimes the addition of a screen might increase the device's usability, adding touch interaction does not necessarily. It even hinders our sense of haptics to contribute to the interaction. Our hands and fingers have more than 200 pressure, friction, and velocity sensing afferences per cm^2 [R. F. Schmidt et al., 2011]. Their temperature sensing allows for sensing of down to $0.2C^{\circ}$ difference [Darian-Smith et al., 1979]. This very high density of sensing capabilities combined with a complex muscular system of 33

Figure 1.4: After the success of the iPhone, many developers of everyday devices also started including touchscreens. Here are some examples: A washing machine with a touchscreen instead of physical buttons or knobs by SAMSUNG, 2020, a vacuum cleaner with included cameras and a touch display by Yanko Design, 2016, a stove with a touchscreen to configure the heat by SEG Hausgeräte GmbH, 2020, a drill with a touchscreen to select the speed, and the drilling profile by Robbox Inc., 2020 (top left to bottom right).

muscles allows us to operate tools very precisely and communicates rich information about the objects we are handling. This information includes an object's texture, stiffness, and size, even if we do not look at it. Arslanova et al., 2020 showed that our sensory system and brain also integrate the information of multiple touches and thus create an even better understanding of the touched object. That means, when we press a physical button, we can feel when the button's mechanism detects the press even before the button hits its end of the movement. Operating a slider, we sense how far the slider moves even without looking at it. We feel the slightest bumps if there are physical cues built into the slider to indicate certain positions within the slider range. Operating a rotary knob enables us to make high precision input far below the millimeter mark. All real-world objects offer such tactile cues, often so small we do not even recognize them in our everyday interaction. However, we still utilize this tactile information to interact with the world.

Human hands are capable of performing highly accurate movements and sense tiny details about an object's texture.

Figure 1.5: The dashboard of a Model 3 as presented by Tesla Inc., 2016. It does not include any physical controls, which leads to a lack of haptic feedback and thus requires drivers to look away from the street when operating the controls.

Touch screens lack haptic feedback in comparison to physical interfaces.

Most modern touch screens consist of a glass surface with a sensor and a display beneath it. Although we feel the glass surface, we cannot use our tactile senses to distinguish between the displayed interface elements. When designers include a touchscreen with virtual controllers instead of physical ones, they omit our everyday tactile cues from the interaction. Thus, the interaction is less rich, and the usability decreases. Additionally, a physical controller is always visible. This is not necessarily the case for virtual controllers since the touchscreen can display menus and submenus on top of each other. Often, controls are hidden behind additional virtual button presses.

Lack of haptic feedback can lead to issues when users interact with screens. E.g., when they have to divide their attention between safety-relevant tasks.

In some cases, this trend even created potentially dangerous situations. Tesla, for example, famously removed all buttons and knobs from dashboards in their cars. Figure 1.5 shows the Model 3's dashboard head on. Except for two four-way directional crosses at the steering wheel and two handles behind it, there are no physical controllers at the dashboard. Instead, controls for multimedia, volume, airflow, and temperature can only be operated using a touch screen located in the front center. Only using the touch screen drivers can access even safety-relevant controls like the always-on lights setting and the wiper interval speed. Without tactile cues, when a user interacts with it, they have to look at the screen to see whether their input is recognized correctly and in which state the controlled feature is. During this time, they cannot look at the street, which has already led to accidents in the past. In a recent case, the Oberlandesgericht in Karlsruhe judged that the touchscreen inside the Tesla Model 3 is considered a technical device that drivers are only allowed to operate briefly, even if safety-relevant features as the wiper speed are located there (1 Rb 36 Ss 832/19 March 27, 2020, *Touchscreen, elektronisches Gerät, Tesla - 1 Rb 36 Ss 832/19* 2020).

In Germany, drivers are only allowed to operate a build-in touchscreen for “brief” moments.

In his “Brief Rant on the Future of Interaction Design”, Bret VictorVictor, 2011 also addressed these issues. While he did not offer solutions, he made clear that it is not the multitouch technology in general that he condemns but the lack of haptics in the interaction.

1.2 Tangible User Interfaces

Tangible User Interfaces (TUIs) combine the richness and interactiveness of haptics with a screen’s versatility. Early TUIs usually were made for tabletops, big horizontal screens that can detect user input, and physical objects that rest on them. However, with the growing amount of Augmented and Virtual Reality devices, tangible interaction also plays a more important role in midair controls. Tangible objects can reenable users to feel the controls they are operating or even literally represent a virtual object.

TUIs combine the richness of tactile interaction with the flexibility of screens.

Since Fitzmaurice et al., 1995 presented Bricks, many researchers have evaluated tangible interaction compared to touch. Fitzmaurice, W. Buxton, 1997 showed that bimanual graspable controllers are more accurate than, e.g., a mouse. Comparing multitouch, mouse, and tangible interaction, Tuddenham et al., 2010 were able to confirm these findings, showing that all three conditions had significantly different manipulation times. Their tangible controllers performed best, while the touch condition performed worst. Weiss

Since their introduction, TUIs have been shown to increase users’ performance, error rates, and applications usability.

et al., 2009a showed that tangible controllers can be operated eyes free, which means that users can focus on their task while operating a controller without looking at it. This finding and Voelker et al., 2015b who showed this effect for tangible knobs help explain why pure touch interaction can be detrimental, and sometimes, e.g., inside a car, even be dangerous. Hancock et al., 2009 let users perform rotation tasks and expressed the potential of tangibles as indirect controllers.

Previous work in tangible research often focused on basic performance of single users.

However, all these studies focused on the basic perception and motor performance of single users. This thesis will focus on evaluating tangibles and tangible interaction beyond task completion times and error rates. We evaluate how tangibles affect users' collaboration, how they affect human behavior towards each other, and how we change our way of thinking when we use tools.

1.3 Contributions

This thesis integrates into existing tangible research by answering the following questions:

As this thesis aims to evaluate tangible interaction beyond their usability features, we present an overview of how tangible interaction can be designed, implemented, described, and evaluated. We take a detailed look at related work in each chapter individually since the presented research differs quite a bit.

How to create your own tangibles?

Chapter 2 "Making Tangibles for Interactive Tabletops: TABULA Tangibles" explains how researchers can create their own tangibles for capacitive tabletops and presents a technical evaluation of the PERCs tangibles as initially described by Voelker et al., 2015a.

How to create applications that support tangible interaction?

Following up, Chapter 3 "Creating Tangible Applications: MultitouchKit" presents a software framework that can be used to implement tangible applications with Apple's software APIs. We used this framework for most of our research projects that include tangibles; it contains logging mechanisms to log interaction data as well as technical logging for the tangibles and the application.

Chapter 4 "The Design Space of Tangible Interaction" introduces the *Design Space of Off- and On-Surface Tangible Interaction*. This design space allows designers and researchers to collect existing tangible interaction designs and identify potential new designs by connecting unexplored areas in this space. Additionally, we present a usability study for a tangible design that combines on-tabletop and midair interaction to manipulate 3D objects in this chapter.

How to compare different tangible designs?

What if we combine on table and midair interaction?

Chapter 5 "Tangible Interaction Beyond Usability" describes a series of user studies regarding tangibles and tangible interaction in higher cognitive processes like awareness in multi-user scenarios and the construal level, which means the abstractness of thinking users have when manipulating a tangible tool.

What benefits do tangibles have in multi-user scenarios? And are there effects on higher cognitive processes?

1.4 Structure

The remainder of this thesis is structured as follows:

- Chapter 2 "Making Tangibles for Interactive Tabletops: TABULA Tangibles" describes how one can create tangibles that work on interactive tabletops with a capacitive touch sensor.
- Chapter 3 "Creating Tangible Applications: MultitouchKit" presents the MultitouchKit for Swift, a framework that allows researchers and developers to create multitouch and tangible applications for macOS with an attached multitouch device.
- Chapter 4 "The Design Space of Tangible Interaction" describes a taxonomy that creates a space for tangible interaction on tabletops as well as in midair. This design space allows to organize existing research in tangible interaction as well as creating new designs by combining unexplored areas in the space.
- Chapter 5 "Tangible Interaction Beyond Usability" describes a series of studies that we conducted on tangible interaction beyond task completion times. We

evaluated users' construal level, motivation, creative problem solving, and awareness in multi-user scenarios.

- Chapter 6 "Summary and future work" collects the results from the different areas presented in this thesis and discuss further research areas in tangible interaction.

Chapter 2

Making Tangibles for Interactive Tabletops: TABULA Tangibles

As described earlier, many researchers have proven tangible interaction to be beneficial by many researchers. Since tangibles are still not available easily to buy, researchers have been exploring different ways to create tangibles for interactive surfaces. This chapter will discuss a set of application examples that show in what a wide variety of applications designers can utilize tangibles. We will derive a set of requirements for tabletop systems that include tangibles and discuss how different approaches fulfill these. Additionally, we will describe and evaluate a tangible design for capacitive touchscreens.

In this chapter, we'll describe the two broad cathegories tangibles can be separated into.

Publications: The work in this chapter is a collaboration with Simon Voelker, Kjell Ivar Øvergård, Chat Wacharamanotham, Matthias Ehlenz, Thiemo Leonhard, Wiktoria Wilkowska, and Ulrik Schroeder. The author is one of the main authors of the papers; he was also responsible for developing parts of the hardware, writing parts of the software, designing the experiments, and analyzing data from the experiments. Part of this work was first published as a paper at the UIST 2015 conference by Voelker et al., 2015a, as a Demo at the ITS conference 2015 by Cherek et al., 2015, and on the Koli Calling conference 2018 by Ehlenz et al., 2018. Several sections of this chapter are taken from these publications. Furthermore, part of this work was created for the Tabula Project, 2016.

PERCs can implement all kinds of tangibles.

Our persistently trackable tangibles on capacitive multi-touch displays are tangibles tracked by modern touch-screens of all sizes. The technology inside our Persistently Trackable Tangibles on Capacitive Multi-Touch Displays (PERCs) can be implemented in many different types of tangibles.

2.1 Tangible Applications

Tangibles can be applied in many different scenarios.

Tangibles are applied in many different scenarios. These scenarios reach from gaming to learning and simulation to programming. Tangibles can be controllers for certain events in a virtual environment or represent meeples on boardgames. There are two main approaches to how tangibles are included in an application.

2.1.1 Tangibles as Tools

Physical controls for virtual actions are tangible controllers or tools.

The first approach is motivated by touch displays' inherent lack of haptic feedback. As Victor, 2011 stated, the only action our fingers perform on touchscreens is sliding, although hands can perform way more complicated actions. Researchers have tried to address this issue by including *Tangibles as Tools* into multitouch applications. And with great success:

Tangible controllers outperform touch as well as relative input device like a mouse in speed and accuracy.

Fitzmaurice, W. Buxton, 1997 have shown that tangible controllers outperform, for example, a mouse in target acquisition tasks. They made the distinction between space multiplexed devices, such as task-specific controllers like a car's brake, steering wheel, gear shift, and time-multiplexed devices like a mouse, which can control everything with a single device by switching the focus. Weiss et al., 2009a showed that a physical knob requires less time in video navigation tasks than pure touch interaction. They stated that virtual knobs need visual attention and thus require the user to switch their focus between the virtual input and the video output. In contrast to that, users could grab the SLAP Knob and feel the input removing the need to

Figure 2.1: A learning application that utilizes *Tangibles as Tools*. Students can learn chemical formulas, animal classifications, regular expressions in computer science, and the classification of german words with this application. Students use a TABULA-Tangible, as presented in Section 2.6.1 to collect objects into the bins at the sides. The tangibles give haptic, auditory, and visual feedback on whether the action was correct or not. Tabula Project, 2016

look back and forth, leading to faster completion times and fewer overshoots in the navigation task. Voelker et al., 2015b revisited rotary knobs on capacitive screens and showed that users significantly outperformed different virtual rotary input widgets. Users were asked to perform a rotary target acquisition task with either a tangible knob, puck, or one- and two-finger virtual inputs. Hancock et al., 2009 evaluated tangibles accuracy and effectiveness for 2D and 3D manipulation tasks and found tangibles to benefit, especially the 2D tasks. For 3D manipulation, users had difficulties because they could not ”reach into the display”.

Tangible knobs also outperform virtual rotary controls in speed and accuracy.

Figure 2.1 shows an application that is used to teach students classifications of different objects. This application was developed in the Tabula Project, 2016. The Tabula Project, 2016 focussed on using tangibles to convey abstract information in a more graspable way, which means a tangible way. Students of different age groups can learn to

We applied tangibles as tools in learning applications in the Tabula Project, 2016 classify german words, chemical formulas, animals, and regular expressions as they are taught in introductory computer science classes with their applications. Using this application, we were able to show in Ehlenz et al., 2018 that personality traits do impact interaction behavior, especially when it comes down to a user's reaction to feedback on individual interactions. There were significant differences in relative times to the next interaction, depending on participants' personality traits when interacting in a pure virtual setting with global announcements of mistakes. This shows that feedback has a definite impact on the learners' performance, especially in groups.

We found introverted players to participate less when errors were announced globally.

In the Tabula Project, 2016, we added tangible controllers to collect the various objects allowing for personalized feedback even silently through a tap into users' hands. To enable such individual feedback levels, the learning-system needs to detect which user is using which tangible and distinguish the tangibles from each other. Additionally, the system needs ways to communicate the feedback to each tangible individually.

Tangible controllers are able to give personalized haptic feedback and thus integrate all learners.

2.1.2 Tangibles as Domain Objects

The second approach to include tangibles is to let them represent a virtual object of the application's domain. Underkoffler, Ishii, 1999's URP is an example of this approach. The tangibles in this application represent buildings that cast a virtual shadow. When a tangible represents a domain object, the virtual object represented by a tangible is only present when a user places the tangible on the screen.

Tangibles also naturally fit as domain objects.

Figure 2.2 shows a sample gaming scenario using tangibles. The game is an adaptation of a tabletop board game. Two players each control a fleet of space ships; their goal is to defeat the opposing player's fleet. Each ship has specific movement patterns, weapons ranges, and talents and is represented by a miniature that acts as a tangible. The interactive table provides a more immersive experience to the user. For example, if a spaceship is shooting at another ship, the table can display this with a nice particle

Increasing players immersion into games they can be space ships, hockey mallets or other domain specific objects.

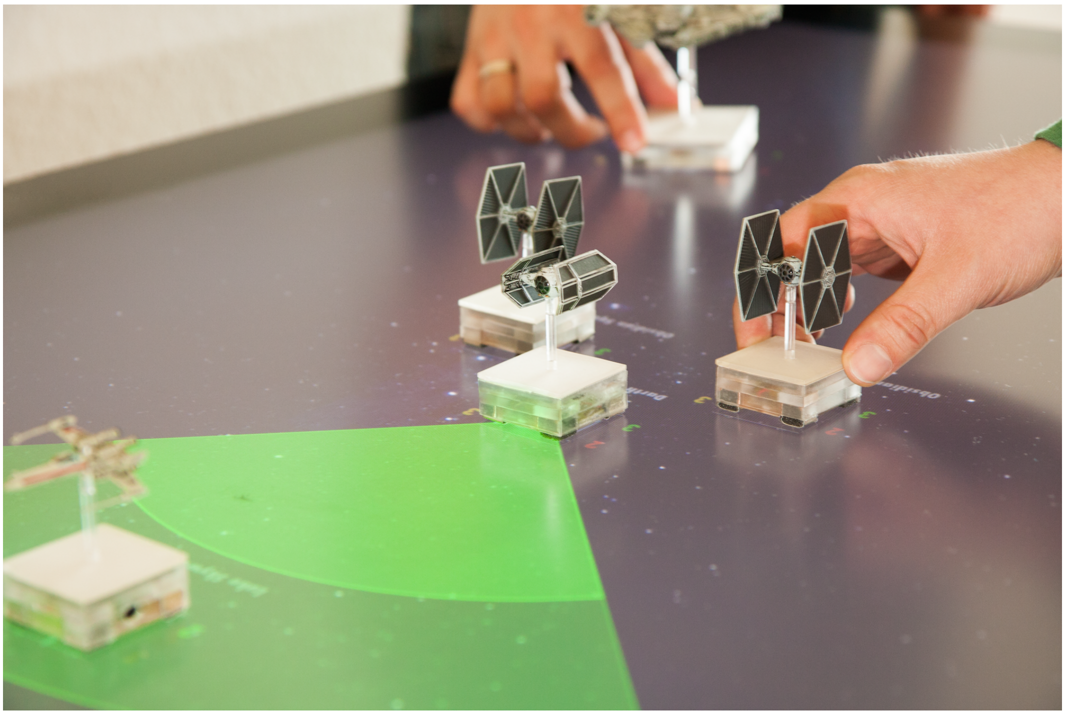

Figure 2.2: PERC-tangibles are used as space ships in an interactive board game on capacitive touch screens. The display increases the immersion by displaying the current weapon range. It can also display movement patterns and ship's stats.

effect. For the system to support this kind of game, for example, by automatically determining and displaying if a ship's weapon can reach an opponent, the tabletop has to identify each individual tangible and continually determine its position and orientation on the touch surface with high accuracy. Furthermore, ships only move one at a time; therefore, static tangibles still need to be detected reliably.

To support this interaction, tangibles need to be detected constantly, even if not touched by a user.

Tangibles are also used in more dynamic settings, Figure 2.3 shows a game of air hockey. In this game, players bounce a virtual puck back and forth using tangible mallets. They try to score a goal on the opponent's side, hitting the puck rapidly and blocking the opponent's strikes with their mallets. For this application, high update rates for the tangibles position is crucial for a good game experience.

Tangibles can bring haptics into a virtual hockey game.

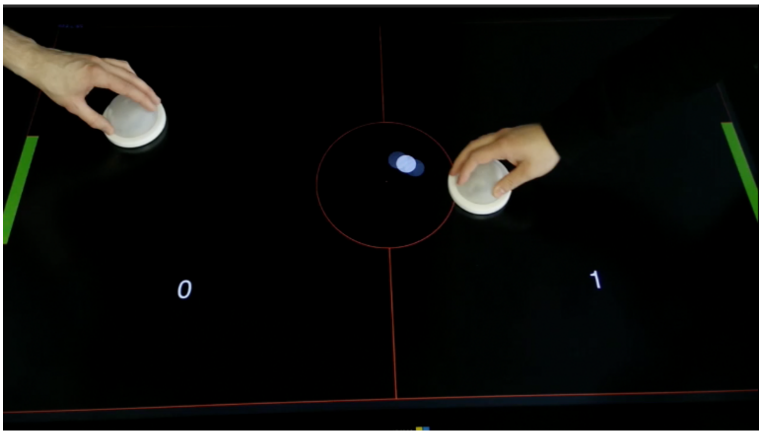

Figure 2.3: A virtual air hockey game with physical mallets. The tangible mallets are detected by the screen and thus can control the action displayed.

2.1.3 Requirements for Tangibles on Tabletops

To fulfill their potential, a tangible tracking system needs to meet certain requirements:

The detection needs to be accurate.

The system must be able to differentiate all tangibles reliably.

The detection needs to be in real-time.

Whether tangibles are included as a tool or as a domain object, both applications require specific properties of the tangible as well as the tracking system. We motivate these requirements with the examples mentioned above; however, we think these requirements also apply to all other scenarios someone would want to apply tangible interaction. If the tangible is used as a tool, it is essential that users' input is accurately detected and the interface updates precisely. Otherwise, human hands' and fingers' precise input can perform would be lost to a lousy tracking mechanism. The system also needs to distinguish each tangible from another and needs to be able to communicate certain events to the tangible. For example, personalized learning feedback as implemented in the Tabula Project, 2016 would lose its benefits if the system cannot address a single tangible reliably. If the tangible is used as a domain object, the detection needs to be fast since noticeable delays would decrease the immersion in games like air hockey. And finally, the tabletop also needs to know at all times whether a tangible is present or not, no matter if the tangible is currently touched or rests on the surface. Otherwise, a tabletop game would not be possible since the users can not contineusly touch all ships of their virtual space fleet.

The previously mentioned scenarios motivate a number of requirements for a system using tabletop tangibles:

1. At any time, the system has to be able to determine which tangibles are currently placed on the interactive surface, whether they are being touched or not.
2. Each tangible has to be uniquely identifiable.
3. The system needs to be able to detect the exact position and orientation of each tangible.
4. Position and orientation updates of fast-moving tangibles should be detected without noticeable delays.
5. The system needs to access internal feedback mechanisms inside each tangible.

In the following we'll describe PERCs, which fulfill all five requirements

In the remainder of this chapter, we will discuss which approaches to implement tangibles on tabletops fulfill which requirements and present the PERCs tangibles originally presented by Voelker et al., 2015a and Cherek et al., 2015. We will also describe how the Tabula Project, 2016 built up on PERCs and present the latest version of tangibles for capacitive multitouch displays.

2.2 Capacitive Touch Screens

Tangibles for capacitive touchscreens often use conductive material to "transport" the touch to the screen.

To detect a touch, capacitive touch sensors create an electric field above their surface. If a human finger enters this field, the finger's high capacitance influences the sensor's field. The sensor picks up this change in capacitance and interprets it as a touch. Tangibles, such as TUIC by Yu et al., 2011, or Capstones by Chan et al., 2012, often use a conductive material connecting their outside to the bottom. Yu et al. created, for example, tangible security tokens that open a folder with secured files only if the correct tangible is present. And Chan et al. created a tangible game of checkers, where the conductive touch is even connected through a stack of tangibles. The conductive material transports a touch underneath the tangible that if a user touches

However, these tangibles are only detectable when touched by a user.

them, their capacitance is increased, and a touch is detected below the tangible. Unfortunately, this also means that the touch disappears as soon as the user lets go of the tangible. This also happens if the tangible is left on the surface, which can lead to discrepancies between the state of the tangible being *On-Surface*, and the state of the detection detecting the tangible to be *Off-Surface*.

Therefore, these tangibles violate our requirement number 1.

PUCs tangibles do not need to be touched.

This issue makes it impossible to distinguish if a tangible has been picked up and removed from the touchscreen or whether the user has just let go of the tangible, leaving it on the touch screen. Additionally, if a user flicks a tangible across the surface, the system has no way of tracking its location. Voelker et al., 2013 addressed these issues by introducing PUCs. PUCs ground themselves through currently inactive sensor electrodes of the capacitive touch screen. Thereby PUCs increase their capacitance beyond the detection threshold. This allows the sensor to detect them, even if the user lets go of the tangible. PUCs can be consistently tracked, even if they are flicked across the surface.

Adaptive filters inside the touch detection hardware, however, remove PUCs after a couple of seconds.

However, most touch screens have adaptive filtering mechanisms that remove touches that have been stationary for too long. This filter is applied to remove interferences and improve users' experience when interacting with such a screen. Especially touches that only create a small change in the field are filtered out after a couple of seconds. Therefore, touches by stationary, untouched PUC tangibles will disappear after around 5–30 seconds, depending on the touch screen controller. This again leads to the problem that we cannot determine from the touch screen output if a tangible was actively removed from the table or merely filtered out by the system.

Different footprints allow the system to distinguish a certain number of PUCs.

To distinguish different PUCs, Voelker et al., 2013 suggested different footprints of the touches created by the tangibles. These footprints distinguish a certain number of tangibles; a software framework can search through all existing touches and identify each pattern. A pattern of three touchpoints is sufficient to identify a tangible's position and orientation. By varying the length of the hypothenuse and angles inside the triangle, different patterns are created.

Unfortunately, in addition to the time-based filtering, touch sensors optimized for human touch also require a touch to be in a specific size range and a minimum distance between touches. This reduces the amount of touch-pattern that can be utilized to distinguish tangibles from each other.

PERCs overcome PUCs' problems with an integrated antenna.

We propose PERC tangibles, an extension of the PUCs concept. PERCs have added active components to the tangibles. They can sense themselves whether they are on a capacitive screen or not. These additional components overcome the limitations of PUCs. An integrated antenna in each PERC detects the signal emitted by the capacitive touch sensor. This allows the tangible to determine whether it is currently placed on a capacitive touch surface or not, even when the touch system filters out its touches. Since PERCs use Bluetooth to communicate this information to our system, each has its own unique ID, which is independent of the tangibles touch pattern. With the sensor electronics being contained in the tangible, PERCs do not require specially designed touch screens. They can be used on many different commercially available devices, including table-sized capacitive multi-touch displays, smartphones, and tablets.

A Bluetooth connection gives each tangible a UUID.

2.3 Tangible Object Detection

This section discusses several ways to create tangibles.

Since Fitzmaurice et al., 1995 introduced the idea, there are several different approaches how to create tangible objects for different multitouch sensors. This section presents an overview of several approaches and describes which system fulfills which of our five requirements.

Before capactitive screens were widely available, vision based TUIs were most prominent.

For a long time, vision-based tracking was the most popular approach. Underkoffler, Ishii, 1999's URP detects a specific dot pattern on top of each tangible building. SLAP-Widgets by Weiss et al., 2009a uses diffuse illumination with reflective markers attached to the bottom to detect each tangible. ReacTable's tangibles as presented by Jordà et al., 2007 have fiducial markers attached, tracked by a camera below the table. The vision-based approach fulfills requirements 1 through 4. However, the presented approaches do not include a way to give feedback inside the tangible. Additionally, vision-based interactive surfaces are error-prone to external lighting conditions like bright lightbulbs or the sun.

To overcome the need of a camera many researchers tried to create tangibles with different tracking techniques.

Because of this, several projects have explored alternative tracking technologies: Audiopad Patten et al., 2002 attached two radio frequency tags to each tangible to determine its position and orientation. Bricks Fitzmaurice et al., 1995 use existing input devices as tangibles. Sensetable Patten et al., 2001 uses electromagnetic sensing to track tangibles. All of the above systems fulfill the first two requirements, but not requirements 3, 4, and 5, since they cannot detect their tangibles' exact position and orientation. Additionally, Bricks and Sensetable are limited in the number of tangibles that they detect simultaneously. Gausstones Liang et al., 2014 track magnetic tangibles using a hall sensor grid below the touch display. Since the small magnetic tangibles can only be detected over a very short range, this technique only works in combination with thin touch screens.

Only after the success of capacitive touch detection, researchers started to create tangibles for these screens.

As described earlier, tangibles on capacitive screens can usually only be detected while the user is touching them. On capacitive screens Rekimoto, 2002's SmartSkin showed how tangibles can be tracked on a custom made capacitive touch display if a user touches them. However, this only works while a user is touching the tangible. CapWidgets by Kratz et al., 2011 applied this concept to commercially available capacitive touch displays such as the Apple iPad. In an update to this, Chan et al., 2012's Capstones extended this concept allowing users to stack tangibles onto each other.

TUIC tangibles have a build-in frequency that enables and disables the touchpoints under the tangibles.

To increase the number of distinguishable tangibles, Yu et al., 2011 created active tangibles that are uniquely identified by enabling and disabling the touchpoints with a specific time-based pattern. With this approach, tangibles are identified by their own unique marker frequency. All these systems violate requirement 1 since they are only detected if a user touches them, and so the system cannot determine if a tangible was removed from the touch screen or if a user just stopped touching it.

PUCs Voelker et al., 2013 solved this problem for moving tangibles by using the capacitive touch screen's inactive sensor parts to ground the tangibles marker on the currently active part of the capacitive screen. This allows detecting PUCs tangibles on commercially available capacitive touch screens, even when users do not touch the tangible. For stationary PUCs, however, capacitive screens filter the tangible's artificial touchpoints after some time. This again violates requirement 1 since the system cannot determine whether a filtered tangible is still on the surface.

As described earlier, PUCs addressed many issues for tangibles on capacitive screens.

PERCs' goal was to develop tangibles for capacitive touch screens that fulfill the first four requirements and allow new interaction concepts for tangibles user interfaces. Since PERCs introduce a Bluetooth connection between the system and the tangibles, they also allow developers to add additional feedback and input inside the tangible. Thus, with additional components, PERCs can also fulfill requirement 5.

With PERCs, we aimed to overcome PUCs' remaining issues.

2.4 PERC Tangibles

This section provides a technical overview of the theory behind PERCs and our prototype construction, evaluates detection rates, timing performance, and positional and angular accuracy for PERCs on a variety of unmodified, commercially available multi-touch devices. PERCs are also the base design for all tangibles that we developed for the Tabula Project, 2016. In addition to the sensors added by PERCs, the TABULA-Tangibles can detect button input and give multimodal feedback.

This section describes PERCs, which also are the basis for our Tabula tangibles.

PERCs utilize the marker concept that is also implemented by Voelker et al., 2013's PUCs. The markers allow for a precise position and orientation detection. However, it has two weaknesses that we need to address: Firstly, without modifications, PERCs would, just like PUCs markers, suffer from the previously mentioned issue that the capacitive touch screen eventually filters out stationary touchpoints. Therefore, the system can not determine whether a user removed a stationary tangible or if the screen filtered out its touch-

PERCs utilize the marker pattern approach from PUCs.

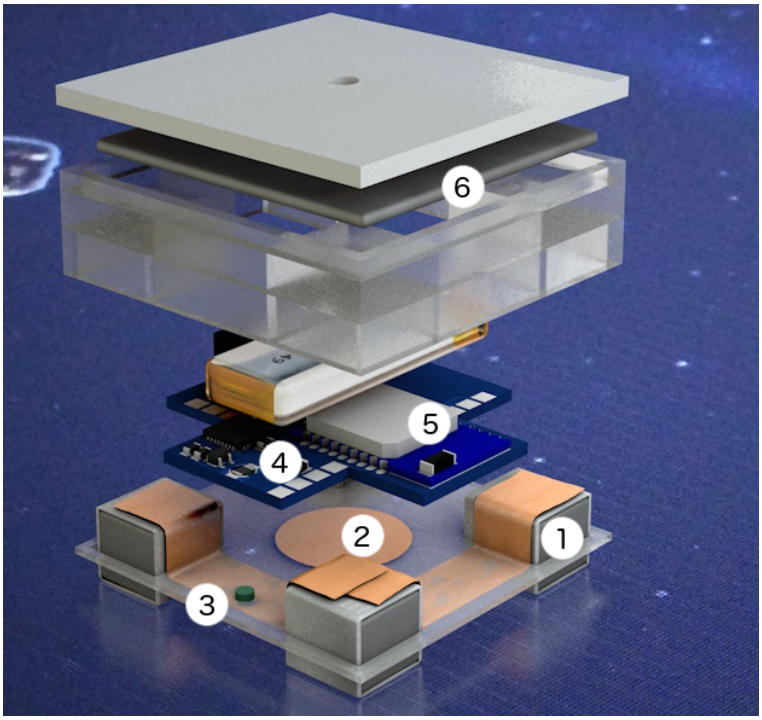

Figure 2.4: A graphic showing the six main components of a PERC tangible: (1) the marker pattern to detect position and orientation, (2) the field sensor to overcome the filter issue, (3) light sensor to triangulate rotation ambiguities, (4) the micro controller, (5) the Bluetooth antenna, and (6) a lead plate for additional weight.

PERCs fulfill all 5 requirements, even though stationary touchpoints are filtered out eventually.

points. Fortunately, only stationary tangibles are filtered out. As soon as the tangible moves across the surface, all touchpoints are immediately detected again. However, this behavior still breaks requirement 1. Additionally, PUCs do not fulfill requirement 2 since their geometric touch pattern identifies each PUC. That limits the number of uniquely identifiable tangibles by the size of their footprint and the number of different marker constellations.

A connection from the tangible to the system fulfills requirement 2.

PERC tangibles solve these problems by sensing the surface of a capacitive touch screen. They communicate changes on the sensor via Bluetooth Low Energy (BLE) to the system. With this information, PERCs can fulfill both requirements: PERCs communicate that they are still on the touch surface even when the touches have been already filtered out, satisfying requirement 1. Each PERC can also be identified through its unique BLE UUID, satisfying requirement 2.

A touchscreen sensor fulfills requirement 1.

2.4.1 Technical Implementation

Figure 2.4 shows the main components a PERC tangible consists of. First, a PUCs marker pattern as described by Voelker et al., 2013. Second, the newly introduced field sensor, which senses the capacitive screen. Third, a light sensor that helps to triangulate the last remaining ambiguities. In addition to these main components, each PERC includes a microcontroller, a BLE chip, a battery, and a weight on top of the tangible. This increases the tangible's touch detection.

The main components of PERCs are: field sensor, touch pattern, bluetooth antenna, and a light sensor.

2.4.2 Marker Pattern

The marker pattern consists of three 8x8 mm pads connected via conductive copper foil (Figure 2.4). Each pad's size is roughly the size of a fingertip since capacitive screens try to sense human touch. Each pad creates a touchpoint that is detected by the capacitive touch screen. In later designs, we increased and decreased the size of our markers. We learned that the capacitive sensor rejects too big pads, and too small pads do not create a strong enough capacitive change to be detected by the screen. For the pads, we use a soft conductive weave that is usually used as EMS shielding. This benefits the pads by not creating scratches on the touch surface and allowing them to remain in good contact with the surface.

The marker pattern enables the system to detect a tangible's position and orientation.

2.4.3 Field Sensor

The field sensor is the part of a PERC tangible that recognizes when a user places the tangible on a touch surface at any given time or not. Each capacitive touch screen creates an electric field above the surface. Figure 2.5 shows

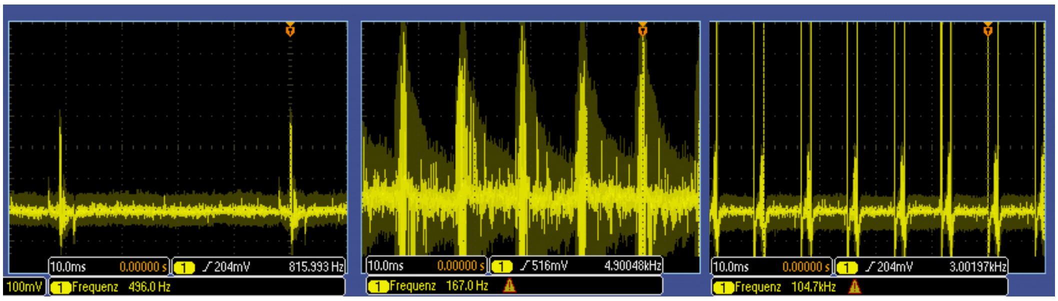

Figure 2.5: Touch detection signals as they are picked up by the field sensor. Though the voltage is different, they all share a regularity in the probing signal. From left to right these signals are measured on an iPad 4, a 3M screen, and a Microsoft 55″ capacitive screen.

touch detection signals from several commercially available touchscreens. We found that all signals exhibit a regular pattern of strong peaks at a fixed frequency, which can be easily distinguished from the noise component of the signal. The field sensor is an antenna plus an operational amplifier that pics up this signature. If the sensed field strength is above the threshold, the tangible knows that it is placed on a capacitive touch screen. We can set the threshold voltage to fit the touch screen's signal. This way, our implementation detects a screen at a distance of about 1 mm.

Touchscreens exhibit an electromagnetic field in a regular pattern.

We pick this signal up and send a status update to the system.

Whenever the field sensor detects the presence of a capacitive touch surface, the tangible sends an *On-Surface* event via BLE to the system. In about 99% of these events, the *On-Surface* event and the touchpoints created by the marker pattern arrive within 144 ms of each other. Therefore, we set the time window to link a BLE UUID and a marker pattern to 150 ms. This eliminates most false-negative detections. However, false-positive links are still possible if multiple PERCs are set down within this 150 ms time window. We resolve the resulting ambiguity between those tangibles with a light sensor.

Only if the tangible sends a *Off-Surface* event, it is considered removed from the table. If touches disappear due to the filtering algorithm, the system will ignore this change and maintain the position of the tangible's virtual repre-

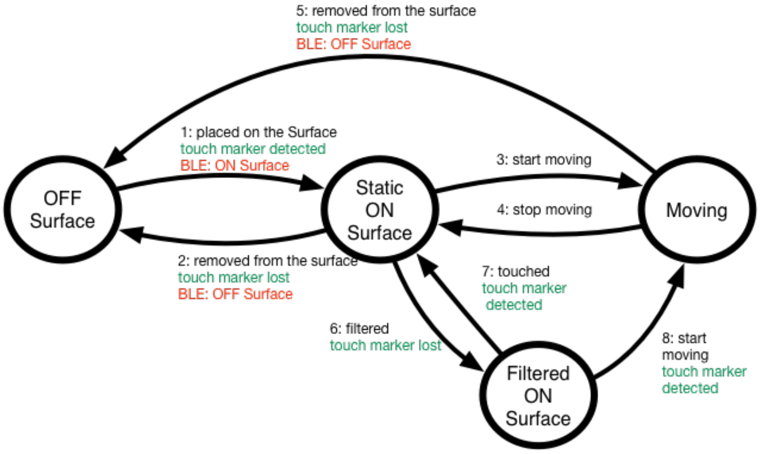

Figure 2.6: This state diagram shows the different events and states in the lifecycle of tangible detection for PERCs. Between (1) placing the tangible, (3) moving it, (4) leaving it alone, and (2/5) removing it, a tangible is always correctly detected by the system, even when the touches are filtered out (6 - 8).

sentation. Figure 2.6 shows a state diagram for the tangible detection with PERCs. First, the tangible is placed on the table, the marker pattern is detected, and the field sensor sends a *On-Surface* event. After this, the tangible is either moved or removed again; if it is removed, the sensor sends a *Off-Surface* event, and the digital representation disappears. Suppose the tangible is left alone on the table. In that case, however, the sensor does still pick up the touch detection signal and thus does not send the *Off-Surface* event, allowing the system to distinguish between removing the tangible and leaving it standing without touching it.

even when left alone, PERCs can reliably detect their *On-Screen* state

The field sensor is a straightforward circuit that theoretically could be trigged by other electrical devices that emit a signal with strong peaks at a similar frequency as a touch screen. However, this approach is relatively robust against stray electric fields for two reasons:

The field sensor can be false positive, however, this is unlikely in this setting.

1. A tangible is only detected if the *On-Screen* event from the field sensor and the marker pattern's touchpoints occur in a short time window.

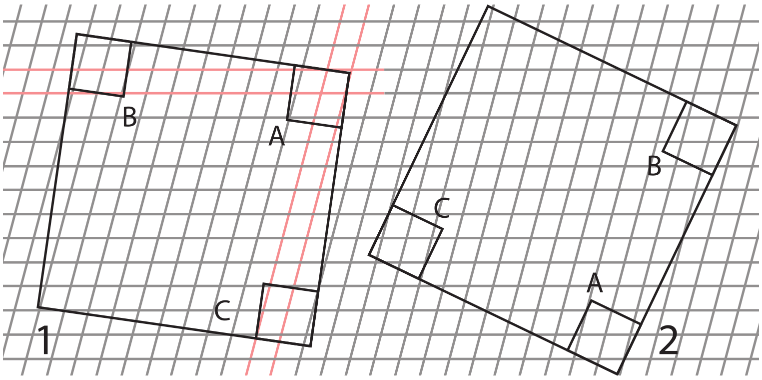

Figure 2.7: PERCs tangibles on the transmitter and receiver electrodes of the Microsoft 55″ capacitive screen. For (1), the marker a is not detectable due to the alignment of the electrodes. In (2), all markers are detected reliably

2. Since electric fields are strongly attenuated over distances, and it would require a powerful electric field to trigger the field sensor from a distance. Electric fields of this strength usually do not exist in an environment where touch screens are used.

For certain arrangements, 3 markers are not enough to detect a tangibles orientation.

While the combination of our marker pattern and the field sensor lets the system reliably detect which tangibles are on the surface, we found that if a PERC tangible is placed on the touch surface at certain angles, only two of the three marker pads are detected. The reason for this is the combination of the way how PUCs markers are detected and the geometric alignment of transmitter and receiver electrodes. These are on top of the LCD of the capacitive touch screen and create the touch surface's electrical field. Since not all screens use the same arrangement of transmitter and receiver electrodes, the angle at which this happens differs from screen to screen.

The orientation can then only be decided up to a 180° ambiguity.

We evaluated PERCs on a Microsoft 55″ capacitive screen, which has transmitter and receiver electrodes at an angle of about 75°. Whenever a tangible is oriented as shown in Figure 2.7, where the corner pad A is located at the crossing of two electrodes also covered by pads B and C, pad A does not create a touchpoint for the marker detection. Since pads

B and C are still detected reliably, the system can detect the tangible's position. However, the orientation can only be detected with a modulo a 180° orientation ambiguity. Similar to the situation with multiple tangibles being placed on the capacitive touch surface simultaneously, these ambiguities can be resolved using the light sensor.

On the 55" screen transmitter and receiver notes are aligned at an angle of 15° degree.

The exact angles at which pad A is not detected depend on the geometric configuration of the electrodes in the touch surface. On many common capacitive touch screens, such as the iPad, 3M screens, and Acer screens, the electrodes are aligned orthogonally. Therefore, for our marker setup, angles around full 90° rotations are critical. On other devices, such as the Microsoft 55″ capacitive touch screen, one set of the electrodes is rotated by 15°, so the critical angles for our marker setup are around 75°, 165°, 255°, and 345°.

Depending on the orientation of receiver and transmitter electrodes, the marker pattern can be optimised.

This problem would be avoided if the pads were arranged in an equilateral triangle, as recommend by Voelker et al., 2013. However, such a pad arrangement does not allow to unambiguously recognize the tangible orientation, even if all three pads are detected. Therefore, we decided to use the marker pattern as shown in Figure 2.7.

In an eqilateral triangle the markers would be detected, but orientation is still unclear.

2.4.4 Light Sensor

We added the light sensor to resolve the two remaining ambiguities. The first is the UUID assignment for multiple PERCs set on the surface simultaneously. The second is the orientation ambiguity when only two touchpoints are recognized. The light sensor faces downwards towards the LCD screen. We did not place the light sensor in the tangible's center between the pads B and C but instead off one side of the diagonal.

A light sensor facing the surface can help to resolve the remaining ambiguities.

The offset position ensures that we can determine the tangible's orientation. Whenever the system receives an *On-Screen* event but only two touches, the system sends a visual ping to one of these possible light sensor locations. The ping is a quick change between bright and dark underneath the position of the light sensor. If the light sensor

A visual ping underneath the tangibles resolves the orientation ambiguity.

A single ping suffices since there are only two orientations possible.

recognizes the ping, it sends this information via BLE, and the system knows the tangible's orientation. Consequently, if the light sensor does not detect the visual ping, it must be located on the other side of the diagonal between the pads B and C. Either way, the system can recover the orientation of the tangible. This approach is similar to how Touchbugs by Nowacka et al., 2013 work.

The light sensor is only needed when users place the tangible at specific angles.

This process is only necessary immediately after setting a tangible down on the capacitive touch surface at one of the four critical angles. Only in these angles and only immediately after setting the tangible down is Pad A not detected. As soon as the user moves the tangible, all three pads are detected reliably. In this case, the system can determine the exact orientation without the help of the light sensor. Our experiments show that the time between the moment in time where the system receives the *On-Screen* event and time the tangible is correctively detected is increased by about 100 ms while using the light sensor (see Figure 2.10).

The light sensor fallback introduces $\sim 100ms$ delay.

The light sensor can also distinguish multiple tangibles if needed.

Apart from resolving the orientation ambiguity, the light sensor also serves to tell apart multiple tangibles if they were placed on the capacitive touch surface within the 150 ms time window between receiving the *On-Screen* event via BLE and detecting the touches of the tangible. In this case, the system sends a sequence of visual pings: One ping to the location of the light sensor of each tangible in question. Then, the sequence of BLE answers resolves the UUID assignment ambiguities.

2.4.5 Components and Power Consumption

PERCs' parts are easily available and cheap.

A significant benefit of PERCs is that the components required to build them are relatively cheap. For the presented implementation, we used an MSP430G2553 microcontroller, a BLE112 Bluetooth module, a TEMD6200FX01 light sensor, and a Renata LIPO battery (3.7 V, 175 mAh). All these parts are available in urban electronic shops. The total cost of all parts, including a casing and the marker pads, is less than €25.

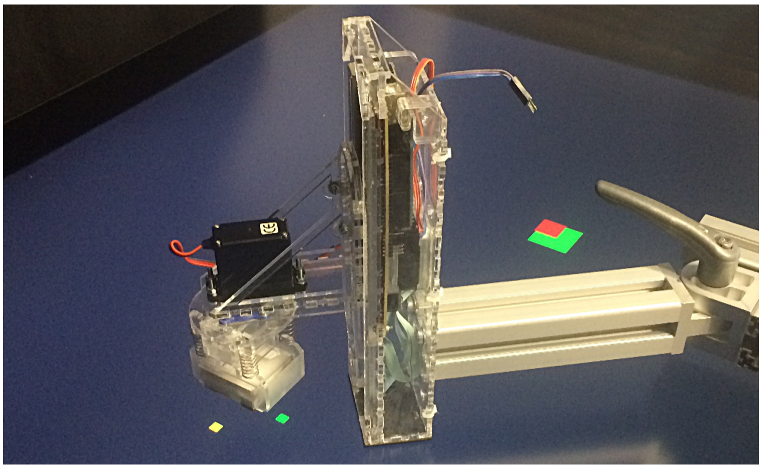

Figure 2.8: This robot performed set and lift operations with our PERC tangibles.

PERCs' energy consumption is mainly limited to the BLE module's needs.

Despite the active electronics, PERCs have very low energy consumption; one battery charge yields approximately 60 hours of continuous use. This is enough for a day's use, even if we add feedback components like a vibration motor or internal LEDs to the tangibles.

2.5 Evaluation

PERCs fulfill all requirements but the 5th, for this we have to add additional sensors and actuators inside the tangibles.

As explained earlier, PERCs fulfill our requirements 1 and 2. They are reliably detected even when not touched and are uniquely identifiable. PERCs fulfill requirement 1 since the tangibles themselves report their *On-Surface* or *Off-Surface* state via BLE. They fulfill requirement 2 since BLE gives each tangible a uniquely identifiable number, and the light sensor resolves any ambiguities regarding the link between the touch pattern and the UUID. Requirement 5 is not fulfilled in the version of PERCs as presented in this chapter. However, since PERCs and the system communicate via a bidirectional connection, we can add internal feedback mechanisms and additional sensors or buttons to each tangible. We did this for the tangibles we used for the Tabula Project, 2016.

We conducted a systematic evaluation regarding the performance for requirements 3 and 4.

To evaluate PERCs performance in requirements 3 and 4, we performed a series of automated experiments. For this purpose, we constructed a robot that performed a large number of test cycles on three different capacitive touch screens: a Microsoft 55″ capacitive touch screen (MS display), a 27″ Perceptive Pixel display (PPI display), and an iPad 4 (iPad). Figure 2.8 shows the robot on the Microsoft 55″ display; the display shows colored dots to debug the application, and the system logs each test cycle. Each cycle consisted of setting down a PERC tangible (40 mm by 40 mm) at a specified location and angle, then waiting for one second, and then lifting the tangible up again. Before the next cycle, the robot changed the angle at which it then starts the next iteration. We used 73 distinct angles at nine different positions on each touch device.

We measured detection success and accuracy.

For each cycle, we measured and logged the positions and time stamps of all touches reported by the touch screen, as well as the time stamps and event types for all incoming BLE communication. Whenever the tangible was detected, the system calculated the position and angle, compared both to the expected values for the cycle, and logged the positional and angular detection errors.

We built a robot that placed and lifted the tangibles at different angles.

Using a robot to test PERCs' performance allowed us to gather a much larger sample size of measurements and granted exact repeatability of each placement cycle. Additionally, only this way, we were able to test PERCs "untouched". When a user sets down a tangible manually, the capacitance of the experimenter's hand results in much more accurate touch locations. This happens even though there is no conductive connection to the pads. Therefore, the experimental setup we used allows us to give a worst-case estimate for the systems' detection accuracy.

We let the system run for 65700 place-and-lift cycles.

We ran the 65700 cycles on the MS 55″ display (900 per angle) at nine different positions on the screen for this evaluation. In addition to that, we performed 2190 cycles on both the iPad and the PPI display (30 trials per angle). This adds up to a total amount of over 70000 trials; given an average number of 64 detection reports from the touch screens over each cycle, we recorded about 4.4 million data points.

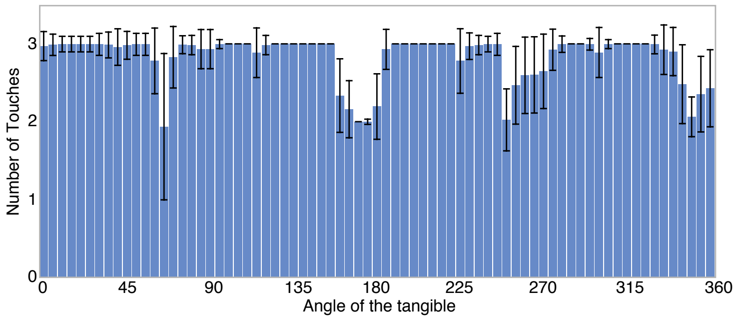

Figure 2.9: Number of marker points found depending of the orientation of the PERC tangible. The whiskers denote the standard deviation. Results were measured on the MS 55″ display.

2.5.1 Results

Our newly introduced field sensor's detection rate was at 100 % across all trials and all touch screens. The field sensor was always able to detect if a tangible was placed on the surface and if it was lifted from the surface. The average time difference between the *On-Screen* event and the *Off-Screen* event is 1.3 s with a standard deviation of 0.038 s.

The field sensor was 100 % accurate.

As expected, the detection rate of the PUCs marker points depends on the angle of the tangible. As shown in Figure 2.9, around 75°, 165°, 255° and 345°, sometimes only touch points for pad B and C are detected. On the iPad and the PPI, we found similar results at 0°, 90°, 180°, and 270°. As explained earlier, these angles reflect the alignment of transmitter and receiver electrodes of the capacitive surface.

At some angles not all touch points were detected.

At precisely these angles, the average detection duration reflects the use of the light sensor and the additional communication overhead. Figure 2.10 shows the detection time for successfully detected tangibles, cases where the light sensor disambiguated the orientation are highlighted in red. When all three touchpoints are detected, the duration between the *On-Screen* event and a correctly detected tangible is 50 ms on average with a standard deviation of 31 ms.

If not all touch points are present, the light sensor acts as a fallback, but introduces some delay.

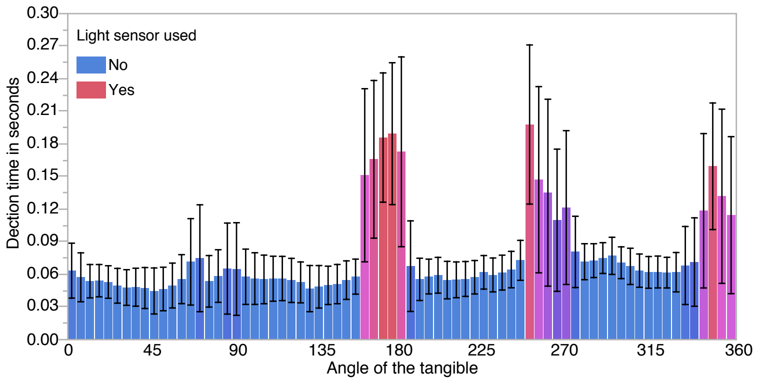

Figure 2.10: Average duration from receiving the information that the tangible is close to a capacitive screen via BLE until the tangible is correctly detected. The red color indicates the usage of the light sensor to determine the tangible's orientation. The whiskers denote the standard deviation. Results were measured on the MS display

The light sensor fallback adds a delay of $\sim$ 110 ms.

If the light sensor fallback is used to solve to disambiguate the orientation, the detection takes 190 ms on average with a standard deviation of 61 ms. iPad and PPI detection durations were similar. On average, the system needed 65 ms on the iPad and 55 ms on the PPI without the light sensor. If the light sensor is used, the detection duration increases to 176 ms on the iPad and 167 ms on the PPI.

PERCs' position is detected with high accuracy at all angles.

Regarding position accuracy, PERCs were detected with a mean distance of 1.5 mm with a standard deviation of 0.76 mm on the MS 55″ display. Figure 2.11 shows more detailed results. The results might also suggest that the displacement of a tangible depends on the orientation of the tangible. The angles at which the position error was high did not overlap with the angles that require the light sensor fallback.

The rotation error was small as well.

The average angular error was -0.78° with a standard deviation of 1.9°. Figure 2.12 shows the angular error for all angles of the tangible. Similar to the displacement, the angular error seems to depend on the angle of the tangible. Therefore, the position and angular accuracy can probably be significantly improved by learning an error compensa-

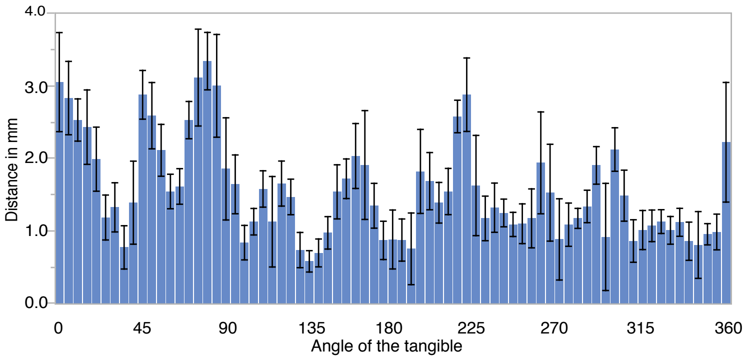

Figure 2.11: The average error between the actual tangible position and the detected tangible position depending of the orientation of the tangible. Overall the error is not grater than 4 mm. The whiskers denote the standard deviation. Results were measured on the MS display.

tion function depending on the angle. However, since the errors are reasonably small overall, we leave this idea for future work.

Our results replicated on other devices.

For the iPad and the PPI, the accuracy in terms of the tangible location and orientation were similar to the MS 55″ display. The average displacement on the iPad was 2.1 mm (2.5 mm for PPI), the angular error was -1.84° (-1.98° for PPI) on average.

Sometimes the system detected only one touchpoint, leaving the marker detection unsuccessful.

In 2.2 % of our trials, the touch screen of the MS 55″ display detected only a single touchpoint. In this case, the system still knows that a tangible has been placed on the table, but it can only approximate the tangible's position and cannot calculate the angle. This occurred similarly often on the iPad (2.5 %) and on the PPI display (3.2 %).

2.5.2 Discussion

After our evaluation, we can reliably state that PERCs fulfill the requirements for a system using tabletop tangibles. Overall our results were promising that the field sensor idea can bring tangibles to a variety of capacitive screens.

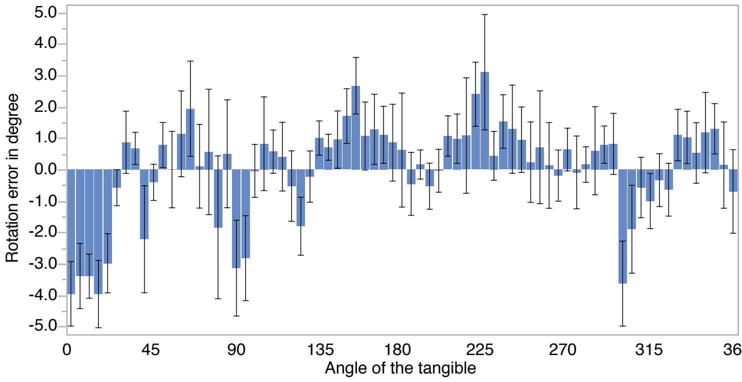

Figure 2.12: Average tangible rotation error depending of the orientation of the tangible. Overall the error is never bigger than 4 degree. The whiskers denote the standard deviation. Results were measured on the MS display.

PERCs are reliably detected, only 2 % would need a user interaction to be detected.

Regarding requirement 1, PERCs can reliably detect (with 100 % accuracy) if they are located on a capacitive touch surface. By applying the PUCs marker concept, about 98 % of the tangibles are correctly detected on an MS 55″ display. This detection is independent of a user's touch since we use the PUCs marker concept to create the touchpoints. The newly introduced field sensor counters the touch screens filter mechanism. Therefore, the system can determine whether a tangible was removed from the surface or just filtered out at any time.

PERCs have a UUID.

PERCs also fulfill requirement 2, since every tangible has its own BLE UUID. If two *On-Screen* events happen at the same time, the light sensor acts as a fallback mechanism for disambiguation. Therefore, PERCs are uniquely identifiable.

PERCs' position and rotation accuracy allow precise user input.

The position and angle of PERCs can be detected with high precision. The mean position error we measured is 1.5 mm; the mean angular error is -0.78°. Therefore, we can reliably claim that PERCs fulfill requirement 3. Our ability to manipulate objects very precisely is not hindered by the position or rotation detection of PERCs. Both position and angular accuracy can possibly be improved upon further by employing algorithms to the collected results.

All three of a PERC's touchpoints are reliably detected if the tangible moves over the sensor's surface. At this point, positional and angular information is obtained directly from the touches, updated with the capacitive touch surface's scan rate. We did not measure exact position and rotation errors during a tangibles movement. However, since the position and rotation are updated with the sensors refresh rate, we can state that PERCs fulfill requirement 4. PERCs detection reliability could possibly be improved even further by applying adaptive filtering based on users' movement patterns. This approach is also used to increase touch detection accuracy for modern smartphones.

PERCs' detection rate is fast enough to feel like real time input.

Regarding requirement 5, PERCs do not inherently bring some other form of input possibilities for users. They also do not include feedback modalities like vibration, sound, or LEDs. However, the BLE connection between the system and each PERC is bidirectional. Therefore, the system can send commands to a PERCs to give feedback and the PERC can send more information from other input modalities. This means, that PERCs can easily be equipped with additional sensors, buttons, LEDs, speakers, or motors.

PERCs do not inherintly come with a way to communicate feedback from the system to the tangible.

2.6 Improvements to PERCs

Since we presented PERCs in 2015, we applied PERCs to different research projects. In the Tabula Project, 2016 we utilized PERCs on a Microsoft Surface Hub. As stated earlier, the PUCs marker concept as well as PERCs' field sensor work on other capacitive screens without requiring much change in the hardware.

PERCs supported a number of research projects.

2.6.1 TABULA Tangibles

TABULA tangibles include a set of additional input and output modalities. During the Tabula Project, 2016 we developed two demonstrators which include tangibles. Figure 2.13 shows users at the first demonstrator learning

TABULA tangibles add feedback modalities to PERCs.

Figure 2.13: A TABULA learning application as presented during the Informationstour Erfahrbares Lernen[a] by the German BMBF. Here, TABULA tangibles are applied as tools to collect virtual cards into bins. If a card is moved into the wrong bin, the tangible gives subtle feedback via vibration.

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[a] https://www.bmbf.de/de/informationstour-erfahrbares-lernen-startet-7168.html

As a tool, TABULA tangibles can give users individual feedback.

about regular expressions. This demonstrator applies tangibles as tools. Users use a tangible to move virtual cards on the table and collect them in bins. If the virtual card fits the bin, all users get positive feedback, and the card disappears. If the bin and card do not fit, there is negative feedback.

We found that subtle feedback can help introverted learners to participate in a collaborative learning environment.

Ehlenz et al., 2018 found that users' learning experience suffers, especially for introverted users, if the negative feedback is publicly announced. Therefore, TABULA tangibles include more subtle feedback modalities. The tangibles can give auditory, visual, and haptic feedback. Especially the visual and the haptic feedback are way less publicly noticeable than feedback displayed on the big screen. Therefore, the TABULA tangibles create a positive learning environment where users can learn in a safe environment.

Later we used TABULA tangibles as domain objects.

An other TABULA learning application utilizes tangibles as domain objects. Each tangible represents a node in a propositional logic circuit. The LEDs and audio feedback inside the tangible give feedback on whether a node is connected correctly and if its' outgoing connection is on or off. The physicality of the tangibles thereby encourages playful exploration of the logic's possibilities.

2.7 Closing Remarks

With PERCs, almost anybody can build their own domain specific or tool specific tangible.

Adding additional capabilities is easy, since the communication can be adapted to fit a specific applications' needs.

In this chapter, we discussed how someone can build tangibles for interactive tabletops. Depending on whether a designer applies tangibles as tools or as domain objects, we derived five requirements for tangibles on interactive tabletops. We presented PERCs, persistently trackable tangibles on capacitive multi-touch displays. These are detected even when no user touches them, and, unlike previous designs, they do not get filtered out over time by the adaptive signal filters of the touch screen. We achieved this by adding a field sensor that detects the electric field of the touch surface. We presented additions to PERCs that include additional feedback modalities to help users explore abstract concepts like logic circuits and increase their enjoyment while learning.

A build-in marker detection would further increase touch screens' abilities to detect tangibles.

Possible improvements to the PERCs base concept include adaptive filtering and learning algorithms that further improve the marker detection. This could minimize the small displacement and angular errors during the tangible detection. A more detailed look into how the pattern of detected markers is geometrically skewed on different touch surfaces and at different angles could yield more precise estimations for the tangibles' positions.

Chapter 3

Creating Tangible Applications: MultitouchKit

> *"This is a white canvas, paintbrush and ink waiting for a Picasso"*
>
> *—Hiroshi Ishii*

This chapter presents a software framework to create tangible applications, e.g., with PERCs as tangibles.

In Chapter 2 "Making Tangibles for Interactive Tabletops: TABULA Tangibles" we presented active tangibles, which are capable of detecting most commercial touch screens. Both the touch pattern to recognize a tangible and the BLE communication need a software framework that researchers and developers can use to create their PERCs-tangible applications. This chapter presents the *MultiTouchKit* (MTK) and its Swift version, a software framework that encapsulates the tangible detection and communica-

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Publications: This work was in part created for the Tabula Project, 2016. Furthermore, parts of this work were also published as master thesis from Linden, 2015 who developed the basic MultitouchKit framework, from Asselborn, 2018 who updated the framework to the Swift Programming Language. The author supervised these theses and the development of both MTK versions.

Apple's frameworks offer many capabilities to create great tangible apps.

tion to them. The MTK builds up on Apple's SpriteKit[2] framework. The integration into SpriteKit also allows developers to integrate the other frameworks that Apple provides to create graphical applications. SpriteKit offers hit detection and simple animations, SceneKit allows the integration of 3D graphics, and GameplayKit allows game logic like menu scenes and agents with artificial intelligence.

The MTK is a joint effort by us, many student researchers assistants

The MTK is a living software framework, which was used by many students in their Bachelor's and Master's theses and also in student group projects. Each contribution enriched the framework with additional functionality and new tangible applications. The apps developed include adventure games, exertion applications, learning applications, and puzzles. For researchers, who want to build their application including PERCs, the framework is downloadable at the TABULA Project[3] website.

We'll describe the MTK's core classes and functionality in this chapter.

Since describing all functionality and applications would go beyond the scope of this thesis, we will present only the core classes in this chapter. We will describe how one can create their own tangible application, what steps are required to include the MTK, and how the communication to the tangible functions.

3.1 MultitouchKit

The MTK was originally made for Objective-C, later we changed the programming language to Swift.

The MultitouchKit exists in two versions. First, it was developed in Objective-C by Linden, 2015. Since Apple introduced the Swift Programming Language, we updated it to utilize this language to support Apple's latest APIs. The basic graphical layer under each application is encapsulated in SpriteKit, which offers drawings, animations, and fundamental physics. On top of this, we developed our own touch detection framework, which first detects tangibles and passes the remaining touches to the application. A core set of interface elements offers buttons, sliders, labels, and other basic interface elements with corresponding events.

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[2] https://developer.apple.com/spritekit/

[3] https://hci.ac/tabula

To manage tangibles and applications, the MTK has a control center bringing all information together.

In summary, the MultitouchKit Swift version offers following features to researchers and developers:

- Support for multitouch input and event handling on macOS.
- Tangible recognition for PERCs and PUCs and other marker pattern based tangible techniques.
- Application development with Apple's native APIs like SpriteKit, SourceKit, and GameplayKit.
- Bluetooth communication to enable smart tangibles with multiple input and feedback modalities.
- A configuration center to manage tangibles, screens, and applications.
- A toolkit of interface objects like buttons and sliders with the corresponding event handling.

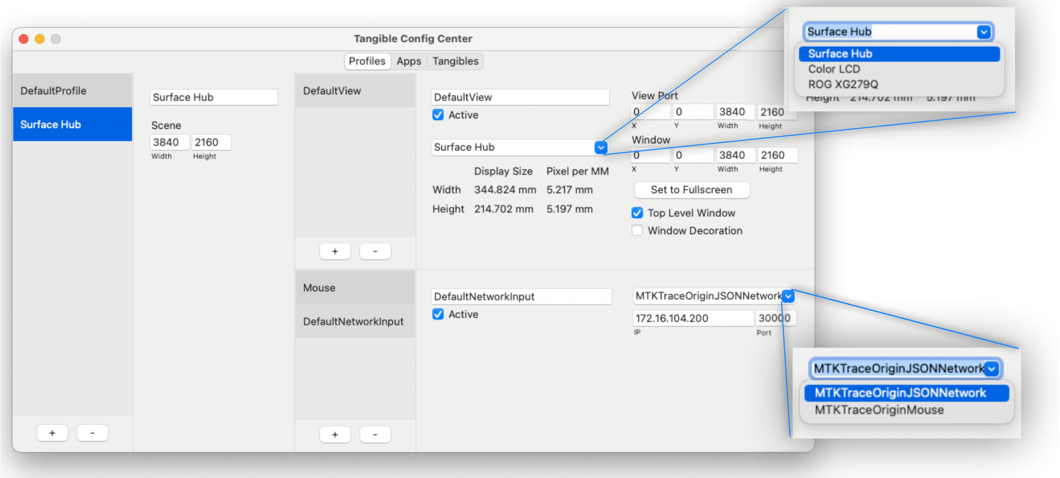
3.2 The Tangible Config Center

The Tangible Config Center (TCC) is the central application to configure tangible applications. It manages screen settings for different attached touch screens, it connects applications and tangibles, and developers use it to train additional tangibles.

The TCC is the core application to manage tangibles and applications.

The TCC has four main functionalities:

1. To configure and switch between different screen setups
2. To configure and switch between different multitouch sources
3. To configure MTK applications, the startup scenes, and which tangibles they use.



Surface Hub
Scene: 3840 (Width) 2160 (Height)

DefaultView
☑ Active
Surface Hub

	Display Size	Pixel per MM
Width	344.824 mm	5.217 mm
Height	214.702 mm	5.197 mm

View Port: 0 (X) 0 (Y) 3840 (Width) 2160 (Height)
Window: 0 (X) 0 (Y) 3840 (Width) 2160 (Height)
☑ Top Level Window
☐ Window Decoration

DefaultNetworkInput
☑ Active
MTKTraceOriginJSONNetwork
172.16.104.200 (IP) 30000 (Port)

Figure 3.1: The TCC's screen profiles tab is used to create and manage screen profiles. Developers can create individual profiles for each screen, select the viewport, add or remove window decorations, and select the touch input source for the profile. This enables to quickly switch between a development and deployment profile, for example.

4. To train tangible patterns and potential BluetoothIDs and make them available in the MTK.

In the remainder of this section, we will look into each of these to document how researchers can use the TCC to create their own macOS applications with touch and tangibles.

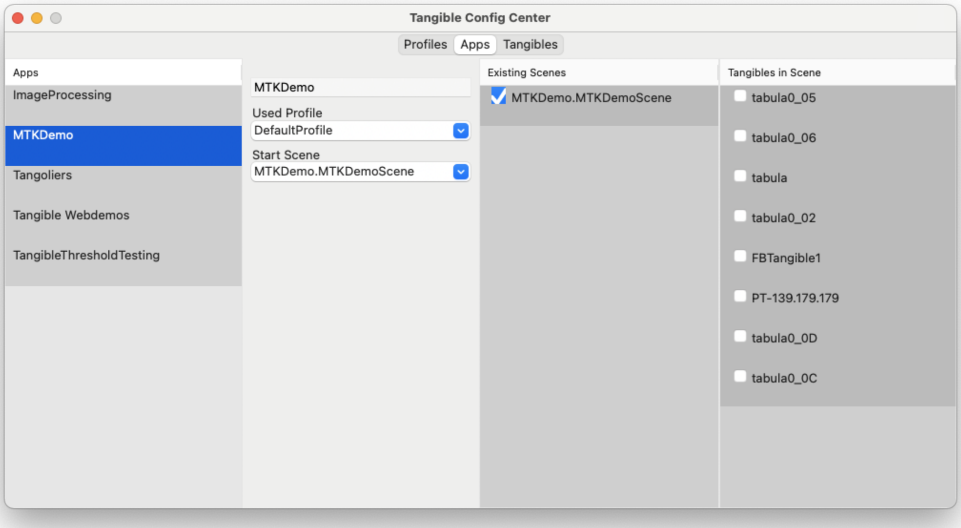
3.2.1 Screen and Touch Setup: The Profiles Tab

The first tab manages screen setups.

Figure 3.1 shows the first tab of the TCC. In this tab, users can create different screen profiles for each attached screen. We created the selected profile for an MS Surface Hub 84". On the left, users select the different screen profiles, name them and select the screen size.

If there are multiple screens connected, one can decide on which screen an application appears.

On the top right side, users control the applications' viewport location and size. The screen selection changes the screen on which the application appears. Users can also set the size and position of the application window. The



MTKDemo

Used Profile
DefaultProfile

Start Scene
MTKDemo.MTKDemoScene

☑ MTKDemo.MTKDemoScene

Figure 3.2: The TCCs applications tab is used to select an app's starting scene, the used screen profile, and which tangibles are available in which scene. To add a tangible into the TCC, it only needs to include the MTK and start the `MTKHub`.

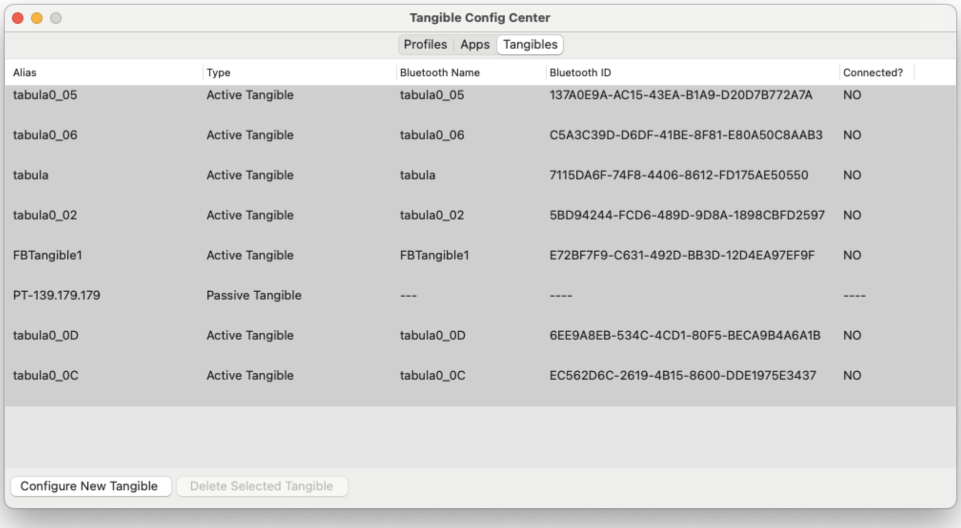
checkmarks can hide the window decorations and force the window to appear always upfront. The middle section allows saving views, making it easy to switch, for example, between 'development', 'testing', and 'run' viewports.

At the bottom mid and right, users can set up different touch sources. Currently available in Figure 3.1 are two input sources. The first one is a network source that sends touch information via JSON packages. The second one is mainly for debugging purposes. Users can create artificial touch points by clicking with the mouse. To create a new input source, one has to subclass the *MTKInputSource*.

The MTK supports multiple sources of touches, e.g., a screen or mouse clicks for debugging.

3.2.2 Application Setup: The Apps Tab

In the second tab, users can configure MTK-Applications. Figure 3.2 shows, from left to right, the available applications, a drop-down menu to select a screen profile, which scene represents the startup screen, the scene selection for



Alias	Type	Bluetooth Name	Bluetooth ID	Connected?
tabula0_05	Active Tangible	tabula0_05	137A0E9A-AC15-43EA-B1A9-D20D7B772A7A	NO
tabula0_06	Active Tangible	tabula0_06	C5A3C39D-D6DF-41BE-8F81-E80A50C8AAB3	NO
tabula	Active Tangible	tabula	7115DA6F-74F8-4406-8612-FD175AE50550	NO
tabula0_02	Active Tangible	tabula0_02	5BD94244-FCD6-489D-9D8A-1898CBFD2597	NO
FBTangible1	Active Tangible	FBTangible1	E72BF7F9-C631-492D-BB3D-12D4EA97EF9F	NO
PT-139.179.179	Passive Tangible	---	----	----
tabula0_0D	Active Tangible	tabula0_0D	6EE9A8EB-534C-4CD1-80F5-BECA9B4A6A1B	NO
tabula0_0C	Active Tangible	tabula0_0C	EC562D6C-2619-4B15-8600-DDE1975E3437	NO

Figure 3.3: The TCC's tangibles tab is used to manage existing tangibles. Users can rename tangibles, debug their tangible designs by checking their connection status, and train new tangibles by pressing the corresponding button.

The second tab is used to manage apps, select the starting scene and attribute tangibles to each scene.

which tangible detection is activated, and all available tangibles to be activated in the scenes. The selected "Start Scene" will be on display when a user runs the tangible application, this way, developers can quickly change between different setups, for example, in an A — B study. Users can deactivate tangible detection on scenes by unchecking the checkmark under "Existing Scenes". If different scenes need different tangibles, users can select a scene under "Existing Scenes", and activate and deactivate tangibles individually.

Adding an application to the TCC is easy.

For an application to appear under "Apps", users have to import `import MultiTouchKitSwift`, and call `MTKHub.sharedHub.start()`. This will activate the central controlling hub, and if the application is not yet available in the TCC, it gets added.

3.2.3 Training a Tangible: The Tangibles Tab

The third tab is used to train and manage the existing tangibles.

The third tab shows an overview of connected tangibles, known touch patterns, and Bluetooth-IDs. For PERCs tangibles, the "Connected?" tab shows if they are currently connected to the system. This helps to debug faulty connections since Bluetooth can be prone to error from automatic connection to other devices or little battery power. Users can also rename the tangibles in this tab and double check the UUIDs from each Bluetooth module.

The TCC has the ability to train new tangibles build-in.

To connect a new tangible to the TCC, users click the "Configure New Tangible" button. This will open a scene on the connected touch screen. Figure 3.4 shows the `TCCCreationScene`. To create a new tangible, users place a tangible in the dark grey area and moves it until all touch-points are displayed. The scene will display the complete touch traces, with all recognized points in time to make this easier. To connect tangibles with a Bluetooth module, users have to select the corresponding Bluetooth ID. The system will only show unknown IDs not to clutter the interface with already existing IDs.

The buttons underneath the training area are used to scan and save tangible pattern.

When all touch points are recognized, users have to click the "Scan for Tangible" button. This will create a temporary tangible, which users can test out by lifting and placing the tangible. If the tangible with its new alias is correctly recognized, the "Save Tangible" button will save the newly created tangible into the "Tangibles" tab.

3.2.4 Consistency: The Config File

All information saved in the TCC is located in a central configuration file.

The MTK saves all these settings in a central configuration file. This file is located in the user's `~/Library/Application Support/MultiTouchKitSwift/` folder. This file is loaded by the MTK and edited via the TCC. Since it is a plist file, it can also easily be edited with a plist editor. For example, to save multiple versions during debugging or demoing. This file is loaded at the start of every application and when the TCC is started. Users have to keep this in mind when working with the TCC and a

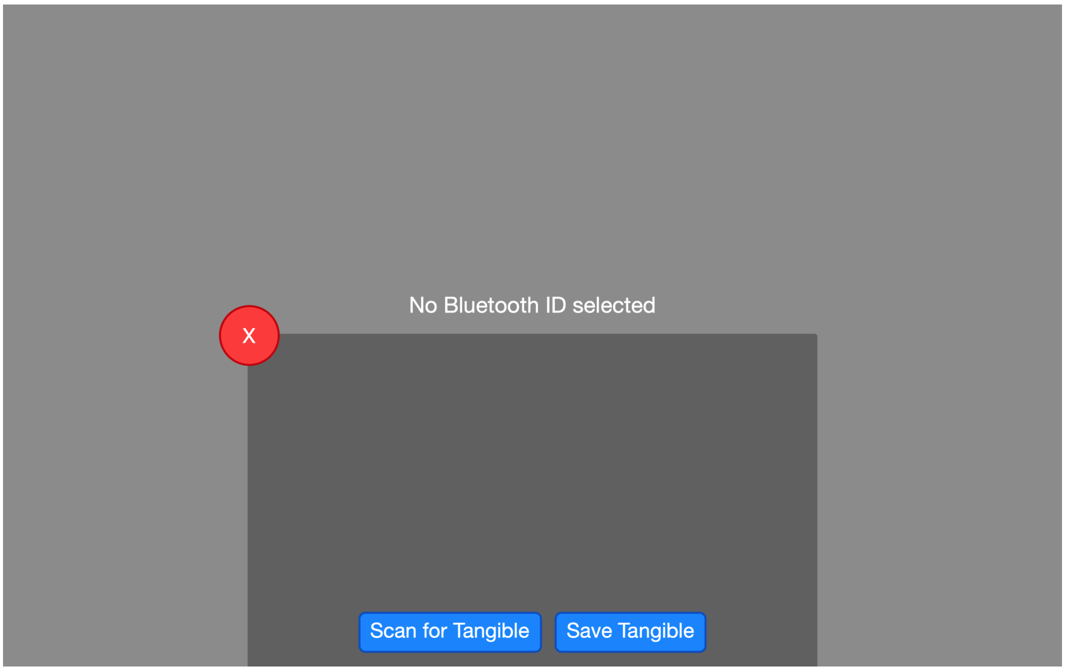


Figure 3.4: The tangible creation scene, users place a PUCs or PERCs tangible inside the dark grey area to train the marker pattern. The "Scan for Tangible" trains a new marker pattern, which then can be tested in the light grey area. The "Save Tangible" button then stores the trained pattern in the TCC.

tangible application at the same time, as the "config.plist" is saved every time the TCC entries are changed.

3.3 The Core Classes

These core classes for each application are `MTKScene`, `MTKPassive-`, and `Active-Tangible`

There are a number of classes that work at the core of the MTK. Each application implements at least one `MTKScene`, it holds the graphical user interface. This is also where developers handle touch and tangible events. The tangibles are represented as `MTKPassiveTangible`. This class contains the central tangible models and events. The `MTKActiveTangible` implements the additional features provided by PERCs. The recognition state, and communication between system and tangible are encapsulated, additional features like actuators or other sensors are provided in subclasses of the `MTKActiveTangible`.

Inside an MultiTouchKit-Application, the `MTKHub`, `MTKScene`, and `MTKTangible` represent the central classes. The `MTKHub` is a singleton inside each tangible application. It manages the scenes, traces, and the active application windows. A tangible application has to start the `MTKHub` in its application delegate. After that the `MTKHub` manages the scene transitions and touch traces.

The `MTKHub` is the central hub for all scenes and events.

The `MTKScene` is the parent class for all application scenes. It is a subclass of the `SKScene` provided by Apple's SpriteKit. To receive touch-traces, users have to connect to the `MTKHub` via `MTKHub.sharedHub.traceDelegate = self` after this user can access traces and tangible information via the class features:

The `MTKScene` is the parent class for all tangible scenes.

- `func preProcessTraceSet(traceSet: Set<MTKTrace>, node: SKNode, timestamp: TimeInterval) -> Set<MTKTrace>`
- `func post3ProcessTraceSet(traceSet: Set<MTKTrace>, node: SKNode, timestamp: TimeInterval) -> Set<MTKTrace>`
- `public var activeTangibles: Array<MTKActiveTangible>`
- `public var passiveTangibles: Array<MTKPassiveTangible>`

The `MTKPassiveTangible` class represents PUCs and is the central tangible model inside the framework. It is meant to be subclassed for different tangibles, for example, the existing `MTKActiveTangible` representing PERCs. The `MTKPassiveTangible` captures the tangible detection out of traces for all tangibles with 3 touchpoints.

An `MTKPassiveTangible` represents a PUCs tangible.

To reference each tangible individually, users can utilize their `public var identifier: String!`. This identifier is the same name that which given to a tangible inside the TCC. If changed during runtime, the name will be overwritten by the TCC the next time the application is

An `MTKActiveTangible` represents a PERCs or TABULA tangible.

loaded. However, the application can use this identifier to send feedback to a specific TABULA tangible, thus offering an identification mechanism for the user currently wielding the tangible.

The `public var trackingState: MTKUtils.MTKTangibleTrackingState?` represents the current state of the tangible. This can be:

- `fullyRecognized`, for a present tangible
- `recognizedAndRecoveringMissingTraces` for a present tangible with filtered touch points
- `notRecognized`, for tangibles currently off-screen.

Inside the MTK, the `MTKUtils` hold all application and tangible detection specific settings.

The `MTKUtils` is the central settings wrapper for the MTK. It holds global settings for all applications. This includes settings for the trace detection like `bufferlength` for the number of trace points saved for each trace, `maxDistance`, and `maxTime` for the distance in pixel and time in seconds two touchpoints can be apart to be calculated as connected in a single trace. Most useful for debugging an application are the globals for:

- `tangibleLogging`, to log everything related to the passive tangible detection.
- `activeTangibleLogging`, to log everything related to the active tangible detection.
- `showCursor`, to show cursors under touchpoints.
- `showTangibleInfo`, to display the available information next to each tangible.
- `traceVisualization`, to draw lines between touch points to follow traces.
- `bluetoothDebugging`, to log all bluetooth related events.

3.4 Closing Remarks

With the information given in this chapter, a developer should be able to write their own MultitouchKit Swift enabled tangible application. We did omit specific details on the communication between the touch sensor and the `MTKHub`, however these are likely a subject of change with new touch screens, thus we want to refer to the MTK's documentation for further detail on the current implementation.

Communication to and from a tangibles is a module inside the MTK as well.

The communication between a tangible and the MTK also heavily depends on the implementation inside the tangible. For TABULA tangibles, we used a protocol addressing sensors and actuators through a tree structure. Sending, for example, `[2:0:1]` will tell the tangible to start sending field sensor updates. Encoded in the first number is the Group, which developers want to address, `1` asks for general information about the device. `2` addresses all sensors and input at the tangible, for example, to start or stop the tangible sending sensor events. In group `3` all actuators are addressed, for example, to set a color for the LEDs or send a vibration signal. Table 3.1 "The protocol to address a TABULA tangible's sensors and actuators." shows the protocol we used to communicate to TABULA tangibles.

Our example implementation is adaptable for other developers.

Group	Sensor \ Actuator	Values	Explanation
1	0	0	Send BLE module vendor information
2	0	0\1	Start\Stop sending field sensor events
2	1	0\1	Start\Stop sending light sensor events
2	2	0\1	Start\Stop listening for button inputs
3	0	0\1	Start\Stop listening for gyroscope data
4	0	FFF	Set the 3-colored LEDs to a hex value each.
4	1	0\1	Start\Stop the vibration motor
4	2	0\1	Start\Stop the beeper
any	any	p	ask for the current value of a sensor\actuator

Table 3.1: The protocol to address a TABULA tangible's sensors and actuators.

However, the protocol of how one communicates to their tangible can be changed easily inside the MTK. For further reference, the documentation of the MTK includes the

The `MTKBluetoothManager` class holds all necessary documentation.

communication functions to TABULA tangibles . Based on this, developers can easily include their own protocol while keep using the same functions inside their tangible application. All Bluetooth functionality is collected inside the `MTKBluetoothManager` class in the MTK.

We hope the MTK enables other researchers and developers to include tangibles in their applications.

We hope that the MTK enables future tangible researchers and developers to write their own tangible applications. We purposefully designed the MTK with high modularity to ensure easy additions by other developers while still keeping existing functionality. The integration into Apple's APIs enables developers to include otherwise hard to implement functionalities. For example, GameplayKit can offer state-based interaction or artificially intelligent agents inside the app. SceneKit allows the integration of 3D graphics for perspective-based research or interaction with 3D objects. In all, the MTK is a good start for future researchers to create and evaluate their tangible interaction designs.

Chapter 4

The Design Space of Tangible Interaction

This chapter will describe a design space for tangible interaction that structures and helps compare the numerous tangible interaction techniques. The *Design Space of Tangible Interaction*, is a taxonomy that builds on Card et al.'s Design Space of Input Devices. We explain how existing tangible designs, with off- and on-surface tracking, are placed within the design space. Based on an initial study of a tangible application that uses surface and midair interaction, we discuss the opportunities and challenges of designs that combine on- and off-surface tangible interaction.

This chapter describes our design space, which enables researchers and designers to systematically compare tangible designs.

Publications: The work in this chapter is a collaboration with David Asselborn, Oliver Nowak and Simon Voelker. The author is the main author of the paper; he was also responsible for developing parts of the hardware, writing parts of the software, designing the experiments, and analyzing data from the experiments. Part of this work was first published as an extended abstract the CHI 2019 conference Cherek et al., 2019. Several sections of this chapter are taken from this publication. Furthermore, parts of this work were also published as master thesis by Asselborn, 2018 who conducted the study on the 5D tangible.

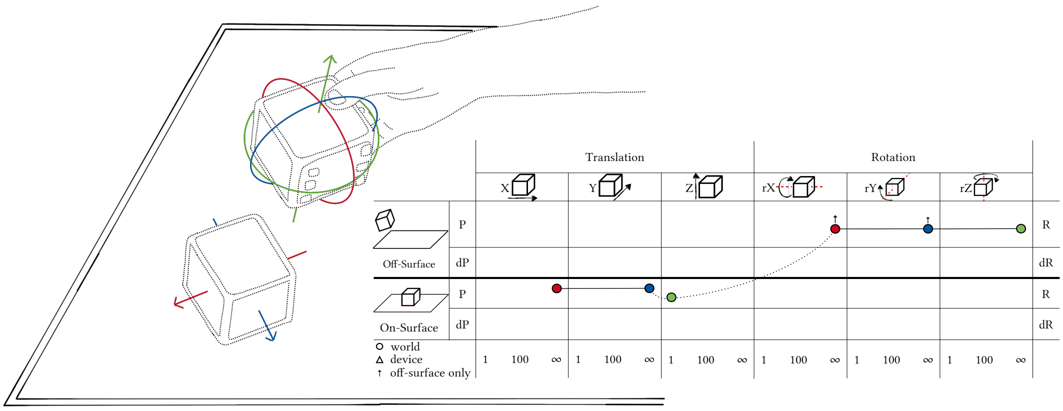


Figure 4.1: A tangible interaction design is placed in the Design Space of Off- and On-Surface Interaction. The tangible is used to control the position and rotation of a virtual object represented on screen. When the tangible is moved around on the surface, it controls the position of the virtual object in X and Y. This is depicted in the lower part of the design space. When the tangible is lifted, its 3D rotation in midair controls the virtual object's rotation. This off-surface interaction is depicted in the upper part of the design space.

4.1 A Taxonomy to Structure Tangible Interaction Techniques

There are multiple approaches to structure interaction designs in spaces.

These spaces give an overview and inspire new designs.

Designing and evaluating new interaction technologies and devices is a major part of human-computer interaction. First attempts to create a taxonomy for the large variety of input technologies available were presented by W. Buxton, 1983, and Card et al., 1990 created the Design Space of Input Devices. Their structured exploration supports comparing different input devices, and even enables designers and researchers to imagine new types of mechanical input devices. Since then, many researchers have adopted this idea and created design spaces, for example, Nigay, Coutaz, 1993 for multimodal systems, Beaudouin-Lafon, 2000 for instrumental interaction, Kern, A. Schmidt, 2009 for automotive user interfaces, and Ahn et al., 2013 even for social media network visualisation tasks. We structure the different possibilities to track tangible input for digital systems in the *Design Space of Tangible Interaction*. This includes tangibles on tabletops, as well as tangible input in midair and for Augmented or Virtual Reality applications.

Developers of tangible applications use these interactive surfaces to track the position and Z-rotation of tangibles on the surface. However, since tangibles are physical objects, they have a strong affordance to be picked up and handled midair. When a tangible serves as a physical handle for a persistent virtual object on a tabletop display, lifting the tangible breaks that connection since the tabletop is needed to track the tangible. Thus, the user can no longer interact with the virtual object through its physical proxy.

While being tracked by a surface, most tangibles have a high affordance to be picked up.

Tangibles have also been brought to Augmented and Virtual Reality environments; for example, Zhou et al., 2004 let users manipulate a cube to experience a story. In recent years, advances in sensors and tracking technologies have enabled new opportunities to use tangibles in Augmented and Virtual Reality. Wacker et al., 2019 use a tangible pen tracked by a smartphone to create virtual drawings in Augmented Reality. In Virtual Reality, the iTurk project by Cheng et al., 2018 uses tracked physical props, such as a ball on a pendulum, to represent varying virtual objects that the user is interacting with.

For tabletop tangibles, however, this ends the tracking, thus breaking the illusion of connection between the virtual and physical object.

Although tangible interaction is applied in midair and on surfaces, there are few attempts to combine the advantages of midair and on-surface tracking. We call tangibles that are tracked on a surface as well as in midair *Off- and On-Surface Tangible*. These *Off- and On-Surface Tangibles* are those entries in our design space that connect the Off-Surface area with the On-Surface area of the design space. 4.1 shows such an entry into the design space. The represented tangible is tracked in X, Y, and Z-Rotation on an interactive surface and additionally tracked in all three rotation axes when in midair.

Tangibles have been brought to AR and VR, but few combine on-table and midair tracking.

The remainder of this chapter is structured as follows: We present the *Design Space of Tangible Interaction* including midair and on-surface tangible interaction. We place existing related work in tangible interaction into the design space and explain how designers and researchers can use the design space to compare devices and invent new interactions. Additionally, we discuss specific design considerations when employing tangibles. For example, the moment when a tangible that serves as a proxy for a virtual

The *Design Space of Off- and On-Surface Tangible Interaction*includes both: on-table and midair detection but also allows to look at the combination of those.

object leaves or returns to an interactive surface is of particular importance, since the tangible and the virtual object it represents do not necessarily underlie the same physical constraints (a physical cube will not stand on its edge, for example). Tangibles used only in midair, e.g., as Augmented Reality controllers, also require important design considerations. For example, the designer needs to consider how users start and end an interaction since users cannot simply drop a physical prop whose virtual representation should remain floating. Lastly, we present several potential interaction designs that we identified using our design space. Using an experimental prototype of an *Off- and On-Surface Tangible*, we performed a study comparing touch interaction, 3-D space mouse input, and *Off- and On-Surface Tangbile* interaction. The study revealed interesting changes in user behavior for different implementations of a 6-dimensional input task.

From an interaction research standpoint, the transition between on-table and midair tracking is especially interesting.

4.2 Tangibles On- and Off-Surface

After their introduction by Fitzmaurice et al., 1995, tangibles first were primarily used on tabletops. Sometimes with a display beneath them, but sometimes just on a standard desk. This is true for Bricks by Fitzmaurice et al., 1995, URP by Underkoffler, Ishii, 1999, SLAP and Magdets by Weiss et al., 2009b; Weiss et al., 2010, fiducial based tangibles like the ReacTable by Jordà et al., 2007, and PUCs and PERCs by Voelker et al., 2013; Voelker et al., 2015a. Even commercially available tangibles like pencils for displays or tablets or the MS Surface Dial Corporation, 2020 only work on a surface. Hancock et al., 2009 evaluated the accuracy and effectiveness for 2D and 3D manipulation tasks with tangibles and found tangibles to benefit, especially the 2D tasks. For 3D manipulation, however, users had difficulties because they could not "reach into the display".

Tangible research mostly started with an *on-surface* tracking.

There are some attempts to track tangible objects above, but in close proximity to the surface, they are made for. Stackable tangibles do not necessarily need to be placed on-surface; they can be stacked on top of a display as presented by Chan et al., 2012 or on top of each other like RFIBricks by Hsieh et al., 2018. Another approach for creating possibly arbitrary 3D tangible structures is Lumino by Baudisch et al., 2010. They used optical fibers to transport the information on how their tangibles are stacked to a camera system in a diffuse illumination table. Liang et al., 2014 presented GaussStones, which can also be tracked when hovering close over the interactive surface enhanced with a Hall effect sensor.

Some tangibles are stackable or tracked in close proximity to a surface.

PaperLenses by Spindler et al., 2009 track sheets of paper above a tabletop display and use these to top-project 3D information on the paper. They performed a formative user study that gave helpful comments for future designs. Lee et al., 2011 were the first who presented tangible objects that could levitate above a top projected surface. They stated that the interaction technique created "many opportunities and leaves many design challenges". They did not evaluate the interaction in a controlled experiment but presented multiple application scenarios.

PaperLenses explored the affordance to hold a tangible in your hands.

The benefit of handling a real-world object when performing a virtual task has been explored by Hinckley et al., 1994, who presented a position-tracked doll head to plan and train complicated tasks like neurological surgeries. Rodrigues et al., 2017 combined Augmented Reality on the phone with an interactive wand on a table to allow editing of 3D objects and viewpoint manipulation with the mobile device. In a preliminary user study, their participants could complete the 2017 IEEE 3DUI Contest challenges. The Specimen Box interaction technique by Zielinski et al., 2017 allows users to inspect 3D objects placed in a real-world transparent box using Augmented Reality. Their study showed that their box allowed users to perform tasks faster than other established techniques. They also included design recommendations, for example, about the maximum weight a midair tangibles should have.

Tangibles have already proven to be beneficial when handling 3D virtual objects in midair.

Zielinski et al., 2017 even included maximum weight recommendations in their findings.

Our Design Space of Tangible Interaction proposes that combining tangible input on a multitouch tabletop with midair interaction can overcome difficulties when interacting with virtual objects on-screen. Sometimes it is difficult to get an understanding of a 3D virtual object since users cannot grab the object, feel it and look at it from all sides.

Combining *on-* and *off-surface* interaction could let users reach "into the display".

Instead of letting users "reach into the display", *On- and Off-Surface Tangibles* let users manipulate virtual objects by picking up and handling a physical proxy in midair.

4.3 Previous Work on Design Spaces

The Design Space of Input Devices was the first design space widely used in HCI.

The Design Space of Input Devices was created by Card et al., 1990. Their taxonomy built up on W. Buxton, 1983 who motivated the need to create an overview of the wide variety of input devices and screen technologies. The Design Space of Input Devices describes mainly the mechanical capability to track how a user manipulates a device. For example, this space does not easily represent voice input or external tracking like optical tracking systems or gesture input. Tangible interaction mainly relies on physical objects tracked by an external tracking system. Thus tangibles cannot easily be described in the Design Space of Input Devices.

Since then, design spaces have been created for many areas, e.g., instrumental interaction, automotive UIs, and multi-surface interaction.

Since then, multiple different domains have adopted the idea. Nigay, Coutaz, 1993 created a Design Space of Multimodal Systems. This way, they can include, for example, voice and gesture interaction instead of only hand-based input. Beaudouin-Lafon, 2000 created an interaction model for instrumental interaction that includes a description of the physical properties in degrees of freedom, indirections, and compatibility. Although he did not combine all these characteristics in a single graphical representation, his taxonomy still supports comparing different instruments based on their capabilities, even if they look fairly different. Kern, A. Schmidt, 2009 created a design space for driver-based automotive user interfaces. They included the placement of controls inside the car as well as input and output modalities. Their graphical representation shows the complete car user interface, allowing designers to compare different setups and generate new ideas. Wagner et al., 2013 created a body-centric design space for multi-surface interaction. They include the number of involved limbs and the level of restrictions on the body. An on-body touch interface, for example, was placed as restricted with many limbs involved.

4.4 The Design Space of Tangible Interaction

In Hiroshi Ishii's vision of tangible computing, the physical world with its everyday objects becomes the user interface to computing systems. Tangibles on tabletops are a step in this direction, offering physical, graspable objects to interact with otherwise flat multitouch screens. However, tangibles on tabletops are constrained because they need to be recognized by the screen that includes the tracking components. If a tangible is moved beyond the screen's boundaries or lifted high up, the system usually does not track it anymore. Also, for rotation, tabletop tangibles are bound to be detected by the surface. If a designer wants to include rotations around X or Y, the tangible needs to support being flipped and still be tracked, for example, by a different marker pattern on each side. Many tangible user interfaces for tabletops do not support more than Z-rotations.

If only tracked by a surface, a tangibles interaction usually breaks down when a user lifts it from the surface.

In midair, the display edges do not limit the sideways movement of a tangible, and users can rotate it to any orientation since it does not need to rest on a flat surface. It can thus be manipulated freely along all six degrees of freedom (DoF). Midair tangibles might still be restricted to a tracking area if moved out of this are the detection stops or loses certain parts.

In midair, a tangibles tracking area is potentially unlimited.

To express the interactive potential of tangibles, we created the *Design Space of Tangible Interaction*, inspired by the Design Space of Input Devices by Card et al., 1990. We adopted, for example, their concept of distinguishing linear and rotary movements of the tangibles from their approach. The *Design Space of Tangible Interaction's* key distinctive features are the additional distinction between on-surface and off-surface manipulation and the possibility to distinguish between real-world coordinates and device coordinates.

The *Design Space of Off- and On-Surface Tangible Interaction*is inspired by Card's Design Space of Input Devices.

In the following, we describe the design space that is depicted in Figure 4.2 The bottom half describes tangibles used on a surface, the top half those used in midair. The **P** rows on the left side describe tangible input for which the absolute position of the tangible is used, like the posi-

We filled our space with many tangible designs.

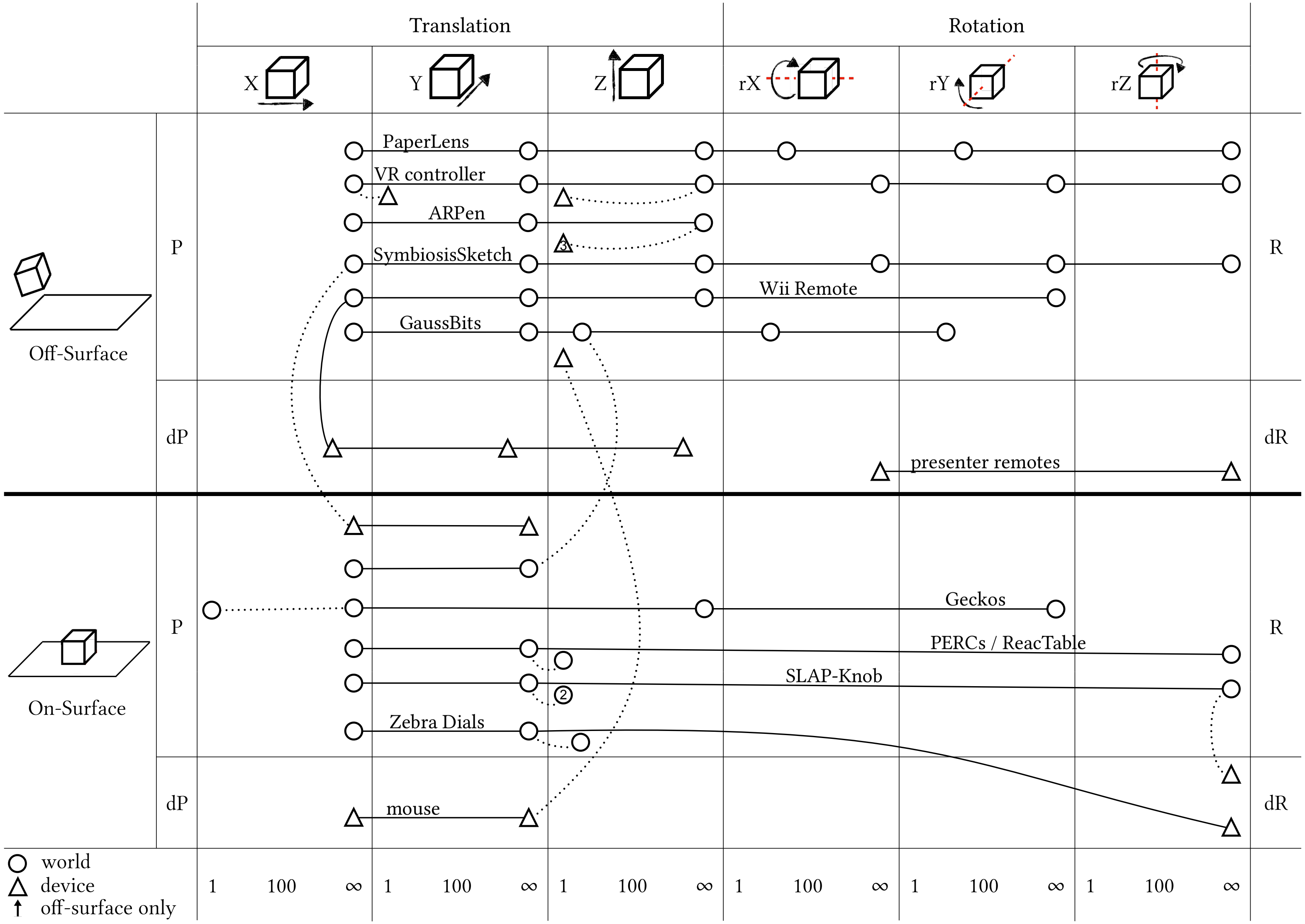


Figure 4.2: The Design Space of Tangible Interaction populated with existing work in tangible interaction. The top half represents tracking in midair, while tangibles on the lower part are tracked on a surface. Circular entries represent tracking in real-world coordinates; triangular entries are in the device's coordinate system. If an entry is placed to its cell's right, the output resolution is very high; binary decisions like a button are placed to the left. Entries connected with a straight line are closely coupled. A dotted line represents those controls inside a shared box, which can be operated separately, for example, buttons.

tion tracking of a tangible on a tabletop or a camera tracking in midair. **dP** rows describe tangibles that only track changes relative to their last position. For example, a computer mouse only tracks motion changes independent of its current position. Users can extend Nintendo, 2020's Wii Remote to track relative movement in midair in addition to the absolute tracking by the infrared grid. The columns indicate whether the input involves translational movement in X-, Y- or Z-direction. In our notation, the X- and Y-axes open up a horizontal plane while Z translations describe a vertical movement perpendicular to that plane. In comparison to this, the rows **R** and **dR** on the right side describe absolute and relative rotational input, respectively. Thus, the columns on the right side describe rotations around the X- (pitching), Y- (rolling), and Z-axis (yawing).

P and **dP** rows describe absolute and relative position tracking.

R and **dR** rows describe absolute and relative rotation tracking.

We describe a tangible by a set of connected circles or triangles. Both shapes represent one-dimensional *manipulation operators*. A manipulation operator could, for example, represent the rotation of a tangible around its Z-axis. Shapes connected with straight lines represent *merged* manipulation operators that are essentially impossible to manipulate independently of each other, like the X and Y coordinate of a touchpoint on a screen. Circles (◯) and triangles (△) connected with dotted lines represent manipulation operators that are *collocated* in the same device but can be manipulated individually. As in Card et al., 1990's design space, the horizontal placement of a shape within a cell describes the input resolution of the manipulation operator from binary (1) to continuous (∞).

A tangible is described by a set of connected circles representing all tracking capabilities.

In the Design Space of Input Devices, one can only describe the movement of the controls in one coordinate system that is conventionally oriented according to the device's surface. For the interaction with *On- and Off-Surface Tangibles*, the tangible device's movement in midair is also relevant. Therefore, we distinguish between the *Device-Coordinate System*(DCS) and *World-Coordinate System* (WCS) (notated as *device* and *world* in the design space). In the DCS, we describe additional controls like buttons, sliders, or rotary knobs independently of the tangible orientation in the world. The design space represents input in the DCS with a triangle (△). Mouse, VR controller and SLAP-Knob

In contrast to Card's design space, our space can distinguish between device- and world-coordinate systems.

A dotted line represents a loose connection that can be operated separately, while a solid connection is almost impossible to operate alone.

in Figure 4.2 demonstrate the usage of the coordinate systems. We use connected circles (◯) to describe movement in the WCS. The VR controller, for example, can be translated and rotated in midair. Its position or orientation is set in relation to the world. Thus, we describe those operators using circles in the design space. If a tangible has a button that users can press independently of the device's orientation in the world, we use a triangle. The dotted line indicates that users can press the button separately of the movement of the tangible (cf. Figure 4.2: VR controller). We place device controls *Off-Surface* if they can be used both on the surface and midair. For example, a mouse button can be clicked even if the mouse is lifted. Therefore, the corresponding entry is in the upper part of our design space. If a control can only be used on a surface, we place the triangle in the *On-Surface* rows. SLAP-Knobs by Weiss et al., 2009b, for example, are tangibles, including a rotary knob whose rotation can only be detected by a tabletop. Therefore, we represent the knob as an *On-Surface* control.

If some interaction is *only* possible in midair, we marked it with an ↑.

In the case that a manipulation operator can *only* be used if no contact to a surface exists, the operator is annotated with an arrow (↑) next to it. For example, Figure 4.1 shows a tangible that can sense rotation in all axes; however, if it is placed on a surface, rotation in X and Y cannot be performed anymore since this would end the surface tracking.

4.4.1 Populating the Design Space

We have populated the design space with tangibles interaction designs from related work for both: tangibles tracked on-surface and used in midair.

Tabletop TUIs

Tangibles on tabletops like SLAP Widgets Weiss et al., 2009a, fiducial markers Jordà et al., 2007 or PERCs Voelker et al., 2015a, are examples for classic tangible user interfaces (TUIs). We place them into the design space by creating a merged device for absolute X-position, Y-position, and Z-rotation, and adding a dotted line to the binary on-surface or off-surface position on the Z-axis (see Figure 4.2: SLAP-Knob/PERCs/ReacTable). The trackable range of these tangibles in Z-position is a binary decision, and therefore the entry is left at '1'; a lift-off can be detected, but any further movement away from the surface is not tracked anymore. The SLAP-Knob has an additional binary decision in Z-position since users can press it; the rotational input of the knob is represented as relative rotational input on the surface.

Tabletop tangibles are mostly in the bottom *on-surface* area.

If tangibles can be stacked on top of each other, this changes the location of the manipulation operator on the translation Z-axis. For example, Zebra Dials by Chan et al., 2012 are tangibles that can be used similarly to pure on-screen TUIs, but they also can be stacked and then rotated independently of each other. The stacked tangibles are only tracked by the system as long as the lowest dial is still in contact with the screen, so the operators in the X-, Y-, and Z-axis, as well as the Z-rotation, are placed in the on-surface cells. Since these tangibles can be placed on different heights, the circle in the translational Z-axis is placed closer to the '100' representing the maximal number of stackable tangibles.

Stackable tangibles are *on-surface*, but the Z-axis tracking is further to the right.

Vertical Screens

Tangibles that adhere to vertical surfaces can be described similarly to tangibles on tabletops. To include Gecko tangibles by Leitner, Haller, 2011 in Figure 4.2, their absolute translational movement is not described on the X-Y but on the X-Z plane.

Tangibles on walls work similarly to tabletop but in other world-coordinates.

Near-Surface Interaction

If the system tracks a tangibles movement or rotation without requiring contact to the interactive surface, we place the circles for its manipulation operators in the upper off-surface part of the design space. For example, GaussBits by Liang et al., 2013 are tracked by the magnetic field of

Close to surface tracking is in midair, but the Z-axis placement is more to the left.

a magnet inside the tangible. This allows their system to recognize the position in X- and Y-direction, and up to 5 cm in Z-direction, thus creating a near-surface midair tangible. Additionally, the inclination of the tangible, and whether it is upside-down or not, can be tracked. GaussBits do not require contact to the screen for any of those interactions. Their translation, as well as rotation, is noted in the off-surface part of the design space in Figure **??**.

Midair TUIs

Midair TUIs like the ARPen or PaperLens are placed in the upper *off-surface* area.

Controllers for Augmented and Virtual Reality systems are tracked independently of a surface. They use position and rotation tracking with near-infinite level input resolution on all six axes (see Figure 4.2: VR controller). For example, Wacker et al., 2019 created a tangible pen that draws in midair while the pen is tracked via a smartphone camera. If parts of the drawing leave the phone's screen, the system does not erase them but stores the whole drawing in a virtual 3D model. It also includes a button to start and stop drawing (see Figure 4.2: ARPen).

Depending on the tracking mechanism, the trackable area might be restricted.

PaperLens by Spindler et al., 2009 is more restricted in its midair movement. Depending on the movement of its tangible controller, it lets the user view different details of a projected image, depending on the height of a tablet the user holds to inspect the image. In a second iteration, this system also reacts to tilting up to 45°. Thus, PaperLens supports continuous absolute translation in X-, Y-, and Z-direction, limited rotation in rX and rY, and continuous rotation in rZ (see Figure 4.2: PaperLens).

Pointing

Remote controls also fit into the design space.

Midair cursor controllers, for example, virtual laser pointers, often use only the relative inclination of a remote to control a cursor on a screen. These tangible controllers show a cursor in the middle of the screen. Tilting the remote around the X- and Z-axis moves it towards the direction of the inclination. We describe these tangibles using triangles in the relative rotation cells for off-surface interaction. Figure 4.2 lists these devices as "presenter remotes".

The latest Wii-Remote has absolute and relative tracking in almost all dimensions. We added the original version as sold in 2006.

The original Wii Remote Nintendo, 2020 uses a combination of an internal accelerometer and an external infrared tracking mechanism. The Wii tracks the absolute position of the controller utilizing an infrared bar at the front of the screen. The accelerometer inside the remote tracks its relative movement. In combination, these sensors detect motion events, for example, when users swing a virtual tennis rack or play on a virtual drumset. This is expressed through the three triangles in Figure 4.2 (Wii Remote). The triangles for the relative position tracking are slightly shifted to the left because the sensor data has an upper limit the movement in X, Y and Z is continuous. All manipulation operators are connected with a straight line because it is almost impossible to use those operators without manipulating the others. For the representation in Figure 4.2 we omitted the Wii Remotes buttons. These would be represented by multiple entries in a binary Z-position inside the device's coordinate system.

Combining On- and Off-Surface Interaction

So far, only few designs combine *Off-* and *On-Surface* tracking.

To overcome accuracy issues while sketching in Augmented Reality, SymbiosisSketch by Arora et al., 2018 uses the haptic support of a handheld tablet to create detailed sketches, which are then transferred to a virtual plane. For this, they use a digital pen tracked in six degrees of freedom for midair actions like moving the virtual canvas. If the user draws with the pen on the tablet, it creates the drawing directly on the canvas. While the pen is tracked absolutely in all six degrees of freedom in midair like a VR controller, it is connected to two on-device translation operators in the on-surface area of the design space that represent the drawing operations (Figure 4.2: SymbiosisSketch).

Apart from SymbiosisSketch, only a few interaction designs combine the on-surface and the off-surface area of the design space. Those *Off- and On-Surface Tabgibles* are mostly tangibles for a surface like a computer mouse with

This combination, however, offers exciting potential for future designs.

operable buttons that still work in midair. Thus, these controllers have a connection from the lower to the upper part. We think that this is a potential area for future design considerations. Tangibles that are only tracked on a surface create an interaction breakdown when picked up, although their physicality highly affords this. Tangibles operated in midair usually need some form of begin- or end- interaction buttons since they cannot hover in midair like their virtual representations. Additionally, if a tangible in midair can represent multiple different objects, users need to be able to switch between those virtual representations requiring further engagement and disengagement capabilities.

We showed that our design space can hold many existing tangible interaction designs.

Design Spaces can also inspire new designs.

The above examples show that existing tangibles can be placed logically into our *Design Space of Tangible Interaction*. The design space thus can help designers and researchers to think about existing tangible interaction models, compare them with each other and structure the approach to new inventions. In the next section, we present possible new interaction designs, which include *Off- and On-Surface Tangibles*. We implemented a prototype tangible we derived from combining areas in the design space that other researchers did not yet explore together. We report the results of a comparative study with this prototype and discuss what challenges designers need to address when creating such interactions.

4.5 Generating New Tangible Designs Using the Design Space

We applied this generative capability by filling empty ares in the space.

As Card stated, one important quality of design spaces is that they help to find new interaction and device designs. We used this generative quality of our space to find novel interaction designs and devices. In particular, devices that combine the *off-surface* and the *on-surface* part have not been explored in detail so far. We think these device designs are especially interesting to investigate further because they utilize the affordance of tangibles to be moved in midair and allow seamless mode switching by going from on-surface to off-surface interaction and vice versa.

We created several possible *Off- and On-Surface Tangible* interaction designs by looking at empty areas in the design space and identifying potential applications for *Off- and On-Surface Tangible* in those areas. Below, we present examples of applications and interaction designs that were inspired by the design space notation and explain how they combine surface and midair input. Figure 4.3 shows the design space with marked areas for these example applications. These examples also serve to illustrate the potential of *Off- and On-Surface Tangibles*.

4.5.1 Spatial Input

Movement in the Z-axis could act as zoom or volume control.

The first example of extending tabletop tangibles capabilities is to add precise Z-position tracking. This supports the tangibles affordance to be picked up without breaking the interaction. For example, combined with position tracking on an interactive display, users can use the position of the tangible in midair to manipulate the viewport on display. For example, users can manipulate position and rotation with translation on-screen and adjust the zoom level freely with a movement in Z. We noted this interaction as red in Figure 4.3.

Combined with volume control, X and Y tracking could place a virtual sound source in a souround sound setting.

Similar to the camera, a physical token may represent an object that is a virtual sound source. As the physical token is passed between users around the table, spatial audio rendering could create the impression that the actual sound source moves along with the virtual object. On-surface rotation of the tangible objects adjusts the volume while the 3-dimensional placement off-surface moves the sound source. We highlighted this interaction concept with a blue form in Figure 4.3.

An *Off-Surface Tangible* could track when a tangible is shared between users.

With knowledge of their 3D position, designers can create *Off- and On-Surface Tangibles* that detect when they are shared between multiple users. Designers can expand the personal space metaphor by Scott et al., 2004 for each user into the air above the surface, and with an *Off- and On-Surface Tangible* it is easy to track in which personal space a physical token currently is, even if it is not placed on

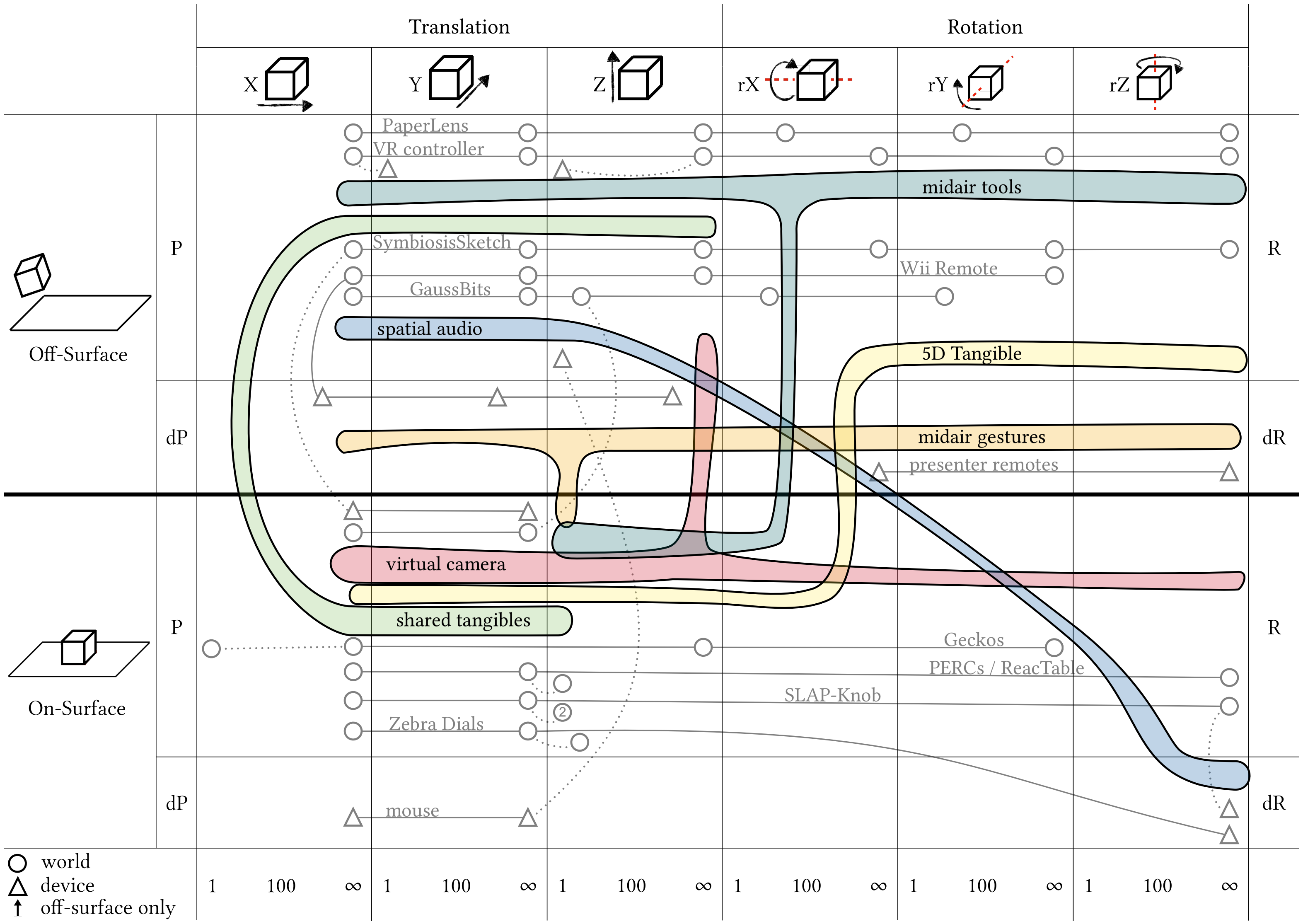


Figure 4.3: The *Design Space of Off- and On-Surface Tangible Interaction*with potential application and interaction designs highlighted. Combining off-surface and on-surface interactions suggests new designs. We especially looked for the combination of *off-* and *on-surface* interaction. We included the previous entries (in light-gray) to increase the visibility of empty areas in the design space.

the surface. This allows application designers to adjust their interface accordingly. Several research projects have explored how physicality benefits sharing and communication among multiple users: Speelpenning et al., 2011 found tangibles to increase ownership and tool announcement Speelpenning et al., 2011, and to help children resolve conflicts over shared tools Olson et al., 2011. We highlighted an area in the design space that could hold such a shareable tangible, tracking the position on-surface as well as in midair in green in Figure 4.3.

Picking up and sharing could further increase the beneficial effects of tangibles in multi-user scenarios.

4.5.2 Midair Gestures

Off- and On-Surface Tangibles also open up new opportunities to augment interactive surfaces with additional midair gestures. For example, the "shake-to-undo" gesture on modern smartphones, which reverts the last user action if the phone is moved back and forth quickly, could be used with a midair tangible controller to undo on-screen manipulations.

Gesture interaction is another potential space to explore.

Similarly, shaking a tangible representing an aerosol can might configure it to create virtual graffiti art. Quickly moving a physical game token across a large distance could be the game's action required to replenish a virtual energy source, enabling exertion games with physical tokens. Finally, another intriguing gesture to explore is quick moves in Z-direction, for example, to switch between different input modes. This way, midair gestures may also help alleviate some of the challenges that *Off- and On-Surface Tangibles* present to users and application designers, discussed next. The area for tangibles supporting midair gestures is highlighted in orange Figure 4.3.

Shaking a tangible could undo previous actions or fit nicely into an exertion game.

4.5.3 Tangible Proxies

A *Off- and On-Surface Tangible* that detects if it is placed on a surface, for example, a desk, could offer a richer interaction for Augmented or Virtual Reality as well. Many applications with tangible controllers in AR and VR allow users to switch between virtual tools that the tangible controller represents. Equipped with surface detection, a *Off- and On-Surface Tangible* controller could present different options in midair than on a surface. For example, switching tools happens when the controller is placed on a surface, while unique options regarding the picked-up tool are displayed in midair. Interactions like this may potentially increase the users' immersion in an augmented or virtual setting since placing a tool down and picking up another one further strengthens the analogy of real-world tool use. We highlighted the area for potential midair controllers with surface detection in Figure 4.3 (midair tools).

Tangibles as tools, could switch their mode while placed on a surface.

Tangibles are often used as "proxies" for virtual objects on tabletops. Since a user cannot reach "into" a display to grab the object, tangible proxies allow a direct and natural manipulation by mapping the movements of the tangible to the virtual object. When using *Off- and On-Surface Tangibles*, users could manipulate not only the location of the virtual object in X and Y, but also its rotation by picking up this proxy. We highlighted this design in yellow in Figure 4.3. Figure 4.1 also shows a prototype drawing of such a tangible next to its entry into the *Design Space of Tangible Interaction*.

Tangibles as domain objects can represent virtual objects visible on a screen and offer intuitive handling of 3D objects.

All these additions to the *Design Space of Tangible Interaction* show that the design space also has the potential to inspire new tangible designs. The combination of on-surface and off-surface tangible detection opens a new modality of tangible interaction; tangibles are not only useful when tracked on a surface or in midair, but especially because they support the transition between these.

Just as Card's design space, our space can inspire new designs.

To evaluate this new idea to approach tangible interaction, we created a tangible prototype of the aforementioned tangible proxy. With our *5-D Tangible*, users can perform five-dimensional input for object manipulation tasks. An object's position is manipulated while the tangible is tracked on an interactive screen while users can control the rotation in midair. Thus we created the metaphor of actually reaching "into the screen" and picking up a virtual potentially completely different object.

We built a tangible proxy with our TABULA tangibles.

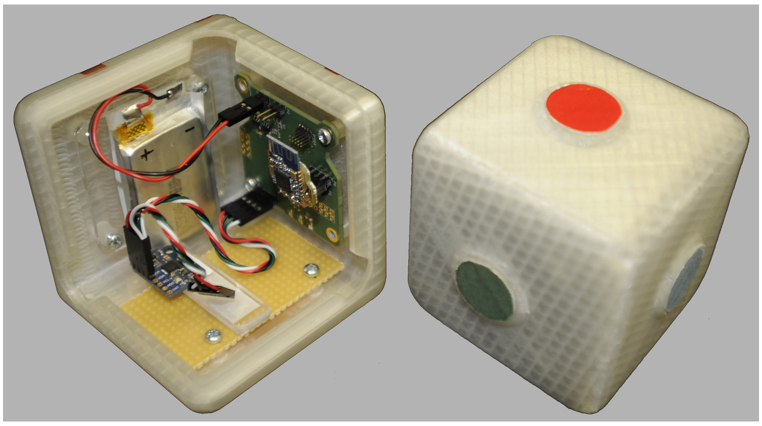


Figure 4.4: The internal parts of our *5-D Tangible*, the battery lasts for multiple days of use. The rotation sensor is placed on the bottom, the mainboard and the BLE module are on the right.

In the remainder of this chapter, we will present the prototype of our *5D Tangible*. We present the results of a comparative study, comparing this interaction to touch and a professional tool for 6D manipulation tasks.

The next section presents our 5D tangible.

4.6 The 5D Tangible

The *5D Tangible* represents a tangible proxy for virtual on-screen objects. It has the generic form of a six-sided dice so that it can represent multiple different objects without confusing the user. Thus, the *5D Tangible* is meant to be applied as a tangible tool for virtual objects. However, if a tangible object that implements the same interaction technique has the same shape as its virtual counterpart, it also can be a tangible domain object.

The 5D tangible is a tool to interact with on-screen virtual 3D objects.

With our 5D Tangible, we designed a user study to better understand the combination of on-surface and off-surface tangible interaction. Additionally, we compared users' performance for when the *5-D Tangible* is implemented as a tool vs. as a domain object.

We conducted a user study with the 5D Tangible.

4.6.1 Implementation

The tangibles components are similar to those in a PERC tangible.

The 5D tangible builds up on the design of PERCs and TABULA tangibles. Figure 4.4 shows the internals of the *5D Tangible*. It consists of two main parts. Detection on the capacitive screen uses the PERCs technique as presented in Chapter 2 "Making Tangibles for Interactive Tabletops: TABULA Tangibles".

It adds a 3-axis gyroscope to track rotation in midair.

The second part is a 3-axis rotation sensor transmitting at 50 Hz, which proved enough to avoid noticeable lag of the virtual object rotation on the 30Hz screen. We used a Bluetooth Low Energy (BLE) module to send the sensor information to our system, which updated the virtual object on-screen accordingly. Figure 4.1 shows where this newly created input device falls in our design space. It also shows the different manipulation axes and where users can manipulate them.

4.6.2 User Study

Our study was designed to understand the interaction between on- and off-surface interaction.

We designed a user study to better understand on- and off-surface tangible interaction, the *5D Tangible* is tracked both on the screen surface and off-surface in midair. On the multitouch display surface, it uses the technology of existing tangibles on tabletops for two-dimensional position tracking. We added active sensors to the tangible that track its rotation along the three axes (roll, pitch, yaw) in midair.

We purposefully designed the study to require users to switch between midair and on-table tracking.

We implemented an application that asks users to move and rotate a given virtual 3D object on the screen to a target position and rotation, indicated by a grayed-out copy of the object. Figure 4.5 shows the two objects next to their greyed out counter parts. The die is an exact virtual representation of the *5D Tangible* while the plane represents an entirely different object. This allowed us to compare users' performance for the tangibles implementation as a tool vs. as a domain object. We used this application to test the *5D Tangible* against two other commonly available 3D manipulation tools.

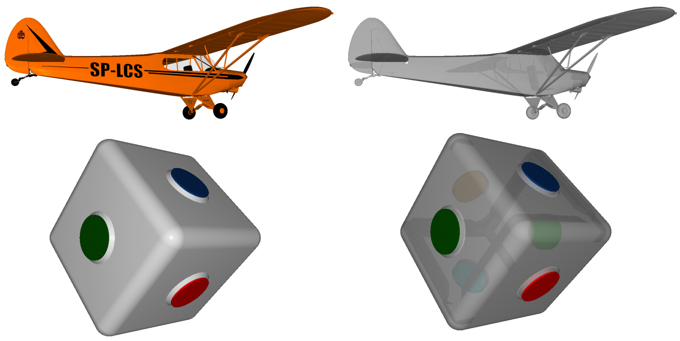


Figure 4.5: The two different objects (left) participants were asked to move to the same position and rotation as the given targets (right).

Input Conditions

Since the *5-D Tangible* implements a completely new interaction technique, we wanted to compare its performance to existing techniques for the same task. On multitouch tables, the primary interaction technique is touch. Therefore we included a touch condition in our study. Additionally we included rotation and translation with a 3DConnexion SpaceMouse by *3DConnexion Space Mouse* n.d. These are also called 3D mice, and many 3D design professionals use these when creating and manipulating 3D objects.

Users performed the task with the 5D tangible, touch, and a SpaceMouse.

We created an on-screen rotation widget for pure touch interaction called "Rotation Gizmo" as seen in many 3D-manipulation applications. This Rotation-Gizmo includes a virtual trackball to allow multiple axes to be manipulated simultaneously. Figure 4.6 shows the rotation gizmo around the virtual die object as used in our study.

Touch was performed with an on-screen rotation gizmo.

For the tangible condition, users were asked to place the tangible on the table. After a small calibration phase, the virtual object rotation was directly coupled to the rotation of the *5D Tangible*.

The tangible conditions were completely free movement, or with an additional button to fix the rotation input.

As discussed above, when a user places a tangible on the screen, and its physical shape does not allow it to remain in the desired orientation (like the *5D Tangible* that won't

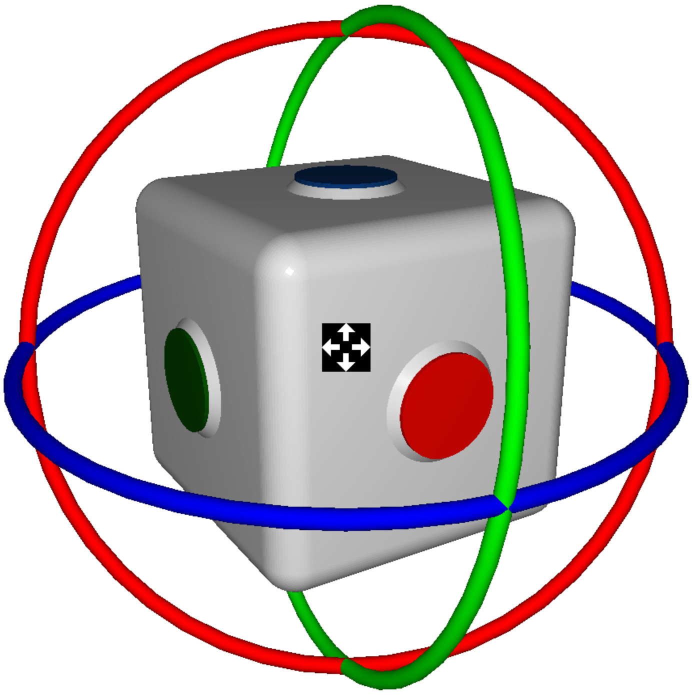


Figure 4.6: In the *Touch* condition, participants were asked to use a rotation gizmo as seen in many 3D manipulation applications. The cross in the center is used for translation.

stand on its edge), the user loses their current rotational input. Therefore, we added a second tangible condition that lets users "save" the current rotation and turn off orientation detection by pressing an on-screen button just below the 3D target object. If a user wants to change the rotation again, they can press the same button, and the 3D object snaps back to the orientation of the *5D Tangible*. This way, users could always determine, for example, which side of the cube was mapped to the bottom of the virtual object. In total, this gave us four different input conditions for our user study.

1. Touch: on-screen touch interaction with a rotation-gizmo.
2. 3D-Mouse: the professional's tool to manipulate 3D objects.

3. Tangible: off- and on-surface tangible interaction combined
4. Toggled: similar as the Tangible condition, but with a way to save the rotational input.

We hypothesized that the best way to move and rotate a virtual 3D object would be to have an exact physical replica of this object in your hands. Since this is hardly realistic in everyday interactions, we created two virtual 3D objects for our study. The first one is a virtual version of our *5D Tangible* so that the virtual and physical object look the same. The second virtual object is a plane since it has little resemblance to the tangible. Figure 4.5 shows the two virtual 3D-objects next to their grayed out target copies.

We thought, handling the exact same physical object would be faster than handling something different.

In total this created a set of eight different input × object conditions:

1. *Touch + Cube*
2. *Touch + Plane*
3. *3D Mouse + Cube*
4. *3D Mouse + Plane*
5. *Tangible + Cube*
6. *Tangible + Plane*
7. *Toggled + Cube*
8. *Toggled + Plane*

Study Setup

During the study, we asked participants to stand next to our multitouch surface, an 84″ Microsoft Surface Hub used horizontally. This resembles a table with a size of 220 × 117 cm and a height of 74 cm. The screen resolution is 3840 × 2160 pixels.

Participants were standing during the study.

Experiment Procedure

Participation in total was always below 60 minutes.

We asked participants first to fill out a consent form and a small questionnaire about their demographics. Afterward, they performed six repetitions of different position and rotation targets for each of the conditions, for a total of 48 repetitions. This took each user about 40 minutes in total. After performing the tasks, we asked participants to fill out a questionnaire about the different input techniques. We offered participants sweets and drinks during and after the study and regular breaks to prevent possible fatigue effects. To address learning effects, we counterbalanced the eight conditions with a Latin square design.

Participants

We had 24 participants, some were familiar with 3D design tools and tangibles.

24 participants (aged 22–30, $M = 25.5$, $SD = 2.1$, 1 left handed, 5 female, 1 divers) participated in our user study. 13 reported at least some experience with 3D design tools, and 4 of these had experience with the 3D mouse. 18 reported at least some experience with tangible user interfaces.

4.6.3 Results

In total there were 1152 tasks fulfilled.

Our users performed a total of 1152 tasks, yielding a total of 737745 log entries including timings, position and rotation for the virtual objects. In 9 cases, participants were unable to match the virtual and the physical object without help from the instructor; we removed these tasks from our evaluation.

We log-transformed the timing data before the analysis.

Since the data for task completion times (*Time*) and total rotation in all three degrees of freedom (*TotalRotation*) was not normally distributed, we performed our analysis on the log-transformed data. Total translation combined in x and y direction (*TotalTranslation*) was normally distributed, so our analysis was performed directly on that data.

There were no significant effects regarding the different target positions or orientations to which users had to move the different objects. Therefore, we present the rest of our results from the combination of the different tasks for each condition.

The different target positions did not affect users performance.

Input and *Object* on *Time*

Regarding task completion time, we wanted to know if the combination of on-screen and off-screen interaction would be able to compete with the existing standards for such interactions. Our ANOVA revealed a significant effect on *Time* for the different input conditions ($F(3, 112) = 72.34 p < 0.0001$). A pairwise comparison with the Tukey-HSD test showed that the *3D Mouse* condition was significantly faster than all other input conditions ($p < 0.0001$ for all 3). Touch performed worst with significant differences to all other conditions ($p < 0.0001$ for *3D Mouse* and *Tangible* and $p = 0.006$ for *Toggled*). The two *5D Tangible* conditions *Tangible* and *Toggled* did not perform significantly different ($p = 0.61$).

The SpaceMouse was fastest, while touch was the slowest.

There also was a significant effect on *Time* depending on whether participants had to place the *Plane* or the *Cube* object ($F(1, 1112) = 6.60, p = 0.010$).

Between *Input* and *Object*, we found a significant interaction effect ($F(3, 1112) = 7.69, p < 0.0001$). A pairwise comparison revealed some interesting effects: For most *Input* × *Object* combinations, there were no significant effects between the two *Object* conditions, only for the *Tangible* condition this was the case. In this condition, placing the *plane* object correctly took participants significantly longer than the *cube* object ($p < 0.0001$).

Using the tangible, participants took significantly longer to complete the plane tasks.

On average, users performed fastest in the *3D Mouse+Plane* condition ($M = 14.15$ sec $SD = 6.9$), while the *Touch+Plane* condition was the slowest ($M = 25.24$ sec $SD = 15.5$). For all input conditions except the *3D Mouse*, the cube object was placed faster than the plane (5.5 sec for *Tangible*, 2.7 sec for *Toggled*, and 1.2 sec for *Touch*). On average, *3D Mouse*

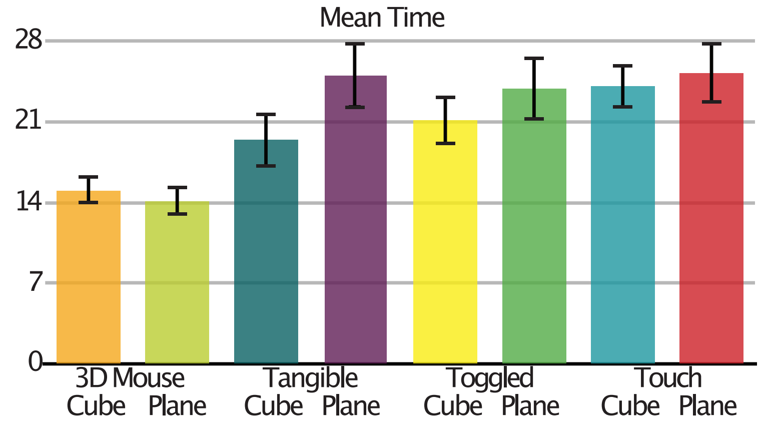


Figure 4.7: Mean *Time* in seconds with 95% confidence intervals for the different input conditions. Participants completed their tasks fastest in the *3D Mouse* condition, and slowest in the *Touch* condition.

was 10 sec faster than *Touch* and 7.8 sec faster than both tangible conditions. Figure 4.7 shows the timings for all input and object conditions with 95% confidence intervals.

Input and *Object* on *Total Translation*

To understand the interaction better we looked how much participants moved the objects.

To see if different input conditions also influence users movement strategy, we measured how far participants moved the virtual object across the surface. We created a set of target positions and pseudo-randomly assigned these to each *Input* × *Object* combination, to make sure that every participant had to move the objects equally far while avoiding learning effects between conditions.

In the tangible condition, users moved the objects significantly less.

An ANOVA revealed a significant main effect on *TotalTranslation* by the *Input* condition ($F(3, 1112) = 11.95, p < 0.0001$). A pairwise comparison with Tukey HSD showed that, compared to *Tangible*, participants moved the virtual objects significantly farther in the *3D Mouse* and *Touch* conditions ($p < 0.0001$ for *3D Mouse* and $p = 0.0117$ for *Touch*). There also was a significant difference between *3D Mouse* and *Toggled* ($p < 0.0001$). Other pairwise comparisons were

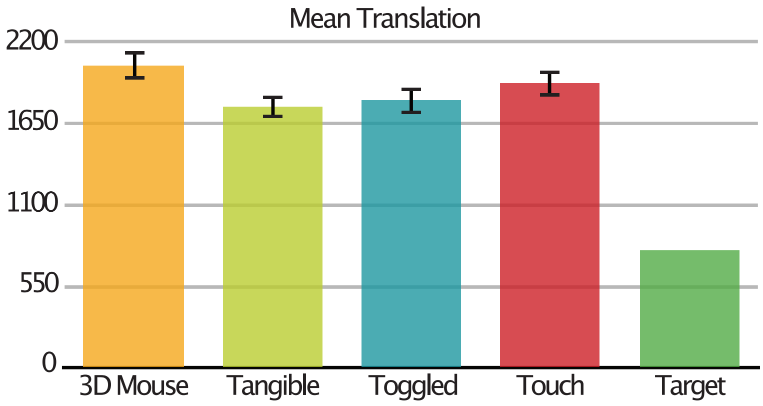


Figure 4.8: Mean *TotalTranslation* in pixels with 95% confidence intervals for the different input conditions. Target shows the minimal distance participants could achieve. Participants moved the objects significantly more in the *3D Mouse* condition, compared to the T-Cube conditions.

not significantly different. This supports our assumption that tangibles afford to be picked up, as participants limited the movement on-surface to a minimum.

As expected, due to our fixed set of target positions, there were no significant effects on *TotalTranslation* by *Object* ($F(1, 1112) = 0.37, p = 0.542$), and no significant interaction effects ($F(3, 1112) = 1.02, p = 0.381$).

On average, the minimal distance players had to move the virtual object to successfully finish a task was 795.8 pixels. In the *Tangible* and *Toggled* conditions, participants moved the objects close to the target position early ($M = 1761.3$ pixel $SD = 511.1$). In the *Toggled* condition, participants performed slightly more translations ($M = 1804.9$ pixel, $SD = 629.1$); however, *Touch* and *3D Mouse* needed even more transitions to finish a task (*Touch*$M = 1920.0$ pixel,$SD = 675.2$ and *3D Mouse* $M = 2043.1$ pixel,$SD = 714.9$). Figure 4.8 shows the total translation in pixels depending on the input condition with 95% confidence intervals.

Especially in the SpaceMouse condition, participants moved the objects around a lot more than in the tangible conditions.

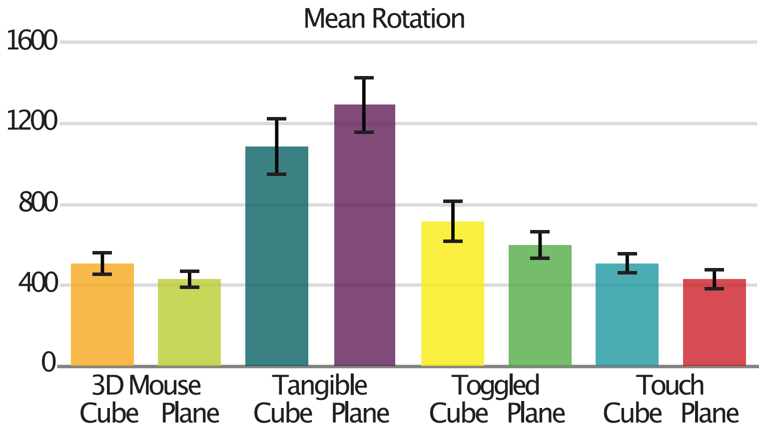


Figure 4.9: Mean *TotalRotations* in degree with 95% confidence intervals for the different input conditions. Especially in the *Tangible* condition, the virtual object was rotated significantly more.

Input and *Object* on *Total Rotation*

We also measured users total rotation input.

In addition to the translations performed, we also measured how far users rotated the object in total, by adding up the object rotation in all axes to a *TotalRotation*.

An ANOVA revealed no significant effect on *TotalRotation* by the *Object* condition. However, there were significant differences for the *Input* condition ($F(3, 1112) = 169.01, p < 0.0001$).

Users also rotated the objects significantly more in the tangible conditions.

A pairwise comparison showed that participants rotated the virtual object far more in the *Tangible* and *Toggled* input conditions than in the other conditions ($p < 0.0001$ for all comparisons). Additionally, the ability to stop the virtual object from rotating led to a significant difference in *TotalRotation* between the *Tangible* and the *Toggled* condition ($p < 0.0001$). There was no significant difference between *Touch* and *3D Mouse*($p = 0.98$).

There were also significant interaction effects on *TotalRotation* ($F = (3, 1112) = 8.79, p < 0.0001$). For most *Input* conditions, there was no significant difference between the two objects. Only for the *Tangible+Plane* condition, participants used significantly more rotation to find the given target compared to the *Tangible+Cube* ($p = 0.009$).

Especially the condition without the toggle lets users rotate the object a lot more.

Figure 4.9 shows the total rotations in degrees for all input conditions. In the *Tangible* condition, participants probably rotated objects more because they were not able to stop the virtual object from following the tangible's rotation when they wanted to perform a translation.

Input on Strategy

The *Touch* condition requires users to explicitly choose between movement and rotation, while the *Mouse* allows them to perform both simultaneously; In fact, the *3D Mouse* makes it nearly impossible to change object position without also rotating the object. The *5D Tangible* conditions allow for some rotation while the object is moved; however, to precisely control the 3D rotation, the tangible has to be picked up.

We found users to choose different strategies to complete the tasks depending on the input condition.

These differences between the interaction techniques may suggest different strategies to solve the given task. The results on *TotalTranslation* and *TotalRotation* also suggest that users applied a different strategy to solve their tasks in the *Tangible* and *Toggled* conditions. One might first solve the translation part and afterward fix the rotation until the software accepts the solution. However, another solution strategy is the opposite approach of first solving the rotation and then moving the object to the correct location. Therefore, we wanted to find out if participants use different strategies depending on the input condition.

Sometimes users first solved the translation part and later the rotation, sometimes they did this the other way around.

We logged precise position, rotation, and the current delta to the solution in real-time to identify these differences. Figure 4.10 shows the mean δ in rotation and in translation for each of the input conditions on a normalized timeline. Using this approach, we can compare the strategies for each input technique. It shows, for example, if for some input condition, users on average solved first the rotation or the translation part.

To understand these differences, we plotted the distance to the target over time on average for our participants.

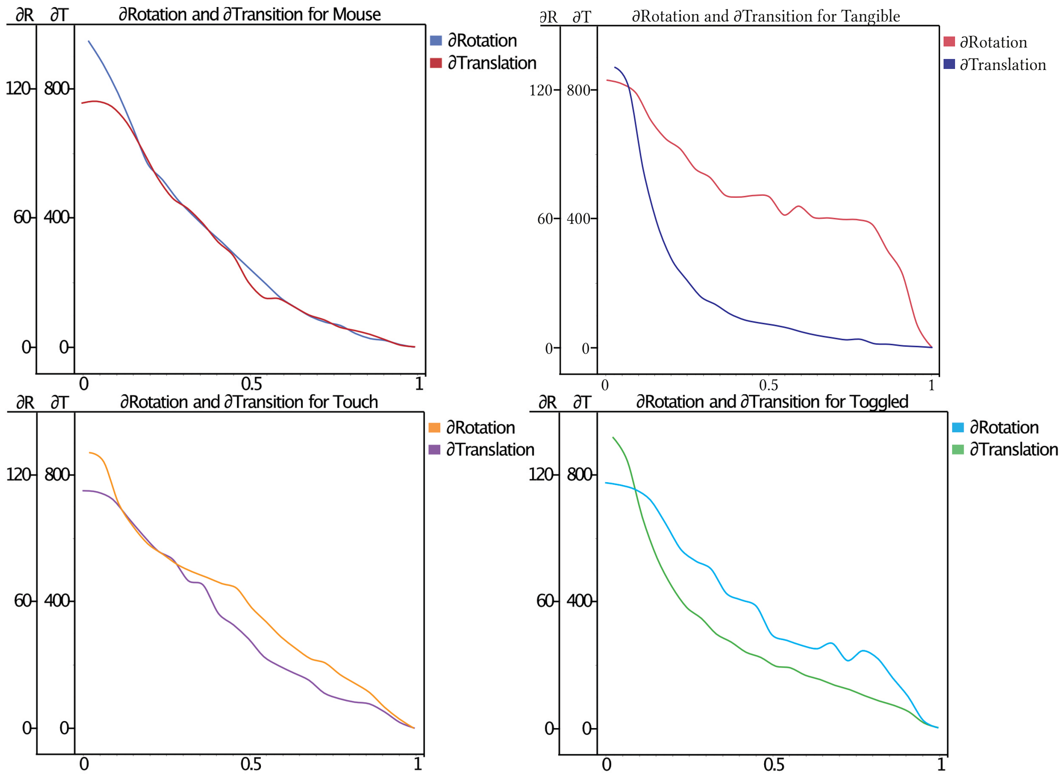


Figure 4.10: *δ-Translation* and *δ-Rotation* over time for all 4 input conditions. One can see that participants chose different strategies for the conditions. In the *tangible* condition, participants first performed the rotation and afterward the rotation part, while in the *toggled* condition the two were much closer. For *touch* and *3D mouse* the distances were even closer linked over time.

For the *3D Mouse* and *Touch* conditions, participants essentially tried to solve the translation and rotation task simultaneously. Both deltas decrease at a similar rate during the tasks.

For the *Tangible* conditions, however, the data looks quite different. Users first placed the virtual object as close as possible to the goal and then solved the rotation task. Sometimes users recognized afterward that they had to move the object a little more, which may explain the local minima in the δ-Rotation. Since the rotation of the tangible and the virtual object were always coupled, users had to give up their progress in rotation to move the object by a bit and afterward find the correct rotation again. The data from the *Toggled* condition suggests a behavior somewhere

In the tangible conditions, users switched their strategy, taking more time so solve both parts of the task individually.

in between the previous two: Participants still moved the object closer to the target first and then solved the rotation with some local minima. On average, however, these minima are closer to the target since participants used the toggle button to save their rotation progress. Only when they had to switch the rotation back on, some could not remember in which position they had held the tangible earlier and therefore had to solve the rotation again.

Only few could recreate a previous rotation input.

Ratings and Qualitative Feedback

We asked participants to rate the different input techniques on a scale from 1 to 4, 1 representing the best rating. Figure 4.11 shows a stacked bar chart with the different ratings. Overall, the *3D Mouse* got the best ratings: 15 participants rated this input technique 1, no one rated it 4. The *Touch* condition was rated worst: No one rated this condition best, and 22 gave it a rating of 3 or worse.

Most participants rated either the tangible or the SpaceMouse best.

Interestingly, many participants rated either the *Tangible* or the *Toggled* condition as second best while they rated the counterpart as worst. Participants who liked the *Tangible* condition often had difficulties with the *Toggled* condition and vice versa. 15 participants reported that they heavily preferred one *5D Tangible* input over the other.

Participants who liked one tangible condition often strongly disliked the other.

This was also represented in participants' qualitative feedback. Participants frequently found the option to toggle rotation tracking either very helpful, or very confusing since the virtual object would rotate abruptly to the rotation of the *5D Tangible* when engaging tracking. Participants were asked how easy to learn the different interaction types were. Many participants told us they initially assumed the rotation gizmo and touch input would be the most intuitive, but when trying out the techniques, found *Touch* to be tedious, in particular since it was difficult to see the connection between axis rotation and the virtual object. Seven of these users reported that they stopped using the rotation gizmo and purely relied on the virtual trackball. Although the *3D Mouse* condition was our fastest input technique, participants reported that they had difficulties to get

Participants mentioned the intuitiveness of the 5D tangible.

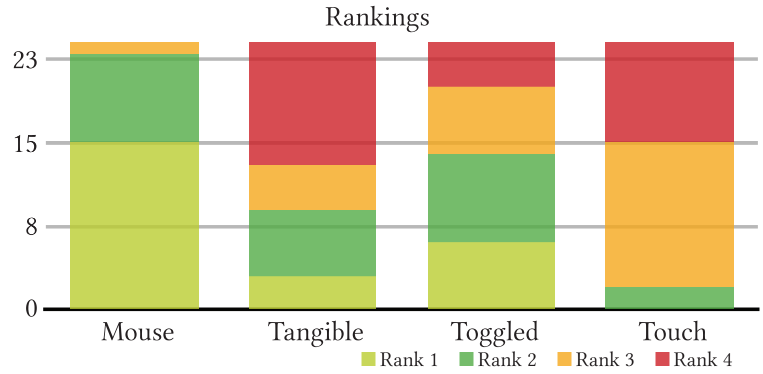


Figure 4.11: Ratings for the four different input techniques. The *3D Mouse* was rated best, the *Touch* condition worst.

used to its rate-based control when manipulating a virtual 3D object.

Participants also gave insight how to improve our 5D tangible.

The *5D Tangible* interaction elicited very positive responses from participants. However, there were differences in how participants would prefer this interaction to work in detail. Nine participants commented that they liked the direct interaction between the tangible and the virtual object. 15 participants, on the other hand, preferred to be able to disconnect the rotation of the tangible from the virtual object when switching between off- and on-surface interaction.

4.6.4 Discussion

This section discusses the results from our study.

Our study revealed some surprising effects when combining tangibles on interactive surfaces with midair interaction. We discuss these results below, and provide some initial guidance for interaction design in this space.

Completion Times

Although most participants were beginners with the input device, the 3D mouse outperformed the *Off- and On-Surface Tangible* and touch input in our user study. However, the low learning threshold and the easy, natural way to provide rotation input are attractive qualities of the tangibles.

As noted earlier, the transition between midair and table is crucial.

As we expected, the transition between on-surface and midair interaction is a key point to design for. Putting a tangible down to rest on a surface forces the tangible into certain rotations, depending on its shape. This may not be a change that the user wants and could frustrate them if the transition is not designed carefully.

As soon as participants lost the connection they had a hard time recovering.

For 3D manipulation, pure touch showed to be the worst choice. Participants quickly lost track of which axis to use to rotate an object into the correct position. This was somewhat expected, since the touch-based 2D input had to be mentally remapped to a five-dimensional interaction. For some participants, this proved worse than starting all over since they first had to overcome the initial confusion of losing track of their previous input.

Translation and Rotation

Users heavily utilized the ability to disconnect translational movement by picking up the tangible.

We did not expect that users would perform less movement across the surface with the *5D Tangible*. Within the standard deviations this difference adds up to a more than 1000 pixel difference, which represents more than a quarter of the screen. Since the translation was performed using the tangible on a tabletop, the benefits of tangible interaction that previous research has demonstrated might explain this difference.

The tangible conditions clearly encouraged rotating the objects as well.

Regarding rotation, the midair interaction clearly encouraged participants to rotate the objects more. If a participant was not entirely sure where, for example, the red side of the cube was, she would simply take a quick look at all six sides to find the correct orientation. This strategy would also apply to scenarios such as exploring an unknown virtual 3D object by looking at it from different angles. For example, 3D designers who continue someone else's work first have to understand the object fully before beginning to edit it. Our finding that the most rotations were performed in the *Tangible+Plane* condition suggest that a *5D Tangible* like tangible, with its easy way to perform rotations, could greatly benefit such tasks. This could be investigated in a future study asking participants to look for a specific side of an object.

Qualitative Feedback and Design Recommendations

The positive feedback from participants encourages further exploration of this interaction.

Combining midair interaction with an on-surface TUI received numerous positive comments from participants. However, there were considerable differences in how participants would prefer this interaction to work in detail. This curious finding illustrates that we are only at the beginning of exploring this design space.

We recommend that designers take a close look at their users' needs when deciding on a toggled or continuous input technique.

There are more open research questions regarding the transition *off-* and *on-surface*.

For now, interface designers may want to consider offering users a choice of absolute, toggled, or relative interaction. Since we found some users to benefit from absolute or toggled input, while others stated they would prefer a relative input device. This would detach the one-to-one physical mapping between tangible and virtual object but may still benefit certain tasks. But what should happen when participants reconnect the *5D Tangible's* rotation with the virtual object? Should the application snap the rotation of the virtual object, which was set in midair, back to the tangible's orientation on the screen? This enforced absolute mapping would most likely lose the previously preserved rotation state. Another possibility might be to instead keep its midair orientation and thus only use relative rotation input from now on? Users might even want to toggle between these conditions by themselves since both variants have their benefits and drawbacks. If they can do this, however, how should the difference between the relative and absolute position of the virtual object and its proxy be resolved for upcoming rotation manipulations?

Bimanual input, on hand on- and the other off-surface looks promising as well.

Finally, the option to combine tangibles with multitouch for bimanual input warrants further exploration. Regardless of the interaction techniques a researcher or designer uses in their on-surface tangible UI, our results suggest that adding midair input is worth considering.

A particular exciting crunch point when interacting with *Off- and On-Surface Tangibles* is the moment in time when users place a virtual object on a surface. At this point, the completely free 6D interaction gets restricted by the physical shape of the tangible. For example, during our study, some participants stated that they would like the cubic tangible to be able to stand on its edge. However, this was not possible since the cubic shape always dropped to one of the six faces. Similarly interesting, when picking up a tangible object, the user removes physical constraints that might have helped to provide more precise input. The transition between on-surface and off-surface interaction is an interesting point to look at in future research about tangible interaction.

Especially the transition between off- and on-surface requires further research.
How to help users recover their input?
What shapes fit for these tangibles?

4.6.5 Challenges

As our prototype implementation of an *Off- and On-Surface Tangible* showed, adding midair input to tangible user interfaces also creates new challenges to designers. For example, fixing a physical object in midair is impossible: if the user lets go of it after interacting with it, it would simply drop to the floor. But even if they put the object down safely, it is not immediately clear when she wanted the interaction to stop. To alleviate these issues, designers have to create smooth transitions. Additional buttons on a screen or on the tangible that serve as mode switches for midair tracking might be a solution. Alternatively, midair gestures can enable and disable midair input; for example, a quick move in the Z-direction, that means, towards the surface or away from it, could serve as the mode switch between on-surface and off-surface interaction. However, there is no clear answer to what design might be the easiest or most reliable option, and we think more exploration of this interaction is required.

Our research is a first step towards exploring the *Design Space of Off- and On-Surface Tangible Interaction*. We hope it inspires other researchers and designers to go deeper into this area of research.

Another issue is resynchronization: If a user can suspend the mapping of their midair tangible input, the position and orientation of the tangible are now detached from the virtual object it was tied to before. When the user reenables this mapping later, how should the interaction continue?

Turning a close coupling between tangible and virtual object on and off is challenging for the users.

The naive solution of snapping the virtual object to the current position and rotation of the tangible can get confusing if the user does not remember how the two entities were coupled ("which side of my tangible represents the bottom of this virtual plane model?") A relative input mapping addresses this problem, but such a mapping ignores the power of natural mappings between the tangible and virtual shapes. Again, there is no clear answer on how to solve this issue best, warranting future research.

4.7 Conclusion and Future Work

In this chapter we presented the *Design Space of Off- and On-Surface Tangible Interaction*.

Design Spaces have a long tradition in technical human-computer interaction research. In this tradition, we presented and discussed the *Design Space of Tangible Interaction*. Building upon the Design Space of Input Devices by Card et al., 1990, we added capabilities to distinguish between on-surface and off-surface interaction and the device and world-coordinate-system. We showed the validity of the *Design Space of Tangible Interaction* by placing existing work in tangible interaction inside the design space. It provides a structured approach to classify different ways of combining midair input with classic tangible on-tabletop interaction. Such a classification can structure the comparison between different tangible designs and visualize connections, which are otherwise hard to see.

We showed its validity and that it can inspire new designs.

As a design space, it also suggests potential interaction designs by combining previously unconnected areas or filling empty spots in the design space. We discussed some sample designs that the design space inspires and identified possible crunch points at the transition between midair and on-surface interaction in a user study on a 5D manipulation tangible.

The combination of on- and off-surface interaction is exciting to look at further.

We are particularly interested in learning more about the transition between on-surface and off-surface interaction, how user input can be saved across that boundary, and how such interactions may be made clear to the user. Additionally, racking Z-axis position above the surface beyond the binary on-/off-surface distinction allows for many interesting yet unexplored interaction designs. The lack of designs that include precise Z-axis tracking is surprising since tangibles, like any other physical object, really afford to be picked up and handled freely with our hands.

We hope to inspire other researchers to join in on exploring this design space.

In all, we hope that the *Design Space of Tangible Interaction* will help future researchers to structure and reason about existing and new designs and get inspired for future research projects in Off- and On-Surface Tangible Interaction.

Chapter 5

Tangible Interaction Beyond Usability

Since the early usability studies, tangibles have been proven to enhance users' interaction with multitouch surfaces. Fitzmaurice, W. Buxton, 1997 showed that bimanual, graspable controllers allow the user to be more accurate than single-handed devices like a mouse. Tuddenham et al., 2010 confirmed these findings for tangibles vs. multitouch input. Weiss et al., 2009b, Hancock et al., 2009 and Voelker et al., 2015b showed that tangibles increase users' ability to work eyes-free, e.g., as indirect controllers. However, these studies focused on the basic perception and motor performance of single users. There are few studies about tangibles' effects on human thinking or interpersonal communication.

We've discussed tangibles' ergonomic and motoric benefits.

Publications: The work in this chapter is a collaboration with Anke Brocker, Sebastian Hueber and Simon Voelker. The author is the main author of the paper; he was also responsible for developing parts of the hardware, writing parts of the software, designing the experiments, and analyzing data from the experiments. Part of this work was first published as a paper at the CHI 2018 conference Cherek et al., 2018. Several sections of this chapter are taken from this publication. Furthermore, parts of this work were also published as master thesis by Hueber, 2018 who conducted the construal study and by Brocker, 2017 who conducted the tangible awareness study.

We look at tangibles' effects beyond usability.

In this chapter, we present the results of studies that evaluate tangibles beyond their primary usability benefits. We show that tangibles increase users' awareness in a competitive multi-user setting and present a study measuring users' construal level when interacting with tangible pens compared to interacting with a handheld tablet.

5.1 Tangibles and Construal

The construal level theory evaluates the level of abstraction users apply when thinking about, e.g., simple activities.

The construal level describes how concrete (low) or abstract (high) a user's interpretation of an event or action is. For example, interpreting "note-taking" as "writing something down" indicates a lower level of construal than interpreting it as "getting organized". Higher levels of construal are associated with thinking about the "bigger picture", while lower levels indicate focusing on small details. At CHI 2016, Kaufman, Flanagan, 2016 presented a study indicating that digital platforms such as tablets trigger lower construal levels than non-digital platforms like pen & paper. This is an alarming finding for the CHI community and beyond as we rapidly move to digital delivery platforms.

A study from 2016 showed potentially problematic effects on participants' construal level when working at a screen.

Because of this, we set out to further examine this effect by controlling for the input modality (touch vs. pen) in addition to the output modality (screen vs. paper). Our results were highly surprising: (a) We found *no* significant difference between any of the digital or non-digital input and output modality combinations, and (b) we were unable to replicate Kaufman and Flanagan's results for the non-digital platform but found our results to be in line with the body of previous research. We discuss the implications of these findings, whether the Behavior Identification Form used in this line of research is the correct instrument, the relationship between input modality and platform, and whether context may overwrite certain effects.

5.1.1 Construal Level Theory

The potential long-term impact of modern technology on human cognition is the subject of an ongoing and crucial debate, not only in the HCI community. Higgins et al., 2012 presented a meta-analysis on research about the impact of technology on children's learning ability. They gather six common myths about the positive influence of technology and clarify these assumptions with results from research. In his article in The Guardian Naughton, 2010 collected statements from neurobiologists, critics, psychiatrists, and writers, discussing whether the internet changes the way we think and read. If our ability to read is affected by the presentation, on paper or on screen, is also discussed by Mangen, 2008.

The potential long-term effects of using modern technology is a long ongoing discussion not only in HCI.

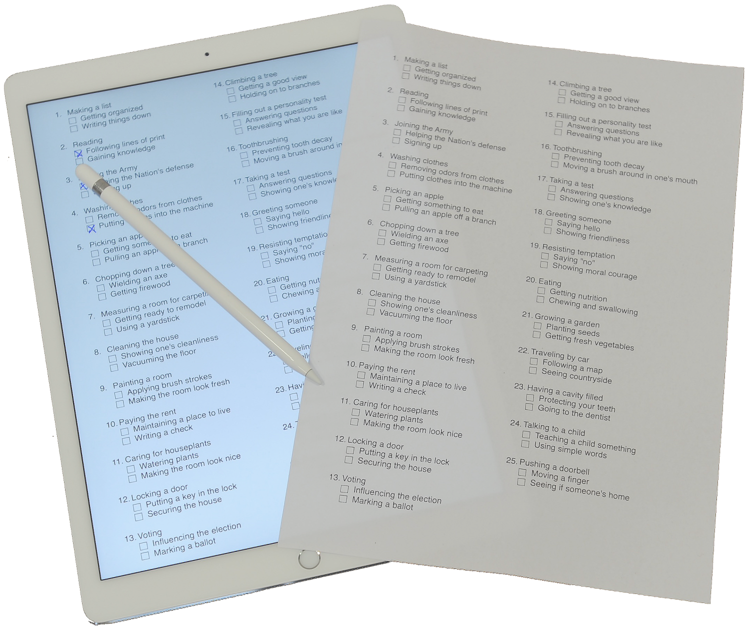
With digital media becoming an ever more integral part of our everyday lives, we need to understand how their consumption differs from how we perceive traditional, non-digital media. Do we perceive and understand differently when reading a text on-screen as opposed to paper? Back in 2007, Coiro et al., 2008 already stated that "we currently lack adequate theories, constructs, and methods" to answer these kinds of questions.

We're even unsure if our methods are sensitive to the effects we're looking for.

One way to approach this sensitive question is to measure the effect on people's mental *construal level*, a measure that determines how concrete (low) or abstract (high) a user's interpretation of an event or action is. The construal level theory was described by Trope, Liberman, 2011. Higher levels of construal are associated with considering the "bigger picture", while lower levels indicate focusing on smaller details. Higher levels are not automatically "better"; it is more important that the construal level is optimal for the task at hand Vallacher, Wegner, 1989. However, if consuming information on a digital vs. non-digital device changes the construal level, there could be important consequences for learning technologies, for example, since learners usually start by focusing on details, while later stages require more abstract thinking. We also know that people tend to think in more abstract terms when they feel more distant to a stimulus or event. At ACM CHI'2016

The construal level theory measures how abstract or concrete humans think.

A high construal level does not necessarily mean better thinking; low construal is good, e.g., for learning a new activity.



1. Making a list
☐ Getting organized
☐ Writing things down
2. Reading
☐ Following lines of print
☐ Gaining knowledge
3. Joining the Army
☐ Helping the Nation's defense
☐ Signing up
4. Washing clothes
☐ Removing odors from clothes
☐ Putting clothes into the machine
5. Picking an apple
☐ Getting something to eat
☐ Pulling an apple off a branch
6. Chopping down a tree
☐ Wielding an axe
☐ Getting firewood
7. Measuring a room for carpeting
☐ Getting ready to remodel
☐ Using a yardstick
8. Cleaning the house
☐ Showing one's cleanliness
☐ Vacuuming the floor
9. Painting a room
☐ Applying brush strokes
☐ Making the room look fresh
10. Paying the rent
☐ Maintaining a place to live
☐ Writing a check
11. Caring for houseplants
☐ Watering plants
☐ Making the room look nice
12. Locking a door
☐ Putting a key in the lock
☐ Securing the house
13. Voting
☐ Influencing the election
☐ Marking a ballot
14. Climbing a tree
☐ Getting a good view
☐ Holding on to branches
15. Filling out a personality test
☐ Answering questions
☐ Revealing what you are like
16. Toothbrushing
☐ Preventing tooth decay
☐ Moving a brush around in one's mouth
17. Taking a test
☐ Answering questions
☐ Showing one's knowledge
18. Greeting someone
☐ Saying hello
☐ Showing friendliness
19. Resisting temptation
☐ Saying "no"
☐ Showing moral courage
20. Eating
☐ Getting nutrition
☐ Chewing and swallowing
21. Growing a garden
☐ Planting seeds
☐ Getting fresh vegetables
22. Traveling by car
☐ Following a map
☐ Seeing countryside
23. Having a cavity filled
☐ Protecting your teeth
☐ Going to the dentist
24. Talking to a child
☐ Teaching a child something
☐ Using simple words
25. Pushing a doorbell
☐ Moving a finger
☐ Seeing if someone's home

Figure 5.1: The Behavior Identification Form displayed on a tablet that could be operated using touch or a digital pen, and printed on paper. Each user was asked to fill out the form in one of these three conditions.

conference, Kaufman, Flanagan, 2016[2] presented an important contribution to this debate. In a series of studies, they showed that users processing the same information on a digital device exhibited a lower level of construal than when using a non-digital platform such as a physical printout. In a nutshell, their results suggested that when operating a digital device like a tablet, people tend to think less abstractly than when performing the same task on pen & paper. Naturally, this result and its implications on technology use were discussed intensely in the community and in online media, for example, by Kurzweil, 2016, Nauert, 2016, and Waghorn, 2016.

Kaufman & Flanagan showed that participants' construal levels are lower for users at a screen.

Our work focuses on the first of Kaufman & Flanagan's studies, in which users filled out the Behavioral Identification Form (BIF), as described by Vallacher, Wegner, 1989, to measure construal level. This questionnaire contains 25

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[2] We will refer to this paper as "Kaufman & Flanagan " in this chapter.

items. Each item lists a behavior with two additional descriptions, one representing a more concrete (low construal level) and the other a more abstract (high construal level) interpretation of that behavior. Participants were asked to mark the description that currently felt more fitting to paraphrase the given behavior.

Kaufman & Flanagan also used the BIF to measure this effect.

Kaufman & Flanagan aimed to keep the digital and non-digital conditions as similar as possible; however, the input modality in their study was different between conditions: On the digital platform (an iPad), users answered using touch as input, while on the non-digital platform (paper), they filled out the questionnaire using a pen. We wondered if this circumstance could have caused the differences they observed. Therefore, we added a third condition in which users worked with the tablet using a digital pencil instead of touch. In the spirit of RepliCHI by Wilson et al., 2011 and Greenberg, B. Buxton, 2008, we also replicated the other two conditions from their study.

We wondered if the use of a pen in the paper version affected users' BIF scores.

Our results, however, were highly surprising: (a) Unlike Kaufman & Flanagan, we found *no* significant difference between any of the digital or non-digital input and output modality combinations, and (b) in particular, we were unable to replicate Kaufman & Flanagan's results for the non-digital platform, but at the same time found our results to be in line with the body of previously published research. We discuss the implications of these findings, whether the BIF used in this line of research is the correct instrument, the relationship between input modality and platform, and whether context may overwrite certain effects.

We were unable to replicate the effect measured by Kaufman & Flanagan.

We discuss this finding in this section.

This chapter, therefore makes the following contributions:

1. Present a replication of Kaufman & Flanagan's study, but with the opposite result, indicating that digital platforms do *not* seem to lower the level of construal after all;
2. An expansion of Kaufman & Flanagan's above study that distinguishes between tangible and non-tangible input modalities when comparing digital and non-digital platforms;

3. A discussion of the reasons behind these surprising differences, and how to deepen our understanding of this effect;

5.1.2 Study

First, we sat out to replicate Kaufman & Flanagan's study, including the BIF.

Our goal was to replicate Kaufman & Flanagan's study and extend it with a third condition using a digital pen on a tablet to investigate if there is an effect of input modality on the level of construal as measured by the Behavioral Identification Form (BIF) as described by Vallacher, Wegner, 1989. Therefore, we had three conditions total: *pen & paper* , *pen & tablet* , and *touch & tablet* .

We added a tangible condition to the digital and physical using the Apple Pen.

In the *pen & paper* condition, we printed the BIF on a single page (paper size A4 = 297 x 210 mm, font Helvetica 12pt, text height around 4 mm, line spacing about 5 mm) and attached it to a clipboard. To fit all 25 items on one page, we used a two-column layout with the two alternative descriptions placed below each other. Figure 5.1 shows the printed version next to the tablet and pen.

We designed all conditions to match as close as possible.

We conducted the digital conditions on an iPad app developed for this study.

In the *touch & tablet* and our additional *pen & tablet* conditions, the BIF was presented in the exact same way but on a digital screen. We used a white Apple iPad Pro 12.9" in both these conditions, as its display and device size closely match an A4 page. We set page and font sizes to exactly match the *pen & paper* condition. In the *touch & tablet* condition, users checked an item by tapping on the checkbox itself or the description next to it. Tapping a checkbox again deselected it to support correcting mistakes. In the *pen & tablet* condition, we used the Apple Pencil as the input device. Our application handled pen input just as if users were in the *pen & paper* condition. To closely mimic filling out the form with *pen & paper*, we did not provide an undo functionality in the *pen & tablet* condition. If users made a mistake, they would strike out the box previously checked and mark the intended one.

Procedure

We approached participants at our lab and on-campus and invited them to participate in our study. Each participant was randomly assigned to one of the three conditions. All conditions started with filling out a consent form and the introduction as originally described by Vallacher, Wegner, 1989 and asked them to fill out the form within 10 minutes. Afterward, we asked them to fill out a short questionnaire on demographics and touch device usage.

We conducted the study on campus and in our lab.

5.1.3 Results

We used a between-subjects design with 120 participants (age: 19–44, mean = 24.27, SD = 3.14, 47 female). All but one participant reported daily touchscreen usage. Most participants reported to rarely use a digital pen as input device (mean = 0.9, SD = 1.24) on a 5-point Likert scale (0–4). Three participants from the *touch & tablet* condition did not answer all questions, so they were removed from the analysis. The descriptive statistics are shown in Figure 5.2. We performed a one-way ANOVA[3] to assess the effect of the three conditions on the construal score.

Almost all of our 120 participants were frequent touch screen users.

The effect of the condition was not statistically significant, $F_{2,112} = 0.14, p = 0.87$, and the effect size was very small[4], $\eta^2 = 0.002$. This absence of an effect contradicts Kaufman & Flanagan's findings. These results were in line with the thoroughly evaluated results by Vallacher, Wegner, 1989. When introducing the BIF, they evaluated the questionnaire in 13 studies all yielding similar results. Therefore, we further analyzed our results using Bayesian analysis as described by Kay et al., 2016.

We had no significant differences between conditions, and the effect size was small.

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[3] The assumptions of normality and homogeneity of variance were met.

[4] Cohen, 1988 described the rule of thumb: small effect size $\eta^2 = 0.01$

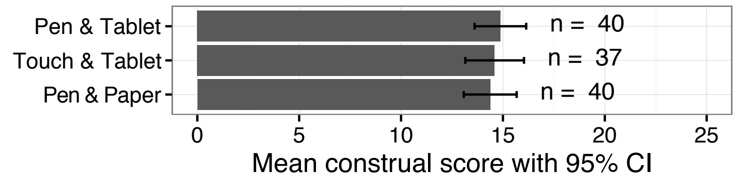

Figure 5.2: Construal scores for the three conditions in our study. The effect of the condition is very small, suggesting that digital platforms do not lead to lower levels of construal as previously reported.

Bayesian Analysis

Bayesian analysis can include results from previous studies.

To incorporate knowledge from the literature, we analyzed our results by creating three Bayesian generalized linear models[5]: (1) with non-informative priors, (2) with priors derived from the results of Kaufman & Flanagan, and (3) with priors derived from the results of Vallacher, Wegner, 1989 (from dataset 3: 285 participants, which was the study with the largest number of participants). Both priors were modeled with Student-*t* distribution (df = 20, scale = 2) centered at the mean of the results from the respective paper.

Even when we include Kaufman & Flanagan's results, there are only minimal differences between the different input conditions.

As shown in Figure 5.3 our results are not highly sensitive to choice of priors. Thus, the analysis of the three models would differ only at the second decimal place of the credibility intervals. To fit into the context of the CHI conference series, below we discuss the results of the second model, which uses Kaufman & Flanagan's results as prior. All credibility intervals are highly overlapping. The BIF score of the *pen & paper* condition lies in the interval [13.09, 15.65] (95% credibility interval). The credibility interval of the *touch & tablet* condition is only slightly shifted: [13.53, 16.11]. 82.17% of this interval overlap with the credibility interval of the *pen & paper* condition. This suggests that *pen & paper* and *touch & tablet* would yield mostly the same BIF scores. Even if a difference is present, it would be very small. The *pen & tablet* condition also yields a similar credibility interval [13.57, 16.17], which again highly overlaps

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[5] All models were fitted using RStan (`mc-stan.org`) with 16 chains each with 20,000 iterations (half warmup), thinned at 8.

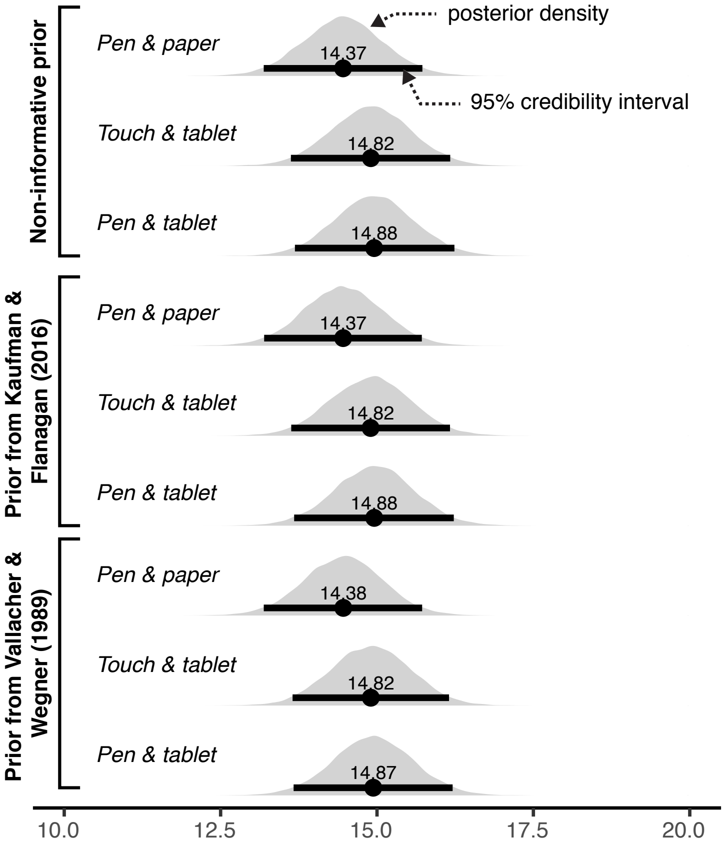

Figure 5.3: Posterior probability distribution of BIF scores from three priors. Even when taking Kaufman & Flanagan's results into consideration, the credibility intervals of all conditions are mostly overlapping.

(80%) with the *pen & paper* condition. Thus, changing from touch to pen is not likely to change the BIF score. This is, of course, highly surprising, as it contradicts Kaufman & Flanagan's results.

5.1.4 Discussion

The first surprising finding is that the replication part of our study delivered the opposite result of Kaufman's first study. We will look at any differences in the setup of these two studies and whether they explain the different results.

We used a different tablet to present the digital condition.

Tablet: Kaufman & Flanagan used an Apple iPad 2 to perform their experiment. We decided to use a white 12.9″ iPad Pro instead for the following three reasons: Firstly, the iPad Pro's dimensions are similar to our A4-size paper, especially with the white bezel (the iPad device diagonal is 3.6% larger than A4), while the iPad 2 is much smaller. Secondly, the device can differentiate between pencil and touch input. Hence, participants could rest their hands on the screen while filling out the form, just like in the non-digital condition. Thirdly, the iPad Pro has a display resolution of 264 ppi, leaving no discernible differences in the sharpness of the text rendered in the two conditions. In contrast, the display of the iPad 2 used by Kaufman has a resolution of 132 ppi, making text look slightly blurred when compared to print. However, suppose this difference had been the cause of our divergent results. In that case, our digital conditions should have performed better than Kaufman & Flanagan's digital condition, while our non-digital conditions should have been similar to theirs. However, that is *not* the case. Instead, we found Kaufman & Flanagan's non-digital condition to have delivered *higher* construal levels than we or the previous literature have been able to observe. We provide potential explanations further below.

Our results matched the results of Kaufman's digital condition.

Participants native language likely had no effect on our results.

Participants' language: The majority of Kaufman & Flanagan's participants were presumably native English speakers, while we conducted our experiment with mostly native German speakers. Since there is no validated translation of the BIF, we conducted the experiment using the English version. English proficiency at German universities usually exceeds C1 Coleman, 2006. Nevertheless, participants asking more than two vocabulary questions were excluded from the analysis. To further support our assumption that language had no effect, we repeated the *pen & paper* condition with a German version of the BIF using the translation by Boell, 2013. This additional group ($n = 30$) showed no significant difference in the construal level we measured with the English version of the BIF (One-way ANOVA $F_{1,68} = 0.17, p = 0.92$).

Context & Environment: Kaufman & Flanagan performed the experiment in an academic laboratory while we asked our participants to fill out the questionnaire directly after we approached them. We avoided noisy places, however, and made sure that participants could fully concentrate on the task. We also discuss this difference later in this section. As the experiment of Vallacher was also conducted at different universities, we assume that this has no impact on the results.

The context might have had an influence; however, this would only explain the surprising high scores found by Kaufman.

After our experiment and analysis, we approached both Kaufman and Vallacher to discuss possible confounding factors further. Unfortunately, Kaufman did not react to our messages. But we had several email conversations with Vallacher on the discussion points we summarize below.

The Effect of Familiarity with the Interaction

As also stated by Vallacher, the BIF was originally not designed to be used as a dependent measure. It was developed as a measure of individual variation in people's characteristic (context-free) level of action identification based on the principles of Act ID theory Vallacher, Wegner, 2012. The theory holds that people prefer to identify actions at higher levels but adopt lower-level identities when an action is difficult, unfamiliar, complex, or when the action's performance is imminent. Nevertheless, according to Vallacher the theory that people prefer higher level interpretations but adopt lower lever interpretations as they are confronted with a difficult or uncomfortable situation is still reasonable.

The BIF might not be a good measure for this, as it was not meant to be a dependent variable.

This would also hold for people who are unfamiliar with the use of a touch device as used to present in the *digital* conditions. However, our participants as well as Kaufman & Flanagan's reported mostly a daily usage of touch devices, therefore we can assume that no one was intimidated because of the output medium. For the *pen & tablet* condition this is not the case, but users seem to adopt the usage easily as it is close to the usage of a normal pen.

Maybe Kaufman's participants felt "pressured" to higher construal levels by the lab setting.

A specially designed questionnaire could measure digital vs. physical construal levels.

A possible addition for further investigation would be creating an action-specific and on users proficiency adopted questionnaire. If the questionnaire closer resembles information grasping, it might yield more detailed results between users of different input- and output modalities.

Platform and Modality

For example, a questionnaire with a focus on information grasping is promising future work.

So far, we cannot state that input or output modalities affected users' construal level. However, this was shown only for a general construal measurement. For further insight, we would follow Vallacher's suggestion to create more action-specific questionnaires. For example, a questionnaire focusing on information grasping might yield different effects depending on the input or output modality. Vallacher, Wegner, 2012 describes the process of creating a questionnaire that fulfills this requirement.

The Influence of Context

"In the wild" people's construal levels gravitate toward the difficulty of the given action.

In contrast to Kaufman & Flanagan, our study was conducted "in the wild". This might affect people's construal level as well. On-campus, users might be disturbed by others or simply not be in the right state of mind to concentrate on filling out a questionnaire. Vallacher stated that "in the wild", a person's construal level is likely to gravitate toward a level that reflects the difficulty or familiarity of a given action. Thus, our results might reflect the originally described values more closely, as they were meant to report a general, uninfluenced construal level.

Participants might want to give the "correct" answer in a lab, thus gravitating to higher construal levels.

In a laboratory setting, as in Kaufman & Flanagan's study, participants tend to feel more observed. Under pressure, people usually lean towards more abstract answers, as many believe this to be the "correct" or "desired" behavior. This effect might explain why people generally scored higher in the lab setting compared to our "in-the-wild" setting. However, in the digital condition of Kaufman & Flanagan's study, the construal scores were not higher than in our digital "in the wild setting". Possibly, more stressful settings are likely to bring out larger differences in people's general construal level. Therefore, a possible way to investigate further would be to use settings such as exams that might yield stronger results in the effect of digital vs. non-digital input or output modalities.

Beyond Kaufman & Flanagan's Evaluation

We did not replicate Kaufman & Flanagan's second and third study, which found further evidence that screens trigger a lower level of construal than non-digital platforms. These studies were performed on laptop screens, suggesting further investigation of the impact of different device types. Since unfamiliar situations usually trigger a lower construal level, it would also be prudent to investigate if using your own device vs. an unfamiliar one affects a person's construal level.

We could not replicate Kaufman & Flanagan's other studies as they did not perform these with established methods.

5.1.5 Conclusion

We presented a study on how digital vs. non-digital input and output modalities influence users' cognitive construal level. In contrast to earlier findings, our results show no significant difference between the three conditions *touch & tablet*, *pen & tablet*, and *pen & paper*. A Bayesian analysis of our data puts it into the broader perspective of related work and suggests that the differences observed by Kaufman & Flanagan warrant further investigation. We discussed the implications of these findings and possible explanations for the differences to earlier results and pointed out directions for future research to further understand this effect.

Neither a digital presentation nor the use of a pencil changed users' construal level.

We believe that further investigation to understand the effects of digital vs. non-digital platforms better is crucial to the field of HCI research. As our world is rapidly moving towards digital platforms, the implications of these effects could be staggering.

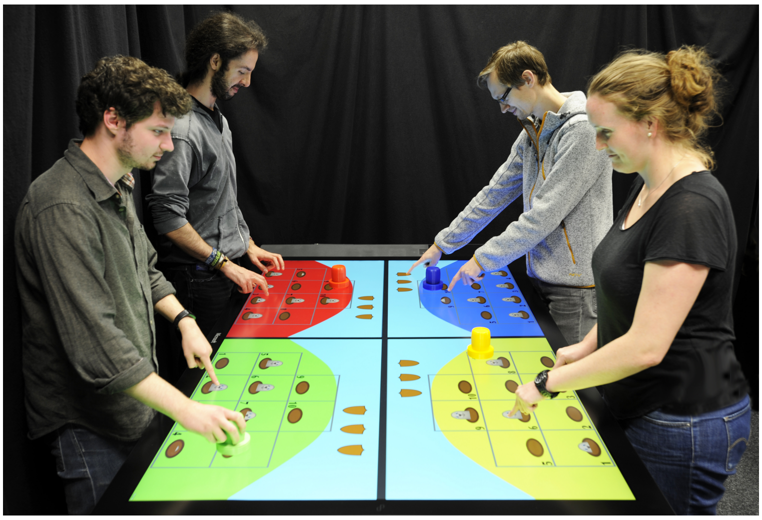

Figure 5.4: Four users playing the tangible version of our tabletop game. While playing Whac-A-Mole, each player also has to become aware of attack and defend events that other players trigger using their tangible, 3D-printed barrels.

5.2 Tangibles and Awareness

Previous tangible research focussed mostly on motor performance.

As described earlier, researchers mostly tangibles' beneficial effects on interaction in single-user scenarios. For example, Weiss et al., 2009b showed that they increase eyes-free performance. Fitzmaurice, W. Buxton, 1997 and Voelker et al., 2015b showed that they increase input precision, and our *5D Tangible* proved to be an intuitive input technique for challenging input tasks. These results, however, consider only the scenario of a single user at the table. Hornecker et al., 2008 stated that, since users can approach a table from different sides, a natural scenario is its use by several users collocated around the table. They were able to show that interactions around a table were more fluid, and their participants quickly resolved interferences. Recent advances in physical screen size, display resolution, and sensing technology have made this multi-user scenario technically feasible. For example, at a size of 220×117 centimeters, Microsoft's largest Surface Hub 84", which we used in our studies, easily accommodates four

On big screens, developers can create collaborative working spaces with enough space for each user individually.

people around it. According to Ziefle, 1998 its display resolution of around 45 dpi also allows users to stand close to the tabletop and still be able to read text efficiently.

We ask: “Do tangibles have beneficial effects on multi-user interaction?”

We asked ourselves: ”Do tangibles provide additional benefits in multi-user scenarios beyond their single-user effects?” Would users on such a table, for example, notice the actions of others more quickly if tangibles were used, and if so, how strong is this effect? Dourish, Bellotti, 1992 defined this “understanding of the activity of others, which provides a context for your own activity” is defined as *awareness*. We thus decided to measure the effect of using tangibles on large tabletops on the collocated users’ awareness.

We’ll present a study on awareness for secondary events created by others while participants were focusing on their primary task.

We report our findings regarding awareness for other players’ events.

After discussing related work in the remainder of this chapter, we first present a game we designed for our study. It supports 2 to 4 players at the table, with or without using tangibles. The game’s primary task continuously captures each player’s attention, while additional “attack” actions by the other players trigger a secondary “defense” task that the player has to switch to momentarily. We then describe our study that measured each player’s awareness of these attacks by comparing how fast they would react when other players triggered them by moving a tangible vs. an on-screen virtual object. We report on the quantitative findings from our study and the qualitative results from post-game interviews. From our findings, we derive a set of design recommendations for creating tangible tabletop games and other applications for multiple users. These recommendations should help decide when and how to use tangibles in such a setting and what side effects the designer may need to be aware of.

The main contributions of this section therefore are:

- An analysis of the effects of tangibles on user awareness when using large multitouch tabletops together, combining findings from a quantitative lab study and user interviews;
- Design recommendations for games and other applications on large multitouch tables.

5.2.1 Related Work

Tables naturally afford multiple actors to stand around them and work simultaneously. *Youtopia* by Antle et al., 2013 is a tangible world-building game for children that runs on a 40″ screen. Fan et al., 2014 found children to communicate more when using tangibles at the *Youtopia* system. A study by Speelpenning et al., 2011 showed that tangibles increase ownership and announcement of tool use in a collaborative work setting. They deduced that users have a higher awareness of the shared tools when working with tangibles. Tangibles help children to resolve conflicts over limited on-screen controllers, as Olson et al., 2011 were able to show with their tangible toolbar. Isenberg et al., 2012 examined collaboration around a 56×53 cm Microsoft PixelSense table and found that group tasks could be solved more efficiently when the group worked in closer proximity to each other. Inkpen et al., 2002 evaluated user communication and awareness around a larger, 150×80 cm table. They observed higher interpersonal interaction and communication when using a stylus over a mouse. *WeSearch* by Morris et al., 2010 proved that tables create benefits for collocated collaborative tasks. They conducted their user study at a 180×120 cm interactive table.

Some studies were able to show that tangibles can have a positive influence on participants' communication.

In summary, these studies illustrate that large tabletops, tangibles, and spatial proximity benefit collocated groups in various ways.

Awareness on Tabletops

Larger tabletops allow users to create their own personal workspaces, but this also means that the display no longer represents a single shared object of focus for all users. To continue to collaborate, users thus now need to recognize and become aware of each other's actions.

Previous awareness studies were conducted on relatively small screens.

Hornecker et al., 2008 found users to have a higher awareness for each other's actions in a multitouch setting compared to mouse interaction. However, at 65×50 cm, their system was probably too small to support parallel work

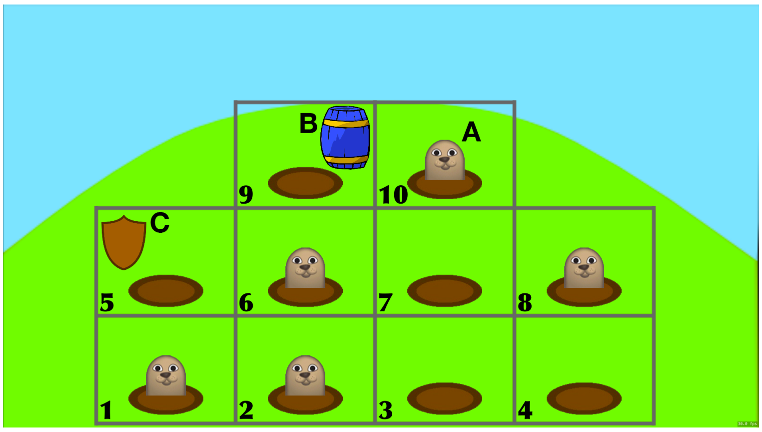

Figure 5.5: The game screen each player saw in our study, with moles (A) and one barrel (B) and shield (C). In a two-player game, this example is the green player's screen, as indicated by the "hill" color.

Secondary tasks need to attract users' peripheral perception to create awareness.

in separate personal workspaces. Chang et al., 2014 developed a timeline feature for an interactive board game and found users to have higher situation awareness when using individual timelines for each user in comparison to shared controls. They conducted the study on a 148×95 cm tabletop; unfortunately, these timelines were purely virtual, on-screen objects. Gutwin, Greenberg, 2004 argue that secondary task awareness can be improved if actions attract the user's peripheral perception: "If the actions of another user are attention-grabbing enough, the user can recognize these actions while executing their own primary task on the multitouch surface."

Based on related work, we wanted to learn if tangibles can create awareness for others.

Based on these results, the goal of our study was to determine if tangibles make it easier to become aware of other users' actions while completing an individual task. The idea was that tangibles attract exactly the peripheral perception that creates awareness for others around a large tabletop. Thus, allowing users to collaborate better while still focussing on their individual tasks.

5.2.2 Study Design

We created an attention-grabbing game for our study.

To measure human awareness for another user's actions in a collocated tabletop environment, we created a highly engaging and attention-grabbing game in single-player mode. An added secondary objective requires players to react to other players' actions. Since reacting to these events was necessary to win, we captured the percentage of successful reactions and their reaction times to determine a user's awareness of these events. This reflects in our main research question:

Does the use of tangibles in a collocated touch-based game on a large tabletop improve a user's awareness of other users' actions, as indicated by the success and speed of his reactions to these actions while completing a primary task?

Game Description

Players compete in a 4-player-Whac-A-Mole.

The game we implemented for our study is based on the arcade game classic Whac-A-Mole Aaron Fechter, Creative Engineering, Inc., 1976. Traditionally a single-player game, it challenges the player to hit or touch moles that appear randomly in holes in front of them. Over time the amount of moles increases, and the time to react decreases. This makes the game more and more demanding over time.

Additionally, players can steal points from each other.

Following the definition of *awareness* by Dourish, Bellotti, 1992 introduced earlier, we added a secondary task to the game that required users to be aware of other players' actions. The game mechanics are described below. The video figure of our corresponding CHI paper gives a better sense of the game in action (c.f. Cherek et al., 2018).

Primary Task: Catch the Moles

Figure 5.5 shows the game screen for a single player. It contains ten holes arranged on a hill that is colored corresponding to the player number. For every player, we

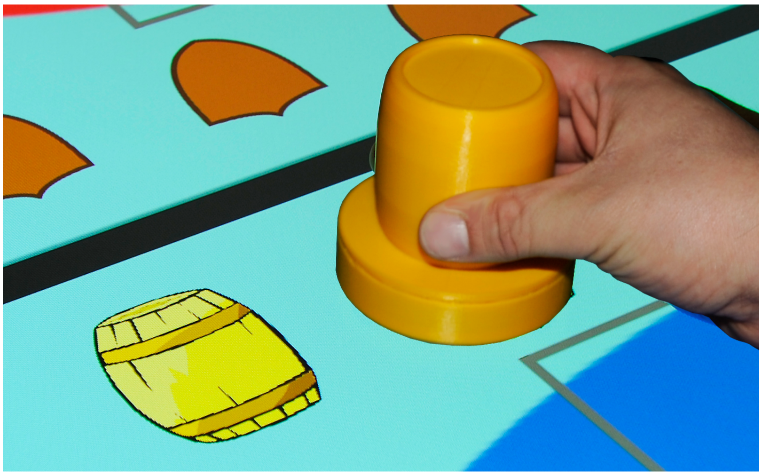

Figure 5.6: Virtual and tangible version of the barrel. To place an attack, players must move the barrel next to a hole in the player's area. This is the action that the defending player needs to notice and react to, and which we used to study players' awareness of each other's actions.

Players can reach a max of 240 points per minute.

generate 10 moles every 2.5 seconds, pseudo-randomly distributed over the ten holes. The primary goal is to catch each mole by tapping on it within 1.5 seconds before it disappears again, for 1 point per mole caught. This primary task thus represents a straight multitouch adaptation of the original Whac-A-Mole. Each player's hill has a different color: red, blue, green, or yellow. Figure 5.5-A shows the green player's playing area.

Secondary Task: Defending "Attacks"

On top, players can steal points from other players.

Our secondary task allows players to steal points from each other. For this, each player has a barrel in their opponent's hill color as shown in Figure 5.5-B. To steal points from another player, the attacker moves their barrel near a hole on their playing field, inside the box around it. As soon as the barrel is placed, all opponents start losing 1 point per second each, which the attacker gains. In the digital condition, the attacker drags an on-screen barrel icon with their finger; in the tangible condition, they grab and move a 3D-printed plastic barrel of similar size. Figure 5.6 shows the tangible and virtual barrel used to attack the yellow player. Players can move the barrels at any time. If a player places the barrel above the line between two fields, we use the center of the barrel to decide which field is attacked.

To stop losing points from an attack, a defending player must place one of their virtual shield icons next to the corresponding hole on their own field. This shield icon is shown in Figure 5.5. This stops and prevents any further attacks on a hole while the shield remains near it. Although players were not aware of this, noticing the attack was the secondary task and key activity we were interested in during our study. We informed players that, since attacks continue to steal points over time, reacting to incoming attacks as soon as possible is crucial to winning the game. This was to ensure that players would try to react immediately to an attack. Players had no other hint than the barrels to recognize incoming attacks. Only at the end of a game, we revealed the score, i.e., the total amount of points collected and stolen. We balanced the scoring mechanics until attending to both the primary task of catching moles and the secondary task of defending attacks was necessary to win the game. Note that the shields didn't need to be tangibles since we were just interested in the "peripheral" awareness of the barrel actions of others.

To defend against such an attack, players have to move a virtual token to the matching position on their field.

Figure 5.7 shows the timeline of a successful attack-defense event. These were the events that we looked for and analyzed to determine awareness. The time to react to an attack is defined by the time between an attacker starting to move a barrel and the defender starting to move a shield.

We show a complete sequence of events in Figure 5.7

Positioning Players Around the Table

All actions of an individual player on the table take place in their personal workspace of about 100×80 cm. We asked participants to stand around the table at four different positions along its long sides, as shown in Figure 5.4. We labeled these player positions as Bottom Left (BL), Bottom Right (BR), Top Left (TL), and Top Right (TR).

Each player had a personal area of about 100×80 cm.

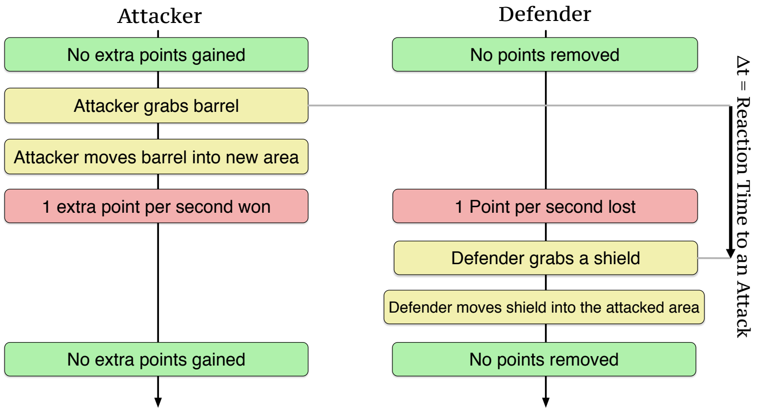

Figure 5.7: Timeline of a successful attack-defend combination. The reaction time is measured between the attacker beginning to move a barrel and the corresponding defender beginning to move a shield.

We rotated players around the table to mitigate position effects.

To understand whether awareness of tangible or virtual actions changes with the position of players around the table, we used five different combinations of player positions. We also included the four-player condition to study how tangibles influence awareness with more users around the table.

1. Bottom Left vs. Top Left (opposite of each other)
2. Bottom Left vs. Top Right (diagonally right across)
3. Top Left vs. Bottom Right (diagonally left across)
4. Top Left vs. Top Right (next to each other)
5. Everybody (4 players at the same time)

Hardware Setup

Players stood around a tabletop with an 84” screen.

We asked players to stand around an 84” Microsoft Surface Hub. The Surface Hub detects up to 100 touch points on a 220×117 cm display with a resolution of 3840×2160 pixels. We placed the display on a frame with wheels, bringing the tabletop surface to a height of 87 cm for use while standing.

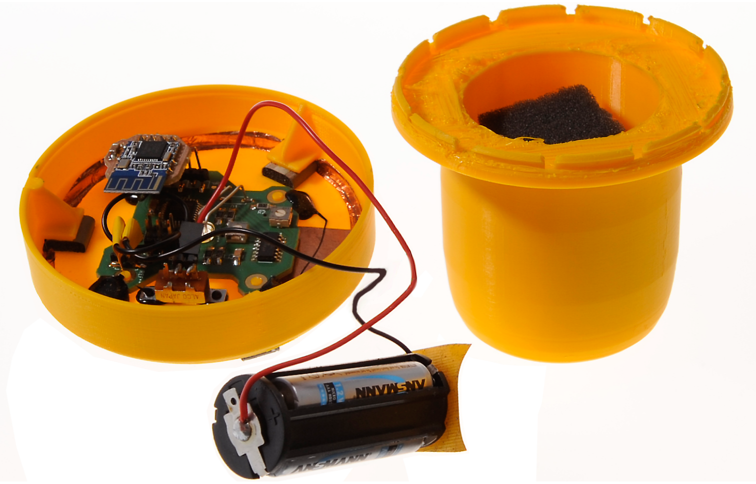

Figure 5.8: Our tangible barrels are based on PERCS tangibles. Using sensing circuitry, a microcontroller, and a Bluetooth module, they are tracked persistently on the capacitive touchscreen of our display, even when players are not touching them.

We added cooling fans to the table to support horizontal usage.

Figure 5.4 shows our setup with four players playing our version of "Whac-A-Mole" with tangible barrels. The manufacturer does not officially support the horizontal use of this display. However, we added additional fans with 3D-printed mounts below the table along its long edges that recreate the convection airflow to cool the display and did not encounter any issues running the system continuously for several hours at a time.

PERCs tangibles fulfill all requirements for our barrel tangibles.

Our barrel tangibles needed to be detected by the capacitive touchscreen even when players were not touching them, and the table needed to be able to tell the different barrels apart. To achieve this, we built our tangibles following Voelker et al., 2015a design of PERCs, which provide these capabilities. Figure5.8 shows the internals of a tangible barrel.

Measures

To evaluate users' awareness, we precisely measured all timestamps for all interactions at the table, including when players hit a mole, move a barrel, or a shield token.

We logged timestamps for every barrel and shield movement. We used these to compute the reaction times of successful defenses as explained in "Defending Attacks" above to determine players' awareness of each other's actions.

We also videotaped every game to identify and review player strategies later and get a rough sense of the players' current locus of attention. After the experiment, participants filled out a questionnaire, rating the effort of the different tasks for each version of the game. We also asked them to briefly describe their strategy, to understand whether they balanced or prioritized their primary and secondary tasks.

Experiment Procedure

We did not share beforehand that we were measuring users' awareness.

To avoid learning effects between the tangible and virtual conditions, we used a between-subjects design. To avoid influencing participant behavior, we did not share beforehand that our primary goal was to measure their awareness of other players' actions.

Participants played two randomly assigned 2-player and one 4-player round.

The experiment was carried out in groups of four players. All participants played twice against one opponent (2-player version) and once against all three opponents (4-player version), for a total of five games per group. Participants were assigned randomly to a position and opponent. The order of the 2-player games was counterbalanced with a Latin square to avoid learning effects.

We asked participants to fill out a questionnaire afterward.

At the beginning of the experiment, we introduced the game and allowed players to ask any rule-related questions. Players who were not currently playing were asked to wait in a separate room to relax, avoid distracting the active players, and prevent learning effects from watching. All participants played the four-player game last. Thus all players had the same amount of experience with the game at this point. After finishing all games, we asked participants to fill out the questionnaire.

Participants

64 participants (28 female), with a mean age of 28 (SD = 10.1), participated in the study. Through our between-group design, 32 participants each played the virtual and tangible version of the game. All participants played in groups of four. Most users stated that they had not used a multitouch device of the size used in our study before. However, all were familiar with portable multitouch devices like smartphones or tablets.

Most participants were not familiar with a touch tabletop of this size.

5.2.3 Results

Since the primary Whac-A-Mole task was quite demanding, some players did not always react correctly to an attack. To remove potential false positives, we focused our analysis on the successful attack–defense events. We thus only considered the reaction time if a player attacked a new area, and the defending player reacted with a correct defense. If a player did not correctly defend an attack, i.e., they moved the shield into the wrong area, we considered the defense unsuccessful.

We only considered successful defense actions for our measurements.

Using our videos and questionnaires, we identified two players who chose not to react to incoming attacks at all. We excluded their timing results from our analysis. We found 1149 successful attack–defense combinations, 785 in the virtual and 364 in the tangible condition. The amount of evaluated tangible attacks is smaller since we only evaluated attacks with complete touch traces; if the tangible was lifted or the touch trace was lost, we did not evaluate this attack. The success rate to evaluated incoming attacks was similar in both conditions, 58% in the tangible and 54% in the virtual condition.

Two players did not react to attacks at all.

We measured 1149 successful defenses.

Since the reaction times were not normally distributed (Shapiro-Wilk test, $p < .0001$), we log-transformed them before performing a one-way ANOVA to check for significance. Although the amount of evaluated attacks is not the same, an ANOVA is valid since the variances of both conditions are equal Field, 2013. It revealed that players

A one-way ANOVA showed significant differences in reaction times.

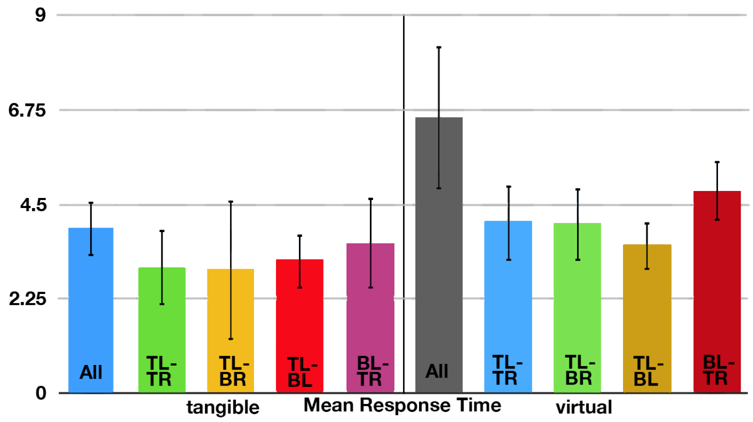

Figure 5.9: Mean response times for tangible and virtual games, with 95% confidence intervals. Players reacted significantly faster in the tangible than in the virtual conditions. Especially in the virtual 4-player version, reaction times were much slower.

Players were able to react more than 1 s faster in the tangible condition.

were significantly faster in the two-player tangible condition $(F(1, 883) = 7.97, p = .0049)$. Participants in the tangible condition needed 3.1 seconds on average to react to an incoming attack $(SD = 3.56)$. Participants in the virtual condition needed 4.2 seconds $(SD = 6.12)$. We also found a significant difference in the four-player version $(F(1, 261) = 15.99p < 0.0001)$. Players needed 3.9 seconds on average to react $(SD = 4.26)$ in the tangible vs. 6.5 seconds $(SD = 8.08)$ in the virtual condition. Figure5.9 shows the different game versions with mean response times and 95% confidence intervals. This shows that tangible attacks were recognized significantly more quickly than virtual attacks.

Players were slowest in the virtual 4-player version. But not significantly slower in the 4-player tangible condition.

We also investigated how reaction times changed when moving from two to four players. In the virtual condition, reaction times went up significantly $(F(4, 832) = 23.73, p < .0001)$. In the tangible condition, however, this was not the case $(F(4, 359) = 1.93, ns)$. A pairwise comparison revealed that the 4-player version was significantly slower than all other conditions ($p < .0001$ each). Players could not react to other players' attacks, as the primary task was too demanding to react to 3 other players. This was not the case in the same game but with tangibles. We also found one of the diagonal conditions (BL–TR) to have significantly slower reaction times compared to the opposing and side-by-side conditions ($p = .0012$ and $p = .0112$). Other pairwise comparisons were not significantly different.

Questionnaire Results

Players reported the 4-player version to be more demanding for both the tangible and the virtual versions.

Players reported that they had to actively look for incoming attacks since the table was too big to use the peripheral vision.

Most users reported that the 4-player version was more difficult and more demanding than the corresponding two-player versions. On a 5-point Likert scale, participants rated an average of 4.3 in the virtual version $(SD = 1.37)$ and 3.9 in the tangible version $(SD = 1.26)$. The tangibles were rated easier to notice than their virtual counterparts both in the two-player games $(M = 3.9, SD = 1.24$ vs. $M = 3.4, SD = 1.27)$ and in the four-player games $(M = 1.7, SD = .79$ vs. $M = 2.4, SD = 1.02)$. However, these differences are small, and again, for both versions, the 4-player version was rated more difficult. The free-form answers revealed interesting strategies performed by the participants. 11 participants in the virtual version reported that they had to look for incoming attacks since they could not react using only their peripheral vision. This shows that the workspaces on the screen are big enough to put content beyond them out of peripheral attention. However, 10 participants stated that they could react to incoming attacks in the tangible version of the game. This shows that users also perceive tangible actions to be more noticeable. 8 players tried to react to the tangibles' sound when they were moved, a fascinating effect we had not considered beforehand. When being asked, players noted the diagonal condition to be the hardest to react to. However, the quantitative results did not support this, as we could not find significant differences in reaction times between the different game versions. Only one player mentioned the tangible barrel to be "in the way" when trying to hit moles.

5.2.4 Discussion

We found tangibles to increase awareness for others' actions.

Our study showed significantly faster reaction times for the tangible version of the game, indicating that players were more aware of others' actions in that version. We expect this difference to become even more noticeable in a less competitive setting. As stated by Gutwin et al. 2002, collaboration is increased by a higher awareness of each other's. Below, we discuss potential origins for the measured effect.

The physicality of the tangibles, standing on the surface, might explain the effect.

Shape: A tangible's physical shape stands out from the 2D tabletop surface. It provides cues through different reflective surface properties, by throwing shadows, through our stereoscopic depth vision, and through motion parallax, all of which likely make it easier for our peripheral perception to notice it than on-screen icons. However, none of our players mentioned these cues as helping them scan for a tangible on the table or when reacting to incoming attacks. We also expected more players to mention the tangibles being in the way when catching moles. However, due to the between-groups setup, no player had the chance to play both versions of the game. These observations may become more pronounced in a within-group study.

Some players reported the sound, a tangible creates while moving, helped them to react faster.

Sound: Our tangibles had soft pads to improve detection and to protect the screen from scratches. This created a sliding sound when moving a tangible that was very different from tapping or dragging with a finger. Eight participants stated that they listened to that specific sound to notice a tangible barrel attack. While we did not intentionally design this effect, it shows that tangibles can provide natural acoustic cues when handled to improve awareness for others' actions even in a somewhat noisy environment (our players were tapping frantically and occasionally shouting at each other.) This highly localized acoustic effect would be difficult to reproduce on a fixed speaker system.

Players' movement might be different when grabbing a tangible.

Player Movement: Picking up or moving a tangible requires a different arm and hand posture than multitouch, which other players may notice. Our players did not mention this as a factor, but a within-group study might reveal more about this potential effect.

Design Implications

Tangibles do increase awareness on a large table.

Our study showed that tangibles increase users' awareness for actions of collocated workers. This is especially useful when attention is captured by a demanding individual primary task. In these situations, the tangibles' properties, like their physical shape or natural auditory feedback, help others to react more quickly to events that are outside their locus of attention.

We showed the initial effect, it might be useful to understand the effects better.

We still need to study if these effects prevail when tangibles are used for most or all interactions on a group tabletop. Therefore, our current recommendations for researchers and designers intending to integrate tangibles into their applications are:

- Use tangibles for special actions that others need to notice, rather than for the primary task.
- Be aware that their shape, and the movements handling them, make them rather attention-grabbing.
- Design to make use of the natural auditory feedback of dragging and placing tangibles for subtle feedback to coworkers.

Conclusion and Future Work

As for every initial research, there are open questions to take a deeper look into.

We showed that users around a large multitouch tabletop react significantly faster to other users' actions when using tangibles instead of multitouch interactions. This indicates a higher awareness of others' tangible actions. We found that this effect increased with more users and provided some initial design guidelines for such systems and other qualitative findings.

A within-group study with user feedback after experiencing both tangible and virtual conditions could help better understand how tangibles improve awareness. If they only have an initial effect that helps when users' are unfamiliar with the application, or if the increased awareness also is helpful to more expert users. There might even be undesirable diversion effects when tangibles are overused in an application.

What effects to tangibles for a primary task have on awareness?

We chose to use tangibles only for the secondary task to isolate their effect on user awareness and because we expect that also using them for a primary task will introduce new distractions and thus decrease their beneficial effects on awareness. A follow-up study could help verify and quantify this theory.

Do the effects persist if tangibles were part of our everyday life?

While commercial tangibles for multitouch surfaces have started to appear, users are not generally familiar with them yet, similar to when smartphones introduced multitouch gestures. Learning effects may thus still play a significant role when studying users interacting with tangibles.

Players' comments about the sound might be worth a follow-up study.

Since some participants stated that they tried to listen to the sound the tangible made when being moved, we suggest investigating further what types of subtle, inherent feedback tangibles may provide to both the user and collocated actors around a large multitouch table.

An eye-tracking study might reveal more details on tangible awareness.

Finally, eye-tracking could reveal even more precise information about users' current locus of attention and reaction times. For example, it might show if a player who already recognized an incoming attack instead decided to catch another mole before performing his defense.

Chapter 6

Summary and future work

"Coming back to where you started is not the same as never leaving"

—Terry Pratchett

Tangible interaction is a promising interaction technique when interacting with touchscreens. Especially on large tabletops, tangibles can be an intuitive interface to virtual objects. They are more precise than on-screen controls; users can find and operate them eyes-free just by feeling for the tangible. This thesis also found that they increase awareness for others when working collocated or next to each other. We found them to be an intuitive interface for complex multi-dimensional input and that they help users think in abstract ways.

6.1 Contributions

This thesis contributes a comprehensive report on existing work.

This thesis provides an overview of the development of tangible interaction over the years since they were first described by W. Buxton, 1983. We built upon existing techniques to build tangibles and evaluated a tangible design for capacitive screens. Our PERCs can be consistently tracked on capacitive screens, even if the user does not touch them anymore. This is the first time researchers were able to create this for capacitive screens.

We presented the *Design Space of Tangible Interaction.*

We created the *Design Space of Tangible Interaction*, a design space that builds upon existing design spaces. Our *Design Space of Tangible Interaction* helps researchers and designers to compare tangible designs to each other. It inspires new tangible designs and motivates further research regarding the transition between off- and on-surface interaction. This is especially interesting since tangible interaction moves more and more to the mid-air space, as augmented and virtual realities become more important in research and everyday life.

We evaluated tangible interaction beyond the initial usability effects.

We evaluated tangibles beyond their simple usability benefits. While tangible benefits are well established when it comes to precision or eyes-free interaction, we were able to show that they have benefits on higher cognitive processes like users reading ability or awareness for collocated workers.

We derived suggestions and lessons learned for all our findings so that future researchers and designers can apply our findings for their own work and build upon our research.

6.2 Future work

This thesis provides a deeper look into tangible interaction based on existing findings in this field. However, as with every piece of research, it also highlighted new opportunities for future research.

Commercially available tangibles would enable many researchers to contribute to the field.

Although there are some tangibles available as commercial products, they are not widely available yet. The development of capacitive touch detection increased the usability of multitouch interaction; however, it made tangible research more difficult. Commercially available tangibles that are designed for existing tabletops would be a great improvement for tangible research. While PERCs and our TABULA tangibles offer tangible interaction for many existing tabletops, they still rely on reverse engineering of the touch detection mechanisms. A tangible system designed to work with capacitive screens would have many benefits for the research community.

Many further research questions go beyond the usability of tangible interaction.

Our findings regarding a user's awareness when interacting with tangibles opened further questions regarding the cause of the effect. Additionally, we would like to look at whether this effect is purely beneficial or if there are downfalls to the effect. We were unable to show the effects of tangibles on participants' construal level. However, by creating a matching questionnaire, we might better understand whether there are effects on users' construal.

Especially in virtual 3D worlds, the tangible interaction off- and on-surface needs further exploration.

There are many follow-up questions regarding the interaction between off- and on-surface interaction. How should one design the transition between midair and on-surface interaction? Can we utilize a pick-up gesture to create a higher immersion into tangible applications? Which areas of the *Design Space of Tangible Interaction* are worth taking a deeper look at, and which areas should be avoided when creating tangible applications? All these questions and more are worth taking a deeper look at. While we share Hiroshi Ishiis' vision for a tangible interactive world of the future, we also want to emphasize the need for a deeper understanding of tangibles, on-surface, and in midair.

We hope that this thesis inspires more researchers and developers to create tangibles and applications that support tangible interaction. Tangible interaction can improve our experience with digital systems because it helps to bridge the gap between digital screens and physical interaction. This includes driving a car, doing chores, playing, and perhaps most importantly, learning. Giving our hands and mind the opportunity to interact with physical objects instead of plain flat surfaces enables humans to do much more than working at a computer.

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