Understanding Back-to-Front Pinching for Eyes-Free Mobile Touch Input

Bachelor's Thesis at the
Media Computing Group
Prof. Dr. Jan Borchers
Computer Science Department
RWTH Aachen University

by
Andreas Link

Thesis advisor:
Prof. Dr. Jan Borchers

Second examiner:
Prof. Dr. Jochen Müsseler

Registration date: 03/08/15
Submission date: 25/09/15

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, September 2015
Andreas Link

Contents

List of Figures

List of Tables

Abstract

Todays's smartphones enjoy great popularity and continuously expand into new areas. As an example, they can be used to control games that are displayed on a remote screen like a television. Nevertheless, while focussing on the distant screen, people cannot see their fingers operating the device and thus need to continuously switch focus between screens. *HaptiCase*, as presented by [Corsten et al., 2015], solves this issue by providing tactile dots at the back of the device which can be used to orientate oneself and trigger commands without visual sight of the smartphone's screen. In this manner, people perform *tactile targeting* by estimating their rear finger's position and transferring this position to the front using their thumb. This so called *back-to-front pinching gesture* heavily relies on *proprioception* which enables people to estimate their body limbs' position without the aid of vision. In this work we developed a deeper understanding of *back-to-front pinching* by collecting 18000 measurement points and showed the existence of a *pinch-offset effect* as assumed by [Corsten et al., 2015]. In addition, we described this offset using *multilinear regression* and extracted 8 underlying models which could be used to counterbalance the effect. We compared our models' performance and verified our results using a *cross-validation*. As a result, developers can take advantage of our findings and reduce the required *target size* by 10% while still maintaining the same *tapping accuracy*.

Überblick

Smartphones erfreuen sich großer Beliebtheit und finden in immer mehr Anwendungsgebieten Verwendung. So kann beispielsweise die Steuerung von Spielen auf einem entfernten Display, wie bspw. einem Fernseher, ermöglicht werden. Hierbei besteht das Problem darin, dass sich die Finger während der Interaktion außerhalb des Blickfeldes des Nutzers befinden, weshalb die Aufmerksamkeit sets zwischen den verschiedenen Displays gewechselt werden muss. *HaptiCase*, eine Entwicklung von [Corsten et al., 2015], versucht diesem Problem entgegenzuwirken, indem taktile Punkte auf der Rückseite des Gerätes positioniert werden, die als Anhaltspunkte fungieren und dem Nutzer eine bessere Orientierung ermöglichen, ohne Augenkontakt mit dem Gerät haben zu müssen. Hierbei können gewünschte Aktionen ausgeführt werden, indem zunächst ein taktiler Punkt auf der Rückseite des Gerätes erfühlt und daraufhin mit dem Daumen auf die Vorderseite des Gerätes transferiert wird. Ein wichtiger Bestandteil dieser Geste besteht darin, Positionen von Körperteilen bestimmen zu können, ohne diese zu sehen. *Propriozeption* ermöglicht die blinde Positionsbestimmung und wird auch als sechster Sinn bezeichnet. In dieser Arbeit haben wir insgesamt 18000 Messpunkte gesammelt, um ein tiefgründiges Verständnis davon zu entwickeln, wie Menschen die *Back-to-Front Pinching* Geste unter verschiedenen Bedingungen durchführen. Neben dem Nachweis des von [Corsten et al., 2015] angenommenen *Pinch-Offset Effekts* konnten wir 8 Modelle erstellen mit deren Hilfe der durch den Effekt verursachte Fehler minimiert werden kann. Neben einer detaillierten Gegenüberstellung der unterschiedlichen Modelle, konnten wir unsere Ergebnisse außerdem mit Hilfe einer *Cross-validation* verifizieren. Entwickler können unsere Ergebnisse dazu verwenden, die erforderliche Größe von Interaktionsflächen um bis zu 10% zu verringern, ohne dabei die Treffgenauigkeit zu verringern.

Acknowledgements

In the first place, I would like to thank everyone who supported me throughout my research project. In particular, I would like to thank all participants who took their time to take part in my user study.

In addition, I would like to thank Prof. Dr. Jan Borchers and Prof. Dr. Jochen Müsseler for your support during my research. The possibility to continue my work even on public holidays and weekends combined with the research environment which offered all utilities necessary, got me familiar with new technologies within a short time.

I am especially grateful to my supervisor Christian Corsten, M.Sc.. You gave me the opportunity for my thesis and provided useful advice whenever I needed it. Our weekly meetings and the clear structure helped me a lot not to loose track and stay focussed throughout the semester. I really appreciate the time effort you spend on my *proposal-* and *final-talk* training. This can not be taken for granted and I learned a lot from you during this time.

Many thanks also to Jan Thar, M. Sc., responsible for the FabLab inventory. Your advice facilitated me to use the *laser-cutter* to built my own measurement tool used for gathering data. In addition, I got fundamental insights into *SMD-soldering*. Now I can solder myself and got my own *soldering station*.

Moreover, I also like to thank Chat Wacharamanotham, PhD student and Marty Pye, M.Sc. for teaching me how to use the *Vicon™ Motion Tracking System*. With your support I managed to get a suitable setup which allowed me to obtain the *tilt angle* necessary to answer my research questions.

Concluding, I also like to thank my family, friends and in particular Hannah who showed me great sympathy even though I often pinched for time. You gave me the strength to carry on finding solutions for problems which initially seemed to be unsolvable.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

For the purpose of politeness, everything is written in *first person plural form*.

In addition, we make use of marginalia in order to summarize important aspects.

This is an important aspect.

The entire thesis is written in American English.

Chapter 1

Introduction

Mobile devices have become an essential part of today's society and have displaced regular desktop computers as a daily driver for many people. Although we could entitle a wide range of application scenarios where smartphones act in as a universal replacement for other utilities, there also exist use cases in which the classic interaction model, to directly manipulate the screen's content by touching the surface, does not apply.

In general, smartphones are equipped with a variety of sensors combined with a *capacitive digitizer* attached to a *lcd-screen* that serves as a large interaction area processing touch interaction. In this manner, users are on the lookout for desired actions presented as signifiers which can be triggered by placing fingers at an appropriate location. Nevertheless, this kind of interaction requires the screen to be in sight of people's gaze whenever they perform an intended action.

The problem arises when the device itself only serves as a remote controller while content presented to the user is shown at a distant screen instead of the regular one built into the device. People have to be able to interact with the remote device without constantly switching focus between the local and distant screen. In short, they have to be capable of interacting with the device *eyes-free*. Since devices like the *Google*™ *TV* or *Amazon*™ *Fire TV* found their

Users should operate the device without looking at it. We refer to this as *eyes-free mobile touch input*.

way into our living rooms, the importance of *eyes-free mobile touch input* increased to a greater extend. [Corsten et al., 2015] attended this challenge by presenting *HaptiCase* that enables *eyes-free interaction* without the need to adjust the software or hardware of the device. *HaptiCase* utilizes *tactile dots* which can easily be sensed by users at the back of the device. In this manner, users can orientate themselves more easily and get a better understanding of the dimensions of the interaction area. In so doing, they can locate desired positions using *tactile landmarks* as reference points.

Tactile dots placed at the back of the device enable better orientation.

The main contribution of our work is composed of a profound investigation of the so called *back-to-front pinching gesture* which is the key component of the *HaptiCase interaction technique*. To perform this gesture, users have to bring fingers into apposition to transfer a sensed location at the back of the device to the front. In addition, we took a deeper look into psychological aspects that have to be taken into account when developing a greater understanding of how people perform *back-to-front pinching* under different conditions. This way, we desired to enhance touch accuracy leading to an overall improvement of the user experience.

We conducted a user study and gained 18000 data points from 30 participants. Based on this data, we could identify an offset between touch locations at the back and at the front of the device, which was significant for the device's thickness and target location. Thus, users tend to *over-* or *under-shoot* the intended target location. As a result, we could confirm the existence of a *pinch-offset effect* as suggested by [Corsten et al., 2015]. Although we also assumed the *tilt angle* with which people are holding the device to influence people's *pinching performance*, it was found to be non significant. In addition, we found the offset to take shape towards people's hands while pinching on either *left-* or *right-* side. This is explained by the nature of people's hands.

The *pinch-offset* as assumed by [Corsten et al., 2015] could be confirmed.

Our data analysis generated 8 models which could describe the *offset* under different conditions. Considering all *thicknesses* in equal measure, yielded a model which reduces the size of the error by $-0.7mm$ on average. Since we also found the *device thickness* to have a significant impact on the resulting *offset*, we also created models for each *thickness* respectively. This way, we could reach an overall improvement of $-1.0003mm$ with respect to the size of the error. As a result, applying these models allows to improve touch accuracy for *back-to-front pinching* by counteracting *offsets* unintentionally induced by the user. Developers can take advantage of these findings and design *applications* in such a way that they also consider people's *pinching performance* alongside the regular touch input provided by a users. This way, applications designed for the *HaptiCase application scenario* can feature buttons which are up to 10% smaller than regular ones while still maintaining the same *tapping accuracy*.

Subsequently, we briefly state the structure of the following chapters.

Initially, we describe in Chapter 2 the *application scenario* used as the foundation of our research, followed by a detailed explanation of *back-to-front pinching*. In addition, we define the *pinch-offset effect* and state how it might be related to people's proprioception, which allows to locate body limbs without looking at them. Besides our approach to extract a model to counteract the *pinch-offset effect*, we finally state our research questions.

While Chapter 3 presents related work which has already been done regarding *proprioception* and *back-of-device interaction*, we directed Chapter 4 to the design and fabrication of the measurement tool we used for our study. We give a detailed description of the steps which are necessary to obtain a measurement tool that guarantees reproducibility. We also consider the software implementation used for our study and briefly explain how we obtained relevant data like *tilt angles* and *measured target positions*.

Furthermore, Chapter 5 focusses on evaluation. Next to our study design, we present the results gained from our statistical analysis and name resulting implications for our research questions. Finally, we conclude our results in Chapter 6 by providing a short summary and state future work in this area.

Chapter 2

Eyes-Free Mobile Touch Input and resulting Challenges

Smartphones have become an essential part of our life and are utilized in many different scenarios. Their manifold capabilities allow them to act in as a replacement for commonly used input devices like remote controllers. However, choosing a smartphone instead of regular input devices generates new challenges one has to deal with. As an example, smartphones heavily rely on visual contact, while controllers rather make use of haptic feed-forward to convey possible actions.

While focussing at the distant screen, visual cues provided by smartphones are occluded from visual gaze.

To deal with the absence of visual cues, HaptiCase provides tactile landmarks at the back of mobile devices to allow eyes-free mobile touch input. The following chapter presents a refinement of the HaptiCase interaction technique, where we additionally consider different sources of errors, which might influence people's *pinching* performance. In addition, we discuss possible consequences in form of the *pinch-offset effect* and state our research aim to verify the existence of the effect, followed by an approach to extract an appropriate model, which can be applied to improve touch accuracy.

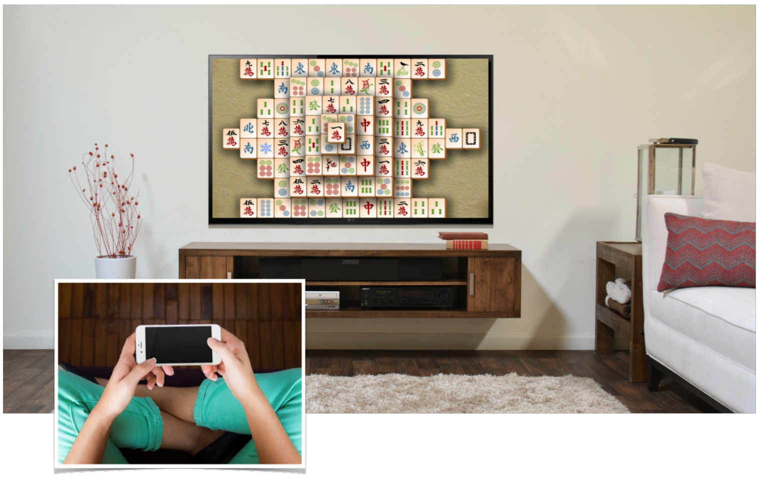


Figure 2.1: Eyes-free interaction controlling a game displayed on the remote screen [TechTalk, 2015],[PlaceIt, 2015].

2.1 Application Scenario

A typical use case for HaptiCase can be described by the following scenario: While sitting on a coach, users can control remote games displayed on a distant screen using their smartphone (2.1). In doing so, they have to frequently switch their attention between screens in order to handle the game properly. To resolve this issue, HaptiCase provides tactile cues, which help users to orientate themselves eyes-free and trigger commands, while still being able to focus on the distant screen.

HaptiCase offers tactile cues that serve as reference points and allow users to orientate themselves, while using the device eyes-free.

Whenever they would like to perform an action offered by the game, they apply an absolute mapping to the rear of their smartphone and locate the corresponding position. During this process, HaptiCase assists the user by providing reference points that can be used as a guideline. Having the finger placed at the desired location, users can transfer the position to the front of their smartphone eyes-free while still focussing on the game's content. To develop a deeper understanding of *back-to-front pinching* and to identify *two* main sources of errors regarding this gesture, we provide a detailed description, which leads us to a refinement of the HaptiCase interaction technique.

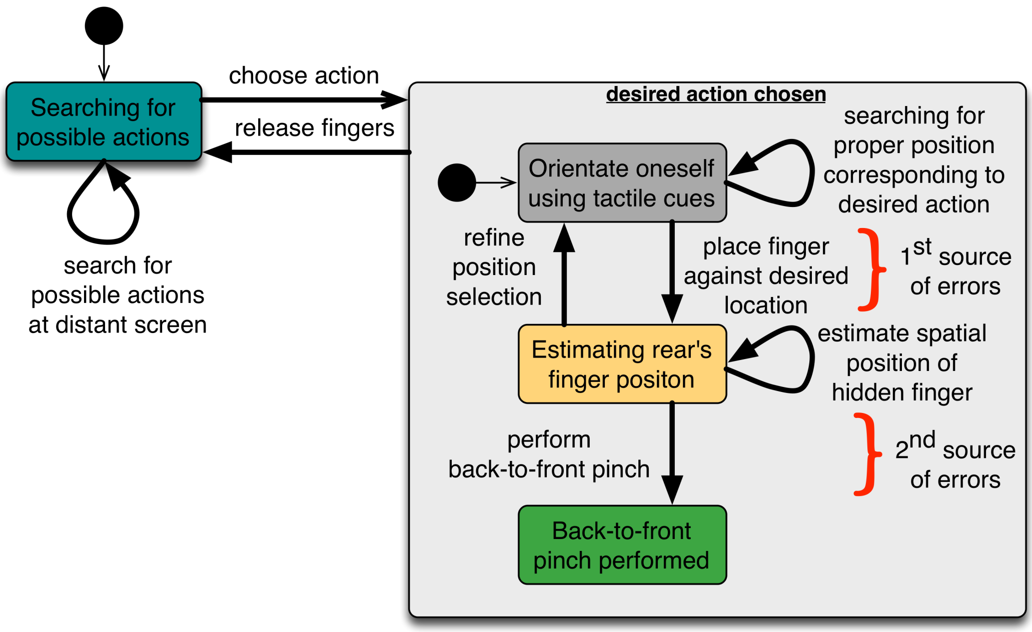


Figure 2.2: Visualization of the *back-to-front pinching gesture* (error sources are marked red).

2.1.1 Back-to-Front Pinching

Smartphones provide signifiers showing controls on screen. Nevertheless, they require users to gaze at the device in order to communicate possible interactions. In our scenario users address themselves to the content shown on the remote screen and are not capable of looking at their device while gaming. Thus, a mechanism is required to bridge the gap of interacting with the device, while still focussing on a remote screen. *Back-to-front pinching* addresses this flaw and forms the essential component of the *HaptiCase interaction technique*.

Back-to-front pinching bridges the gap of triggering commands using a smartphone while still focussing at the distant screen.

Initially, in the *first* state (Figure 2.2), users search for possible actions offered by the remote application, which can be initiated using their smartphone. Whenever they have determined the desired action, they switch to the *second* state and start orientating themselves using tactile cues at the back of the device. When they have found the intended location corresponding to the intended action, they change to the *third* state and rest their finger at the rear.

This section can be identified as the *first* source of errors. An error occurs, if a user does not map the position of the intended action to the rear properly (i.e the position corresponding to the desired action is confounded with another one). Having their finger placed against the chosen location in state *three*, they estimate the spatial position of their hidden finger and go to the *fourth* state by matching the sensed position to the front using their thumb as precisely as possible. This last step of *back-to-front pinching* contains the *second* source of errors. If the touched position at the front differs from the one at the back, an error can be identified as the size of the distance between corresponding touch locations. Importantly, a user can always go back to the first state by releasing his fingers from the back as shown in Figure 2.2.

Offsets induced by an incorrectly performed *back-to-front pinch* might execute a wrong action or no action at all. Two main sources of errors can be identified, when *back-to-front pinching*.

In this manner, users can orientate themselves using tactile cues to locate possible touch locations without visual contact to their smartphone. Nonetheless, their interaction accuracy varies with the precision they transfer positions from the rear to the front. If touch positions differ from each other, it is likely that no action is performed or a wrong action sequence is executed instead. Thus, we have to consider different sources of errors which might have an impact on users' *pinching performance* to improve eyes-free tapping accuracy. This extension, to additionally consider sources of errors, symbolizes our refinement of the *HaptiCase interaction technique*.

Even though HaptiCase was found to significantly improve eyes-free tapping performance, Corsten et al. observed a strong offset between touch locations, especially when having the device tilted at certain angles. We call this observation which was made from time to time among different users the *pinch-offset effect*.

2.2 Pinch-Offset Effect

Back-to-front pinching requires an accurate decoding of the spatial position of unseen fingers. In the following we will briefly explain our definition of the *pinch-offset effect*.

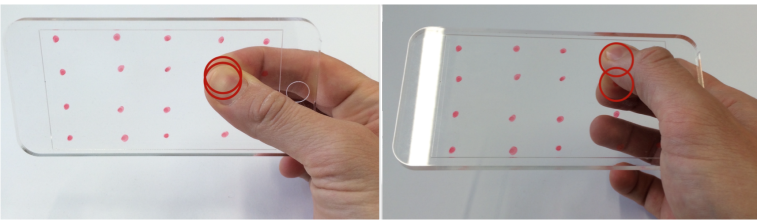


Figure 2.3: *Visualization of pinch-offset effect. The offset seems to increase with increasing tilt angle. (Image: [Corsten et al., 2015])*

While *pinching*, fingers are occluded from visual gaze. Thus, people have to rely on their abilities to match the position of their unseen fingers using their thumb. The impact generated by the *second* source of errors, as stated before (i.e. errors which occur while transferring the rear finger's position to the front), is responsible for offsets between the *actual*- and *sensed position* of fingers. In short, the *pinch-offset effect* describes the offset induced by a *back-to-front pinch*, where index-finger and thumb are not precisely in apposition to each other.

The offset induced by a *back-to-front pinch*, where index-finger and thumb are not in apposition to each other is called: *pinch-offset effect*.

This observation could be caused by the material separating fingers and thumb. Noteworthy, people who performed the *back-to-front pinch* are of the mind that they have matched the position properly, although locations might be different. Interestingly, the offset seems to grow with increasing tilt angle (Figure 2.3).

The ability to estimate body limbs' position is facilitated by one of our senses called *proprioception*. It delivers feedback about position changes and thus is essential for body movements.

2.2.1 Proprioception

Our body is unable to manage daily activities without relying on information gathered by our five senses: smell, touch, vision, hearing and taste. *Proprioception* is used to follow the location of body limbs and collect information generated by stretch receptors in our muscles.

Lee called *proprioception* the *sixth* sense.

[Lee, 2008] described *proprioception* as a feedback system used by the human body to adjust muscles for desired movements and added it as a *sixth* sense. Without the aid of *proprioception*, people would have to make use of information produced by vision, where deeper thinking would be involved. In contrast, *proprioception* enables people to subconsciously estimate the distance or angle of a specific movement and makes this information available to the brain.

Proprioception is a subconscious process that supplies movement and position information to our brain.

As an example, positioning one's foot is simply done by moving it slightly. Gathered *proprioceptive* information can then be used to determine the precise location in space. As stated by Lee, proprioceptors in muscles collect knowledge about length, tension and pressure stimuli, which can be used by the brain to calculate angles and corresponding distances. Importantly, *proprioception* is a subconscious process which constantly collects data. Especially during childhood, *proprioception* is essential to acquire skills in new movements.

To be capable of developing a richer understanding of *back-to-front pinching* and to predict possible error sizes, our aim consists of extracting a model, describing the *pinch-offset effect* under different conditions.

2.3 Model to counteract the *Pinch-Offset Effect*

Mobile touch input obviously depends on selecting the proper position which triggers the action leading to the intended result. Performing this interaction eyes-free supplementary encounters the difficulty of not confusing alternative positions with the desired one.

Our aim: minimizing the impact of the *second* source of errors.

To improve touch accuracy, our aim is to minimize the impact generated by the *second source of errors* (i.e. the *pinch-offset* induced by a *back-to-front pinch*). Thus, we developed an experiment which allowed us to measure the *pinching performance* among different users (i.e. the offset between touch locations at the back and at the front depending on different factors). In this manner, we aim at generalizing our findings to a larger population and drawing conclusions about how people perform *back-to-front pinching*. We will subsequently state our approach used to extract an underlying model using performance data collected in our study.

2.3.1 Model Extraction

Minimizing the *second source of errors* requires a model which can be used to improve touch accuracy. We refer to this model as *corrector function*, which enables the system to process incoming touch events by translating measured positions into locations actually meant by the user. Importantly, our intended *corrector function* is represented by two functions modeling the offset in the *x*- and *y*- *component*, since we consider touch locations represented by 2-tuples $(x, y) \in \mathbb{R}^2$.

We assume the *pinch-offset effect* to be affected by three factors, namely *thickness of the device*, *tilt angle*, and *target position*. Our proposition is justified by observations from [Corsten et al., 2015] who observed a strong offset for tilt angles around $\approx 40°$. In addition, *proprioception* seems to be influenced by the material separating fingers from eachother. Thus, it is likely that *thickness of the device* has an impact on *pinching performance*. Due to the nature of human hands, certain positions might be harder to reach than locations being in scope of the user's hand. Thus, we can justify our decision to also consider *target position* as another factor.

Assumption: the *pinch-offset-effect* depends on:

- *thickness*
- *tilt angle*
- *target position*

Our approach to obtain a *corrector function* makes use of *Training sets* T^i which include k measurements for each participant i of the form:

Idea: Use a training set to obtain a *corrector function to counteract the pinch-offset effect.*

$$T^i := \{((x_m^{front}, y_m^{front}), (x_m^{back}, y_m^{back}))^{i_1}, \ldots, \\ ((x_m^{front}, y_m^{front}), (x_m^{back}, y_m^{back}))^{i_k}\},$$

where x_m^{front} represents the *x-component* of a *measured* touch positions at the front of the device (y_m^{front}, x_m^{back} and y_m^{back} analogous). Then our complete *Training set* T, comprising measurements from all users, can be defined by:

$$T := \bigcup_{i=1}^{n} T^i,$$

We use *multilinear regression* to determine corrector functions for the *x*- as well as the *y*-component of a touch position.

where n is the number of participants, who perform *back-to-front pinching*. By applying *multilinear regression* for each component, we will try to model the impact of our independent factors (*tilt angle*, *thickness* and *target position*) on the resulting dependent variable, the *x*- or *y*- component of a measured touch position at the front. Observe that the result of applying *multilinear* regression for the *x*- component (*y*- component analogous) is of the from:

$$x_m^{front} = \ldots + c * x_m^{back} + \ldots$$

The *second source of errors* can then be counterbalanced by deriving the corrector function $f^*_{x,\alpha,\theta}$ ($f^*_{y,\alpha,\theta}$ analogous):

$$f^*_{x,\alpha,\theta} : X_m^{front} \times \mathbb{R} \times \mathbb{R} \rightarrow X_m^{back},$$

(with X_m^{front} being the set of all *x*- components of measured touch positions at the front, tilt angle $\alpha \in \mathbb{R}$ and the device's thickness $\theta \in \mathbb{R}$) by converting the equation for x_m^{back} as follows:

$$f^*_{x,\alpha,\theta}(x_m^{front}, \alpha, \theta) := x_m^{back} = (x_m^{front} - \ldots)/c$$

Please note that using $f^*_{x,\alpha,\theta}$ ($f^*_{y,\alpha,\theta}$ respectively), the system can for a measured touch position at the front $(x_m^{front}, y_m^{front}) \in \mathbb{R}^2$, a current tilt angle α and a device's thickness θ calculate the position the user actually intended to touch:

$$(f^*_{x,\alpha,\theta}(x_m^{front}, \alpha, \theta), f^*_{y,\alpha,\theta}(y_m^{front}, \alpha, \theta)) \in \mathbb{R}^2$$

and thus can counteract the *pinch-offset effect*.

2.4 Research Questions

Having stated our approach to minimize the offset evoked by the *second* source of errors, our aim will be to test our assumption that *thickness*, *tilt angle* and *target position* are factors having an impact on the resulting offset. In addition, we focus on identifying additional factors which might influence people's *pinching performance*. Our principal object consists of finding a *corrector function* $f^*_{x,\alpha,\theta}$ ($f^*_{y,\alpha,\theta}$ respectively) that fulfills the previously stated properties. This leads us to the following research questions, we are primarily focussing on:

1. Which factors lead to a *pinch-offset effect*?
2. How can the *pinch-offset effect* be modeled to improve touch accuracy?

Answering these questions requires us to build an appropriate measurement tool, which allows us to quantifying subjects' *pinching performance*. Since we are interested in counterbalancing the *second source of errors*, we defined a fixed set of targets, which did not change throughout our study. Participants had to absolutely map these positions to the rear by sensing a corresponding tactile dot.

Our research requires a measurement tool that is capable of recognizing touch positions at the back as well as at the front of the device.

Obviously, it makes a difference how people rest there finger against the intended tactile dot. Thus, we require our measurement tool to also recognize touch positions at the back of the device. This way, we can accurately calculate the *pinch offset* induced by a *back-to-front pinch* between touch locations. Chapter 4 provides a detailed description on how to build a suitable measurement tool that serves our requirements.

Chapter 3

Related work

Back-to-front pinching requires spatial encoding of an unseen finger and is connected to different research topics. We will give an overview of two areas, which we think, are most related to a possible *pinch offset effect* and will state the implications resulting for our research.

Proprioception is responsible to estimate the location of our body limbs, whenever visual cues are unavailable. Research in this field mainly focuses on investigating, to what extend different cues, like *proprioceptive, tactile* or *visual* cues, contribute to localization accuracy. Besides bringing hands into apposition or several fingertip matching tasks, an apparatus, which allows to analyze the proprioceptive performance of subjects, belongs to this area. In addition, limitations of proprioception and the role of *visual* and *tactile* cues to overcome these limits are investigated. As an example, it is examined, how interfaces can be used without having visual feedback available. Many work has been done to study errors that occur when only relying on proprioception and to identify patterns, from which conclusions about the ratio between different localization cues can be drawn. Systematic errors, which have been observed throughout this field, hint at the existence of a *pinch offset effect* and motivates us to do further exploration.

Proprioception and *Back-of-device interaction* are ares closely related to back-to-front pinching

Observed systematic errors indicate the existence of a *pinch offset effect*

Back-of-device interaction forms the second area, which is closely related to our research. It focuses on the performance and accuracy of *rear-interaction* in comparison to commonly used *front-interaction*. Most work concentrates on taking advantage of using all ten fingers, instead of only relying on our thumbs. This promises to allow faster input speeds and enhanced interaction techniques. Difficulties arise from occlusion of fingers, which can not be spotted while interacting at the rear. Research suggests that proprioception helps to reduce errors occurring due to the lack of visual feedback; but these errors can not be eliminated in total. Current work in this area tries to make use of passively provided interaction by the user in form of grip-changes to increase responsiveness of commonly used devices.

3.1 Proprioception

Research in Proprioception is closely related to psychology and has been studied for decades. For instance, [Paillard and Brouchon, 1968] conducted an experiment consisting of a fingertip-matching task, where subjects had to match the position of their left index-finger with their right index-finger on a vertical scale, while both visual and tactile cues were absent. They found position information from *active movement* (median error: $\pm 6mm$) to be significantly more accurate than when positioned passively (m. error: $\pm 22mm$). Interestingly, they observed a temporal increase in offset size, which for both active and passive movement becomes identical after $\approx 15s$. Since fingers located on tactile landmarks are resting while performing a pinch, precision of position information might decrease while using *HaptiCase* and may result into the *pinch-offset*. In addition, Paillard and Brouchon found that whenever audio, or visual cues are absent, proprioceptive information arises from *joint receptors*, *afferents from muscles* and *pressure signals from skin*.

position information from *active movement* is significantly more accurate than when positioned passively

In a follow up paper [Paillard and Brouchon, 1974] further investigated the influence of vision on task accuracy. They used the same experimental setup but additionally allowed vision of the target hand in a separate condition. Surprisingly, vision only increased matching performance, when combined with *active* or *passive stabilization*. In contrast, position cues relied only on proprioception.

[Tillery et al., 1994] chose an experiment slightly different compared to Paillard and Brouchon, but could even observe systematic errors. Participants right arm was passively replaced and was brought back to their sides. Their task was to point at the remembered location with the other hand while having their eyes closed. Targets were restricted to 25 possible places. By only utilizing proprioception subjects performed poorly. Interestingly, errors showed strong patterns, but these could not be generalized to a larger population, since they were found to be user-specific. A variation of the described experiment prevented tactile feedback, by meeting a threshold of $1cm$ above the surface. Performance was found to be slightly better, when tactile feedback was allowed.

Participants performed poorly, while only using proprioception as position cues.

To allow measurement of proprioception in the hand [Wycherley et al., 2005] demonstrated a portable device, with which proprioceptive acuity could be determined. Proprioceptive acuity is defined by the average error over a range of angles. After observing an angle $\alpha \in [-10°, 50°]$, indicated by a finger silhouette, subjects had to match their unseen finger with the desired angle. Between each angle, the silhouette was reset to $0°$ to avoid learning effects. To deliver accurate results, the apparatus was calibrated by running initial tests, where subjects were allowed to see their otherwise hidden finger. *Offset* was calculated by subtracting *visual test values* from *non-visual test values*. Importantly, results showed high reproducibility, since they indicated little variation during repeated tests. Wycherley et al. reported an average acuity of $\approx 5.72°$, which strengthens our assumption of the existence of a *pinch offset effect*. Variation is reported to appear due to differences between joints and might even depend on people's age. Although, [Ferrell et al., 1992] discovered that peoples capability to estimate their body parts position using only proprioception declines with increasing age, we will not consider this in our research. Instead, we are encouraged by Wycherley et al. findings, that the error between dominant ($5.11°$) and non-dominant hand ($6.33°$) was found to differ slightly, to look into the impact of either

Subjects digressed from predefined angles, while matching their unseen finger to a silhouette by $5.72°$on average.

left or right hand on the resulting offset in our research.

As previous research stated, systematic errors seem inevitable when using proprioception. Awareness of unseen body parts is essential to interact using *HaptiCase*, since it is meant to be used while looking at distant screens. [van Beers et al., 1996] put effort into extracting details about how humans combine proprioceptive and visual cues. The procedure used by van Beers et al. is most similar to what we did in our research. While fingers are separated by the device which uses the *HaptiCase* interaction technique, van Beers et al. used a table to segregate left and right hands. In either way, proprioception sense seems to be influenced, since fingers can not sense each other.

Work of van Beers et al. is closely related to our work regarding the *pinch-offset effect*.

Especially details like finding the right target using tactile cues placed underneath a table, remind us of the modality used with *HaptiCase*. After reaching the intended tactile target, participants had to transfer the position of their unsighted left hand with their right hand, which refers to the *back-to-front pinch*. The approach differs slenderly since van Beers at al. used both hands instead of only a single hand in *HaptiCase*. That is why we expect their offset to be more significant than ours. *Three* conditions were used, whereas the first one corresponds to our *HaptiCase* setting. In the *first* condition subjects were only allowed to make use of proprioception only to match their unseen hand. The *second* condition allowed to use visual information about the reaching hand, while avoiding proprioceptive cues. Condition *three* combined visual and proprioception information.

Interestingly, striking systematic errors were observed, since subjects tend to point too far beyond predefined targets. Van Beers et al. denoted their discovery as *overlap effect*. Different arm postures were also found to affect the error size. Subjects performed remarkably better when both visual and proprioceptive cues were available.

Pointing too far beyond pre-defined target is called ”overlap effect”

Findings presented by [van Beers et al., 1996] motivate us to study the impact of different *tilt angles* and *device thicknesses* on the *pinch-offset* in detail. Moreover, the fact that subjects performed worst while only relying on proprioception provides evidence for a *pinch-offset effect*.

Based on previous research, Van Beers et al. continued their work on humans' *proprioceptive sense*. For instance, they analyzed its precision in a follow-up paper [Van Beers et al., 1998]. Using only *proprioception*, localization in rational direction was identified to be more precise. Targets, closer positioned to the shoulder, could be estimated more accurately. These results depend on the geometry of humans arm. The *overlap-effect*, which they observed in previous studies, was confirmed.
The *pinch-offset* could be caused by less precision of proprioception in *azimuth* direction, since users do not gaze their hands while using *HaptiCase*. [van Beers et al., 2002] identified a weighting ω between vision ($\omega_v \in [0.6, 0.8]$) and proprioception ($\omega_p \in [0.2, 0.4]$). Thus, position cues seem to rely more on vision than proprioception. But ω_p increases, whenever visual cues are absent. In addition, estimates regarding *depth* are more accurate when using proprioception.

Position cues about *depth* are more accurate when using proprioception. In Contrast, vision is more precise in *azimuth* direction.

Although specializing in a different research area than work previously presented, conclusions drawn by [Gustafson et al., 2013] report interesting results for the *HaptiCase interaction technique*. They investigated, how palm-based imaginary interfaces can be used without having visual feedback available. Even though a screen is absent, visual sense remains the dominant source. Users position sense increases, when seeing their hands interact. Whenever users are blindfolded, tactile cues of both hands act in as a replacement. Gustafson et al. differentiated between tactile cues sensed by the pointing finger (*active touch*) and cues sensed by the palm (*passive touch*). They found *passive touch* to support interaction with an imaginary interface best, since touch accuracy increases. In contrast, *active touch* only contributed little. This might bias the *pinch-offset effect*, since only *active touch* is available while using *HaptiCase*.

3.2 Back-of-Device Interaction

HaptiCase makes use of tactile landmarks placed at the rear of a device. This way it enables users to locate targets on a touchscreen without looking at it. Proprioception forms the *first* component which is essential for *back-to-front pinching*. The *second* component consists of *back-of-device interaction*, which permits expanding the available interactive surface to the back and represents the *second* fundamental area related to our research.

HaptiCase is inspired by *BrailleTouch*, which uses a similar interaction technique.

[Southern et al., 2012] demonstrated a solution, which provides visually impaired people with a reasonable fast text input application. *BrailleTouch* uses *back-of-device interaction* and can be easily adapted to commonly used devices like an iPod Touch. Thus, it bridges the gap between expensive hardware solutions and software, which only offers slow typing speeds. Braille code provides the basis for Sotherns et al. eyes-free text entry application. It is an efficient binary encoding of the alphabet including 63 different symbols in total ($63 = 2^6 - 1$). In comparison to *HaptiCase*, *BrailleTouch's* back faces the user and it's rear points away from him. This is precisely the other way around as it is used for *HaptiCase*. The chosen approach provides evidence for eyes-free operation of touchscreen-based devices. Evaluation of user feedback emphasized issues while using raised lines at the front, which should assist as a mental map. Overall, users could transfer positions from the front to the rear, but occasionally made mistakes. Unfortunately, [Southern et al., 2012] did not provide information about how participant held devices in their hand. Reported angles would have allowed us to specify, whether the issue is angle-related.

Especially when using *back-of-device interaction*, people count on proprioception, since fingers behind the devices are occluded. [Wolf et al., 2012a] studied, which amount of additional guidance is necessary for proper *back-of-device interaction*. They compared pointing accuracy when having visual feedback present and absent. Participants had to select targets appearing on screen by touching and releasing from underneath. User performance was measured by the number of successfully selected targets and the amount of corresponding trials. Their findings revealed that removing visual feedback does not lead to a major drop in performance. Instead, proprioception can overcome the lack of visual feedback, why visualization is

Proprioception can overcome the lack of visual feedback.

redundant. Unfortunately, they did not explain the exact error size between having visual feedback included or not. This would have been interesting for our research.

Current research in *back-of-device interaction* probes, how subconsciously produced data can be used to enhance responsiveness of common devices. While using touch-screen based devices, users perform grip manipulation to reach specific screen ares. [Mohd Noor et al., 2014] spotted patterns in grip changes and run further exploration. Surprisingly, finger position can be predicted by applying machine learning algorithms. This way devices can preload content before the user actually touched the screen and thus are much more responsive. Mohd Noor et al. reported that time of contact can be estimated up to $0.5s$ beforehand. Moreover, touch contact position can be predicted up to several hundred milliseconds before touch. Mohd Noor et al. used different factors to predict actual touch positions. These findings encourage us to counteract the *pinch offset effect* based on changes in different factors.

Potential touches can be predicted by analysing data extracted from back-of-device grip manipulations.

Combining front and back interaction evokes new challenges one has to deal with when designing appropriate gesture commands. As evidence of this, grasping hands occlude the content shown on screen while holding the device in a proper position. Thus, gestures have to be designed such that they can be performed without visual feedback of the unseen fingers. [Wolf et al., 2012b] spent further exploration in this field and focussed on interaction with grasp-devices. They designed four gestures, named *initial pinch*, *rested pinch*, *circled pinch* and *slided pinch* to analyze their performance using a measurement tool called *PinchPad* (i.e. two *iPads* facing back to back to each other). They designed these gestures based on the *body schema*, which serves as an underlying model explaining people's ability to determine the spatial position of unseen body limbs. Their findings are significant for our research, since the *rested pinch* by Wolf et al. corresponds to our *back-to-front pinching* gesture. Interestingly, they found error patterns for the *rested pinch* in the form of an *x-offset* of thumb position towards the hand palm, which provides evidence for the existence of the *pinch-offset effect*. The fact that they identified the form factor of the measurement

The *rested pinching* by Wolf et al. corresponds to the *back-to-font-pinching* gesture.

Wolf et al. identified error patterns, but did not provide an appropriate model.

tool having an impact on *pinching-prformance*, motivates us to consider different *thicknesses* of the device. They found people to better perform spatial localization when moving fingers simultaneously instead of resting fingers statically at the rear. Unfortunately, they did not undertake further exploration into extracting an underlying model to counteract error patterns, even though they could identify them. This would have allowed us to do further comparisons with our findings. Wolf et al. stated the importance of *end-of-gesture feedback*, which was replaced by *body-feedback* in their research. As a result, participants perceived their own *pinching-performance* to be worse than it really was. In contrast to the work done by Wolf et al., we will focus on *eyes-free* interaction and thus will prevent visual cues. Beyond dispute, their work opens a wide range of new opportunities using *back-of-device interaction*.

Chapter 4

Design and Fabrication of the Measurement Tool & Software

Gathering data describing people's *pinching performance*, requires an appropriate measurement tool. Unfortunately, omnipresent smartphones like the iPhone™ do not offer touch input at the rear side. Thus, any interaction performed at the back of the device cannot be recognized. In this chapter we will state our approach, as well as our initial ideas on how to meet the challenge of designing an appropriate measurement tool combined with details on the measurement software's implementation.

Today's smartphones for the rank and file do not feature *back-of-device interaction*.

4.1 Design of the Measurement Tool

We are interested in investigating the *offset* induced by a *back-to-front pinch*. To preserve comparability, we chose a fixed set of targets that should be transferred to the front throughout the study. Targets are shown at the distant screen. Thus, participants have to initially map presented targets to corresponding tactile dots at the back of the device. This likely results into dissimilar placements of people's fingers on the corresponding tactile dot. To receive more accurate results, we are also interested in identifying the position, where subjects rest their finger to perform the *back-to-front pinching gesture*. This permits us to also focus on the offset between measured positions at both sides instead of only considering the *offset* in relation to the real target position. As a result, we require our measurement tool to recognize touches on either sides.

Besides regular *front-interaction*, we require our measurement tool to feature *back-of-device interaction* as well.

Since we assumed thickness to be a factor influencing people's *pinching performance*, we desired to easily change thicknesses of the measurement tool, while still maintaining the lightweight starting from the thinnest configuration possible. This way, we can gradually increase the thickness by inserting specifically designed separators. Enabling touch interaction on both sides, while still keeping a lightweight and thin design poses a challenge. Unfortunately, current smartphones do not support *back-of-device interaction*. We will briefly note our initial ideas followed by a more detailed description of the final iteration including explanations on design decisions made.

4.1.1 Idea & Initial Prototype

Our initial prototype used *wax-plates* as a simple and cheap approach to store touch positions. In this manner, the pressure used to perform a *back-to-front pinch* results in a deformation of the *wax-material*. Thus, touch locations can be extracted by analyzing the distortion of the *wax-layer*. Since *wax* requires a certain amount of squeeze to store locations properly, we refined our approach by using *floral foam* which is a lot more sensitive.

Wax-plates and *floral foam* were not capable of recognizing reoccurring touches.

A huge drawback of both approaches is that the gesture can only be performed once at a certain position. As soon as the gesture has been executed, the layer will already be deformed and thus repeated touches cannot be distinguished anymore. Hence, we looked for a more flexible approach to also measure reoccurring touches while minimizing the effort needed to quantify a large set of trials.

Since the *iPod Touch*™ features accurate touch input, we tried to attach two *iPod Touches 5G* facing back-to-back to each other. Unfortunately, this alternative approach results in a significant increase in weight ($\approx 172grams$) and thickness ($12.2mm$) of the measurement tool. Adhering to this idea would have limited our research to devices with a thickness of $\geq 12.2mm$, losing sight of thinner devices. Instead, we aim at a more general approach, which even applies to future smartphones, which might get thinner and more lightweight.

Attaching two *iPod Touches 5G* to each other resulted into a significant increase in weight.

Thus, we decided to build a thinner measurement tool that only offers touch input without visual feedback and does not feature components like *battery*, *lcd-screen* or *body housing* which leads us to our final iteration.

4.1.2 Material used for the Measurement Tool

Our key requirement to choose an appropriate material is described by the property of being lightweight and at once stable enough to resist normal usage from ≈ 30 participants. Throughout the study, users should be able to interact with the measurement tool as natural as possible without taking care of doing damage to the measurement tool.

We found *Finn-paperboard* to meet our requirements best. Not only is it stable enough, it can also be easily brought into different shapes using a *laser-cutter*. We used *Finn paperboard* in different strengths of $0.9mm$, $1.5mm$ and $2mm$ from [ArchitekturBedarf.de, 2015]. This way, we got desired device thicknesses by combining separators of abovenamed strengths. Regarding measurement tools' dimensions we tried to provide easy access to the interaction area of the measurement tool.

Finn-paperboard fulfilled our requirements to be lightweight while at the same time featuring sufficient stability.

Dimensions of the Measurement Tool

We designed *two* variations of the measurement tool. The *first* concentrates on making the tool as thin as possible . That is the minimal thickness which still enables us to get

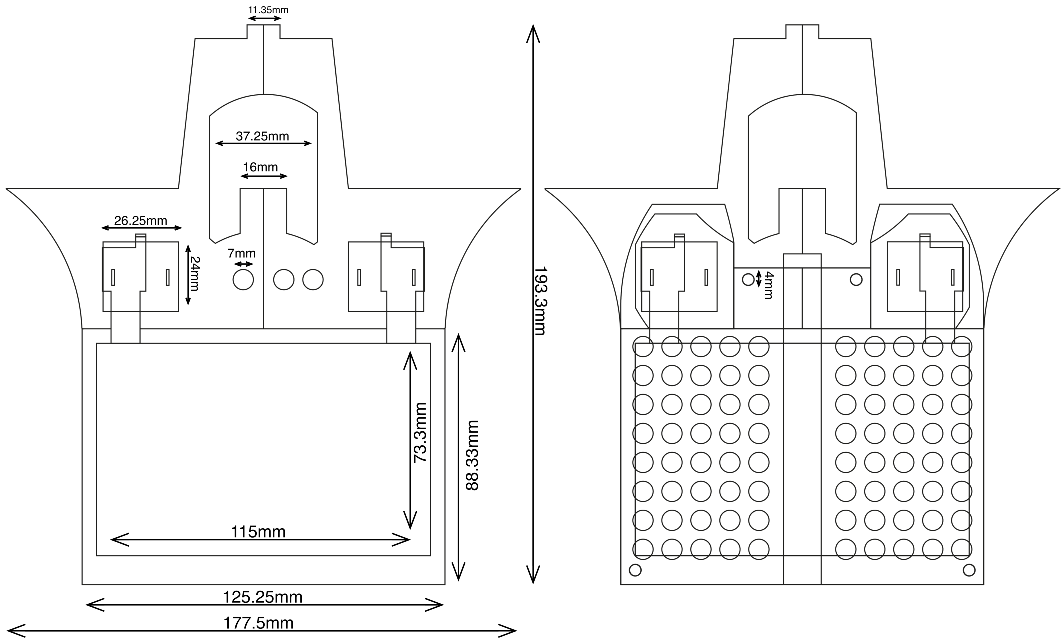


Figure 4.1: Physical dimensions of the measurement tool.

accurate results. As reported in Figure 4.1, we used digitizers ($115mm \times 73.3mm$) which feature an interaction area of $109.6 \times 66.4mm$ for both variants. Importantly, the distance between the interaction area and the left border equals the distance towards the right border. This design decision is justified by the fact that reaching a target in the interaction area should be as convenient from the *left-* as from the *right-*side.

We designed both variants of the measurement tool to correlate with each other and to only vary in the thickness adjustment mechanism.

We especially took care that both variants have the same form factor, which is important to get comparable results. According to this, the maximal height of both variants measures $193.3mm$ compared to the maximal width of $177.5mm$. The bottom area of the measurement tool comprises $125.25mm \times 88.33mm$ (see Figure 4.1). We decided to add some additional space to the interaction area to prevent unintentional touches. Without this extra space, people would trigger commands by simply holding the device, since their skin would fit around the measurement tool's sides such that it interferes with the capacitive area. The only difference between the two variants, is the possibility to change the thickness of the *second* one. To do so,

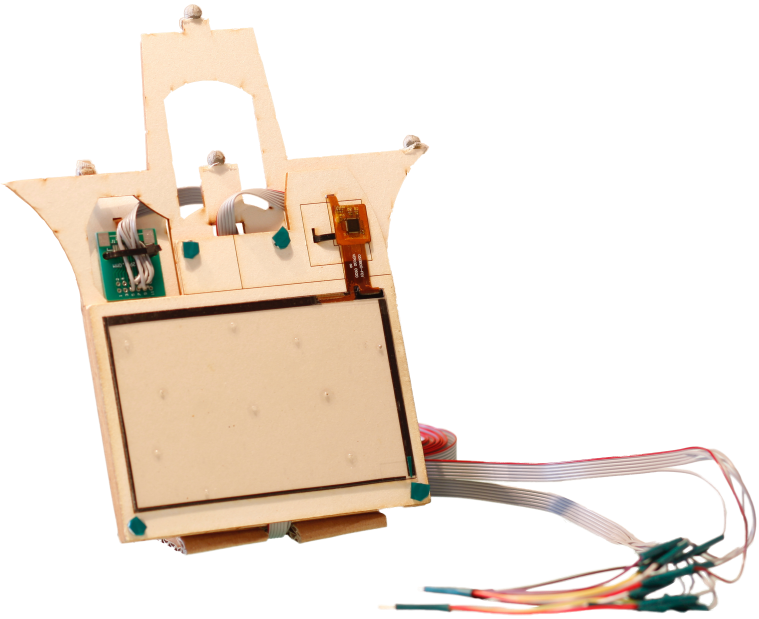


Figure 4.2: Second variant of the measurement tool consisting of a *front-*, *middle-* and *back-* component.

threaded bars are inserted into $4mm$ holes holding the device together in the proper position using 4 *hexagonal screws*. By this means, the measurement tool's thickness can be configured like a "sandwich". Thus, adding (removing) intermediate separators results into a thicker (thinner) device.

The *second* (adjustable) variant (Figure 4.2) consists of a *front-*, *back-* and *middle-component* combined with different separators. The *front-* and *back-component* enable the measurement of touch positions. In contrast, the *middle-component* is used to determine the tilt angle of the device when hold by a participant. Since separators are not visible throughout the study, we decided to include an arrangement of $7mm$ holes to reduce the weight caused by the added material. As a result, the layer underneath the interaction area is not continuous anymore. However, we chose the arrangement of holes in such a way that even strong pressure on the interaction area could not deform the outermost layer. In this way, we could reduce the weight by more than *50%*.

The *second* variant consists of *three* key components: *front*, *middle* and *back*.

The key component of the measurement tool are two *capacitive digitizers* mounted to the *front-* and *back-component* of the measurement tool to facilitate touch interaction.

4.1.3 5″ Digitizer

Separating *digitizers* by *finn-paperboard* sufficed to prevent them interfering with each other.

Capacitive touch panels create an electric field which can be manipulated by the electrostatic charging of human fingers. In this manner, each touch panel can recognize up to 5 individual touch positions. To prevent *digitizers* from interfering with each other, we tried different materials such as *black adhesive tape*, regular paper, aluminum foil, plastic and *finn-paperboard* to shield them from each other. Since *finn-paperboard* sufficed our needs to avoid wrong measurements caused by the respectively other *digitizer*, we decided to choose *finn-paperboard* as a protective barrier. This way, we could avoid adding additional material to the measurement tool.

Regarding screen dimensions, we decided to choose 5" *capacitive digitizers* from [BuyDisplay.com, 2015] with a resolution of 800×480 pixels. This design decision is justified by the fact that today's smartphone have a tendency to grow in size. As an example, Apple Inc. recently decided to exchange the 4" iPhone 5s™ with two larger versions, the iPhone 6™ (4.5") and iPhone 6 Plus™ (5.5"). Thus 5" is a reasonable size to look at. Importantly, both *digitizers* include the *GSL 1680 controller*, which grants easy access to the data provided by the *digitizers*. Moreover, it can be used to start, initialize, configure and recalibrate them whenever needed.

Breakout boards were attached to the measurement tool to allow longer distances using regular *6-strand* wires.

We utilized two *Arduino Mega*™ to receive measured touch positions and to process instructions. We used the following wiring as can be seen in Figure 4.3. Since the *digitizers* only provide a small *Flat flexible cable* (short: FFC), we needed to attach two *breakout boards* to the measurement tool to transmit data over longer distances. Regarding our *first variant*, we used three $7mm$ holes to point the wires connected to each *breakout board* in an appropriate direction (Figure 4.4). In combination with a cable holder, it was possible to have an appropriate cable management with-

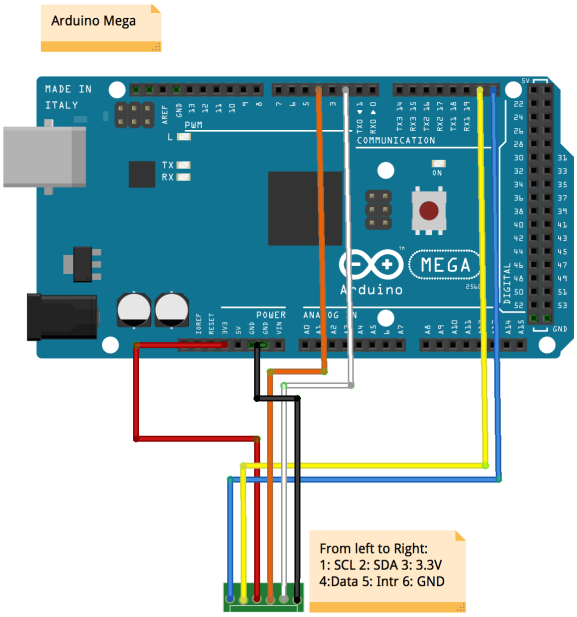


Figure 4.3: Wiring used to receive touch positions recognized by a digitizer.

out having an impact on people's *pinching performance*. In contrast, the *adjustable variant* follows a different approach. Because of the thickness, we can include a *cable duct* in between the different components to direct wires to the bottom (Figure 4.5). Since they leave the measurement tool precisely in the middle, they do not hinder participants interacting with the conductive area.

Another important detail we had to take care of was to properly align the *digitizers* such that their positions correspond to each other. Otherwise, even the smallest deviation would have caused a systematic error resulting in a *pinch-offset*, even though positions were transferred precisely to the front. To ensure the proper position, we used the *engrave-line* functionality offered by the *laser-cutter* to mark the dimensions of the *interaction area*. As a result, we could precisely align the *digitizers* taking the marked frame as a reference. Thus, we guaranteed to eliminate possible *offsets* induced by wrong placement of components.

We ensured *digitizer* positions to correspond to each other by marking the interaction area using a low powered *laser-setting*.

Figure 4.4: Wiring used for the first variant ($4.2mm$).

4.1.4 Vicon™ Motion Tracking Mount

A *motion tracking system* was used to determine the tilt angle of the device while being hold by a participant.

Alongside the *device's thickness* we also assumed *tilt angle* to be a relevant factor influencing people's *pinching performance*. Since our measurement tool does not include a *gyroscope*, which would have allowed us to determine the *tilt angle* of the device, we used the *Vicon™ motion tracking sys-*

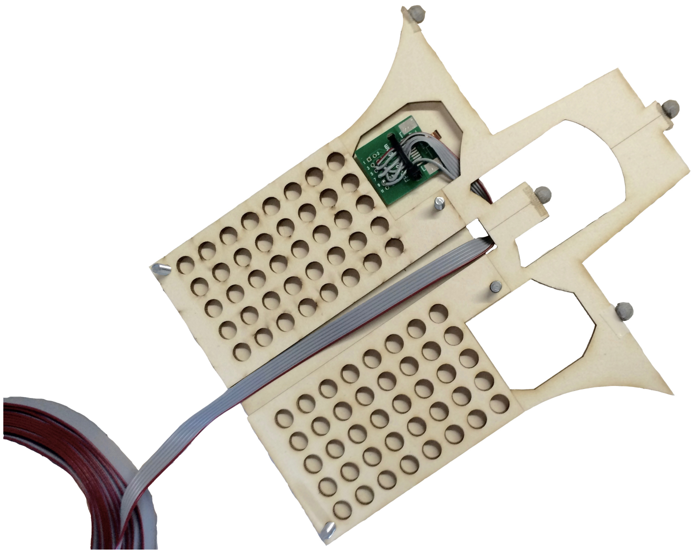


Figure 4.5: Cable duct used with the *second* variant.

tem instead ([Ltd., 2015]).

Infrared cameras being arranged in a circular shape define a *tracking area*. Within this area, objects can be tracked using *markers* which reflect the *infrared light* transmitted by the surrounding cameras. An object is uniquely defined by 3 markers. Importantly, markers have to be arranged in an asymmetric way to ensure that the object is tracked properly. Whenever a symmetric arrangement is chosen, it is likely that the defined object looks the same from either sides. Thus the *tracking system* cannot distinguish between different orientations.

Regarding our purposes, we built a specifically designed *tracking mount* which includes 4 *markers*. As can be seen in Figure 4.2, we asymmetrically arranged the *left* and *right* marker in relation to the markers placed in the *middle*. Referring to the bottom one, we improved tracking accuracy by integrating a small platform that allows better visibility by the cameras while being hold by a participant. Throughout the study, markers have to be seen by at least 3 *infrared cameras* in order to determine the position of the measurement tool in the three-dimensional space. Rounded edges

Four markers sufficed to track the measurement tool properly.

connecting the *tracking mount* with the *interaction area* enables holding the measurement tool without disruption.

To conclude our design of the measurement tool, we refer to the placement of the *tactile dots* used in our study.

4.1.5 Tactile landmarks

Since we aim at understanding *back-to-front pinching*, we used a fixed set of targets to compare *pinching-performance* among users. In our study, shown targets at the distant screen correspond to tactile landmarks placed at the back of the measurement tool to allow more comparable results. But note that in the application scenario of HaptiCase as previously mentioned, tactile dots do not need to match the position of a target on the remote screen. In fact, tactile cues are rather used as a reference by users to orientate themselves using the device eyes-free. We focussed on creating tactile dots which can easily be sensed by users, while at the same time not reducing the *capacitive touch panels'* sensitivity. We used *capacitive foil* which was included with the *5″ capacitive digitizers* from [BuyDisplay.com, 2015]. This way, we could include tactile dots to the foil and attach it back to the *digitizer* placed at the rear side.

As a result we have stated our design of the measurement tool including design decisions made. In the following section we will briefly go into the fabrication process used to obtain our two variants of the measurement tool.

4.2 Fabrication of the Measurement Tool

Vector drawings offer high reproducibility which is important for reasonable results.

All parts needed to build the measurement tool were cut out using the *Epilog Zing 6030 laser-cutter* [FabLab, 2015]. Vector drawings were previously created in *Adobe™ Illustrator CS5* according to our measurement tool's design and processed using *VisiCut*. We used the settings as shown in Table 4.1 to cut out the required components.

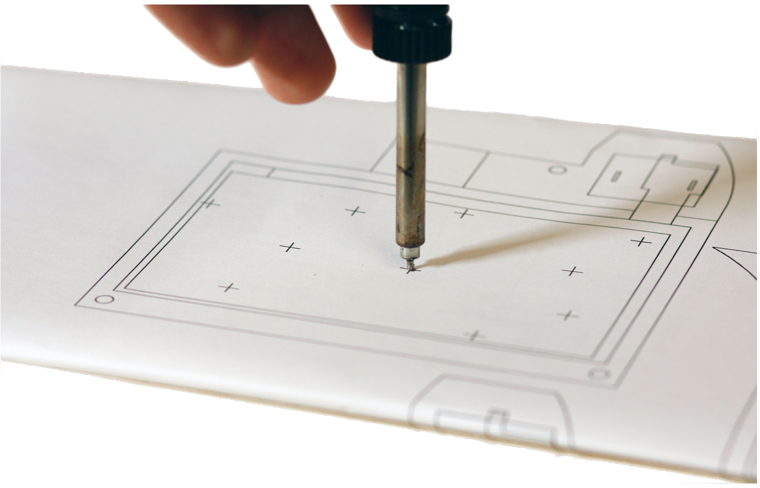


Figure 4.6: Creating tactile dots using a soldering gun at $\approx 150°$.

The first variant only consists of a single part compared to *three* components used for the *second* variant of the measurement tool. As soon as all required components are cut out, the tool can be assembled by attaching *digitizers* to the marked locations. To obtain tactile landmarks, we use a soldering gun (temp.: $\approx 150°C$) to puncture the *conductive foil* at the desired locations (Figure 4.6). We enforced all landmarks to have the same size by using a $1.5mm$ thick piece of cardboard which served as a bedding layer. In this manner, we created tactile dots by holding the soldering gun in an upright position puncturing through the paperboard until we reached the ground. After tactile dots were successfully

Tactile cues were created by puncturing through a *capacitive foil* using a soldering gun.

material	power	speed	focus	frequency
0.9 mm (Cut_Line)	30	100	0	2500
1.5 mm (Cut_Line)	50	100	0	2500
2.0 mm (Cut_Line)	55	100	0	2500
0.9 mm (Mark)	5	100	0	2500
1.5 mm (Mark)	5	100	0	5000
2.0 mm (Mark)	5	100	0	5000

Table 4.1: *Laser-cutter* settings used in *VisiCut*.

mapped to the foil, we attached it as quickly as possible back to the digitizer to avoid air bubbles caused by dust.

We designed the measurement tool in such a way that it can be reproduced at any time with the exact same dimensions. Reproducibility is a key requirement to get reasonable results. Thus, we included vector drawings of each component, which can be used to easily cut out a measurement tool.

4.3 Measurement Software

Collecting *performance data* among users does not only require an appropriate measurement tool but also software which is capable of communicating with different data sources while extracting useful information out of a continuos data-stream. We developed the *pinch-offset measuring tool*, a small application including all actions required to run our study. We will briefly focus on two main aspects: the aggregation and management of data.

4.3.1 Data Aggregation

We distinguish two key types of data managed by our measurement software. Despite touch positions, we also concentrate on the device's tilt-angle measured with the *Vicon™ Motion Tracking system*.

Retrieving Touch Positions

Two *Arduinos* were used to communicate with the *GSL1680* controller of the two digitizers.

Initially, data has to be collected from different sources. To obtain touch positions, we used a tutorial by [Helgelangehaug, 2015] which offered an *Arduino Sketch* specifically designed for the *GSL 1680 Controller* including the necessary firmware. Since the firmware does not fit to a regular *Arduino Uno*, we decided to choose two *Arduino Mega 2560* which feature enough space to control each digitizer respectively. Unfortunately, we could not control both panels using a single *Arduino*, since these panels share the same hardware encoded address $0x40$. Thus, we would not have been able to distinguish between them, using only one *Arduino*.

We adjusted the provided sketch to fit our needs. Whenever either one of the two *Arduinos* gets powered, an initialization sequence is called to prepare the *digitizers* to recognize touch input. In addition, we developed an efficient communication protocol which is used to transfer measured touches to our software tool.

A data-stream using this protocol is of the following form:

$$
\begin{aligned}
&!x_{pos}^{1,1}, y_{pos}^{1,1}; x_{pos}^{2,1}, y_{pos}^{2,1}; \dots ; x_{pos}^{m,1}, y_{pos}^{m,1} \#, \dots , \\
&x_{pos}^{1,2}, y_{pos}^{1,2}; x_{pos}^{2,2}, y_{pos}^{2,2}; \dots ; x_{pos}^{m,2}, y_{pos}^{m,2} \#, \dots , \\
&\vdots \\
&x_{pos}^{1,n}, y_{pos}^{1,n}; x_{pos}^{2,n}, y_{pos}^{2,n}; \dots ; x_{pos}^{m,n}, y_{pos}^{m,n} \#, \dots
\end{aligned}
$$

with start symbol "!" used to trigger the parsing process, "#" being the protocols delimiter separating measurements chunks from each other, $m \in \{1, \dots, 5\}$ being the number of fingers recognized simultaneously and $n \in \mathbb{N}$. This way, a measurement chunk represents a set of up to 5 different positions represented as 2-tuples $(x, y) \in \mathbb{R}^2$. As an example, the measurement chunk $!30, 50; 260, 90\#$ would signify that at the same time 2 fingers are recognized at position $(30, 50) \in \mathbb{R}^2$ and $(260, 90) \in \mathbb{R}^2$.

Note that our data-stream is an infinite sequence of measurement chunks that supplies position information as long as the controller receives touch interrupts. To retrieve position information send by the *Arduinos*, we opened a *Serial Port* using the *OSRSerialPort Framework* published by [Madsen, 2015]. The incoming data-streams (4.7) are then parsed for each *Arduino* respectively.

Whenever a user touches one of the *capacitive panels*, measurements are sent immediately to the processing software. As a result, we end up with a huge amount of data which has to be filtered in order to only extract the relevant touch

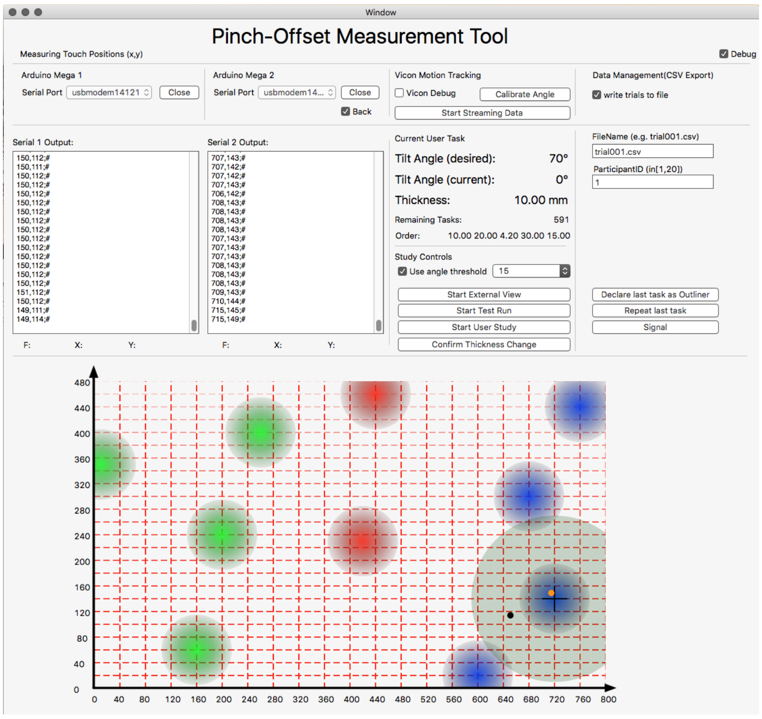


Figure 4.7: Threshold area used in the pinch-offset measurement tool.

positions corresponding to a *back-to-front pinch*. In the following we briefly describe our approach to reliably identify the *back-to-front pinching* gesture.

Recognizing *Back-to-front pinching*

Threshold areas were used to ascertain measured touches corresponding to the intended target.

The gesture can be characterized by *two* phases. Initially, when a user has decided to perform a *back-to-front pinch* at the intended position, he rests his finger at the back. In so doing, touch measurements are transmitted to the measurement software. Since we want to ensure that a user chose the desired target, we only proceed if a touch could be located in a threshold area induced by the target location (Figure 4.7). If this is the case we proceed with the second phase, otherwise we judge the current measurement as irrelevant.

In the *second* phase, we have already recognized a touch in the desired area at the back and wait for a related touch at the front. If a subject completes the gesture by transferring the sensed position to the front, we have identified a *back-to-front pinch* successfully and save corresponding positions. Otherwise, we discard the measurement and go back to the *first* phase. The other key type of data managed by our software is the tilt angle of the device.

Retrieving Tilt Angle

We designed the measurement tool to include a *Vicon™ motion tracking mount*. In this manner, we could asymmetrically arrange 4 markers to constantly track the measurement tool's motion while being hold by a participant. Since we are interested in the device's tilt-angle, we used the *Vicon™ data-stream framework* by [Pye, 2015] to obtain *Euler angles*. These values represent the amount of rotation needed to translate the global coordinate system in relation to the tracking area, into the local one used by the object we defined. As a result, we had to perfectly match both coordinate systems to each other such that the tilt angle can be derived from the rotation around the *x-axis*.

To obtain proper angles, the local coordinate system of the measurement tool had to fit the coordinate system of the tracking area.

Since angles are reported in radian, we converted them into degree to meet our requirements. In addition, we implemented a calibration method to reset the angle to $90°$. Since we adjusted the measurement tool's thickness throughout the study, we could easily recalibrate the angle to ensure legitimate results. Moreover, we added the ability to set the sensitivity with which desired tilt angles should be enforced by the software. Thus, we can stabilize the tilt angle recognition by allowing several degrees threshold.

To communicate intended angles as well as target positions to the user, we designed an appropriate *external view* in combination with a graph visualization to easily check current touch positions.

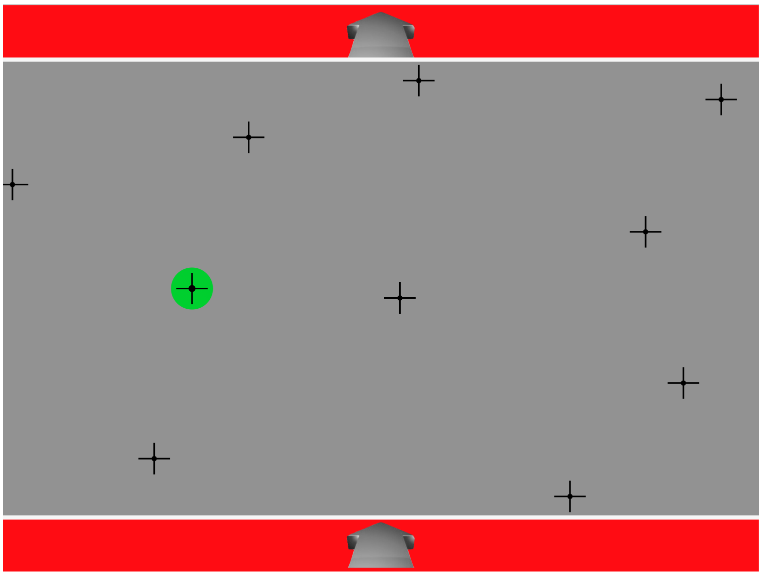


Figure 4.8: External View presented to the user throughout the study. *Top-* and *bottom-* bars combined with *three-dimensional arrows* guide the user to set the proper angle. The current target is highlighted with a green circle.

Graph Visualization & External View

The *graph visualization* could be utilized to assist users finding the desired target location.

The *graph visualization* (Figure 4.7) can be understood as a *live-view* mechanism. Incoming data corresponding to touch locations is parsed by the software and immediately visualized using small colored dots shown in a coordinate system of 800×480 pixels. We used orange-color to refer to touches performed at the rear side, while black indicates measurements occurring at the front (Figure 4.7). Thus, finger positions could be tracked in real-time throughout the study. This allowed us to provide guidance to users whenever they could not find the intended target or confused it with another one. Since we split target positions into *three* sets, namely *Left*, *Middle* and *Right*, we used different colors to indicate their membership.

In contrast, the *external view* (Figure 4.8) is responsible to communicate intended targets and tilt angles to the user. The current target which should be *pinched* by the user is highlighted by a green circle. We used a $1.8\times$ scaling. Nevertheless, targets shown at the *external view* can be easily mapped to the measurement tool by applying an absolute mapping.

Regarding the angle, a top and bottom bar combined with *three-dimensional* arrows indicate, whether the proper angle is currently set. If this is the case, bars turn green immediately. Otherwise, a wrong angle is signaled by red colored bars. In addition, two arrows guide the user reaching the desired setting by pointing forward or backward. This way, users can easily find the intended angle. Moreover, we included an acoustic sound to notify participants, whenever the angle has changed. To conduct a user study using the measurement software two modes are available.

Test Run & User Study

To let participants get familiar with the procedure of our study, the software tool provides a *test run*, where different angles are presented in each trial. Moreover, users can get used to construing the acoustic sound utilized to indicate that the angle has recently changed. Aside from a *test run*, our measurement software also provides the functionality to start a *user study*.

If a *user study* is started, the sequence in which device thicknesses are chosen and tilt angles are applied are randomized. That is, a random value is picked from a set containing all thicknesses (tilt angle analogous) and subsequently deleted. If the set has become empty it is set back to the original set. Regarding the selection of target positions we divided targets into *two* sets. In so doing, we randomized the selection alternating between the *Left* and *Right* set. If all targets and tilt angle combinations have been *pinched* by the user, the study is stopped until the investigator has confirmed the thickness change in software.

Throughout the study the assignment of tasks consisting of a desired thickness, tilt angle and target position was randomized.

Subsequently, we will go into *data management*, the second main aspect of our software.

4.3.2 Data Management

A study consists of 600 trials. Thus, we have to find a suitable data format such that the data can be easily accessed for our later analysis. We found *CSV* to meet our requirements best. To store measurements in a *CSV-File* we used the *CHCSVParser* framework by [DeLong, 2014]. In addition, we were interested in offering a reverse functionality to allow participants to repeat the last task.

Since users sometimes accidentally trigger a *back-to-front pinch*, we included the feature to repeat the last task.

Sometimes it might happen that a target is pinched although unwanted by the participant. This unintentional *back-to-front pinch* might get caused by subjects' fingers briefly referring to the *capacitive surface*. We asked participants to inform us whenever they triggered a *pinch* they rather not intended to touch. In this manner, we minimized the impact of wrong measurements on our final results.

Chapter 5

Evaluation

To better understand how people perform the *back-to-front pinching gesture*, we conducted *two* user studies which in retrospect merged into one main study. In a *preliminary study* with 10 participants we initially investigated the effect of the factors *tilt angle*, *device thickness* and *target position* on the resulting offset. Since all factors were found to be significant for touch locations' *y-coordinate*, we decided to collect more data in our *Main Study* by keeping our initial design. This way, we could apply *multilinear regression* to a larger training set ($10 + 20 = 30$ participants) and got more insights about a potentially underlying model. We considered different polynomial regressions, but found a *linear* regression to fit our data best. A statistical analysis regarding measurements from all 30 participants revealed that *tilt angle* is non significant in x- as well as y- direction. In contrast, the device's *thickness* was found to be significant for both directions.

Likewise *Pinching-time*, we especially focused on the resulting offset between touch positions measured as *euclidean distance* and *angle-offset* between touch locations. Overall, our aim consisted of extracting a model as described in Chapter 2 which can be used to counteract the *pinch-offset effect* and thus improve tapping accuracy. Subsequently we will state our study design including design decisions made followed by the statistical analysis and final results.

We focused on the following dependent factors: *Pinching-time*, the *euclidean distance* between touch locations and the corresponding *angle-offset*.

5.1 Experiment: User study on the Effect of different Factors

A *preliminary study* was used to get first insights into the influence caused by the device's *thickness*, *tilt angle* and *target positions*.

We expected the *pinch-offset effect* to depend on different target positions, *tilt angles* and *thicknesses* of the device. To confirm our intuition, we initially chose a small group of 10 participants to examine, whether these factors have a significant impact on the resulting offset. If one of the factors had not been significant for neither the *x*- nor *y*- coordinate of the measured touch locations, we would have discarded this independent variable to concentrate our attention to the remaining factors. Moreover, we used the *preliminary study* to answer the more general question about the existence of a *pinch-offset effect* and to give a rough estimate if the offset can be modeled using a *multilinear* model.

The *preliminary study* which was used to obtain rough estimates, merged into our main study with 20 additional participants such that we gathered a *data set* of 30 users in total. We decided to maintain our study design and applied our statistical analysis to the entire set of participants. Thus, the following explanations are related to our main study which originates in the *preliminary study*. Regarding our research we investigated the following hypotheses.

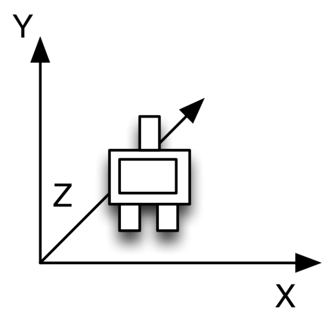


Figure 5.1: Used Coordinate System throughout the study.

5.1.1 Hypotheses

Given hypotheses are stated in null form (i.e., we expect them to be rejected).

H1 Tilting the apparatus along the x-$axis$ (Figure 5.1) for $angles \in \{0°, 40°, 70°, 90°\}$ does not alter the offset for *back-to-front-pinching*. That is, the error between touch positions at the back and at the front is independent of the tilt angle.

H2 An increased thickness does not influence the offset for *back-to-front pinching*. That is, the error between touch positions at the back and at the front is independent of the apparatus's thickness.

H3 There is no tilt angle thickness interaction effect for an increased offset for *back-to-front pinching*

H4 Targets randomly chosen from difficult sections lead to the same error size as targets randomly chosen from simpler sections. That is, the error between touch positions at the back and at the front is independent of target positions.

5.1.2 Participants

In our *user study*, 30 participants (8 of them female) were asked to perform *pinching tasks*. Their age ranged from 21 to 58 and 4 of them were left-handed. Throughout the study, participants were asked to put on glasses which have been modified to occlude their fingers from visual gaze. To be able to explain a possible decrease in *pinching performance* for certain target locations due to reachability issues, we measured participants' *index-finger* and *thumb* length of both hands as well as participants handedness beforehand.

Modified glasses were used to prevent participants from looking at the *measurement tool*.

5.1.3 Task & Procedure

Subjects were asked to perform *back-to-front pinching* tasks, while tilting the apparatus to predefined angles. Throughout the study, different thicknesses and target positions were applied. To complete a task, the apparatus had first to be grabbed in *landscape-* orientation by the participant. This design decision is based on previous results from Corsten et al. [2015], who suggested *HaptiCase* to be more suitable in *landscape-* than in *portrait-* mode.

A *top-* and *bottom-* combined with *three-dimensional* arrows indicated, whether the proper tilt angle was set by the user.

While being seated in front of the measurement table (as can be seen in Figure 5.2), subjects had to focus on the distant screen placed on top of it to gain feedback about the current tilt angle. As long as the intended angle had not been reached yet, red bars combined with arrows indicating the intended tilt direction were displayed on top and at the bottom of the screen. Whenever the proper angle had been reached these bars turned green immediately. Since we observed in a *pilot study* that the bars continuously jump between colors, we used a tolerance filter ($\pm 15°$) allowing values close to the desired angle.

In addition, we decided to use the distant screen in *full-screen mode* to eliminate unwanted influences. Thus, participants could better focus on presented target locations. To design our setup as realistic as possible, participants should not stabilize throughout the study to match the situation when sitting on a couch.

There exists an *absolute mapping* between target positions shown at the distant screen and *tactile dots* placed at the rear of the device.

While the target view was scaled by a factor 1.8 to fit the size of the distant screen, the current target (indicated by a green circle) could easily be transferred using an absolute mapping to the *back* of the device. To face the issue that subjects might not have sensed the desired landmark, the investigator could ensure the proper position using the measurement software's graph visualization (Figure 4.7).

A *back-to-front pinch* is only logged by the measurement software if a touch was recognized in a predefined threshold area, defined as a circle around the target location ($r_{back} = 55px$,$r_{front} = 130px$). The allowed threshold at the

Figure 5.2: Participant were seated in front of a $73.5cm$ high and $70.0cm$ wide measurement table, being away $100cm$ from the distant screen (height: $31.5cm$,width: $50cm$). To avoid participants from stabilizing throughout the study, we decided to choose a chair (length: $44cm$,width: $43.5cm$, height: $55cm$) without arm rest.

front is more than doubled the amount at the back. This design decision is due to our expectation that participants do not match their rear finger's position precisely. A task is completed if a *pinch* could be successfully logged by the measurement software (i.e. the proper angle is set and a touch was recognized at the back as well as at the front).

Tasks were repeated with different tilt angles, measurement tool's thicknesses and target positions.

5.1.4 Test Run

An initial test run is used to get participants familiar with the study procedure.

As stated in Chapter 2, we offered participants the ability to get familiar with the study's procedure by offering a *test run*. Since we wanted to eliminate learning effects, we chose a small set of targets which should be *pinched* by users. In so doing, our *test-set* suffices to briefly get insights into the procedure used throughout the study, while still not getting biased in any way. Subsequently we present our study design.

5.1.5 Study Design

Independent Variables (IV)

We controlled the following Independent Variables:

1. Measurement tool's **Tilt Angle** with levels: $tiltAngle \in \{0°, 40°, 70°, 90°\}$. Tilt Angle is controlled by indicating the desired angle at the distant screen and letting the participant tilt the measurement tool until he has reached the proper angle.
2. Measurement tool's **Thickness** with levels: $thickness \in \{4.2mm, 10mm, 15mm, 20mm, 30mm\}$, where $4.2mm$ is the measurement tool's standard thickness. To control the thickness of the measurement tool, we used specifically designed separators to match the measurement tool's form factor in combination with 4 *screws* which hold the measurement tool's back and front in place. This way, we could easily change between desired thicknesses.
3. **Target Position** (Figure 5.3) with levels:

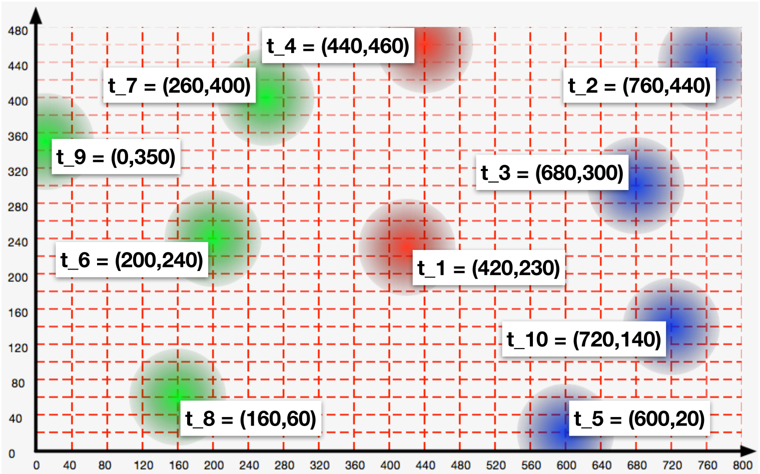


Figure 5.3: Target positions used throughout the study.

- In pixel (px):

$$targetPos_{px} \in \{(420, 230), (760, 440), (680, 300), (440, 460), (600, 20), (200, 240), (260, 400), (160, 60), (0, 350), (720, 140)\}$$

- In millimeters (mm):

$$targetPos_{mm} \in \{(57.54, 31.817), (104.12, 60.87), (93.16, 41.50), (60.28, 63.63), (82.20, 02.77), (27.40, 33.20), (35.62, 55.33), (21.92, 08.30), (00.00, 48.42), (98.64, 19.37)\},$$

where $(x_i, y_i) \in \mathbb{R}$. We only used a small amount of targets, but include 3 repetitions to get more reliable data to apply *multilinear* regression. For unit conversion from $px \to mm$ we used the following formulas:

Target repetition was included to obtain enough data for a *multilinear analysis*.

$$f^{height}_{px \to mm}(x) = \frac{66.4\ mm}{480\ px} \times x\ px = 0.138\bar{3}\frac{mm}{px} \times x\ px$$

$$f^{length}_{px \to mm}(x) = \frac{109.6\ mm}{800\ px} \times x\ px = 0.137\frac{mm}{px} \times x\ px$$

We decided to only pick a limited number of 10 target positions with repetition as suggested by [Gilliot et al., 2014]. In this manner, more data can be collected regarding a single target, which may result into a better fit model when applying *multilinear* regression. Moreover, we can limit the amount of time needed for the user study to avoid potential fatigue of the user.

Dependent Variables (DV)

Participants were requested to perform the *gesture* as precisely as possible. An error occurs whenever a touch position at the back (T_B) does not fit with the touch position at the front (T_F). Thus we only had to measure touch positions provided by the participant. Based on T_B, T_F, we could calculate values of the following Dependent Variables:

1. The **Euclidean Distance** between touch positions $\vec{t_1}, \vec{t_2} \in \mathbb{R}^3$, where $\vec{t_1} = \begin{pmatrix} T_B^x \\ T_B^y \\ b \end{pmatrix}$ and $\vec{t_2} = \begin{pmatrix} T_F^x \\ T_F^y \\ 0 \end{pmatrix}$ with b being the measurement tool's thickness, defined as:
$$\begin{aligned} distance_{\vec{t_1},\vec{t_2}} &= \left|\overrightarrow{t_2 t_1}\right| = \left|\overrightarrow{t_1 t_2}\right| \\ &= \sqrt{(T_B^x - T_F^x)^2 + (T_B^y - T_F^y)^2 + (b-0)^2} \end{aligned}$$
with $distance_{\vec{t_1},\vec{t_2}} \in \mathbb{R}$. That is, the ordinary distance between the touch position at the back and at the front in the euclidean space.
2. The **Angle Offset** between touch positions $\vec{t_1}, \vec{t_2} \in \mathbb{R}^3$, defined as:
$$angleOffset_{\vec{t_1},\vec{t_2}} := \arctan\left(\frac{T_B^x - T_F^x}{T_B^y - T_F^y}\right) \times \left(\frac{180}{\pi}\right)$$
That is, the angle between touch positions in the x, y-plane of the measurement tool.
3. The **Pinching Time** between touch positions $\vec{t_1}, \vec{t_2} \in \mathbb{R}^3$, where $\vec{t_1} = \begin{pmatrix} T_B^x \\ T_B^y \\ b \end{pmatrix}$ and $\vec{t_2} = \begin{pmatrix} T_F^x \\ T_F^y \\ 0 \end{pmatrix}$ with b being

the measurement tool's thickness. That is, the elapsed time between a touch being recognized at the back and at the front. A stopwatch is used, which starts when a touch is recognized in the threshold area at the back and stops precisely when a touch is measured in the front threshold area. Whenever a participant reenters the threshold area at the back the stopwatch is reset.

5.1.6 Experimental Design

Since we assigned participants to conditions at random, we conducted a true experiment. Thus, we had to take care of removing potential biases, ensuring that target positions are presented at random and satisfying replicability. As mentioned above, *three* independent variables are used. Thus, we decided to choose a *factorial design*. This allowed us to study a potential interaction effect between $tiltangle$ and $thickness$ as intended in our research questions.

Randomization was required to guarantee representable results.

The total amount of *tasks* per participant was obtained from the levels shown in Table 5.1. As a result, each user had to pinch $5 \times 4 \times 10 \times 3 = 600$ times. Since we considered an average *pinching time* of $6sec.$ per *task* we derived a total study duration of 600×6 sec. $= 3600$ sec. (60 min.).

Regarding experimental design decisions, we wanted to efficiently isolate the impact of individual differences and

condition	levels	# of levels
thickness [mm]	{4.2mm,10mm,15mm, 20mm,30mm}	5
tilt angle [deg]	{0°,40°,70°,90°}	4
target position [px]	{(420,230),(760,440), (680,300),(440,460), (600,20),(200,240), (260,400),(160,60), (0,350),(720,140)}	10

Table 5.1: Levels of *independent variables*.

Since we decided to choose a *within-group design*, we had to take care of possible fatigue of participants. Possible *learning-effects* had to be avoided by *randomization*.

limit the number of needed participants. Hence, we decided to choose a within-group design such that each participant had to perform 600 *pinches* in total. As a result, we had to take care of challenges, which arise from our design decision.

First of all, we had to reduce possible learning effects by randomizing thicknesses and tilt angles. It is crucial that the device's *thickness* was only adjusted whenever 120 *tasks* had been completed by a user. In contrast, *tilt angles* were randomly changed after 30 *tasks* had been performed. This design decision is justified by the fact that we wanted to prevent changing thicknesses too often. Moreover, possible fatigue of subjects had to be taken into account by offering suitable breaks among different device thicknesses. In addition, we tried to avoid potential biases by preparing a *checklist* to ensure that every user gets the exact same initial information before the study.

Subsequently we present our final results.

5.1.7 Results

To decide whether to accept or reject our hypotheses (H1-H4), we run a statistical analysis using a *three-way repeated-measures* ANOVA. Since the *tilt angle* with which participants were holding the measurement tool was found to be non significant in both directions, we finally accept H1 against our initial expectations. In contrast, the device's *thickness* was significant for *x-* as well as *y-direction* (x: $F(4, 17911) = 9.7750, p < 0.0001$, y: $F(4, 17911) = 20.6873, p < 0.0001$). Thus, we reject the *second* hypothesis. As a result, operating different *thicknesses* of the device has an impact on people's pinching performance. Interestingly, we could identify two classes of *thicknesses*, namely $\{4.2mm, 10mm, 15mm\}$ and $\{20mm, 30mm\}$ which were significantly different.

Two classes of *thicknesses* were identified:

- 4.2mm, 10mm, 15mm
- 20mm, 30mm

Regarding a possible interaction effect between *tilt angle* and *thickness* we concluded that there is no effect in *y-*, but in *x-direction* ($F(12, 17911) = 2.2788, p < 0.01$). As a result, H3 can only be rejected for *x-direction*. Finally, we reject the *fourth* hypothesis, since *target location* was significant for both directions (x: $F(2, 17911) = 22.6119, p < 0.0001$, y: $F(2, 17911) = 5.8547, p < 0.01$). Thus, *target location* influenced people's *pinching performance*. In our *first* attempt, we started our statistical analysis by considering all data points equally. This approach was followed by a partition of the target set into *three* groups, namely *left*, *middle* and *right*. In this manner we could derive models which significantly improve touch accuracy for *right* targets. The final step of our analysis considered different device thicknesses and focussed on extracting models for each thickness respectively.

In the following, we briefly state a modification of our strategy described in Chapter 2 to extract an appropriate model.

Model Extraction

Our initial attempt to extract an underlying model had to be changed to such a degree that *multilinear regression* was applied to the exact *target's location* rather than the position of a finger sensing the corresponding *tactile landmark* at the back of the device. This simplification is justified by the nature of *multilinear regression* which requires fixed independent variables to predict the value of a single dependent variable.

Multilinear regression was applied to the exact *target's location* rather than the position of a finger sensing a *tactile dot* at the back of the device.

As can be seen in Figure 5.4, a predefined *tactile landmark* is pinched to the front of the device multiple times (indicated by blue arrows). Using positions measured at the front, we could apply *multilinear regression* (indicated by a green arrow) and obtained a position minimizing the error between all measured touches at the front regarding a specific target. In so doing, we obtained a *predictor function* (indicated by red arrows) as described in Chapter 2 which can be used to calculate the touch location the user actually intended to touch. As shown in Figure 5.4, measured positions at the front as well as predicted touch locations at the back induce an ellipse which contains 99% of either predicted or measured locations. To test a *model's performance* we have to

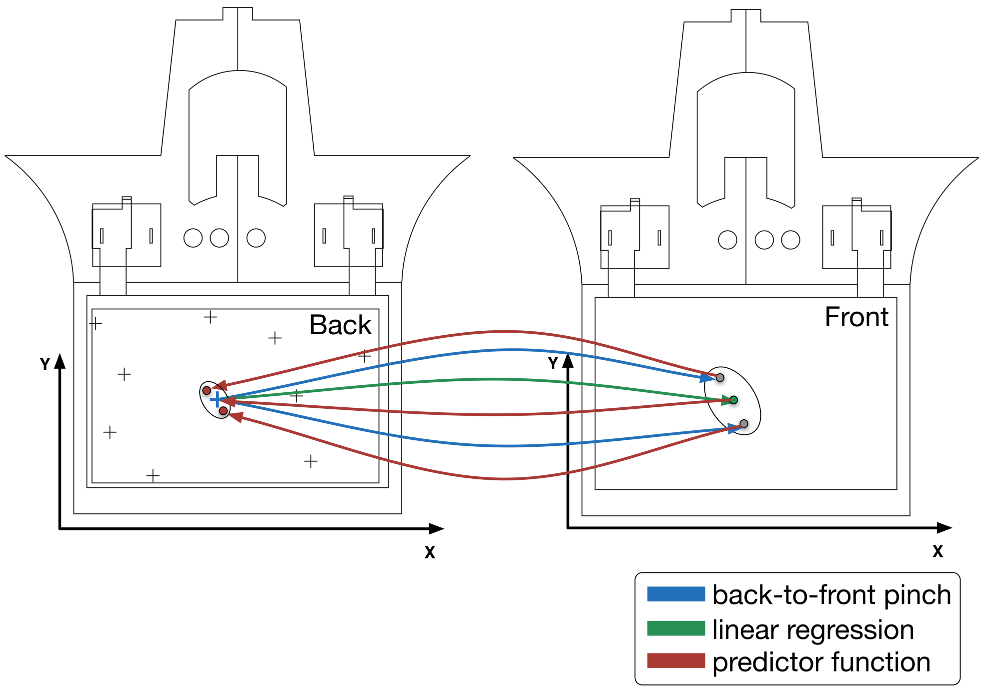


Figure 5.4: Modified approach regarding model extraction.

compare the average offset induced by the exact target's location and the measured touch location ($:= O_{FB}$) with the average offset induced by the exact target's location and the predicted one ($:= O_{BB}$). Whenever it holds for a specific model that $O_{BB} \ll O_{FB}$, the model does improve touch accuracy. Thus, we take the comparison between O_{BB} and O_{FB} as a *performance measure*.

In the following section we present 8 models including one for each device thickness respectively. In addition, we present *performance measurements* as well as a *cross-validation* to justify our results.

Models

Our user study yielded a dataset containing 18000 measurements corresponding to *back-to-front pinches* performed

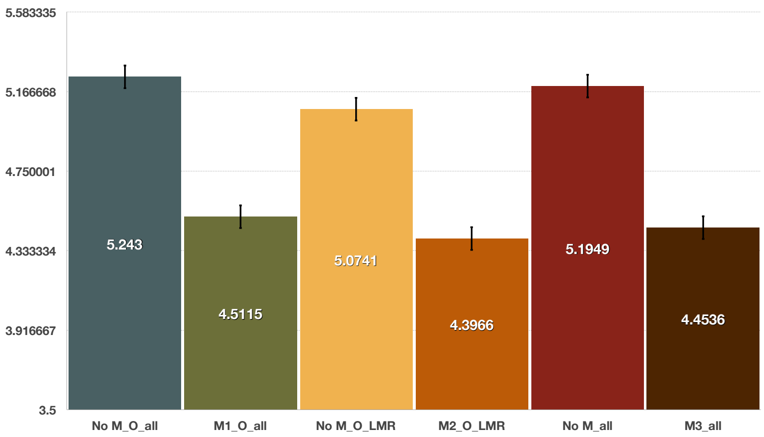


Figure 5.5: Performance data M1-M3 regarding the average offset in x-direction [mm] with and without model.

by 30 participants. Multiple *multilinear regressions* were run to predict the touch position at the front ($:= T_F$) based on different predictors like *Target X [mm]*, *Age* or *Gender*. The assumption of linearity, independence of errors, homoscedasticity, unusual points and normality of residuals were met. Regression coefficients and standard errors for all models can be found in Table 5.3 on page 56. Our statistical analysis revealed that the offset could be modelled for both directions, but only showed significant improvements for models regarding the *x-direction*. To get further insights, we decided to split targets used throughout the study into *three* groups, namely *left*, *middle* and *right* to find models for each group respectively. Model 1 and 3 consider the whole set of targets, while model 2 splits targets according to above-named groups. Since we found the *device's thickness* to have a significant impact on people's *pinching performance*, we created models $4, 5, 6, 7$ and 8 for each *thickness* respectively.

Regarding the *first* model, *Target X [mm]* statistically significantly predicted T_F, ($F(1, 17998) = 588631.784, p < 0.0005, adj.R^2 = 0.970$). *Target X [mm]* added statistically significantly to the prediction, $p < 0.0005$. Performance tests revealed that the first model reduces the offset in *x-direction* by $-0.7315mm$ considering all targets equally.

The average offset could be reduced by $0.7mm$ in *x-direction*.

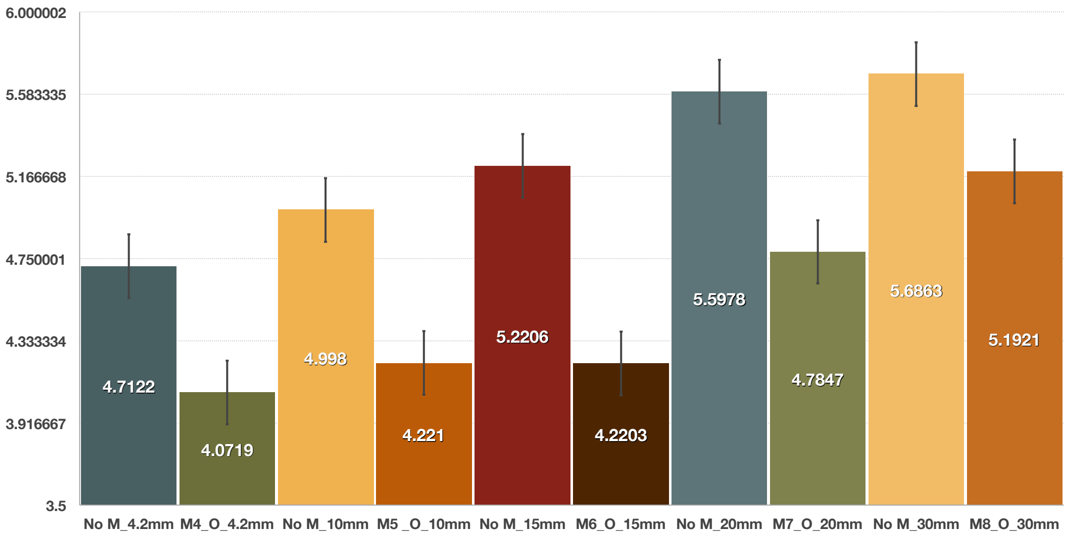


Figure 5.6: Performance data M4-M8 regarding the average offset in x-direction [mm] with and without model.

The *second* model rather focuses on different target groups and only depends on *Target X [mm]*. This variable statistically significantly predicted T_F with respect to targets located at the *right*, $(F(1, 7198) = 15432.644, p < 0.0005, adj.R^2 = 0.682)$. It added statistically significantly to the prediction, $p < 0.0005$. Please note that models describing the error for *left-* or *middle-targets* could not reduce the size of the offset and thus were not considered. Regarding *performance data*, model 2 could reduce the offset in *x-direction* by $-0.6775mm$.

Model 3 considered the entire target set, but also removed potential outliers. Regarding the *third* model, *Target X [mm]* statistically significantly predicted T_F, $(F(1, 17922) = 606506.266, p < 0.0005, adj.R^2 = 0.971)$. The variable added statistically significantly to the prediction. Model 3 was found to reduce the error induced by a *back-to-front pinch* by $-0.7413mm$.

Model $4, 5, 6, 7$ and 8 consider each device *thickness* respectively.

In contrast to the models mentioned above, models $4, 5, 6, 7$ and 8 rather concentrate on a *single device thickness* in $\{4.2mm, 10mm, 15mm, 20mm, 30mm\}$. *Target X [mm]* statistically significantly predicted T_F for models $4, 5, 6, 7$ and

8 (see Table 5.2). In matters of *model performance*, model 4

model	statistical result
M4_O_4.2mm	$F(1, 3598) = 142671.474, p < 0.0005, adj.R^2 = 0.975$
M5_O_10mm	$F(1, 3598) = 135481.690, p < 0.0005, adj.R^2 = 0.974$
M6_O_15mm	$F(1, 3598) = 130571.118, p < 0.0005, adj.R^2 = 0.973$
M7_O_20mm	$F(1, 3598) = 105219.810, p < 0.0005, adj.R^2 = 0.967$
M8_O_30mm	$F(1, 3598) = 093081.432, p < 0.0005, adj.R^2 = 0.963$

Table 5.2: Statistical results regarding models for each thickness in $\{4.2mm, 10mm, 15mm, 20mm, 30mm\}$.

($4.2mm$) was found to reduce the error induced by a *back-to-front pinch* by $-0.6403mm$, model 5 ($10mm$) by $-0.777mm$, model 6 ($15mm$) by $-1.0003mm$, model 7 ($20mm$) by $-0.8131mm$ and model 8 ($30mm$) by $-0.4942mm$. As a result, we can conclude that the *pinch-offset effect* can best be counterbalanced at $15mm$ thickness, since using either the *thinnest* or *thickest* variant of the measurement tool seemed to provoke a decrease in handling performance which led to offsets which are difficult to model.

The *pinch-offset effect* could best be counterbalanced at $15mm$ thickness.

To sum up, we can report an overall improvement of $0.7mm$ on average. This can be achieved by considering all *tilt angles* and *device thicknesses* in equal measure. Against our initial expectations, changing the device's tilt angle did not result into significant changes in *pinching performance*. In contrast, *thickness* was found to be significant, why we decided to create models for each *thickness* respectively. Concentrating on a single *device thickness*, allowed us to achieve improvements up to $-1.0003mm$ ($15mm$). Referring back to our *research questions*, we conclude that the desired *target location* and chosen *device thickness* have a significant impact on the resulting offset and thus lead to a *pinch-offset effect*. Regarding our *second* question we can report model *M1* to counterbalance the effect best without paying attention to different device thicknesses. In so doing, the model reduces the size of the error by $-0.7315mm$. If we also differentiate between different *thicknesses*, we get improvements starting from $-0.4942mm$ ($30mm$) up to $-1.0003mm$ ($15mm$).

Differences in *tilt-angle* were not significant for the resulting offset.

model	predictor	B	SE_B	β
M1_O_all	*constant*	-0.877	0.092	
	Target X [mm]	1.045	0.001	0.985*
M2_O_LMR	*constant*	8.368	0.722	
	Target X [mm]	0.945	0.008	0.826*
M3_all	*constant*	-0.780	0.91	
	Target X [mm]	1.045	0.001	0.986*
M4_O_4.2mm	*constant*	-1.571	0.187	
	Target X [mm]	1.048	0.003	0.988*
M5_O_10mm	*constant*	-0.248	0.191	
	Target X [mm]	1.041	0.003	0.987*
M6_O_15mm	*constant*	-0.877	0.196	
	Target X [mm]	1.052	0.003	0.987*
M7_O_20mm	*constant*	-0.725	0.218	
	Target X [mm]	1.047	0.003	0.983*
M8_O_30mm	*constant*	-0.966	0.229	
	Target X [mm]	1.038	0.003	0.981*

Table 5.3: 1: Prediction of $TouchFront_x[mm]$ without outlier removal. 2: Pred. of $TouchFront_x[mm]$ at the *right*, without outlier removal. 3: Pred. of $TouchFront_x[mm]$ with outlier removal. 4-8: Pred. of $TouchFront_x[mm]$ with outlier removal for each thickness in $\{4.2mm, 10mm, 15mm, 20mm, 30mm\}$. Note. * $p < 0.0005$ B = unstandardized regression coefficient SE_B = Standard error of the coefficient β = standardized coefficient.

Cross-Validation

A *cross-validation* can validate results, without getting more samples.

Having stated our results, we applied a *cross-validation* to our dataset in order to guarantee the correctness of our statistical analysis. This way, measurements from all 30 participants are split into *two* sets, namely *training-* and *test-set*, such that they are uniformly distributed regarding *handedness*, *gender*, *age*, *thumb-length* and desired *user tasks*. As soon as a *training-set* could be derived, we extracted a *model* out of it and checked it's *performance* by applying it to the

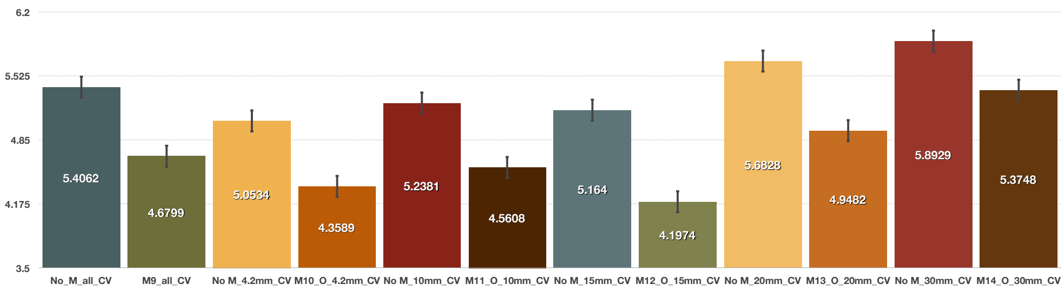


Figure 5.7: Comparison of performance data (cross-validation) regarding the average offset in x-direction [mm] with and without model.

predefined *test-set*. In this manner we could validate our approach without having to conduct another *user-study*.

Initially, we conducted a *cross-validation* without removing outliers and considering all targets equally. This way, a *multilinear regression* with respect to the *training set* yielded the following results. *Target X [mm]* statistically significantly predicted T_F, $(F(1, 8998) = 304099.020, p < 0.0005, adj.R^2 = 0.971)$. *Target X [mm]* added statistically significantly to the prediction, $p < 0.0005$. Applying the model derived from the *training-set* to data from the *test-set* yielded an overall improvement in error offset of $-0.7263mm$. Regression coefficients and standard errors regarding all *cross-validations* can be found in Table 5.5. In addition, we also applied a *cross-validation* with respect to different *device thicknesses*. *Target X [mm]*

training model	statistical result
4.2mm	$F(1, 1798) = 76085.527, p < 0.0005, adj.R^2 = 0.977$
10mm	$F(1, 1798) = 73954.421, p < 0.0005, adj.R^2 = 0.976$
15mm	$F(1, 1798) = 62234.323, p < 0.0005, adj.R^2 = 0.972$
20mm	$F(1, 1798) = 54850.372, p < 0.0005, adj.R^2 = 0.968$
30mm	$F(1, 1798) = 49064.826, p < 0.0005, adj.R^2 = 0.965$

Table 5.4: Statistical results of our *cross-validation* for each device thickness respectively.

statistically significantly predicted T_F for each thickness in $\{4.2mm, 10mm, 15mm, 20mm, 30mm\}$. Statistical results can be found in Table 5.4 as well as corresponding *performance data* in Figure **??**. We could identify an overall improvement of $-0.6945mm$ for $4.2mm$, $-0.6773mm$ for $10mm$, $-0.9666mm$ for $15mm$, $-0.7346mm$ for $20mm$ and $-0.5181mm$ for $30mm$ thickness. Thus, we can conclude the correctness of our statistical analysis, since the *cross-validation* yields the same trend regarding thicknesses as previously reported.

A *cross-validation* could confirm our previous results.

training model	predictor	B	SE_B	β
Training_O_all	*constant*	-0.428	0.127	
	Target X [mm]	1.040	0.002	0.986*
Training_O_4.2mm	*constant*	-1.185	0.254	
	Target X [mm]	1.038	0.004	0.988*
Training_O_10mm	*constant*	-0.584	0.256	
	Target X [mm]	1.032	0.004	0.988*
Training_O_15mm	*constant*	-0.429	0.283	
	Target X [mm]	1.048	0.004	0.986*
Training_O_20mm	*constant*	-0.356	0.301	
	Target X [mm]	1.046	0.004	0.984*
Training_O_30mm	*constant*	-0.752	0.315	
	Target X [mm]	1.034	0.005	0.982*

Table 5.5: 1: Prediction of $TouchFront_x[mm]$ without outlier removal restricted to *training-set*. 2-6: Pred. of $TouchFront_x[mm]$ with outlier removal for each thickness in $\{4.2mm, 10mm, 15mm, 20mm, 30mm\}$ restricted to *training-set*. Note. * $p < 0.0005$ B = unstandardized regression coefficient SE_B = Standard error of the coefficient β = standardized coefficient.

Since we also aimed at considering qualitative data, we decided to create a *questionnaire* to get a general idea of participants' perception of their *pinching performance*.

5.1.8 Questionnaire

Understanding *back-to-front pinching* not only requires to collect quantitative measurement data about touch locations in order to arithmetically determine whether people tend to *over-* or *under- shoot* the desired target location, but also qualitative data which allows us to get an insight into people's sensation about their pinching performance. Thus, we created a *questionnaire* that should be answered by users throughout the study.

A *questionnaire* allowed us to also consider *qualitative data*.

Besides demographic data like *age* and *handedness* we included questions about how participants experienced different thicknesses. We used statements like *back-to-front pinching was easy to perform at* 4.2 *mm device thickness* which users could rank using *likert scales* with values in $\{1, 2, 3, 4, 5\}$, where 1 stands for *totally disagree* and 5 for *totally agree* respectively. Since we did not want participants to forget about their impressions among several thicknesses, we decided to let them answer the corresponding row in the *questionnaire* after they have finished all tasks for a specific thickness. We also payed attention to targets which users thought to be difficult to pinch for a specific condition. To collect this data, we gave users the chance to encircle difficult targets for thicknesses in $\{4.2mm, 10mm, 15mm, 20mm, 30mm\}$. In addition, users should also rank the statements concerning different tilt angles analogous to the ones we used for device thicknesses. To identify fingers most frequently used by participants, they could encircle fingers (incl. thumb) used to perform the *back-to-front pinching gesture*.

Participants could encircle target positions they found difficult to pinch.

At the end we additionally included several statements regarding the user's overall impression. As an example we asked whether subjects experienced their touch locations at the back and at the front to differ from each other. In this manner, we could conclude whether users' sensation matches the result we got from our data analysis. We also desired them to rank our three conditions *thickness*, *tilt angle* and *target position* with respect to their level of difficulty. On a final note, we offered some additional space for comments regarding the study.

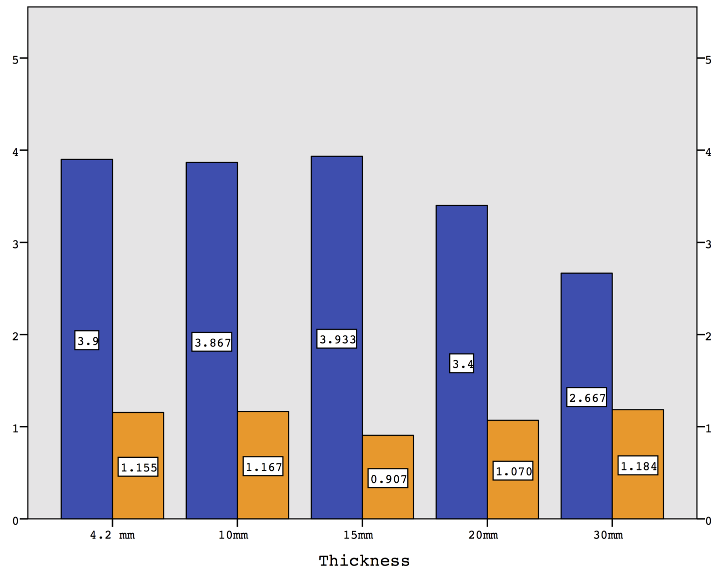


Figure 5.8: Means (blue) and Std. Deviation (orange) of participant's level of agreement regarding the following statement: *Back-to-front pinching was easy to perform at 4.2/10/15/20/30mm.* (1 $\hat{=}$ totally disagree, 5 $\hat{=}$ totally agree)

In the following we will state conclusions drawn from the data analysis regarding our questionnaire.

5.1.9 Questionnaire Results

We gathered data from 30 participants in total. As can be seen in Figure 5.8, means decrease from 3.9 ($4.2mm$) down to 2.667 ($30.0mm$). Only at $15mm$ we noticed a slight increase (3.933) in the level of difficulty experienced by the user in comparison to 3.867 at $10mm$. As a result, we can conclude that the thicker the device, the more difficult participants experienced *back-to-front pinching*.

The thicker the device, the more difficult participants experienced *back-to-front pinching*.

Furthermore, we conducted a *Friedman test* to determine whether there are differences in *thickness preferences* among users. We utilized pairwise comparisons (SPSS, 2015) with a *Bonferroni correction* for multiple comparisons. User's *preference* was statistically significantly different at the different device thicknesses throughout the study ($\chi^2(4) = 22.954$, $p < .0005$). Post hoc analysis revealed statistically significant differences in preference from 30mm (Mdn = 3.00) to 10mm (Mdn = 4.00) (p = .008), 30mm (Mdn = 3.00) to 15mm (Mdn = 4.00) (p = .005) and 30mm (Mdn = 3.00) to 4.2mm (Mdn = 4.00) (p = .004), but not from 30mm to 20mm, 20mm to 10mm, 20mm to 15mm, 20mm to 4.2mm, 10mm to 15mm, 10mm and 4.2mm and 15mm and 4.2mm. Thus, participants reported a noticeable difference between the thickest and all thinner measurement tools.

Regarding *tilt angles*, we could identify a ranking. Hence, users classified $90°$ as most difficult (Mdn = 2.00), followed by $0°$ (Mdn = 3.00), $70°$ (Mdn = 4.00) and $40°$ (Mdn = 4.50) which was the angle participants felt most comfortable with. A *Friedman test* revealed participant's *preference* towards the *tilt angle* to be statistically significantly different ($\chi^2(3) = 42.034$, $p < .0005$). A post hoc analysis found statistically significant differences in preference from $90°$ (Mdn = 2.00) to $70°$ (Mdn = 4.00) ($p < .0005$), $90°$ (Mdn = 2.00) to $40°$ (Mdn = 4.50) ($p < .0005$), $0°$ (Mdn = 3.00) to $70°$ (Mdn = 4.00) (p = .003) and $0°$ (Mdn = 3.00) to $40°$ (Mdn = 4.50) ($p < .0005$). In contrast, differences in preference from $90°$ to $0°$ and $70°$ to $40°$ were not statistically significant. Thus, we can identify two classes of *tilt angles*, $\{0°, 90°\}$ and $\{40°, 70°\}$ which were experienced similar.

We identified *two* classes of angles:

- $\{0°, 90°\}$
- $\{40°, 70°\}$

Regarding the statements we asked users to rank on a five point *likert scale*, we could obtain that people could easily map targets shown at the distant screen to the back of the device (Mn = 4.07). In addition, they slightly had the impression that their touch position at the rear and at the front differs from another (Mn = 2.6). The small breaks between device thicknesses helped users to recover (Mn = 4.3). This is important, since we aimed at avoiding fatigue of the user. Last but not least, people felt their *pinching performance* to be most influenced by *tilt angle* (Mn = 4.5), followed by the thickness of the device (Mn = 4.17) and the desired target location (Mn = 4.1). These findings are especially interesting, since we found the *tilt angle* not to be significant which is inconsistent with people's overall impression. Moreover, users rated their *pinching performance* a lot better than it really was.

Participants slightly had the impression that their touch position differs from another.

Subsequently, we dwell on a few aspects users mentioned throughout the study.

User Comments

Middle targets were experienced difficult to reach.

We offered participants the opportunity to mention important aspects in a *comments section*. Two users noted that not their arms, but heir shoulder got stressed over time. In addition, most of the users found targets placed towards the middle of the measurement tool to be more difficult and harder to reach.

Interestingly, some users reported a better handling using the thickest tool. That's why, they experienced themselves to perform better using a thicker device. Interestingly, some participants stated that they came up with strategies speeding up the process to find the corresponding tactile dot.

Chapter 6

Summary and future work

6.1 Summary and Contributions

Our results indicate that performing *back-to-front pinching* eyes-free induces an offset between the actual intended target and the measured touch position. These findings were obtained by designing an appropriate experiment which allowed us to investigate people's *pinching performance* by quantifying the offset induced by a *back-to-front pinch*. Thus, we could prove the existence of the *pinch-offset effect*.

We could confirm the existence of the *pinch-offset effect*.

As can be seen in Figure 6.1, the *pinch-offset effect* can be visualized by comparing measured touches at the front and at the back of the device. Obviously touch positions are a lot more spread regarding $30mm$ thickness. This can be explained by reachability issues people face with increasing device *thickness*. As a result, we can recommend to avoid using devices in context of the *HaptiCase interaction technique* which are thicker than $20mm$. In addition, we observed offsets towards people's hands which could be observed by *left-targets* being shifted towards the *left* and *right-targets* being shifted towards the *right* respectively. Overall the *average offset* induced by a *back-to-front pinch* could be

In our *application scenario*, devices should not be thicker than $20mm$.

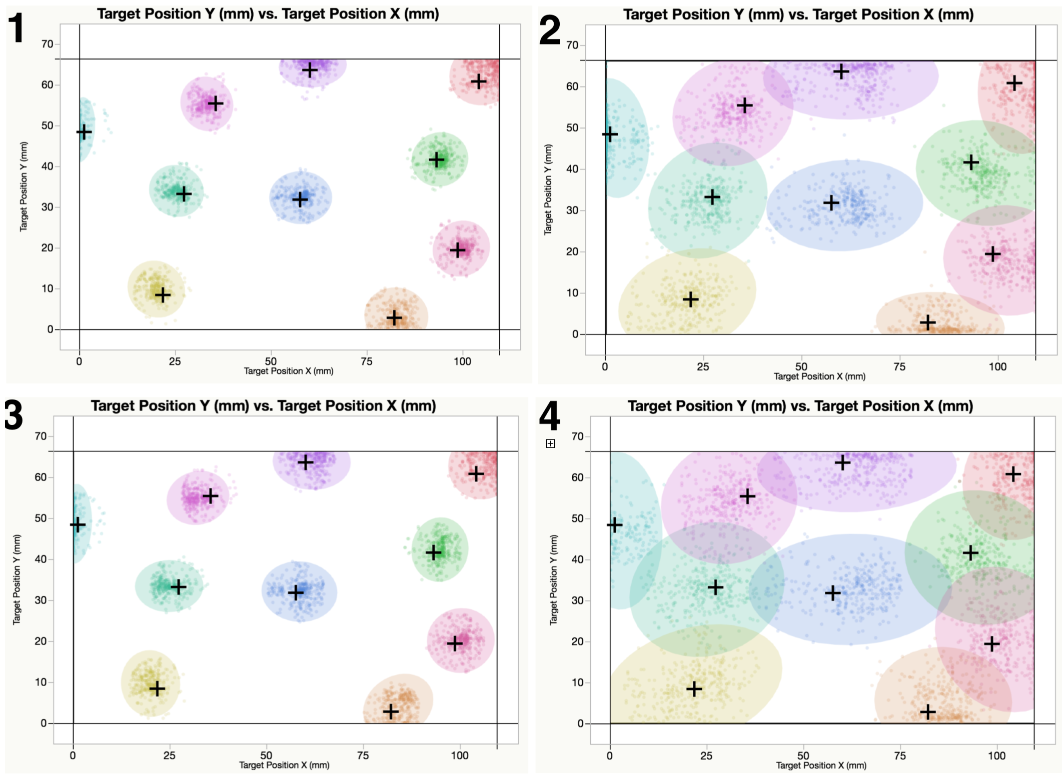


Figure 6.1: Visualization of the *pinch-offset effect*. Images 1 and 2 show the resulting *offset* between touches which are recognized at the back and at the front of the measurement tool at $4.2mm$. In contrast images 3 and 4 visualize the offset regarding $30mm$ thickness. Obviously, the offset increases with increasing device thickness.

improved by $0.7mm$ using a *linear model*. These results were confirmed using a *cross-validation*.

The required target size could be reduced by $\approx 10\%$.

Developers can take advantage of our results by reducing the required target size, while still keeping the same *tapping accuracy*. For instance, if you consider a button featuring a $15 \times 15mm^2$ tapping area, we can efficiently reduce the required target size by $0.7mm$ in *x-direction* on both sides. This yields a reduction of $100 - (((15 \times 13.537)/(15 \times 15)) \times 100) \approx 10\%$. In addition, we can improve further by considering the model for $15mm$ thickness which let to a reduction of $100 - (((15 \times 12.994)/(15 \times 15)) \times 100) \approx 13.5\%$.

6.2 Limitations and Future Work

Although we tried to design our experiment as general as possible, there are a few limitations we could not avoid. Regarding the measurement tool, we decided to choose *5″ capacitive digitizers*. Although this is a suitable size, bigger devices might become more popular in future. Thus, different *digitizers* sizes should be considered in future work. Moreover, used *digitizers* could only provide *x*- and *y-coordinates* corresponding to touch locations. It would be useful to also consider additional values like the angle with which fingers are touching the panel as well as the area occluded by the touch. This way, models could be extracted which show further improvements in counterbalancing the *pinch-offset effect*, since they can describe the *back-to-front pinching gesture* in more detail.

Different *digitizer sizes should be considered in future work.*

Finally, our research did only focus on counterbalancing the *first source of error* which we identified in Chapter 2 as *pinch-offset effect*. Future work in this area might also consider the *offset* induced by an absolute mapping of targets which are shown at the *distant screen* to the back of the device.

Future work should also focus on the *first source of error*.

Appendix A

Questionnaire

QUESTIONNAIRE

Participant ID: _______

---

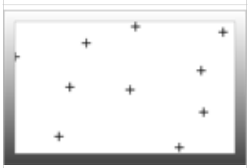
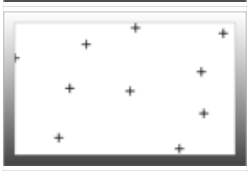
(1) Gender: ◯ Male ◯ Female

(2) Age: _______________

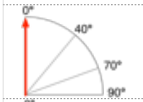
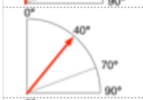
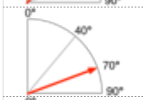
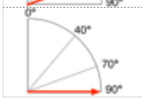
(3) Your dominant hand? ◯ Left ◯ Right

---

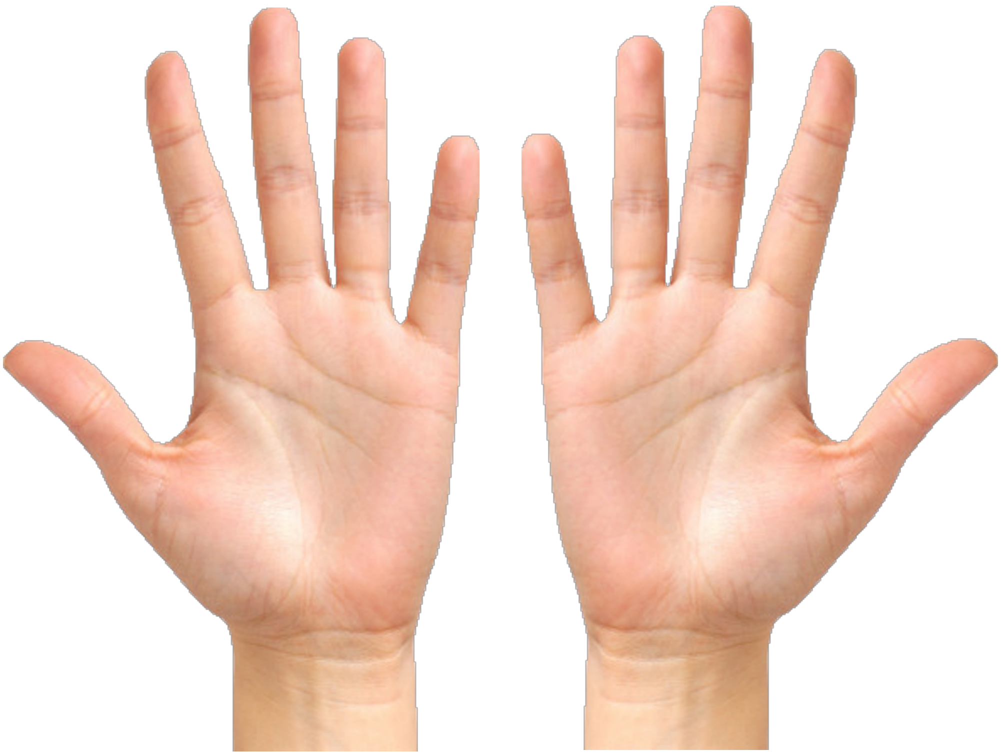
(4) Please rate your **level of agreement** on the following **statements** and **encircle targets** which you found to be **difficult to pinch** at the **specific thickness**

	totally disagree		**neither**		**totally agree**	**I found** the **following targets difficult to pinch** at the specific thickness:
(A) **Back-to-front pinching** was **eas**y to perform at **4.2mm** thickness	☐	☐	☐	☐	☐	
(B) **Back-to-front pinching** was **easy** to perform at **10mm** thickness	☐	☐	☐	☐	☐	
(C) **Back-to-front pinching** was **easy** to perform at **15mm** thickness	☐	☐	☐	☐	☐	
(D) **Back-to-front pinching** was **easy** to perform at **20mm** thickness	☐	☐	☐	☐	☐	
(E) **Back-to-front pinching** was **easy** to perform at **30mm** thickness	☐	☐	☐	☐	☐	

(5) Please rate your **level of agreement** on the following **statements:**

		totally disagree		neither		totally agree
	(A) Independent of thickness and target position, **pinching at 0°** was **easy** to perform.	☐	☐	☐	☐	☐
	(B) Independent of thickness and target position, **pinching at 40°** was **easy** to perform.	☐	☐	☐	☐	☐
	(C) Independent of thickness and target position, **pinching at 70°** was **easy** to perform.	☐	☐	☐	☐	☐
	(D) Independent of thickness and target position, **pinching at 90°** was **easy** to perform.	☐	☐	☐	☐	☐

(6) Please **encircle fingers used** to perform **Pinching Tasks:**



(7) Please rate your **level of agreement** on the following **statements**:

	totally disagree		neither		totally agree
(a) Target positions shown at the distant screen **could be easily mapped** to the back of the measurement tool using tactile cues.	☐	☐	☐	☐	☐
(b) My arms got heavy while holding the measurement tool at the desired angles.	☐	☐	☐	☐	☐
(c) I had the impression that my **touch positions** at the back and at the front **differ from each other.**	☐	☐	☐	☐	☐
(d) The small breaks between different device thicknesses helped me to stay concentrated and relaxed throughout the study.	☐	☐	☐	☐	☐
(e) I felt **comfortable** while holding the measurement tool.	☐	☐	☐	☐	☐
(f) I had the impression that my pinching performance was affected by the desired **tilt angle**.	☐	☐	☐	☐	☐
(g) I had the impression that my pinching performance was affected by the desired **thickness**.	☐	☐	☐	☐	☐
(h) I had the impression that my pinching performance was affected by the desired **target position**.	☐	☐	☐	☐	☐

(8) Any **Comments**?

Figure A.1: Questionnaire used in our user study.

Appendix B

Consent Form

Informed Consent Form

Understanding Back-to-Front Pinching for Eyes-Free Mobile Touch Input

PRINCIPAL INVESTIGATOR Andreas Link.
Media Computing Group
RWTH Aachen University
Phone: +49 15256806987
Email: andreas.link@rwth-aachen.de

Purpose of the study: The goal of this study is to investigate the Pinch-Offset Effect. People rely on proprioception when localising unseen body limbs. Our aim is to investigate the performance of pinching under different conditions. Target Positions will be displayed on a distant screen combined with a desired tilt angle. When a tactile landmark's position gets highlighted, participants can sense the proper landmark at the back of the measurement tool and perform the pinching gesture after ensuring that they have set the proper angle. The system will measure touch positions at the front as well as at the back combined with the current tilt angle.

Procedure: In this study you will perform back-to-front pinching tasks while holding the measurement tool with several thicknesses at predefined tilt angles. Before the study, users are allowed to do an initial test run to get to know the back-to-front pinching gesture and to pinch a small set of targets. Throughout the study vision of hands will be prevented.

Throughout the study we will ask you to fill out a short questionnaire.

Risks/Discomfort: You may become fatigued during the study. You will be given several opportunities to rest, and additional breaks are also possible. There are no other risks associated with participation in the study. Should completion of either the task or the questionnaire become distressing to you, it will be terminated immediately.

Benefits: The results of this study will be useful for developers to counteract the Pinch-Offset effect and to improve eyes-free tapping performance for touchscreen devices.

Alternatives to Participation: Participation in this study is voluntary. You are free to withdraw or discontinue the participation.

Cost and Compensation: Participation in this study will involve no cost to you.

There will be sweets for you during and after the participation.

Confidentiality: All information collected during the study period will be kept strictly confidential. You will be identified through identification numbers. No publications or reports from this project will include identifying information on any participant. If you agree to join this study, please sign your name below.

___ I have read and understood the information on this form.
___ I have had the information on this form explained to me.

Participant's Name	Participant's Signature	Date
	Principal Investigator	Date

If you have any questions regarding this study, please contact Andreas Link at +49 1525 6806987
email: andreas.link@rwth-aachen.de

Figure B.1: Consent Form used for our user study.

Bibliography

ArchitekturBedarf.de. Finn Paperboard. https://www.architekturbedarf.de/index.php/katalog/artikelinfo/8895-1-show-finnpappe_70_x_100_cm_20_mm.html, 2015. [Online; accessed 17-August-2015].

BuyDisplay.com. 5 inch Multi Touch Screen Panel with Controller GSL1680. http://www.buydisplay.com/default/5-inch-multi-touch-screen-panel-with-controller-gsl1680, 2015. [Online; accessed 12-August-2015].

Christian Corsten, Christian Cherek, Thorsten Karrer, and Jan Borchers. Hapticase: Back-of-device tactile landmarks for eyes-free absolute indirect touch. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 2171–2180, New York, NY, USA, 2015. ACM. ISBN 978-1-4503-3145-6. doi: 10.1145/2702123.2702277. URL http://doi.acm.org/10.1145/2702123.2702277.

Dave DeLong. CHCSVParser. https://github.com/davedelong/CHCSVParser, 2014. [Online; accessed 13-August-2015].

RWTH FabLab. Epilog Zing 6030. http://hci.rwth-aachen.de/lasercutter, 2015. [Online; accessed 16-August-2015].

WR Ferrell, A Crighton, and RD Sturrock. Age-dependent changes in position sense in human proximal interphalangeal joints. *Neuroreport*, 3(3):259–261, 1992.

Jérémie Gilliot, Géry Casiez, and Nicolas Roussel. Impact of form factors and input conditions on absolute indirect-touch pointing tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, pages 723–732, New York, NY, USA, 2014. ACM. ISBN 978-1-4503-2473-1. doi: 10.1145/2556288.2556997. URL http://doi.acm.org/10.1145/2556288.2556997.

Sean G Gustafson, Bernhard Rabe, and Patrick M Baudisch. Understanding palm-based imaginary interfaces: the role of visual and tactile cues when browsing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 889–898. ACM, 2013.

Helgelangehaug. 5″ capacitive touch panel with GSL1680 up and running with Arduino. https://weatherhelge.wordpress.com/2015/02/09/5-capacitive-touch-panel-with-gsl1680-upn-running-with-arduino/, 2015. [Online; accessed 12-August-2015].

Shannon Lee. Proprioception: how and why? http://serendip.brynmawr.edu/exchange/node/1699, 2008. [Online; accessed 12-August-2015].

Vicon Motion Systems Ltd. Motion Tracking System. http://www.vicon.com/products/camera-systems/bonita, 2015. [Online; accessed 18-August-2015].

Andrew Madsen. ORSSerialPort. https://github.com/armadsen/ORSSerialPort, 2015. [Online; accessed 15-August-2015].

Mohammad Faizuddin Mohd Noor, Andrew Ramsay, Stephen Hughes, Simon Rogers, John Williamson, and Roderick Murray-Smith. 28 frames later: Predicting screen touches from back-of-device grip changes. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems*, CHI '14, pages 2005–2008, New York, NY, USA, 2014. ACM.

J Paillard and M Brouchon. Active and passive movements in the calibration of position sense. *The neuropsychology of spatially oriented behavior*, 11:37–55, 1968.

J. Paillard and M. Brouchon. A proprioceptive contribution to the spatial encoding of position cues for ballistic movements. *Brain Research*, 71(2–3):273 – 284, 1974. Motor Aspects of Behaviour and Programmed Nervous Activities.

PlaceIt. iPhone Mockup image reference. `https://placeit.net/#!/stages/girl-uses-iphone-6-on-yoga-mat-mockup-generator?f_devices=iphone&f_tags=landscape`, 2015. [Online; accessed 25-September-2015].

Marty Pye. Vicon Data Stream Framework - Simple Vicon Streaming for Your Cocoa Apps. `https://hci.rwth-aachen.de/vicon_datastream_cocoaframework`, 2015. [Online; accessed 14-August-2015].

Caleb Southern, James Clawson, Brian Frey, Gregory Abowd, and Mario Romero. Braille touch: Mobile touchscreen text entry for the visually impaired. In *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services Companion*, MobileHCI '12, pages 155–156, New York, NY, USA, 2012. ACM.

TechTalk. TV Set image reference. `http://techtalk.currys.co.uk/media/695785/tv%20wall%20mounted_647x352.jpg`, 2015. [Online; accessed 25-September-2015].

SI Helms Tillery, M Flanders, and JF Soechting. Errors in kinesthetic transformations for hand apposition. *Neuroreport*, 6(1):177–181, 1994.

RJ Van Beers, Anne C Sittig, and Jan J Denier van der Gon. The precision of proprioceptive position sense. *Experimental Brain Research*, 122(4):367–377, 1998.

Robert J van Beers, Anne C Sittig, and Jan J van der Gon Denier. How humans combine simultaneous proprioceptive and visual position information. *Experimental Brain Research*, 111(2):253–261, 1996.

Robert J van Beers, Daniel M Wolpert, and Patrick Haggard. When feeling is more important than seeing in sensorimotor adaptation. *Current Biology*, 12(10):834–837, 2002.

Katrin Wolf, Christian Müller-Tomfelde, Kelvin Cheng, and Ina Wechsung. Does proprioception guide back-of-device pointing as well as vision? In *CHI '12 Extended*

Abstracts on Human Factors in Computing Systems, CHI EA '12, pages 1739–1744, New York, NY, USA, 2012a. ACM.

Katrin Wolf, Christian Müller-Tomfelde, Kelvin Cheng, and Ina Wechsung. Pinchpad: performance of touch-based gestures while grasping devices. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, pages 103–110. ACM, 2012b.

AS Wycherley, PS Helliwell, and HA Bird. A novel device for the measurement of proprioception in the hand. *Rheumatology*, 44(5):638–641, 2005.

Index

Typeset September 25, 2015