Chair for Computer Science 10 (Media Computing and Human-Computer Interaction)
RWTH AACHEN UNIVERSITY

Combining Back-of-Device Finger Pressure with Multi-Touch Thumb-Gestures on Smartphones

Bachelor's Thesis

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Abstract

Whith this thesis we investigate the feasibility of using force sensing resistors at the back of the device together with thumb performed gestures at the screen of a smartphone while holding it. For this we use a prototype with six force sensing resistors which are mounted at the back of a standard iPhone 6s. To analyze it we conduct two studies.
One of which shows the characteristics of one- and two-handed gestures performed in landscape orientation while holding the smartphone. In the second one we explore pressure selection with gestures afterwards. In it we test different menu pressure ranges, target forces and fingers for the pressure interaction.
The results of our first study give target areas for the swipe, pinch and rotate gestures on 4.7" smartphones in landscape orientation. It also shows which pressure at the front of the device is used for each individual gesture and which force is applied by the holding fingers.
In our results of the second study, we conclude an overall 90% accuracy of the back of device pressure and show that the non-dominant middle finger is the most accurate when performing a gesture with the dominant hand or both hands. We show, that with the increased pressure at the back of the device the pressure at the front also increases. Also we prove that a tinier target pressure space limits the capability of hitting it accuratly. The same goes for increased target force.

Überblick

In dieser Thesis untersuchen wir die Möglichkeit der hybriden Eingabemethode vom Druckinteraktion auf der Rückseite in Verbindung mit Berührungsgesten auf dem Bildschirm eines Smartphones im Querformat. Diese Gesten werden mit den Daumen durchgeführt, während das Smartphone in den Händen gehalten wird. Hierzu führen wir zwei Studien durch.
Während der ersten Studie untersuchen wir die Charaktaristika der Wisch-, Zoom- und Rotierungsgeste, welche mit den Daumen auf einem 4,7 Zoll großen Bildschirm ausgeführt werden, während das Gerät vom Nutzer gehalten wird. In der zweiten Studie wird die Möglichkeit der Druckinteraktion auf der Rückseite des Geräts vor und während der Geste geprüft. Es werden verschiedene Druckbereiche, Zielkräfte und Finger getestet.
Aus den Resultaten der ersten Studie können wir Zielbereiche der verschiedenen Gesten für zukünfitge Tests ableiten. Zusätzlich beschreiben wir die Kräfte die auf der Vorder- und der Hinterseite des Gerätes während der Gesteneingabe enstehen. Von den Ergebnissen der zweiten Studie können wir darauf schließen, dass Druckselektionen mit 90-prozentiger Wahrscheinlichkeit in einem vorher definierten Zieldruckbereich liegen. Wir können zeigen, dass die nicht dominate Hand die besten Resultate für die Druckinteraktion liefert, falls die Geste mit der dominanten Hand oder mit beiden Händen ausgeführt wird. Die Ergebnisse werden schlechter, wenn der Zielduck erhöht oder der Zielbereich verkleinert wird.

Chapter 1

Introduction

Smartphones are the most sophisticated mobile companion. Since the invention of the iPhone new models provide new usability features. The software running on a smartphone touches almost every existing area in human life and replaces other things that people usually carried along with them. A calender, a camera, an notepad, the newspaper and a mobile gaming console, just to name a few of them.[1] But with all the capabilities, new input interactions are needed to use these types of software fast and accuratly.

The software and hardware of smartphones replace more and more gadgets of the everyday life.

A smartphone offers mostly just its screen and its buttons on the side as input. The screen can only be interacted by using the thumb of the holding hand or the fingers of the other hand. This leaves the fingers of the holding hand useless for input interaction. The issue that the input is mostly occours on the front of the phone leads to a partial occlusion of the display during this interaction [Vogel and Baudisch, 2007]. One way to solve this problem would be to make the back of the device (BoD) touchable, which has already been tested in various studies before and is already used in some commercial devices.

Usually only the screen and the buttons on the side of a smartphone serve as input.

[1]https://www.geckoandfly.com/13143/50-things-smartphone-replaced-will-replace-future/

Some commercial products use back of device interaction.

The Huawei Mate S for example has a fingerprint sensor on its back which can be used for different interactions. It be operated for binary input like picking up a call or stopping an alert or using a swipe gesture to scroll or do other actions.[2]

Force interaction is also a growing field in commercial devices.

Another important improvement of smartphones in the last years is the addition of force interaction. Instead of getting just the position of smartphones, an additional force vector is added to the touch information. An example for the commercial use of this input possibility is Apple's Force Touch and the Apple 3D Touch. This kind of interaction is used to access information in applications more easily.[3]

There is less data over smartphones operated in landscape orientation.

The landscape orientation is almost forgotten in a lot of research of smartphones even if it sees a lot of use. Navigation, internet browsing, messaging and video players are proven to be used in this orientation.[Sahami Shirazi et al., 2013]

The BackXPress combines force and back of device interaction. We will show its usefullness with front gestures.

In an ealier paper, BackXPress from Corsten et al. [2017a] combined these two interaction methods and showed possibilities how the back of the device can be used for force interaction. They combined this with finger taps at the front of the device. In this thesis we show how the combination with thumb touch gestures will work. We also will show how the pressure interaction will influence these gestures.

We investigate thumb touch gestures in landscape orientation.

Another investigation we do is the analysis of thumb touch gestures on smartphones in landscape orientation without any Back of Device Interaction (BoDI). Using Apple's 3D touch gives us the advantage of tracking the pressure which is produced by the gestures. We perform user studies to gather statistical, relevant data and also analyze it.

[2] https://consumer.huawei.com/en/phones/mate-s/touch/
[3] https://developer.apple.com/ios/3d-touch/

Furthermore, we introduce a new prototype artifact which is used for these studies. At last we give a few design guidelines and describe future work which can be done based on our studies.

A new prototype artifact will be introduced.

This found data could be used to give a discrete continuous input vector in application which uses touch gestures to navigate. The zoom in map navigation, the scrolling of large texts, the navigation in stock charts and video games are possible applications of this interaction method. The last one could offer the most possibilities from force controls. This input device could act like a trigger in a modern game-controler and substitute it with a smaller depth.

Our findings could be used for new interaction techniques.

Chapter 2

Related and Recent Work

This thesis is combining the work of three different fields of HCI. We are using:

- Multi-Touch-Screens and Multi-Touch-Gestures
- while using Pressure Interaction
- at the Back-of-Device

In this chapter we give a brief introduction on the history and an overview of the recent breakthroughs related to this thesis' topic in each field. Since we are using the device in landscape orientation, there is also related work included which relates each field to this orientation. At last we take a look at the BackXPress device and its development process until the day we started this thesis.

In the following we give an overview on the history and recent work in this field.

2.1 Touch- and Multi-Touch-Interaction

2.1.1 History

Touch development began in the 1960's and continues to evolve since then.

The history of Touchscreen-Interaction is well studied and Buxton [2010] a good overview over this topic. The story of Touch-Interaction began in the mid-1960s where Betts et. al. at IBM built the first touchscreen device with the Light Beam Matrix Terminal. In the early 1970s the first touchscreens left the laboratories and start beeing used in grade-school classrooms with the PLATO IV system. Consumer Products developed in niche markets like the Casio PF-8000, which is an address book and a calculator in one device. It has the option of entering alphanumeric characters by mimicing them with a Touch-Gesture on the Touchscreen. One of the first predecessors to the modern smartphones with touchscreen capability is the Simon in 1993. It could be operated by a Stylus and Finger Touch.

Multitouch capable Tablets were developed in 1984.

Another important development was the research in multi-touch capabilities. In 1984 Lee et al. [1985] created at the University of Toronto a Touch-Tablet which was the first peer reviewed device of its kind. This tablet was able to sense multiple Touch-Points as well as their degree of touch.

2.1.2 Related and Recent Work

Wolf et al. [2014] performed studies about gestures on tablets in landscape orientation.

Since we want to use the Smartphone in landscape orientation in our study we look into other studies which describe the gesture shapes and positions performed with thumbs.Wolf et al. [2014] investigated this. Their target was to look into the gesture set of tap, press, drag and swipe performed with the thumb on the front of the device and with the each of the other fingers on the back of the device. They tested only on a tablet device with a display size of 10.4".

Another study on this topic was performed by Tiefenbacher et al. [2016] which also included simple two handed gestures. It was also performed on a tablet, this time with a display size of 11.6". Their study consisted of two parts where in one the participants were under time pressure. The gesture set in this study was just the swipe in different directions which was performed with both thumbs independently and together.

Tiefenbacher et al. [2016] did the same with simultaneous gestures with both thumbs.

2.2 Pressure Interaction

2.2.1 History

In 2004 Ramos et al. [2004] made one of the first studies which combined pressure interaction with touch input. They used a tablet with a stylus which was capable of sensing the pressure applied to the tablet. In this study they investigated different selecting techniques with the stylus and also which pressure space is applicable by users. In their results they state that it is difficult to move the object (in this case the stylus) which is applying the pressure. Also they have discovered that dividing the pressure space into more than six levels leads to a performance drop by the users. Another additional finding is that applying pressure without visual feedback is difficult and cannot be learned within one hour.

In 2004 studies were done in which pressure and touch input are combined.

McCallum et al. [2009] augmented the old T9 system of entering text on mobile phones with pressure. Instead of multiple tapping it was possible to pressure select the right character. For example soft pressure applied on the '1' button selects the character 'a', medium pressure the 'b' and hard pressure the 'c'. In their findings they show that pressure selection outperforms the standard of tapping one button multiple times.

Pressure control on mobile phones outperformes multiple button presses in the T9-System.

2.2.2 Related and Recent Work

Combined pressure and Touch control was also the topic of McLachlan et al. [2014].

In the recent years pressure interaction is more commonly used to augment touch input. McLachlan et al. [2014] put a force sensing Resistor on the bezel of a tablet device. In this way the user could hold the device and apply pressure with the same hand. The free hand can be used for touch input.

They show the capabilities of pressure interaction on tablets with tapping on the screen.

In a study they showed that applying pressure with the non-dominant-hand and tapping with the other is feasible. The mean accuracy of selecting the right pressure level was 93%. A different finding was that releasing pressure as well as applying pressure from a non-zero starting point can be performed with a high level of accuracy. Also Mclachlan pointed out that the users are capable to maintain pressure around a given target over longer time periods($\approx 20s$).

In 2015 they did another study with touch gestures and pressure interaction with promising results.

One year later McLachlan and Brewster [2015] did another study with their artifact. This time they augmented touch gestures with pressure. They selected the most common multi-touch gestures (swipe, pinch and rotate) and evaluated them in combination with pressure applied with the non-dominant-hand. They showed that with increasing pressure the ability to select the right pressure space dropped. Gesture accuracy decreased significantly with increasing menu items but it was just a slight increase on the error distance.

Pelurson and Nigay [2016] developed an example application with stock charts on this results.

At ICMI Pelurson and Nigay [2016] used the results of McLachlan to program a navigation widget for stock charts. They showed that a combined pressure and gesture interaction is superior to performing multiple gestures.

Corsten et al. [2017b] displayed multiple force selection techniques at the front of the device and evaluated them. The most accurate results achieved the *quick release* technique where a user lifts the finger after apply the target force and the *dwell time* technique, where the user after applying the target force for a given time. Both showed an accuracy of over 97% but the quick release is preferable due to its increased speed.

Force selection techniques are still in research with quick release as most promising.

2.3 Back of Device Interaction

BoDI is a recent development without a large history on mobile devices. The emerge of smartphones and the need for new interaction possibilities paved the way for it.

Wolf et al. [2012] tested various gestures on the back of a smartphone when it is held in one hand. In a study they tested different gestures performed with the holding hand on the back of the device. They conclude that dragging a finger along the back and lifting it up are feasible gestures in the back of device interaction.

In 2012 Wolf et al. investigated touch-gestures on the back of a device.

A prototype by Wilson et al. [2012] made it possible to sense the grip pressure of the holding hand as input when the device is held in portrait orientation. Most of the measurement points were on the side of the device but their test device included also a force sensor at the back of the device. The discussion of this study did not mention the force sensing resistor on the back since is was not the best choice for this type of interaction. Another finding of them is that when three or more digits are used in pressure control the accuracy decreases.

Studies were also conducted with the hoding grip of smartphones in portrait orientation.

The reachability problem of smartphones in portrait orientation can be solved with BoDI.

To solve reachability issues in portrait orientation Löchtefeld et al. [2013] made the back of a smartphone sensitive to touch input. With their prototype it was possible to tap the parts of the smartphone on the back which were not reachable with the thumb on the front. They put an Apple track pad for this on the back of a Samsung Galaxy Nexus. In their results they state the users preferred the BoDI even if it took longer than the usual approach and it allows for accurate and safe input.

2.4 BackXPress

To solve the occlusion problem, back of device interaction with pressure is a proposed solution.

In the original BackXPress paper of Corsten et al. [2017a] the interaction technique of combining Back-of-Device Pressure interaction and thumb-tipping was first introduced. Their target was to target the occlusion problem and want the user to use her else useless fingers on the back of the device when in landscape-orientation. The advantage of BoDI in this orientation is that it is more stable and eight fingers are available.

2.4.1 Studies and Results

To investigate this interaction three studies were conducted.

Three studies were performed for their paper. In the first one they wanted to find out which fingers can be used for pressure interaction at the back of the device. For this they used a dummy device in 5.5" and 4.7". The participants had to hit different targets with their fingers on the back.

The middle finger is the most preferred finger for doing BodI pressure interaction in landscape orientation.

In the results they stated that the index middle and ring finger are possible candidates for back of device Pressure. Especially index and middle finger are preferred. Another finding was that users preferred a device with a 4.7" display rather than a 5.5" display device for this interaction method.

The second study has the BoD finger pose as topic. For this study they used two 4.7" iPhones and mounted them back to back. To test where the fingers for the BoDI hit. In their results they state that the different fingers have distinct rectangle hitbox where the fingers hit. There was only a small overlapping one user has caused.

Each finger has a individual hitbox in BodI.

Now with all the data they were able to do perform tests like McLachlan et al. [2014] did. This was the third study they performed. They tested a preselection with the pressure on the back in different menu sizes and different targets in a pressure range of 0.5 to 4N. Their study was splitted into to parts. In the first users had to perform a single tap and another where the pressure must be held for various time spans while the user performed multiple taps. In the one tap part users have to first select the pressure. The applied pressure was displayed by an indicator bar and the users had to place a cursor in a target range on this bar via force control. When this was the case the user had to tap a target on the screen. The same was the case for the second part of this study with the difference that the user had to hold the pressure in a target range and tap as many targets as they can for the hole timespan.

With these results in mind they can finally test the combination of back of device pressure with tapping.

In their results they stated a few design guidelines based on this study. One is that the landscape orientation offers the user full access with both thumbs at the front on the screen. They also stated that that the BoD pressure increases as users tap at the front of the screen. Another important finding was that the pressure history over 500ms should be evaluated to show if the user selects the right pressure range. They suggest that only pressure menus with three or five items should be used for this kind of interaction. In their last guideline they state that the middle finger has the highest accuracy for the pressure selection at the back of the device.

Based on their finding they proposed some design guidelines.

In their proposed future work they suggest one study that we now perform. Also they described their limitations they got because of the sandwich device. We have solved this with a new prototype.

One of the proposed future work is now the topic of this thesis.

Chapter 3

Artifact

For CHI 2017 Corsten et al. created a new artifact for demonstrating the capabilities of this interaction technique. This device will be used for our studies.

It is a common 4.7" iPhone 6s which has a special casing. On the case there are a Redbear BLE nano micro controller and six force sensing resistors (FSR) of type 'FSR 402 short' from Interlink Electronics. These resistors are capable od reducing their resistance if force is applied on them. As their data sheet states, they are capable of working from 0 to 10 N of force applied on them.

We equip a common iPhone 6s with six force sensing resistors.

The BLE nano is an Arduino compatible micro controller. For the small place it takes up it also includes a Blue tooth communication device and an antenna. It has enough I/O pins so that the six force sensing resistors can be read by it. The reading is an analog to digital one. With this in mind we know that the 0-3.3V analog input is transformed to an unsigned integer with a 10 bit length. So we have 0-1023 digital units in which the 0-3.3V range is transformed. But the FSR does not increas the voltage linear to the force applied on them. Instead it is a logarithmic dependency which changes whith the pull-down resistors which are used. For this artifact 10 kilo ohm resistors where used.

The communication device between the sensors is a BLE nano with blue Tooth capabilities.

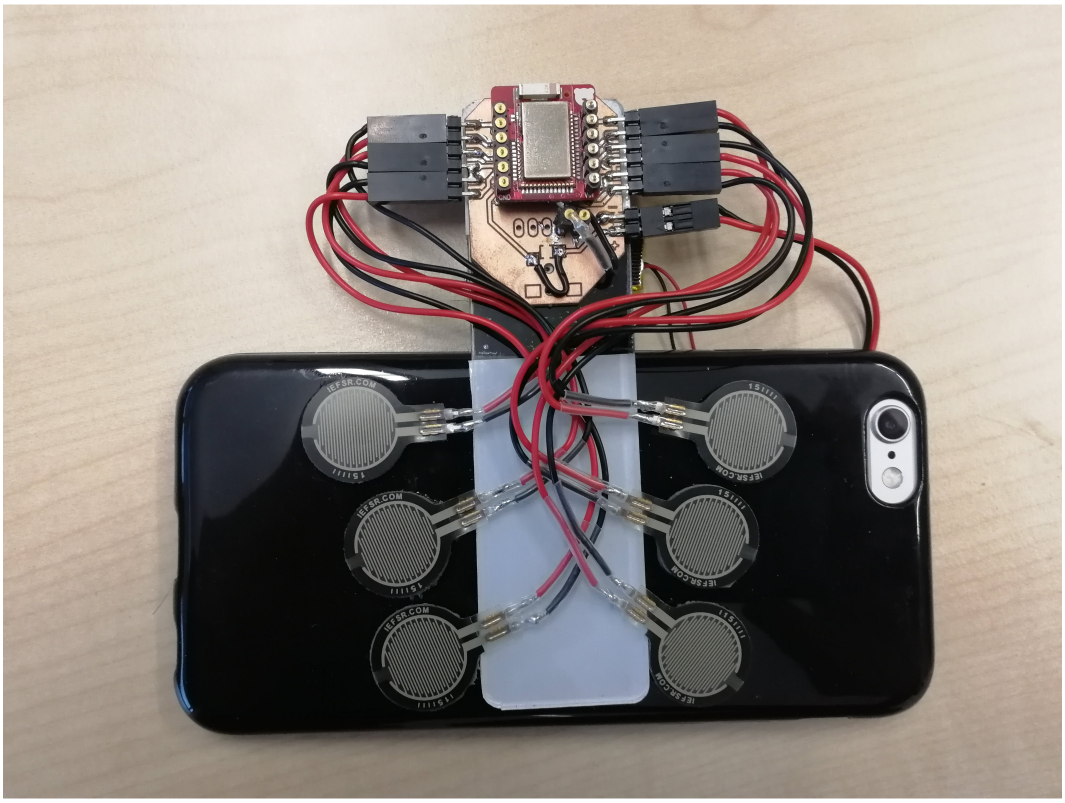


Figure 3.1: The BackXPress Artifact. The six force sensing resistors and the micro-controller are mounted on the back of the device.

The sensors need to be calibrated.

Another point is that each individual sensor has up to a 5% deviation at the force to voltage conversion. So we have to conduct a few tests with the sensors so we can create a approximation function.

3.1 Design Space

We place the artifact in the design space of linear force.

To place this device into the design space by Mackinlay et al. [1990] is an easy task. The input measure is linear force since it is measured in terms on how much actual pressure is applied to the sensor. We got six sensors which measure pressure in 1024 steps. The hole apparatus is mounted on a smartphone which links these six sensors to the design space of its host smartphone layout.

3.2 Measuring and Approximation Function

To create an approximation function we have to callibrate the sensors with standard weights. For 0-2N we use 0.2N steps and from this up to 10N we added 0.5N for every data point. This decision is based on the logarithmic scale of the applied force. We tested three different sensors and repeated the measurements three times. As measuring test we use a calibration guide[1] by tekscan, which is recommended for this type of sensor

We calibrate the sensor based on a reference guide of a distributor.

For this we connect a FSR to an Arduino digital to analog input with a 10k Ohm Resistor as a pull down. We send the read voltage level at the pin with the same 10 Bit precision over a USB interface to a computer where we can process the data.

For this we build a small test circuit with an Arduino.

To deviate the standard weights over the whole measuring field of the sensor we use a circle of 3 mm thick foam rubber. Each measurement began with a saturation of the FSR with a force applied to it which is greater than 11N. Then we start repeated measurements. We took the mean over ten seconds of pressure for each data point.

We use foam rubber to deviate the weight over the whole sensor and do repeated measurements.

After the measurements are taken we use the average for every measurement with the same force applied to it. We decide to split the pressure range into two ranges to increase the accuracy of the approximating functions. These functions are $f(x < 879) = e^{((x-539)/298.39)}$ and $f(x \geq 879) = e^{((x-804.74)/65.402)}$. We use this later on to measure the applied force on the sensor which we read of the analog to digital converter of the BLE nano.

For higher accuracy we split the pressure range and approximate two different functions.

[1] https://www.tekscan.com/support/faqs/how-do-i-calibrate-my-flexiforce-sensor

Chapter 4

Preliminary Study: Exploring Thumb-Gestures in Landscape Orientation on Smartphones

4.1 Background

Touch Gestures on hand-held devices are not very commonly researched when they are held in Landscape Orientation. Especially, when the thumbs of the holding hands are used as input.Wolf et al. [2014] made a study about swipe touch gestures performed with thumbs. We orientate our preliminary study on this work. Tiefenbacher et al. [2016] also did some work on this topic with the focus of the thumb ergonomics and simple two-handed gestures. Both studies worked on tablet devices of 10.1″ and 11.6″.

There are no studies available for Thumb-Touch-Gestures on smartphones in landscape orientation so we do our own.

Sufficient data for changing the size of the hand-held device and its impact on the gesture size is not available. Additionally, we are testing which parts of the display are reachable by the thumbs while holding the smartphone in landscape orientation, without changing the position of the holding hands. Our aim is to identify the gestures by their form and create feasible gesture targets for our main study.

4.2 Design

4.2.1 Research Questions and Hypothesis

We are trying to answer the following research Questions:

Q1 What does the touch gesture footprint on the device look like if the gesture is executed by the thumbs while holding it in Landscape Orientation?

Q2 What is the pressure to the smartphone that will be generated while performing the gestures?

Q3 Which part of the smartphone is reachable with which thumb?

H1 Knowing the thumb ergonomics, the form and the size of the swipe gesture will be the same as in the studies performed on a tablet.

4.2.2 Participants and Layout

The study is split in two halfs. We are starting with a reachablity test and afterwards the gesture investigation.

We decide to choose an within design in two blocks and test 16 participants (Age 19-30, Mean = 25.38, SD = 3.93). Five of them are female and four are left-handed. The first block is a reachability test. The second consists of the three GESTURES *Swipe*, *Rotate* and *Pinch* in different directions.

4.2.3 Variables

The independent variables are the GESTURES with their different directions and for the one-handed tests (*Swipe* and *Reachability*) also the starting HAND. These independent variables are randomized by the Latin-Square principle to counterbalance learning effects.

We test different GESTURES in different directions with various HANDS.

The dependent variables are the location and force of every touch event of the smartphone and the force applied on the force sensors on the back. We also look into the *trial time* and the *length* of each GESTURE footprint.

4.2.4 Task and Procedure

The participants will be ask to hold the smartphone with both hands in landscape orientation and with their fingertips on the force sensors mounted at the back of the device. They have to operate the touch-screen with their thumbs. All tasks will be performed in with the hands in this position.

During the study the participants operate the screen with their thumbs and rest their fingers on the sensors.

I. Reachability

The reachability test will be executed by stretching the tip of the thumb as far from the hand away as they can and 'draw' a boarder from the bottom of the screen to the top. Each thumb is tested separately and ten repetitions are required.

Participants have to reach as far to the middle as they can with their thumbs and touch the screen from the button to the top.

II. Gestures

We have chosen the *Swipe*, *Rotate* and *Pinch* as touch GESTURES for the participants to perform. Those are chosen because we want to be able to compare this study to the study made by McLachlan and Brewster [2015] which used the same GESTURES. All GESTURES will be done without giving any feedback like it would be the case in applicative

Swipe, Pinch and Rotate will be used as GESTURES in this studies.

use. The *Swipe* gesture is executed with the left and right thumb separately, as well as in the four directions up, down, left and right. After the user performs the *Swipe* with one hand in one direction. Their next task will be to execute a *Swipe* in the same direction with the other hand before the direction changes. The *Pinch* gesture is done in the two directions inwards and outwards. For the *Rotate* the directions are clockwise and counterclockwise.

For every combination there will be ten repetitions and five test trials

For every GESTURE and direction there will be ten repetitions and five test trials. If the user accidentally touches the display there is a possibility to repeat the trials. To counterbalance learning and effects we shuffle the GESTURES, DIRECTIONS and the beginning HAND of the *Swipe* according to the Latin-Square principle for each user individually.

4.2.5 Apparatus

We use an iPhone 6s with the latest prototype of the BackXPress device. We choose the iPhone because of it typical size of 4,7" and the ability to sense the pressure applied on multiple points of its display with Apple's 3D touch. With both devices combined we were able to estimate the pressure to the device produced by every finger for a following study.

Program

Users do not see any feedback or targets for the gestures.

Our test application is designed to give the user no feedback of their performance. Programming it in this way we are able to analyze the GESTURES under natural circumstances. Wolf et al. [2014] did the same in their study with tablets. The participants get their orders from a screen before starting the trials.

Each trial has five repetitions.

Each trial had five test-trials so the user get a feel for the GESTURES which they have to perform. After the tests an information screen showed up which told the users the test-trials were over and now the tracked trials begin.

We tracked every touch with its X- and Y-positions and the timestamps given by the iPhone as well as its pressure values returned by Apple's 3D-Touch. Additionally, we saved the force which is applied to the force sensors of the BackXPress. All collected data is saved into two csv-files per user. One with the raw data and one with aggregated data for each trial, including the length and the duration for each trial.

The collected data is saved in csv-files for later processing.

Log-entries with raw-data are created on every touchesBegin, touchesMoved, touchesEnded, touchesCanceled event noticed by the iPhone. The tracking begins with the first touch. When all fingers are released from the front of the smartphone a trial automatically ends and a new one begins.

If a repetition for a trial is needed (e.g. the user accidentally touches on the screen) we include a hidden interface. When four fingers are pressed against the screen the last trail will be repeated and all log entries of it are deleted.

4.3 Results

We have categorized the results of the different GESTURES. We begin with the *Swipe* and move over to the *Pinch* and the *Rotate*. At first we will present some statistic data we acquired in the study and then talk about the targets we will create for them for the main study. At last we will discuss the accumulated pressure data.

Direction	Hand	Length	Length SD	Duration	Duration SD	Speed
Up	Left	4.20cm	0.99cm	0.25s	0.12s	34.41 cm/s
Up	Right	4.20cm	1.01cm	0.23s	0.12s	35.72 cm/s
Down	Left	3.97cm	1.09cm	0.25s	0.12s	32.53 cm/s
Down	Right	4.23cm	1.00cm	0.24s	0.12s	34.66 cm/s
Average		4.15cm	1.02cm	0,24s	0,12s	32.62 cm/s

Table 4.1: The average measurements of the vertical Swipe Gesture

4.3.1 Reachability

In the reachability test users are able to reach close to the middle line of the screen.

In the results of reachability test we see that the left thumb reaches on mean the x = 628 line of the screen which is just short of the middle line at x = 672 of the screen. The same goes for the right thumb which reaches the x = 699 on average. We told the user not to stretch their hands uncomfortable and so the main reachability is greater with some other GESTURES.

4.3.2 Swipe

For the *Swipe* we decide to make a split analysis for the horizontal (left and right) and the vertical (up and down) ones.

Vertical Swipes

We do not find any significant evidence that the HAND has influence of the length and duration of a swipe.

In table 4.1 we see that vertical *Swipes* do not deviate much in length and duration. We observe that the left hand *Swipe* downwards is a little bit slower. We test this by a two-way repeated ANOVA on *Length* with *Direction* and *Hand* but the results failed to reach the significance level of $\alpha = 5\%$. The same holds true for the duration of the trial.

Vertical swipes look like an arc bent towards the middle of the screen.

The form of the *Swipes* seems to look like a half arc which is bend outwards on the upper side of the screen. Since we want to have symmetric targets later on we mirrored the right side to the left at the middle for the analysis of the position. If we look at the plot in figure 4.1 we notice that there

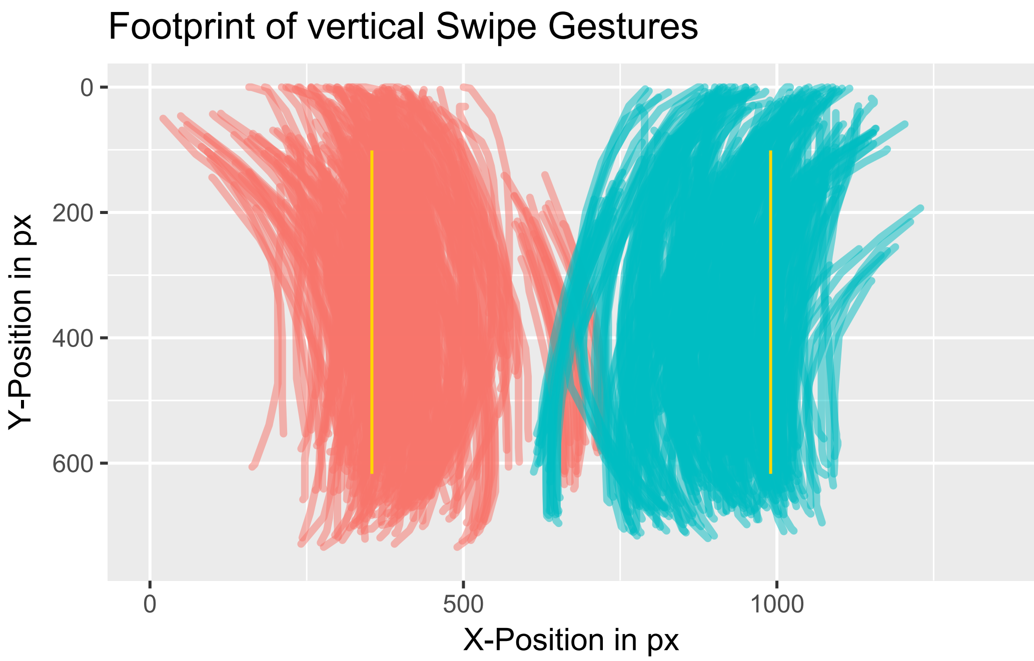


Figure 4.1: Footprint of Vertical Swipes with Median (yellow)

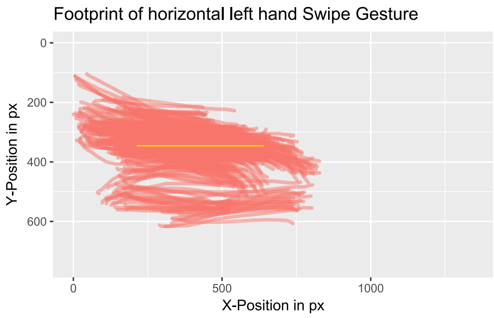
is a high deviation on start and endpoints at the X- and also on the Y-axis. 90% of the Start and Endpoints are between 268px and 595px away from the left side of the screen on the X-axis. On the Y-axis they are between 33px and 652px away from the top of the screen.

For our target in the main study we decide to take the median length as our target length on the Y-axis and choose the average value of all points collected as the middle of the target. So our target is from 101-617px on the Y-axis and two target indicator lines (start and end) are drawn at 268px till 595px at the X-Axis. For right-hand targets we mirror it at the middle.

We distinguish a rectangle target for our main study out of this data.

Direction	Hand	Length	Length SD	Duration	Duration SD	Speed
to the Left	Left	3.50cm	0.98cm	0.27s	0.12s	21.93 cm/s
to the Left	Right	3.40cm	1.06cm	0.23s	0.12s	25.25 cm/s
to the Right	Left	3.27cm	0.88cm	0.25s	0.12s	28.04 cm/s
to the Right	Right	3.85cm	1.09cm	0.25s	0.12s	32.98 cm/s
Average		3.51cm	1.00cm	0.25s	0.12s	27.07 cm/s

Table 4.2: The average measurements of the horizontal Swipe Gesture



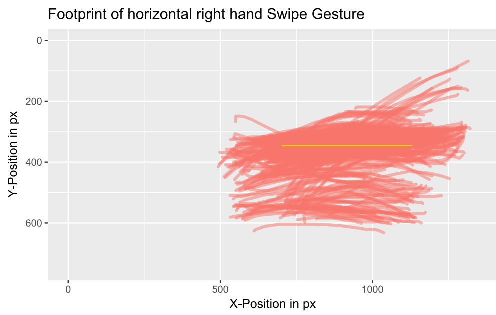


Figure 4.2: Footprint of Horizontal Swipes with Median (yellow)

Horizontal Swipes

Left handed horizontal swipes are shorter than right handed ones.

As before we also find some deviation in *Pathlength* and *Duration* (See Table 4.2). This time it is significant. In a two-way repeated analysis of variance (ANOVA) on pathlength with both independent variables. We find HAND (F(1,636)= 7.567 p-value < 0.01) and the combination of HAND and DIRECTION (F(1,636)=21.053 p-value < 0.01) significant. In a Post-Hoc Tukey HSD we find that when performing a horizontal *Swipe* with the left handiIt is not as long as with the right one. In the analysis of the combination we see additionally that the *Swipe* inwards of the right hand is significant shorter than the outward ones of both hands (p-value < 0.001).

Direction	right Path	SD	left Path	SD	Duration	SD
Inwards	2.88cm	0.98cm	3.30cm	1.11cm	0.40s	0.19s
Outwards	2.98cm	0.98cm	3.49cm	1.16cm	0.40s	0.19s
Average	2.93cm	0.98cm	3.40cm	1.13cm	0.40s	0.19s

Table 4.3: The average measurements of the Pinch Gesture

The investigation of form and position is similarly difficult as with the vertical ones. Some users perform their horizontal *Swipes* more diagonally, following the natural movement of the thumb, but most of them prefer to make a clean horizontal line without much deviation on the Y-axis. Some users also prefer to perform their *Swipes* lower than others.

The horizontal swipes are diverging from user to user.

For the position analysis we again mirror the trials performed with the right hand at the middle of the X-axis. We find 90% of the start and endpoints between the 102nd and the 740th pixel of the X-axis and between the 269th and 548th of the Y-axis. We also construct our targets as with the vertical *Swipes*. The target length is 428px between the 213-648px of the X-axis. Again, we mirror the whole target for the right hand.

Again we decide to build rectangle targets with the median length in width.

4.3.3 Pinch

The analysis of the *Pinch* gesture yields some interesting findings. For instance we find that the pathlength of the right hand is usual longer than the left one, see 4.3. The duration is almost double the time a *Swipe* takes. The outwards *Pinch* is significantly longer than the inwards one. For the duration the direction makes no difference.

In the analysis of form and location of the *Pinch* gesture we have gathered more striking results. Our first assumption that the *Pinch* will have a similar appearance as when it is performed with index finger and thumb of one hand does not hold true. Just a few users prefer to move their thumbs diagonally in- and outwards of the middle of the screen when performing a *Pinch*.

The pinch gesture looks mostly like a horizontal swipe in- or outwards with both thumbs.

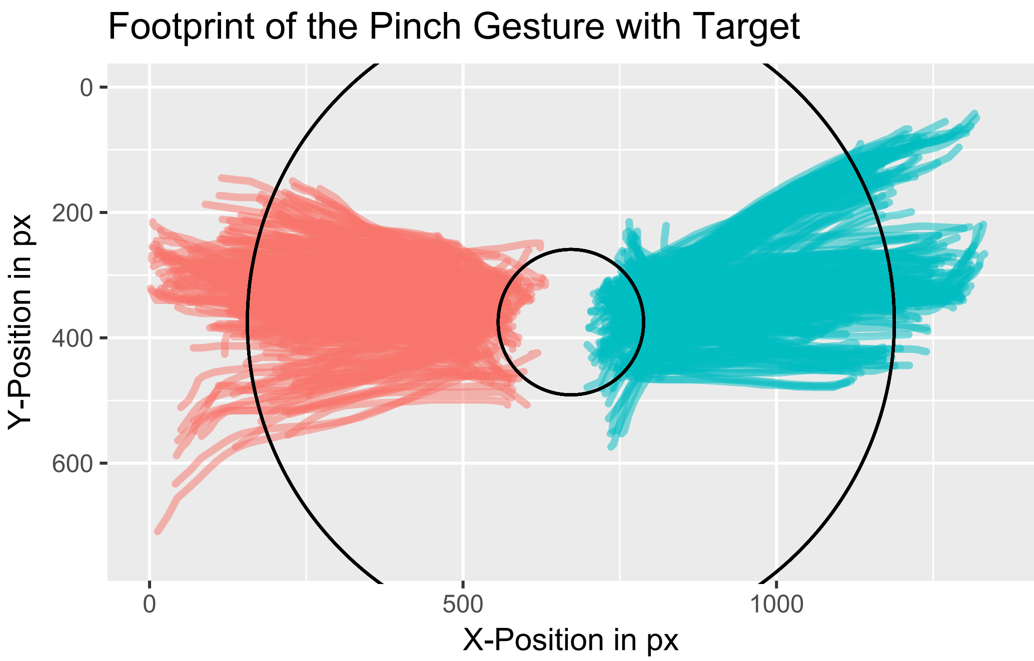


Figure 4.3: The Footprint of the Pinch Gesture with its Targets

The most users just do a synchronous horizontal *Swipe* with both thumbs. A user preferred to do the inwards *Pinch* as two diagonal lines from the upper corners of the display to the middle.

A fitting target for al pinches are two circles. One at the beginning and one at the end.

To create a target that fits the controversial types of *Pinches* we decide to look into the distance of the start and endpoints of the *Pinch* in regards to the middle of the screen. 90% of all start and endpoints are located in the ring of 106px to 601px around the middle point. The median path-length was 400px. The target we decided to create is a begin and a end circle around the middle point with a radius of 116px and 516px, see Figure 4.3.

Direction	right Path	SD	left Path	SD	Duration	SD
clockwise	4.91cm	1.52cm	5.21cm	1.61cm	0.67s	0.27s
counterclockwise	4.81cm	1.46cm	4.98cm	1.31cm	0.67s	0.27s
Average	4.86cm	1.49cm	5.10cm	1.46cm	0.67s	0.27s

Table 4.4: The average measurements of the Rotate Gesture

4.3.4 Rotate

For the *Rotate* we see that it is on average slower than the Pinch and the *Swipe*. We also find that the individual paths of both fingers on the screen are the longest ones in comparison to the other GESTURES. The pathlength of the right hand in the clockwise Direction is the longest one of all GESTURES tested. Astonishing the gesturetime is once again not influenced by the Direction. In the analysis of the footprint we observe that the user usably rotates around the middle of the screen with point symmetric finger positions.

The right hand travels a longer path at a rotate.

Again we look at 90% of the start- and end-points in respect to the middle of the screen. Those are in a ring of 182px to 522px around the middle. For our target we decided to choose a 90 degree rotation. Its start and end positions are on the lines which go in the 45, 135, 225 and 315 degree of the middle point, 0 degree is the straight angle to the top. As radius we select the median radius of the start and endpoints towards the middle which is 318px. We can see the the measurements of the final target in Figure 4.4.

The most fitting target is a ring with to start and two end points on it.

4.3.5 Pressure

At last we look at the pressure data we obtained. We notice that on average the maximum pressure which is produced up front on the screen by each GESTURE does not exceed 1N on average (95% CI =[0.961,1.015]). The same goes with the Back of Device Pressure. Here the average lays by 0.44N (95% CI =[0.433,0.447]).

The average front pressure was around 1N at the front and 0.44N at each finger on the back.

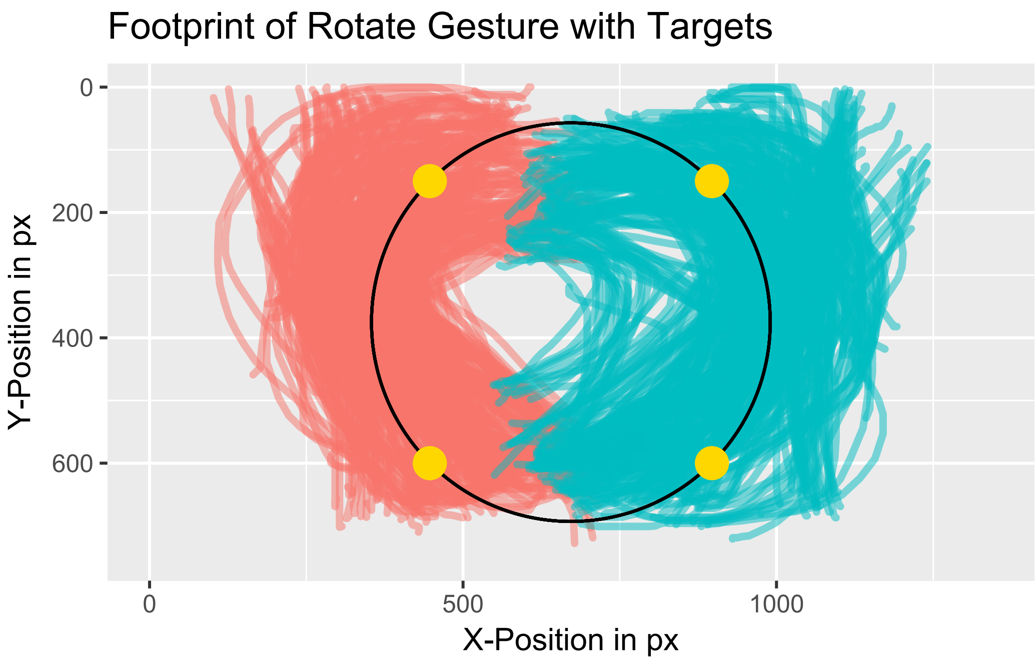


Figure 4.4: The Footprint of the Rotate Gesture with its Targets

Maximum pressure reaches 1N at the back of the device.

The 90% quantile of the maximum in each BoD pressure is around 1N. In Figure 4.5. We observe that the pressure quickly increases when the touches begin and then raises slowly while the thumbs are moved, until they are being released. It is interesting to see that the pressure while performing the *Pinch* gesture mostly in- and decreases simultaneously with both hands while it is not the case with the *Rotate* gesture.

When we take a look at the force measured on the back by the holding hands we see that the force of the index fingers holding the device increaseds until the middle of the trial and then drops again. For the middle finger we measure no notable difference throughout the trial. The grip strength of the ring finger increases as the GESTURE is released.

Each finger has an indistinguishable pressure path.

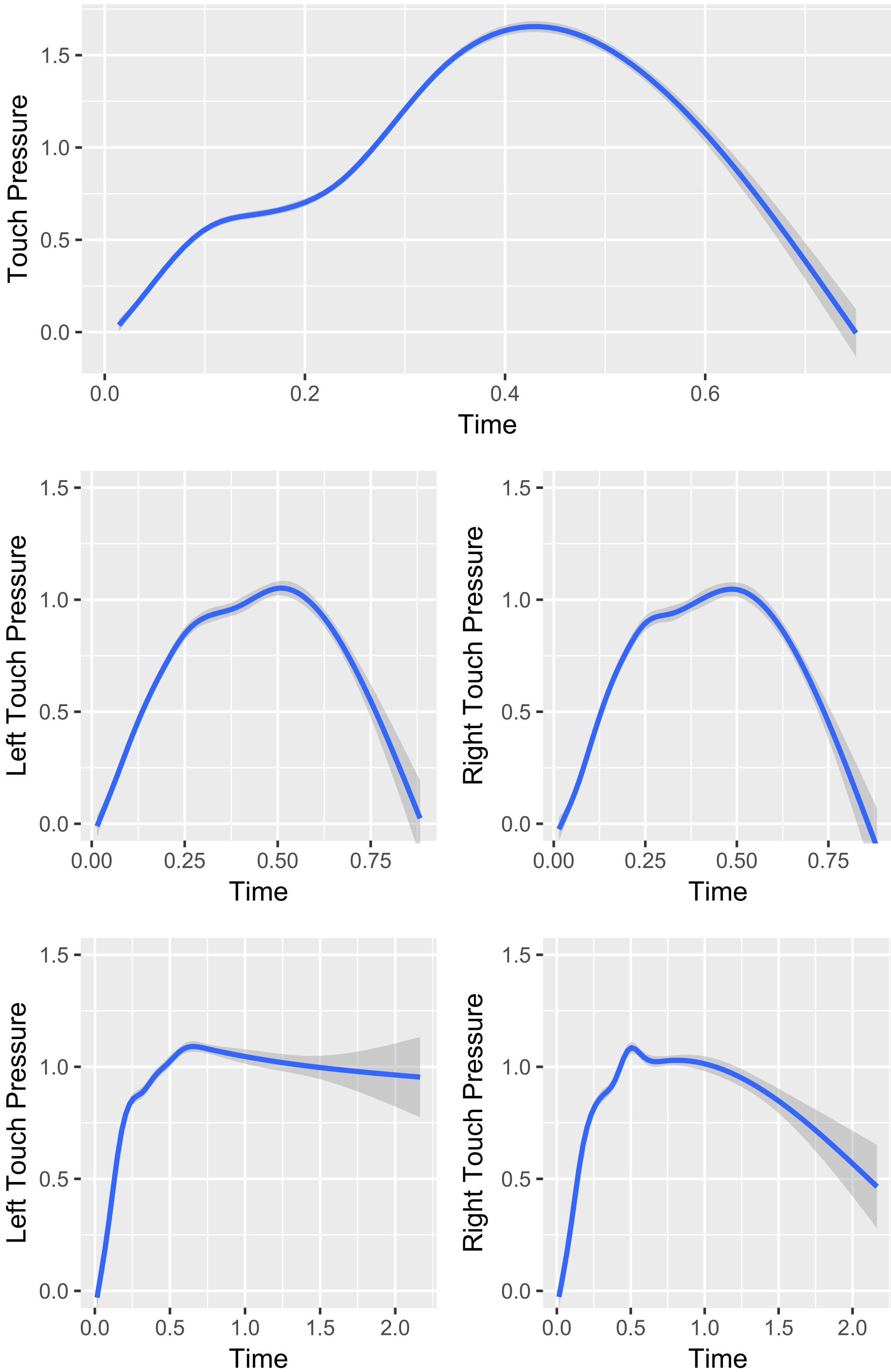


Figure 4.5: The average pressure applied on the front with the Swipe (upper),Pinch (middle) and Rotate Gesture (lower) with 95% CI (gray) in N over time.

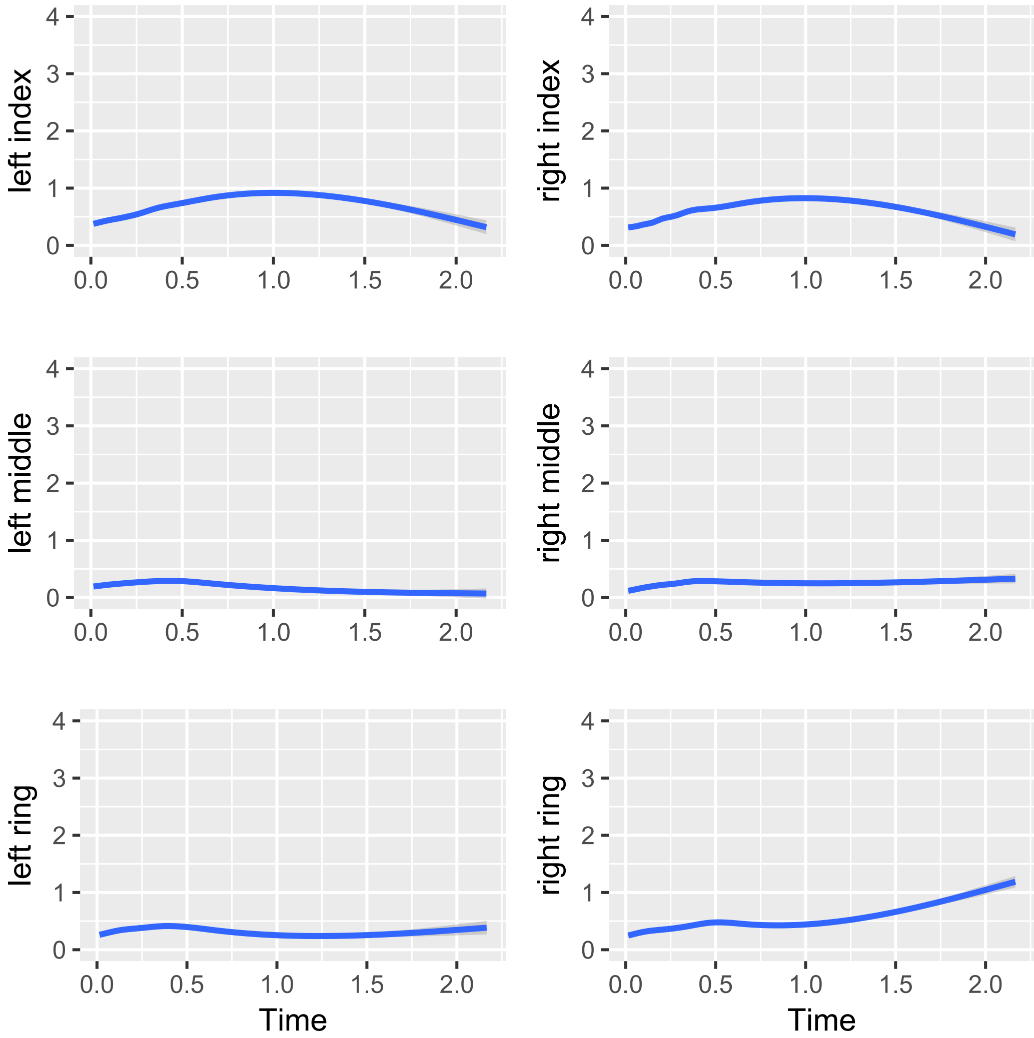


Figure 4.6: Average pressure course of the back pressure applied by the FINGERS while holding the smartphone in N over time.

Chapter 5

Main Study: Using BoD-Pressure-Interaction in Combination with Thumb-Gestures

After we got the results from the preliminary study we can now start with our main goal to explore the feasibility of combining these one- and two-handed GESTURES with the BackXPress. As an inspiration we took the study of McLachlan and Brewster [2015] and the latest study of Corsten et al. [2017a] using the BackXPress.

5.1 Research Questions and Hypothesis

Q1 Is it possible to accurate select menu items with BoD-Pressure in different menu sizes?

Q2 Which influence does various pressure target have?

Q3 Which finger on which hand is the best to perform BoD-Pressure?

Q4 Is there a difference if a gesture performed with the left, right or both hands?

Figure 5.1: A Participant performs a Trial of the main study

Q5 How fast can the pressure be selected using the BackXPress?

Q6 How does the pressure change while the gesture is applied?

5.2 Apparatus

We used the same apparatus as in our first study.

We use the same hardware as in our preliminary study. An iPhone 6s which an 4.7" display, a resolution of 750 x 1334 Pixel and a pixel density of 325.61 ppi and for BoD force detection we again use the BackXPress artifact with its six force sensing resistors.

5.3 Procedure and Measurements

5.3.1 Task and Procedure

Like in our preliminary study the participants have to hold the smartphone in landscape orientation. While doing this, they first have to perform GESTURES at the front without applying any BoD Pressure. This give the users a feeling for the targets and us reference data for the baseline condition. When this is done, the attendants have to hit a target pressure at the back of the device first and then perform a GESTURE with both thumbs at the front while holding the pressure.

At first users perform the gestures without force interaction and then with it.

5.3.2 Design

For this study we choose 4x3x3x8 within design with three repetitions. This makes a total of 864 trials. All independent variables are randomized by the Latin-Square. Every new combination had a test trial of its own and the option of repetition is given if the user e.g. accidentally touches the screen during the pressure selection. The study pilot is 90 minutes long. Participants are not payed for attending.

5.3.3 Variables

Independent Variables

We had four major independent variables.
The first one is GESTURE. As we have analyzed in our preliminary study *Swipe*, *Pinch* and *Rotate* are the main GESTURES for Smartphone usage. We notice that the *Swipe* gesture could be applied with the left and the right hand. For the others both thumbs were necessary. Each GESTURE is executed in two directions.

Gesture has the manifestations of swipe, pinch and rotate.

A swipe will be done with both hands. For pinch and rotate both are needed.

So there are four possible *Swipes* (left-hand/right-hand to the right/left) and two for the other GERSTURES. We decide to do left and right *Swipe* against up and down ones because they make more sense in the given scenario of holding the phone in landscape orientation. *Pinch* is performed inwards and outwards. For *Rotate* the directions are a 90 degrees clockwise and counterclockwise rotation. The target distances are the results of our preliminary study.

The targets which we proposed on our prelimnary study will be used here.

As targets we use the ones we proposed in our preliminary study but mostly the same as McLachlan and Brewster [2015]. Two lines for *Swipe*, two circles for *Pinch* and two times two targets for *Rotate*. So all in all we have four GESTURES in two directions. You can observe them in figures 5.2 to 5.4.

The pressure space is split in the menusizes of three, five and seven menu items.

All other IVs are dependent to the BackXPress System. We have MENUSIZE which divide the available pressure space into *three*, *five* and *seven* intervals. Corsten et al. [2017a] did the same in their original study with the BackXPress on touch operation.

The total force range is in the interval of 1-7N.

The available pressure-space is from one up to seven Newton in width. We choose the minimum because of the resting pressure that we showed in our preliminary study. This maximum resting pressure is almost around one Newton. For the maximum pressure we did a little bit of experimentation. Even if the sensor is capable to measure up to ten newton through its logarithmic output scale it looses precision at high values. Additionally, we test the 10N maximum in a small user group which reported that it is to hard to reach with the BackXPress. So we repeatedly decrease the maximum to 7N which the test users rate as hard but possible to reach and hold.

Dividing this pressure room into *three items* means that each item covers a pressure range of 2N. Respectively its 1.2N for 5 *menu items* and 0.86N for *seven items*.

Each menusize is tested with three different pressure targets each.

For these different MENUSIZES we decide to test three common PRESSURE TARGETS on them. This is the usual approach which was used before by Ramos et al. [2004], Corsten et al. [2017a] and McLachlan et al. [2014]. As these targets we choose the middle of the *three* menu pressure space. So the common targets are at *low* (2N), *middle* (4N) and *high* (6N) force. For the *five item menu* the first (1-2.2N), third (3.4-4,6N) and fifth (5.8-7N) targets include the common ones. In the *seven item menu* the targets fall into the second (1.86-2.72N), fourth (3.58-4.44N) and sixth target (5.3-6.16N).

The last remaining independent variable is the FINGER which is applying the force at the back of the device. Of the four fingers Corsten et al. [2017a] discarded already the little finger. After looking into the results of his study we decided to also remove the ring finger because it has the same performance as the index finger. What Corsten did not test is the difference between the hand which is applying the pressure so we tested all combinations with both hands. Which gave us four fingers in total. The left and right index and the left and right middle finger.

For back of device interaction we test the index and the middle finger of each hand.

Dependent Variables

The dependent Variables are straight forwarded form McLachlan and Brewster [2015]. We have GESTURE ERROR, the TRIALTIME and the SUCCESSFUL PRESSURE SELECTION. But for further analysis we look deeper into the TRIALTIME and split it up into PRESSURE SELECTION TIME and GESTURETIME.

The GESTURE ERROR is the misplacement of the front side touches in respect to the given targets. We also did this in respect to the study of McLachlan and Brewster [2015]. Since we have different targets for each GESTURE we have to calculate the the GESTURE ERROR for each individually. Beginning with the *Swipe*. Since its target were two vertical lines we have chosen to value the displacement at the x-axis of the begin of the touch from the start line and the end of the touch to the end line.

The gesture error is computed from the missplacement of the touches beigin and end towards the tagets.

The same goes with the *Pinch* gesture. Although we replace the displacement towards the x-axis of the target with the direct euclidean distance to the target circles.

The measurement for the GESTURE ERROR on the *Rotate* is estimated by the euclidean distance of the start and end point of the touch towards the start and end point of the target.

For each trial the total trial time will be measured as well as the time before and after the first touch hit the screen.

For taking a comparable TRIALTIME at each trial we decide to start each trial with a press on a button which is located at the bottom middle of the screen. Additionally, the press on this button is timestamped as the begin of the trial. Other time-stamps are fetched with the first touch after the button press and the last touch that is lifted off the screen. The last time-stamp marks up the end of the trial. With these three timestamps we can calculate the PRESSURE SELECTION TIME which is the time before the touch and the GESTURETIME which is the time the display is touched for executing a GESTURE.

Also the success of the force selection is saved.

PRESSURE SELECTION SUCCESS can only be measured as a boolean value. It is saved as true if the given PRESSURE TARGET is hit as the first touch is registered on the display after starting the trial.

5.3.4 Interface

Targets are displayed in green and red in front of a black screen.

The design of the study interface is a whole task of its own. Users need to know their task from a brief look onto the display. Due tp the abstract nature of the targets, the task is unclear users were told the corresponding GESTURE. For identifying the direction of the GESTURE the first touch point is marked in green and the release point in red color. The color of the background is black since the iPhone is white. So the touchable screen has a higher contrast to the casing.

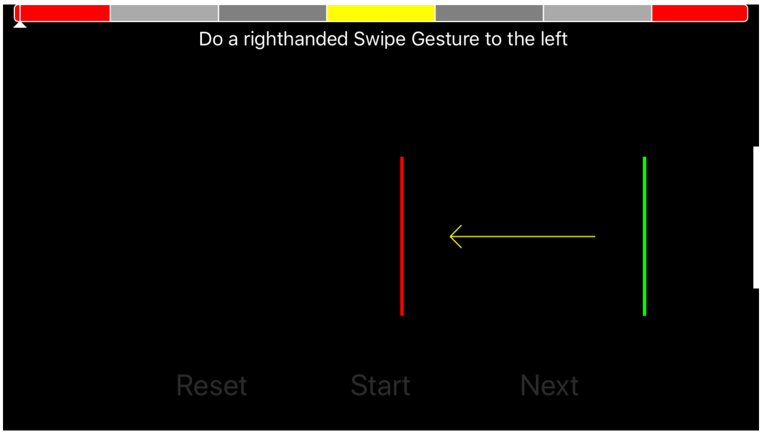


Figure 5.2: The Swipe target interface with a five item menu

In early prototype tests users sometimes got confused which FINGER to use for BoD pressure. We solve this problem with a white indicator on the side of the screen. The height of the screen is divided by three. When the the *index finger* is active the indicator in the upper third is active and when the middle finger is active the middle one displays. We do this respectively for both hands.

The active finger is displayed with a white index on the side of the screen.

To display the applied pressure we built an indicator bar which mapped the applied pressure linear to the width of it. For this we used the function which we calculated on measuring the force sensing resistors (see 3.2). A white triangle indicator shows the currently applied pressure at the active sensor. The dead zone of one Newton is marked in red color as it is the end of the bar which displays if the user overshoots the target range. For this overshoot range we decided to make it one newton big as well to give the bar some symmetry. The rest of the bar is split by the MENUSIZE. We choose two different shades of gray which take turns of coloring the menu items. The active PRESSURE TARGET is first shown in yellow when the the Pressure indicator is not inside of it. When it enters the Target it turned green. This is implemented to support the user for knowing that he is in the target's range. We noticed that indicating the raw data on this bar will lead to some jittering of the cursor.

The currently acting force is displayed in a linear bar on the top of the screen.

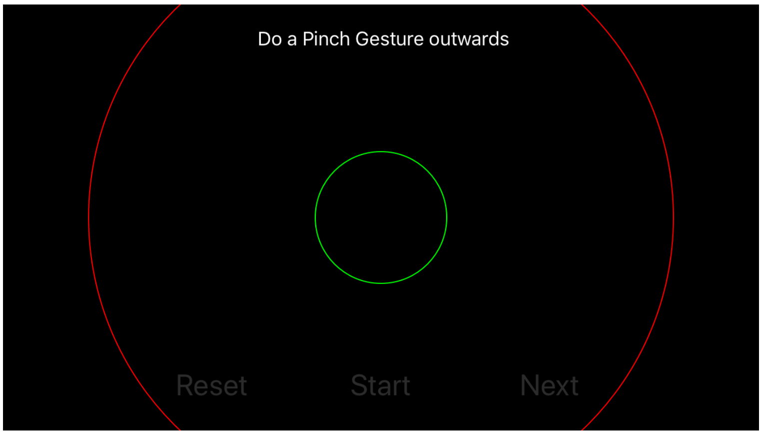


Figure 5.3: The Pinch target interface

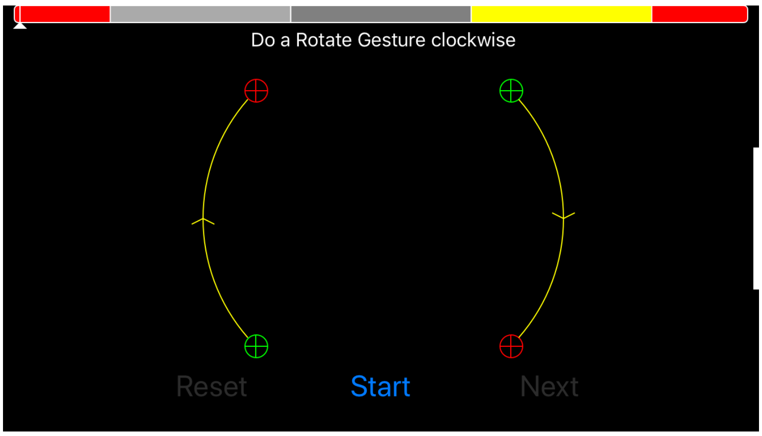


Figure 5.4: The Rotate target interface with a three item menu

We filter the force data with a first order low-pass filter before displaying.

To counter this we applied a first order exponential smoothing on the raw data. We experimented with different alpha values earlier and estimated 0.25 to the best compromise between acceptable delay and jitter reduction. This filter acts like a first order low pass filter. The interface is updated every 15ms (66.7 Hz).

5.3.5 Questionnaire

In addition to the study the participants are asked to fill in a questionnaire (see appendix A.3) afterwards. We first ask some demographic data concerning age, gender and handedness. After this some questions over the given tasks in the study are asked. The questions are in the style of a Likert-Scale with seven answer possibilities to a given statement. In the first block users are questioned about the accuracy of applying GESTURES in combination with the BackXPress. The following block is about the ease of applying pressures with different FINGERS. Moving on to the third block users have to rate the ease of different PRESSURE TARGETS and MENUSIZES. The last two questions ask if users liked performing a *Swipe* and applying the pressure with the same hand or with different hands. The last task is to rank the FINGER for the ease of applying pressure. The questionnaire is designed to be anonymous.

A questionnaire is used to get demographic and qualitative data.

5.3.6 Pilot and changes for the Main Study

Since we have a lot of independent variables we made a pilot study with four users (all right handed, all male between 25-29 years old) with the aim to reduce the study to save some time. The pilot was not statistically valuable but gave us a first clue of some influence of the independent variables. Especially we looked into the effects of MENUSIZE and GESTURE.

We carry out a pilot study to reduce the scope of our study.

As a result of this pilot we decide to remove the *Rotate* gesture as well as the *seven item menu*. Reasons for this are that the *Rotate* gesture is not easy to execute while applying force at the back of the device. Another reason for this is that the *Pinch* gesture is also a both handed GESTURE which is easier comparable to a *Swipe* which is done with one hand.

Subsequently to the results of the pilot, we drop Rotate and the seven item menu.

The *seven item menu* is discarded because in the first BackXPress study of Corsten et al. [2017a] one of the results is that five menu items are the maximum for back of device pressure. Our pilot seems to show the same results, but

The seven item menu is dropped because of its lack in accuracy.

a study only focused on MENUSIZE has to be done since we have a bigger pressure space here than in the earlier study. In this study we just want to investigate the general conditions of using back of device pressure and thumb gestures together.

The total study contains now 600 trials and takes 30-45 minutes each.

This meant we reduced our study to a 6x2x3x4 (GESTURE with direction x MENUSIZE x COMMON TARGET x FINGER). With three repetitions and one test trial, this adds up to a total of 576 trials + 18 (+ 6 test) trials for the GESTURE without any pressure interaction. Additionally, the questionnaire is updated and questions for now missing values were removed. The new time for conducting one user's trial is 30-45min.

5.3.7 Participants

12 right-handed participants took part in the study.

After the pilot we recruited 12 additional participants. Five are female and seven male. Their age is between 22 and 29 years with a mean around 25.5 and a standard deviation of 1.88. All users are right handed and do not suffer from color blindness. They take part in the study voluntarily without given any kind of payment. A supply of beverages and snacks is provided and a pause can be taken at any time. The possibility of withdrawing is also given at every point in the study.

5.4 Results

We tracked 5373 trials for the evaluation.

In total we gathered 5400 trials without tests. We removed 27 trials because in these trials the touch mismatched the touch count of the GESTURE or the TOUCH ERROR exceeded the 1000px range. This leaves us with 215 trials without the usage of the BackXPress and 5158 trials with the BackXPress.

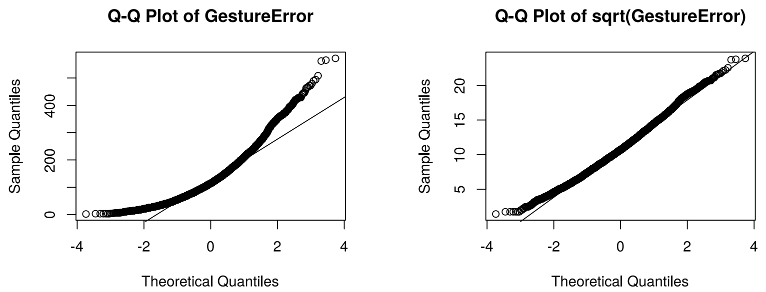


Figure 5.5: Q-Q Plot of TOUCH ERROR w/o transformation (left) and with square root transformation (right)

Figure 5.6: Boxplots of GestureError on different Gestures

5.4.1 Gesture Accuracy

We want to test our results with an analysis of variance (ANOVA). This test has a few assumptions on the data. One of them is that the data is normal distributed. We check this while analyzing the quantile-quantile-plot. There we see that the data needs some transformation. After applying the square root function the data is normal distributed, see Figure 5.5.

We transform the data so it is normal distributed.

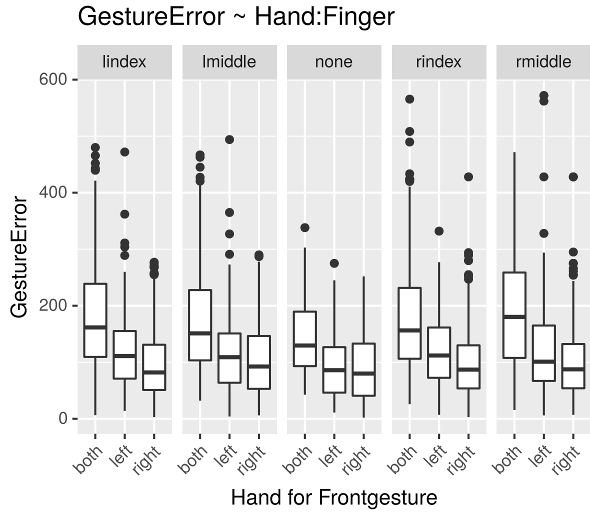


Figure 5.7: Boxplots of GestureError on Gesture x Finger

The usage of the BackXPress, different fingers and the combination of various FINGERS and GESTURES has influence on the GESTURE ERROR.

We can now apply a four-way repeated ANOVA on this data with our independent variables (GESTURE X FINGER X MENUSIZE X ACTIVETARGET). We find that the GESTURE has a major impact $F(2,5371) = 581.35$ (p-value < 0.001) on the GESTURE ERROR which is expected since we have different measurements for each GESTURE. Another finding is the significance of the combination of GESTURE and FINGER with an F-value of $F(6,5367)= 2.34$, p-value $= 0.029$. We also do a one-way ANOVA and compared the usage of the BackXPress on our ground truth. There we find that the usage of the BackXPress has a significant influence on the GESTURE ERROR $F(1,5372) = 18.87$, p-value < 0.001.

The error of the right-handed swipe is lower then the left-handed one. Both swipes are more accurate than the pinch.

A Post-Hoc Tukey HSD is carried out and we find that the right-handed *Swipe* performed significantly better than the left-handed *Swipe* ($p < 0.001$). This analysis shows also that both *Swipe* gestures performed better than the *Pinch* Gesture (both with a p-value < 0.001). The Post-Hoc analysis of GESTURE and FINGER showed no significant deviations from the previous analysis with only the GESTURE.

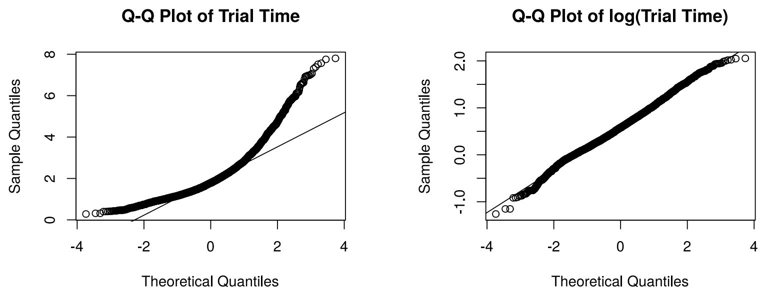


Figure 5.8: Q-Q Plot of TRIAL TIME w/o transformation (left) and with a logarithmic transformation (right)

On the boxplots of figure 5.7 we can see that the deviation and the height of the GESTURE ERROR is changed when the BackXPress is not used. Additionally, we see that in this case the GESTURE ERROR of the *Swipe* does not deviate from left to right hand usage p = 1.

When the BackXPress is not used there is no difference between left and right hand swipes.

5.4.2 Speed

Trialtime

TRIALTIME is also analyzed with a four-way repeated ANOVA on the independent variables and a one-way-ANOVA on the usage of the BackXPress. To do this Analysis we have to transform our data again. In this case a logarithmic transformation to the base of two gave us the expected results, see Figure 5.8.

We find significant evidence that the GESTURE (F(2,5371)=95.35, p < 0.001), MENUSIZE (F(1,5372)=285.63, p < 0.001) and the ACTIVE TARGET (F(2,5371)=241.75, p < 0.001) have an influence on the Trialtime. Also the combination of GESTURE X FINGER shows significant influence (F(6,5367)=241.75, p < 0.001). Also in the findings of the one-way-ANOVA we can estimate that the BackXPress has a significant influence on the TRIALTIME as well (F(1,5372)=839.26, p<0.001).

Gesture, menusize and the active target have influence on the trialtime.

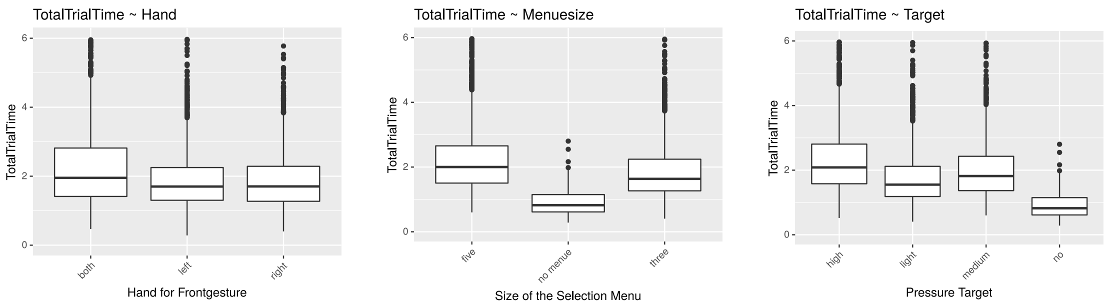


Figure 5.9: Boxplots of Trial Time with Gesture, Menusize and Active Target

Swipe is faster then pinch. Also the trial time is shorter when using a smaller menu size.

The Post-Hoc analysis is again done with a Tukey HSD. The results on GESTURE showed that the left ($\bar{x}$ = 1.90s) and the right hand *Swipe* ($\bar{x}$ = 1.87) are significant faster than the *Pinch* ($\bar{x}$ = 2.28) with a p-value < 0.001. Between the two *Swipes* there is no difference (p = 0.35). The deviation when comparing different MENUSIZES is also significant between those two. The mean TRIAL TIME while using a *three item menu* is 1.86s while for a *five item menu* it is 2.26s, which is more than one second slower than the average TRIAL TIME without the use of the BackXPress ($\bar{x}$ = 0.94s).

Light force is faster then higher ones to apply.

When comparing the different ACTIVE TARGETS the *light* PRESSURE TARGET is the fastest ($\bar{x}$ = 1.77s). The next fastest is the *medium* ($\bar{x}$ = 2.03s) and the slowest the *high* pressure ($\bar{x}$ = 2.38s) target. All differences here are significant (p < 0.001).

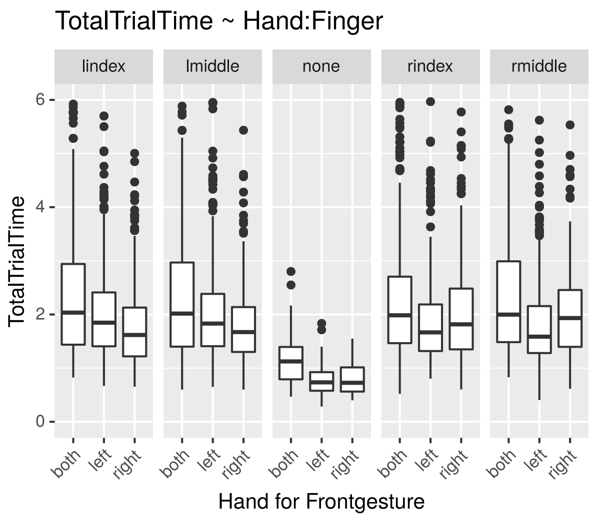


Figure 5.10: Boxplots of Trial Time on GESTURE X FINGER

The analysis of the combination of FINGER and GESTURE reveals different results than the analysis of GESTURE on its own. When using the FINGERS of the right hand for applying pressure on the back of the device, the right hand *Swipe* is significantly slower than the left-handed one (both with a p-value < 0.05). For both handed GESTURES there is no significant contrast between the FINGERS.

When pressure application and gesture execution is done with different hands the trialtime is faster.

Gesture Time

For GESTURE TIME we do the same transformation as for the TRIAL TIME and additionally apply the same tests. First of all we do not find enough evidence in the one-way-ANOVA that the BackXPress is influencing the speed of the GESTURE after a touch is recognized on the screen (F(1,5371) = 2.87,p = 0.0902). As expected for the varios GESTURES we find that they have a significant influence on GESTURE TIME (F(2,5371)= 261.58, p < 0.001). Again the combination of GESTURES and FINGER is also significant (F(6,5367)=241.75, p < 0.001).

The BackXPress is not influencing the gesture time.

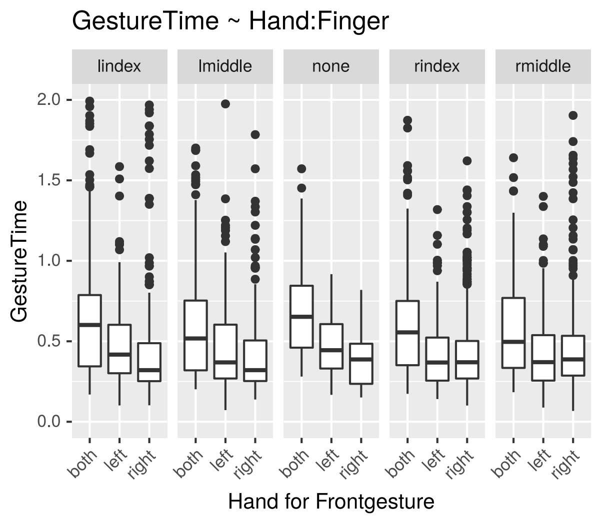


Figure 5.11: Boxplots of Gesture Time on Gesture x Finger

Again we see that the Swipes are faster when the force control and the gestures are done with different Hands.

In consulting Tukey HSD tests it is shown that both *Swipes* are faster than the *Pinch* ($p < 0.001$) and the left-hand *Swipe* is significantly faster than the right handed one ($p = 0.016$). By reviewing the combination of GESTURES and FINGER we see that there is no difference to a significance level of $\alpha = 5\%$ between left- and right handed *Swipes* if the FINGER of the right hand are used for force control.

Pressure Selection Time

The time before a touch happens is 0.42s without the BackXPress.

After investigating the time after the first touch is recognized, we now analyze the time before a touch happens. For this we look only into the trials where the BackXPress is used, since there is no force selection without it. The mean time a user takes to go from the start-button until the first target is touched without applying pressure is 0.42s.

We again apply a logarithmic transformation. In a four-way repeated ANOVA we find significance that GESTURE,MENUSIZE and ACTIVETARGET have an influence on the PRESSURE SELECTION TIME. Also the combination of GESTURE and FINGER has a significant result (all with a $p < 0.001$). The FINGERS alone have no influence on the PRESSURE SELECTION TIME.

Gesture, menusize and the active target have influence on the pressure selection time.

The Tukey HSD reveals that the pressure selection is faster when applying a *Swipe* instead of a *Pinch* ($\bar{x}$ = 1.72s) afterwards ($p < 0.001$). But there is no difference between a left- ($\bar{x}$ = 1.51s) and right-hand *Swipe*($\bar{x}$ = 1.48s) ($F(2,5156) = 28.66$, $p = 0.881$).

Pressure selection is faster with swipes.

While investigating the MENUSIZES the *three item menu* ($\bar{x}$ = 1.38s) has a smaller PRESSURE SELECTION TIME then the *five item menu* ($\bar{x}$ = 1.76s) ($F(1,5157) = 307.68$, $p < 0.001$).

With lager menu items the trialtime increases.

Also the selection time increased with the force which is applied on the back of the device. To perform a GESTURE after applying *light* pressure user needs on average 1.27s to select it. 1.56s are needed for *medium* pressure and 1.91s for *high* pressure. The differences are significant to a p-value < 0.001.

The higher the target force, the higher the selection time needed.

At last we look into the combination of GESTURE and FINGER. Looking at the boxplots of figure 5.12 we see that the *Swipe* is faster when a *Finger* of the other hand is used for pressure control. We cannot find any evidence for this in the Tukey HSD except for the left index finger which selects pressure significantly faster when the right hand is used for a *Swipe* gesture afterwards ($p = 0.0031$).

Again some indication shows that the application pressure is slightly faster when different hands are used.

5.4.3 Pressure Accuracy

In 4641 of 5158 trials users selected the *Active Target* successfully. This sums up to a 89.99% PRESSURE SELECTION SUCCESS of all trials. Since Pressure Accuracy is only measured boolean we decide to evaluate it with factorial logistic regression with χ^2 as test statistic. This test is

Pressure selection accuracy is in mean around 90%.

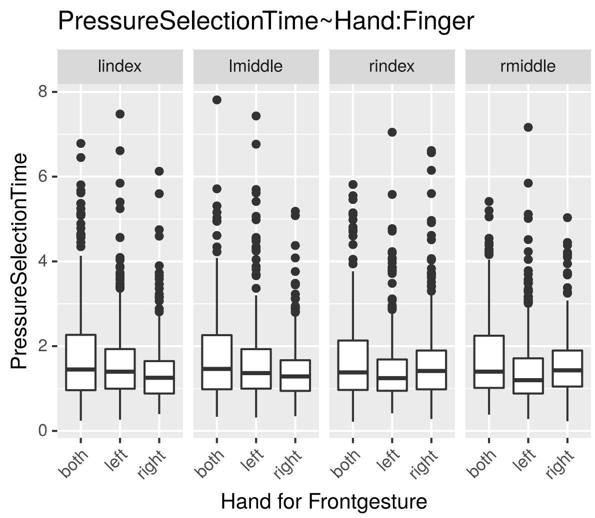


Figure 5.12: Boxplots of Pressure Selection Time on GESTURE X FINGER

chosen after consulting a statistical guide of the University of California, Los Angeles[1]. We test again only the trials with usage of the BackXPress since there is nothing to measure without it.

All independent variables have influence on the pressure selection.

Interestingly, we find that every single one of our independent variables has influence on the ability to hit a given PRESSURE TARGET. GESTURE and FINGER have a significant effect to a p-value < 0.01, ACTIVE TARGET and MENUSIZE even to a p-value of < 0.001. Some combinations of this IVs have significant influence. The analysis of GESTURE and FINGER, GESTURE and ACTIVE TARGET, ACTIVETARGET and MENUSIZE as well as the combination of GESTURE, FINGER and ACTIVETARGET are significant according to a p-value < 0.01.

[1]https://stats.idre.ucla.edu/other/mult-pkg/whatstat/

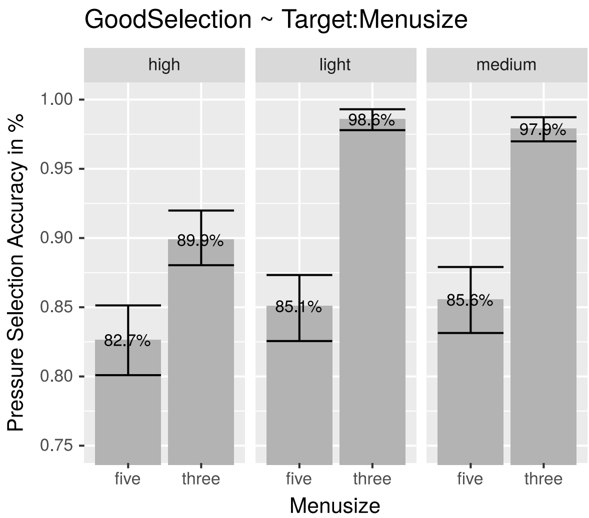


Figure 5.13: Plots of Pressure Accuracy on Active Target x Menusize

We first discuss the influence of one independent Variable. As Post-Hoc test we are using a Pearsons Chi-Squared-Test. Starting with the GESTURE, we find that when the users performed a right handed *Swipe* (92.07%) afterwards, pressure selection is significantly more likely to be successful ($p < 0.01$) than in other two possibilities. Between the left hand *Swipe* (88.64%) and the *Pinch* (89.2%) we cannot find any contrast.

The pressure selection before a right handed swipe is the most precise.

The impact of using different FINGERS shows that the left middle finger performs better (91.16%) than with the right index finger (87,75%) to a p-value of 0.0042. Between every other combination we cannot distinguish any significant deviations. While comparing the *Active Target* Post-Hoc we see that the *light* (91.87%) and the *medium* target (91.86%) are more likely to be hit than the *high* PRESSURE TARGET (86.3%) to a p-value < 0.001, but we cannot identify any disparity between those two. For the MENUSIZE we discover a significant better selection with the *three item menu* (95.47%) than the *five item menu* (84,45%).

The left middle finger performs better than the others.

Using different hands for front and back of device interaction has a better accuracy then the other possibilities.

Now we are looking into the combinations. The analysis of GESTURE and FINGER reveals that the highest accuracy is achievable with the left index finger when performing a right handed *Swipe* afterwards with 95.4%. The lowest is when using the left index finger for a swipe with the left hand (85.2%). In general we can say if the user is using the right hand for pressure control there is no distinguishable deviation of accuracy when performing any GESTURE afterwards. This stands in contrast to the left hand, when force is applied with it, the accuracy is significantly increased if a right handed GESTURE is applied afterwards.

The highest force target is hardest to reach when a left-hand swipe or pinch gestures follows.

The investigation of combination of GESTURE and ACTIVETARGET reveals that almost every combination is more accurate than the combination of the left-hand *Swipe* and the *Pinch* gesture with the *high* target. Every distance between those two groups is significant to a p-value < 0.05. In those groups we find no differences.

Light and medium targets in a three item menu reach a almost 100% accuracy.

The study of the co-dependency of ACTIVETARGET and MENUSIZE indicates that the *three item menu* in combination with the *light* and *medium* ACTIVETARGET has an accuracy which is almost always achievable (98.6% and 97.9%) as we see in figure 5.13. It is significantly lower when the *high* target pressure has to be selected (89.9%). Between each other combination we cannot discover significant evidence.

Differences between hands can be observed when the target force gets higher.

The last combination we have left is the three-way dependency on GESTURE, FINGER and ACTIVETARGET. While investigating Pearson's χ^2 test on it, we do not find any significant deviation between any combination within the *light* PRESSURE TARGET. In Figure 5.14 we can observe that higher the target pressure is the lower the accuracy is when using the same hand for a GESTURE and the pressure interaction.

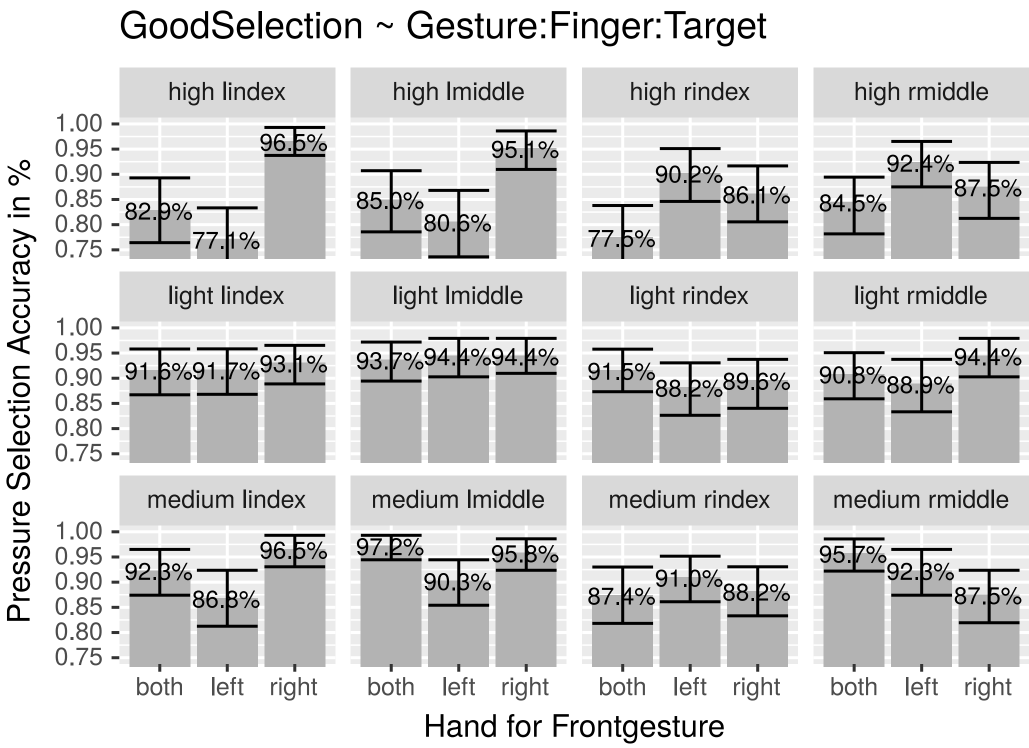


Figure 5.14: Plots of Pressure Accuracy on Gesture x Finger x Active Target

5.4.4 Pressure Course

Front-Pressure increases with the use of the BackXPress.

Again we observe the pressure over time with the usage of the BackXPress. The force which is applyied by the thumbs when the user is performing a gesture at the front has risen in comparison to our Preliminary Study in subsection 4.3.5. The mean is now 2.01N (95%CI = 1.998678 2.011451). This is more than double as high as without the usage of the BackXPress.

The Frontpressure exceed the limits of the screen when using medium and high pressure.

Another finding is that the maximum force at the front reached the maximum value on the screen when used with *medium* or *high* pressure at the back. So an exact analysis can not be carried out.

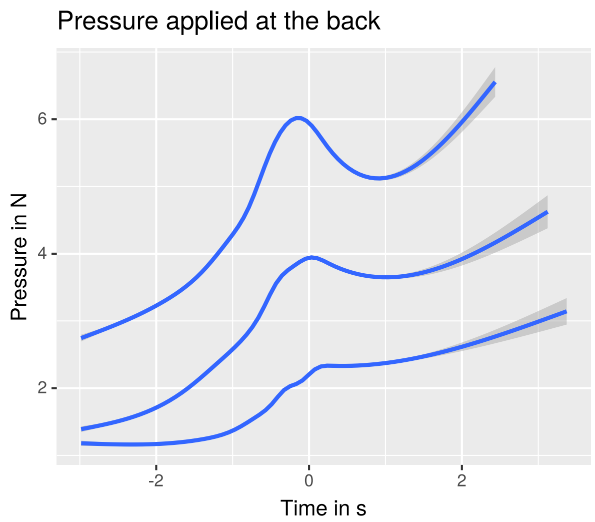


Figure 5.15: Average Pressure Course of the Back Pressure applied by the FINGERS while pressure selection for different Active Targets. At the time-stamp zero the first touch appears.

At the moment of touch, the pressure at the back decreases for a short time with high and medium pressure targets. With the low one it is the other way around.

Also the pressure at the back of the device shows in combination with the ACTIVE TARGET some interesting findings, see figure 5.15. After the pressure selection, the users lighten the force when beginning the touch. Afterwards the participants try to go back into the selection level. This phenomena is not observable with the low PRESSURE TARGET.

5.4.5 Questionnaire

Now after reviewing all the quantitative data, we go towards the qualitative data we have gathered. Summarizing the results of the questionnaire (see appendix A.3) gives us some interesting results.

Most users state that applying pressure at the back of the device and performing a swipe is an easy task.

The first block of the questionnaire is focused on the *Gestures* in regard to the BoDI.
Out of the twelve users eight agreed with the statement that the it is easy to apply gesture at the front while performing back of device interaction in general (66,6%

agree 8.33% neutral 25% disagree). When it comes to the specific GESTURES, the users' agreement with the ease of usage declines with the complexity of the gesture. The easiness right-handed *Swipe* has the highest agreement ratings (75% agree 16.66% neutral 8.33% disagree) and is followed by the left handed one (41.66% agree 33.33% neutral 8.33% disagree). Performing a *Pinch* gesture with two hands is stated by the users as not an easy task (33.33% agree 16.66% neutral 50% disagree).

The participants disagreed that performing a pinch and BodI is an easy task.

For the third block the questions are about the PRESSURE TARGET and the MENUSIZE. Most users do not agree that they could apply strong force accurately (33.33% agree 8.33% neutral 41,66% disagree). For the light force the opposite is the case (33.33% agree 8.33% neutral 41.66% disagree). Also users tend to agree that they keep force inside the bounds of a three-item-menu item (91.66% agree 8.33% disagree) rather than in a five-item-menu item (33.33% agree 16.66% neutral 50% disagree).

Users stated they can apply light force more accuratly than strong force and stay inside the bounds of a three menu item target rather than a five menu item target.

In the third block the participants fill in their agreement towards the easiness of applying pressure with the different fingers. In general users agreed that it is easy to apply pressure at the back of the device (66.66% agree 33.33% disagree). Then, the users were asked if they agree if it is easy to apply pressure with a single finger. Almost all users agreed that it is easy to apply BoD pressure with the right middle finger (91.66% agree 8.33% neutral). The second highest agreement is with the right index finger (66.66% agree 25% neutral 8.33% disagree). Essentially the same agreement is scored by the left middle finger (66.66% agree 25% neutral 8.33% disagree). This leaves the left index finger with the lowest but also mostly positive agreement(58.33% agree 16.66% neutral 25% disagree).

Most users agreed that applying pressure at the back of the device is easy. Especially the right middle finger which has over 90% agreement.

The last two Likert-Scale-Questions are about if the users prefer applying force and performing a *Swipe* with one or with different hands. The results here are very contrasting. While most users disagree that it is easy to apply a swipe and back of device pressure with the same hand (16.66% agree 25% neutral 58.33% disagree), they mostly strongly agreed that it is easy with different hands (91.66% agree 8.33% disagree).

The users agreed that it is easy to use different hands for applying pressure and performing a swipe to the opposite with the same hand.

Participants rated the left index and the right middle finger the easiest for applying BoD force. They are followed by the left middle finger. The right index is ranked the hardest.

Also the users had to rank the fingers for the easiness of applying force at the back of the device from 1 (easy) to 4 (hard). The results are not very conclusive. With a median of two the right middle finger and the left index finger have the same results. They are followed by the left middle finger with a median of 2.5 and the hardest is the right index finger with a median of 3.

The participants give also some interesting comments towards the study. So one user wrote down: "Applying force with the index finger leads to a tilting of the phone in my grip." With this they meant the tilting around the y-axis of the phone. Another user stated that the pressure sensors at the back of the device are not ideally positioned for them. This could be an indication that we may have to change the sensor position or the sensor type to sensors which take up a larger space on the device's back in the next iteration of the prototype.

Chapter 6

Evaluation

With the gathered results we can now evaluate the system and give guidelines for future work in this sector.

6.1 Thumb Touch Gestures at the Front

In our preliminary study we came up with the individual footprints of the gestures. In the footprint of the pinch we find surprising results. Instead of being diagonal they are mostly horizontal movement of the thumbs. This is different from the one handed pinch in which the hand's natural form seems to favour diagonal movement of the thumb and the index finger.

In our preliminary study the footprint of the pinch is surprising.

In comparison to the study of Wolf et al. [2014] we see that the size of the swipe gesture does not differ if it is performed on a tablet or the smartphone when holding the device in both hands. On the tablet the average horizontal swipe length was 3.25cm and for the vertical one 4.25cm. In our study they were 3.5cm for the horizontal and 4.15cm for the vertical ones. Regarding this we can state that the size of the device does not influence the gesture length. Even the gesture time seems to be identical.

The quantitive data of the swipes is the same as the ones gathered with a tablet.

Front pressure with thumb gestures is around 1N and peaks with 1.5N for two handed gestures.

The force which is applied on the front has its maximum around 1.5N for one handed and 1.0N for two handed gestures. More interestingly, the holding force in the landscape design is around 0.5N on average but peaks to 1N at every trial. We also show that two handed gestures take a longer time than one handed ones. At last we can state that almost the whole smartphone is reachable with both hands for almost all people.

The middle of the screen is difficult to reach in landscape orientation.

At hardest it is to reach to the top middle screen in landscape orientation. In the questionnaire of our main study some users especially the female ones with small hands also stated that the start button on the lower middle screen was difficult to reach.

6.2 Back Pressure

Gesture time and accuracy decreases when the BackXPress is used.

At first we see that tusing of back of device pressure interaction and thumb gestures at the front of the device is feasible. But we can state that the accuracy of the front gestures and its application time will decrease, especially when using more than one hand for the gesture.

When using BoD the middle finger is the best finger for it. Gestures and BoDI should be done with different hands.

An additional finding is that the middle finger outperforms the other fingers in the subject of pressure accuracy. We guess this is because the phone will twist when pressure is applied with the index or ring finger but more investigation is needed on this topic. When using the same hand for a gesture and the back of device interaction all time and gesture error increases and accuracy decreases. These has to be kept in mind when software for this device will be designed.

6.3 Design Guidelines

Out of the results we gathered we advice the following guidelines for the use of the BackXPress in combination with thumb gestures.

- The users are mostly unable to reach the upper part at the middle of the screen. There should not be any button in Landscape Orientation. Also the rest of the middle is difficult to reach. The users will have it a lot easier if any buttons are closer to the sides.
- We advice a dead zone of at least 0 to 0.5N for the sensors of the BackXPress.
- Moreover if the touchscreen of the smartphone is used with one hand the user should use the other one for pressure control of the BackXPress.
- If the BackXPress is used with both hands the non-dominant hand should be used to apply BoDI force.
- As in the paper of Corsten et al. [2017a], the results suggest that the middle finger is the most accurate finger to apply the pressure.
- Furthermore, the pressure range up to 7N is on the upper limit for precise force input on the back of the device. We recommend to use a lower upper bound for the pressure input to be more accurate.
- The menu size could stay at maximum at five items. The three item menu is significantly better.
- If the user uses the BackXPress with the gestures, they take more than double the time. This should be kept in mind when designing software for it.
- We used an exponential filter to reduce the jitter. This also helped the accuracy since it reduced small changes of the indicated pressure.
- When higher force levels should be reached in the BodI, a increase in the front pressure will also appear so only one kind of pressure interaction can be used at a time.

Chapter 7

Summary and future work

7.1 Summary and contributions

In this thesis we proove the viability of back of device pressure interaction in combination with thumb-touch-gestures on smartphones.

In our preliminary study we fetched data of thumb touch gestures in landscape orientation on smartphones. We discussed their footprints as well as their meassurements. On this data we build some targets for testing gestures on 4.7" display in landscape-orientation and used them for our main study. Since our data matched the one Wolf et al. [2014] and Tiefenbacher et al. [2016] geathered, we can assume that the thumb-gestures do not change with the size of device.

The preliminary study shows footprints and data of gestures performed with the thumbs in landscape orientation.

In our main study we introduced the interaction method of using back of device pressure interaction in combination with thumb-touch-gestures on smartphones. This was mostly derived from McLachlan and Brewster [2015], but included a lot of additional hardware specific tests.

Our main study tested back of device pressure interaction with thumb touch gestures.

Based on our findings we introduce some design guidelines for the use of force interaction on the back of the device.

We found proof that a higher target pressure leads to less accuracy on the pressure and touch control. Also we have shown that users who used the device for the first time can achieve a 90% accuracy of hitting a pressure interval with their fingers on the back of the smartphone. The impact of different independent variables has been investigated and their influence documented. At last we have given design guidelines for future development with this device.

7.2 Future work and Limitations

We tested only right handed persons in our main study. Left-handed Participants needed to be tested in future work.

Despite coming to a plethora of new insights, some remaining questions ought to be addressed in future studies. In our main study we excluded left-handed people. This user group represents 10%-15% [Hepper et al., 1990] of the population and we think that the results might differ than the mirrored ones of the right-handed groups. We suggest to repeat some parts of the study with left-handed participants for comparison. Also we tested only on a 4.7" device. Since the smartphones get bigger every year we recommend to test BoDI on bigger devices.

More testing on different pressure spaces is required.

We just tested two menu sizes. We see a drop of speed and accuracy when participants used a five item menu but we missed the two and four item menu. This system should also be tested in order to determine the scope of the human capability of selecting the right target. Another field of future research would be of finding the ideal pressure ranges for these menu sizes we just tested the static pressure range of 1-7N in this thesis; more research is needed in this field.

Continuous interaction needs to be explored for more application possibilities.

The BodI is only tested first tap on the screen was recognized by the system. For a new interaction method with this device we propose the use of continuous methods of interaction. One application could be an increased zoom speed when the user is applying pressure to the back of a device. This can be compared with the usage of repeated gestures.

Appendix A

Questionnaires and Consent Forms

Informed Consent Form

Marten Junga - Ergonomics of Thumb Touch Gestures on Smartphones in Landscape Orientation

PRINCIPAL INVESTIGATOR Marten Junga
Media Computing Group
RWTH Aachen University
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Email: marten.junga@rwth-aachen.de

Purpose of the study: The goal of this study is to show the feasibility of using back of device pressure interaction with thumb touch. Participants will be asked to hold the phone in Landscape Orientation and perform touch gestures with their thumbs. Touch signals and finger pressure will be used in the analysis.

Procedure: Participation in this study will involves two phases. In the first phase, you will be asked to slide your thumbs from the bottom to the top of the touchscreen as far as you can reach towards the middle of the device. In the second phase, you will be asked to perform multiple touch gestures not the touchscreen while resting your fingers of the back of the device. This study should take about 15 minutes to complete.

After the study, we will ask you to fill out the questionnaire about the tested system. In this questionnaire, we will ask some general questions about you and your habits and practices with respect to smartphone use.

Risks/Discomfort: You may become fatigued during the course of your participation in 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 understanding touch gestures performed with

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 snacks and drinks 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 Marten Junga at +491773090294
email: marten.junga@rwth-aachen.de

Figure A.1: Form of Consent for the Preliminary Study

Informed Consent Form

Back of Device Pressure Interaction in Combination with Thumb Touch Gestures on Smart Phones

PRINCIPAL INVESTIGATOR Marten Junga
Media Computing Group
RWTH Aachen University
Phone: 0177/3090294
Email: marten.junga@rwth-aachen.de

Purpose of the study: The goal of this study is to show the feasibility of using back-of-device-pressure-interaction in combination with thumb-touch-gestures at the front of a smart phone. Participants will be asked to hold the phone in landscape orientation and maintain force with their fingers within a given space. When they reach the given target space they have to perform a touch gesture at the front. Touch signals and finger pressure will be used in the analysis.

Procedure: For each gesture you will first perform some test trials without force. Afterwards you have to apply force with one finger within the indicated target on the force-indicator and then you have to perform the demanded gesture.

This study should take about 45-60 minutes to complete.

After the study, we will ask you to fill out the questionnaire about the tested device. In this questionnaire, we will ask some general questions about you and your experience with the device.

Risks/Discomfort: You may become fatigued during the course of your participation in 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 understanding touch-gestures in combination with force-interaction

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 snacks and drinks 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.

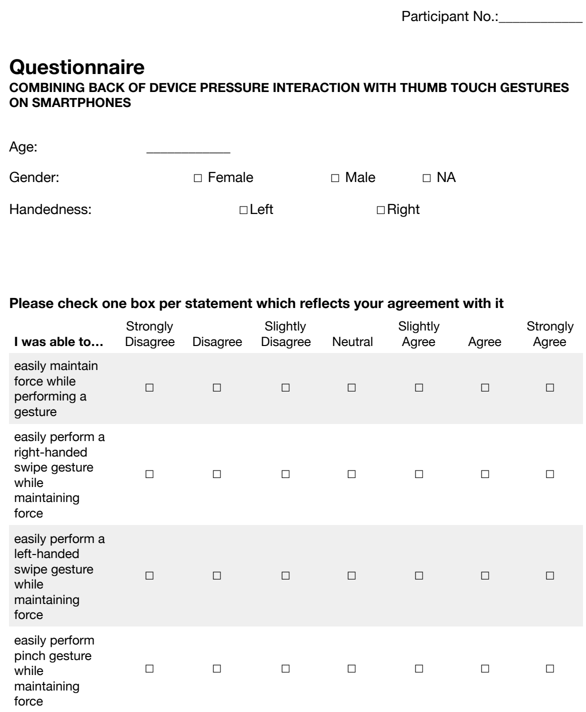
_____ I have read and understood the information on this form.
_____ I have had the information on this form explained to me.

Participant's Name | Participant's Signature | Date

Principal Investigator | Date

If you have any questions regarding this study, please contact Marten Junga at +491773090294 email: marten.junga@rwth-aachen.de

Figure A.2: Form of Consent for the Main Study



Participant No.:___________

Questionnaire

COMBINING BACK OF DEVICE PRESSURE INTERACTION WITH THUMB TOUCH GESTURES ON SMARTPHONES

Age: ___________

Gender: ☐ Female ☐ Male ☐ NA

Handedness: ☐Left ☐Right

Please check one box per statement which reflects your agreement with it

I was able to…	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
easily maintain force while performing a gesture	☐	☐	☐	☐	☐	☐	☐
easily perform a right-handed swipe gesture while maintaining force	☐	☐	☐	☐	☐	☐	☐
easily perform a left-handed swipe gesture while maintaining force	☐	☐	☐	☐	☐	☐	☐
easily perform pinch gesture while maintaining force	☐	☐	☐	☐	☐	☐	☐

Figure A.3: Page one of the Questionnaire of the Main Study

Participant No.:___________

I was able to…	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
apply strong force accurately	☐	☐	☐	☐	☐	☐	☐
apply slight force accurately	☐	☐	☐	☐	☐	☐	☐
maintain force in the target area of a 3 Item-Menu	☐	☐	☐	☐	☐	☐	☐
maintain force in the target area of a 5 Item-Menu	☐	☐	☐	☐	☐	☐	☐

For me it was *easy* to…	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
apply force at the back of the phone	☐	☐	☐	☐	☐	☐	☐
apply force with the right middle finger	☐	☐	☐	☐	☐	☐	☐
apply force with the left middle finger	☐	☐	☐	☐	☐	☐	☐
apply force with the right index finger	☐	☐	☐	☐	☐	☐	☐
apply force with the left index finger	☐	☐	☐	☐	☐	☐	☐

Figure A.4: Page two of the Questionnaire of the Main Study

Participant No.:___________

For me it was *easy* to…	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
apply force and perform a swipe with the same hand	☐	☐	☐	☐	☐	☐	☐
apply force and perform a swipe with different hands	☐	☐	☐	☐	☐	☐	☐

Rank the fingers regarding (the perceived) ease of applying force from 1(easy) to 4 (hard`)

Left Index-Finger ____________

Right Index-Finger ____________

Left Middle-Finger ____________

Right Middle-Finger ____________

Any Comments?

Figure A.5: Page three of the Questionnaire of the Main Study

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