Bauhaus-Universität Weimar
Faculty of Media
Degree Programme Human-Computer Interaction M.Sc.

A practical approach for thumb-to-index interaction as input for ubiquitous screen

Master's Thesis

Dang Thi Hoang Yen
Born Feb. 3, 1993 in Vietnam

Matriculation Number 119433

1. Referee: Jr. Prof. Dr. Jan Ehlers
2. Referee: Prof. Dr. Eva Hornecker

Submission date: October 7, 2020

Declaration

Unless otherwise indicated in the text or references, this thesis is entirely the product of my own scholarly work.

Weimar, October 7, 2020

. . . .
Dang Thi Hoang Yen

Abstract

The breakthrough of ubiquitous computing increases the demand for unconventional input interface. In recent years, thumb-to-finger interaction has attracted much attention in the research field. This study tries to investigate the interaction between the thumb and the index finger from a practical point-of-view. It first explores the possible gesture and input capability of the thumb-to-index interface, then it researches into the potential application of the interface in multitasking, smart-home controller, VR/AR, and assistive device for disabled people. The study also delves into building a working prototype to evaluate the pragmatic aspect of the interface for eye-free single-hand input. The evaluation section requires participant to use the thumb-to-index interaction to control the smartwatch with one hand, and perform the same task with two hands. The result indicates some insights for the performance and adoption of the novice user for the new interface. In general, it takes three times longer to complete the task with just one hand comparing to using both hands. Sliding towards the thumb is easier to perform than sliding toward the fingertip. The participants show a tendency for the trade-off between speed and accuracy, and this tendency is different for two gender groups. Tactile feedback is considered a critical factor for eye-free input. Some indications for the design and functionality of the interface have been captured during the evaluation section which can help to develop the interface in the future.

Acknowledgements

I would like to take this opportunity to express my appreciation for all the support that I received during the time working on this thesis. First of all, I want to thank Jun.-Prof.Dr. Jan Ehlers for his extraordinary guidance and encouragement on the idea and process of this work, and Hannes for his advice on the hardware. I also want to give deep gratitude for Quan Dinh who had dedicated his knowledge in supporting me with the technical challenges. Moreover, I would not able to complete the project without the voluntary participants, so I want to say thank to all ten participants who spent their time on performing the experiment in my work. Especially in the period of the pandemic, their help means a lot to me.

Contents

Chapter 1

Introduction

The growth of internet-of-thing and ubiquitous computing has led to an increasing demand for cutting-edge input interface. As the aspiration for novel digital experience goes on, researchers keep looking for new interaction and technology such as voice interface or even brain-computer interface. Recently, on-body touch interface and specifically thumb-to-fingers touch input have gained the attention of many researchers since it enables eyes-free and subtle interaction. Comparing to voice command, thumb-to-fingers interaction provides more privacy and is more acceptable in public.

Today, people's daily life is full of innovative technology and interaction. The house is smarter with the equipment of the internet-of-thing devices, for example, the light can automatically change its brightness and color depending on the environment, the speaker can talk to people and help them to make online reservation or shopping, and a head-mounted display is an astonishing entertainment device for a short adventure to the virtual world. People are living in the future that they imagined twenty years ago, and there are more to come. Researcher in technology keeps questioning what will be the next innovation and how to add magic to our daily life with technology. A numerous number of ingenious prototypes have been proposed every year, and using body or hand gestures to control the computer system seems to be an interesting topic for many research groups. People often see on movie or futuristic video featuring using the hand gesture to slide and navigate around multiple projected screens floating in the air. The rise of virtual reality has made the hand gesture a potential input for controlling and navigating in the 3D environment. While the spotlight is focusing on using the whole body's gesture, micro hand interaction such as thumb-to-fingers interaction also provides room for many applications.

There are two main approaches to detect the full range of all possible interactions between the thumb and other fingers. The first one is a vision-based approach that uses a camera image to estimate the hand posture and touch position. This approach is convenient for the user since they do not need to wear any sensing device, but it is a challenge for the researcher to come up with a solution to maximize accuracy. Besides, this approach is not suitable for the mobility concept because the set up of the whole sensing system is complicated. The second approach is using a wearable device that can sense the interactions. These devices often leverage the advancement in sensor technology that often has higher accuracy in sensing touch input. The downside of this approach goes for comfortability. The user will not be comfortable to wear a glove or a bulky device with many sensors and wires. This problem can be solved with careful consideration of wearable things.

This study was inspired by the practical application of thumb-to-finger interaction in daily context. To suit the purpose of mobility, the input interface should be wearable and convenient to carry around. After consideration some options to simplify the interface, a straightforward solution is only adopting the interaction between the thumb and the index finger. The index finger has pronounced advantages over other fingers because the index finger seems to be the most accessible finger for the thumb due to the hand anatomy. This is not only a perception, the result from Kuo et al. [2009] also supports the prominent position of the index finger. The paper studied the functional workspace for precision manipulation between thumb and fingers via numerical methods based on the maximal workspaces obtained of the thumb-tip and fingertip motions. The ratios of the functional workspace with respect to the maximal workspace of the index, middle, ring, and little fingers were 33.7 %, 27.1 %, 23.5 %, and 19.1 %. From these numbers, if we need to pick one of the fingers for the thumb interaction, the index is apparently the winner.

Besides exploring the possible gestures between the thumb and the index finger in the first part of this study, it is also critical to approach the concept from a practical view. Being able to use only one hand for controlling the input is one of the main motivations for this study. Karlson et al. [2006] suggested the tendency for using the mobile device with one hand. Therefore, the concept of one-hand thumb-to-index input has huge potential to match the user desire of a convenient and intuitive input interface. Besides, this study also takes into consideration of minority group. Disabled people are often forgotten when building a commercial product for the majority. A case study in this research, which focuses on people with one hand availability, is going to investigate the navigation of smartwatch with one hand. From the case study of smartwatch, the performance with one-hand in general take longer time to complete the task than using both hand to do. However, it prove the possible practical applications of the interaction. The result from the study also suggests some insights for designing and developing an interface for daily usages of controlling ubiquitous system and multitasking.

Chapter 2

Related Work

2.1 Thumb-to-finger Interaction

Thumb-to-finger interactions are ideal for one-handed eyes-free input, mentioned in Huang et al. [2016], due to the capability of the hand's motor. Some studies have tried to investigate and structure these interactions into a comprehensive guideline. This study was developed based on the work of Soliman et al. [2018]. The paper proposed the four-dimensional design space that define an interaction between thumb and other fingers. The four dimensions include touch initiator, touch location, gesture action, finger flexion. Figure 2.1 from Soliman et al. [2018] shows a summary of the whole concept. The figure also visualizes the anatomy terms of the hand that will be used throughout the report. These terms include those indicating the segments of the hand which are distal (toward the tip of the finger), middle and proximal, and those specifying the interaction side of the finger which are ulnar, radial, volar, and dorsal. As mentioned in Soliman et al. [2018], the majority of researches put the focus on the input performed on the radial and volar side, and there are only a few studies that considered other sides.

It is natural that the thumb has the capability to reach other fingers on the hand. By segmenting each finger into three parts, Huang et al. [2016] conducted a study to investigate which position on the volar side of the fingers are more comfortable to reach due to the hand's anatomy. A visualization of the result is shown in Figure 2.2 A below. According to the result of the study, handedness does not have an impact on the rating of the comfort area for touching. Both hands have the most comfortable area in the distal segment of the finger. For the index and the middle finger, the middle segment also has a high comfortable rate. The research also conducted an experiment to explore how precisely users could perform eye-free tapping in the comfort

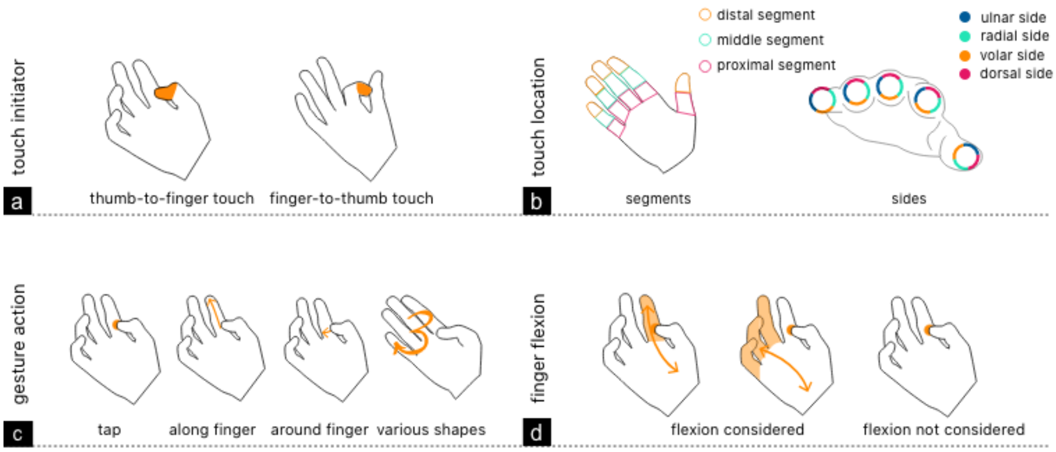


Figure 2.1: *borrowed from Soliman et al. [2018]*: **Four dimensions define thumb to fingers interaction**

region of the operating fingers. Figure 2.2 B shows the result for the index finger. According to the experiment, the accuracy rate reduces significantly if there are more than 5 touch points in the comfort region.

2.2 Prototype Approaches

Garg et al. [2009] mentioned "Data-Gloved based" and "Vision-based" as the two main approaches for making the computer understand the hand's gestures. By leveraging the advancement in sensor technology, data-gloved based approach can easily detect hand movements and gestures. One drawback of this approach is the redundancy of the device that the user has to wear. In contrast, the vision-based approach uses a camera and advanced algorithm to predict the hand's gesture that allows the user to be free from wearing a bulky sensing device. However, there are more technical challenges in a vision-based approach to attain the same level of accuracy as glove-based approach. Besides these two approaches, there is another one that uses magnetic tracking to enable tracking of micro-movement of the thumb such as Chan et al. [2013]. The following part is going to explain these approaches in detail.

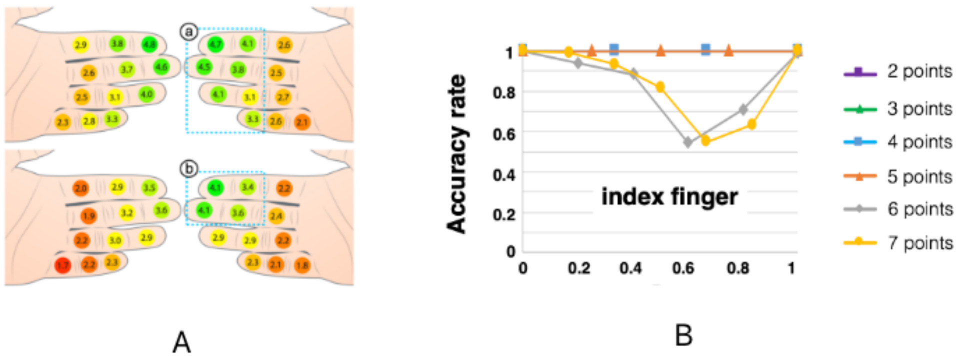


Figure 2.2: *borrowed from Huang et al. [2016]*: **A - voting results for comfort regions; B - accuracy experiment for different number of touch points**

2.2.1 Glove-based approach

With the glove-based approach, the input device can cover the whole hand like a glove or it can be some textiles that the user can wear on one of their fingers. An implementation of a glove often comes with the evaluation of the text input capability of the glove such as in Whitmire et al. [2017] and Mehring et al. [2004].

In Whitmire et al. [2017], each finger is equipped with a partially conductive fabric strip and wire fabric interface while the thumb is assigned a conductive patch. The input signal can sense the resistance of the fabric, and through the calculation of processing the input data, the position, and pressure of the touch input can be estimated. The user need to wear the glove named Digitouch with conductive strips on both hands to perform the text-input task of a virtual QWERTY layout. With this approach, Digitouch has been able to reach the performance of 16.5 words per minute.

It is also common that many implementations only attach the device on the thumb and the index finger; for example, Yoon et al. [2014], Yoon et al. [2015], and Tsukada and Yasumura [2004]. Yoon et al. [2014] introduced Plex, a finger-worn textile sensor that uses conductive elastomers and threads to transform the touch pressure and bending of the finger into the digital input to control digital devices. A similar approach also applies to Yoon et al. [2015]. Researchers can also take advantage of the sensor to build the prototype. Tsukada and Yasumura [2004] has used a bending sensor, an acceleration sensor, and a touch sensor to detect the motion of hand and finger such as a bending degree of an index finger, tilt angles of a wrist, and operations of touch sensor by a thumb. The whole system must include an Ubi-Finger device, Ubi Appliance (attached to the home appliance), Ubi Host, and Ubi Finger. The main application of the device to control the home appliance from a distance by sending an infrared to the device to initiate the connection.

2.2.2 Magnetic approach

To preserve the tactile feedback on the finger, some studies use magnetic tracking as a solution for this problem. The works from Huang et al. [2016] and Chan et al. [2013] apply the same machenism for the prototype. Chan et al. [2013] presents FingerPad, a nail-counted device that enables touchpad functions by using the thumb to manipulate the index finger tip. The proposed technology is realized through magnetic tracking by adding a magnet and Hall sensor grid on the finger. This enables the user to enter the password number in a subtle and private way. Besides addressing the ergonomic factors, Huang et al. [2016] also introduce DigiSpace which is an expanded version FingerPad. A long sensor chain is attached to the dorsal side of the index finger to help user perform sliding and tap while preserve the tactile cues of touching the skin. This approach is innovative, but user still also needs to wear the bulky wire and sensor. The question about the accuracy is still left open, if there is any magnetic field influence the input signal.

There are some other applications of magnetic to create a wearable device that takes form as a ring such as Harrison and Hudson [2009] and Ashbrook et al. [2011]. By changing the magnetic fields, it also changes the input signals. The user wearing the ring can control the selection on the screen by rotating the ring from left to right or moving the device around the sensor. Even though the ring is the device to wear on the finger, this approach does not base on thumb-to-finger interaction and offers a limited set of gestures.

2.2.3 Vision-based approach

The advancement in image processing provides many potential applications in research, for example, real-time replicating people's movement in physical space to a character's movement on the computer Maiocchi and Pernici [1990]. The vision-based approach is widely used in the production of computer animation by capturing live movements and reproducing on the computer. Besides this major application, it also enables recording inputs for the ubiquitous interface. Virtual reality is a potential field for this approach since it allows the computer system to provides emerging experience in 3D space since the user does not need to wear any cumbersome device that limits their movement.

When talking about the vision-based approach for hand gestures, Garg et al. [2009] provides a concrete overview of using a vision-based approach for hand gesture recognition. The work mentions two vision approaches for detecting hand gesture: 3D hand model based approach and appearance based approach. The first approach can offer a wide class of hand gestures but it requires a large image database. The second approach has the advantage of real-time performance due to the 2D comparison of image features and image extracted from the video. In this approach, lighting and environmental factors contribute a lot to the performance of the system.

Many studies using the vision approach investigate a wide range of hand gestures since it is more difficult to recognize micro hand gestures due to visual occlusion. The work from Soliman et al. [2018] has tried to develop a system that can recognize thumb-to-finger interaction by building the classifier for depth image and generate a touch model to estimate the touch position. In order to capture the thumb-to-finger gestures, the user needs to mount a depth camera on their head or on the shoulder. The system has an overall accuracy of 91.06 % for gesture classification.

Chapter 3

Research Concept

3.1 Thumb-to-index Interaction

While the other papers works on a wide range of possible interactions, this research only pays attention to the interaction between the thumb and the index finger. In this study, the thumb plays the role as an initiator for the touch interaction and there is no reverse interaction or no finger-to-thumb input. The work from Soliman et al. [2018] has summarised the design space of thumb-to-finger gestures in detailed. It mentions that the finger segments, which are proximal, middle and distal, defines the touch location. It is natural that people can do eye-free interaction of touching the knuckles and wrinkles on the finger. The study also points out that many other researchers focus on the interaction with radial and the volar side of the finger, which are also the common touch regions. This study also considers this two side of the index finger since the interaction is intuitive and easy to perform.

In Figure 3.1, five touch positions have been added for each side, so it provides a total of ten positions for tapping. The number five is derived from the research of Huang et al. [2016] that proves the accuracy rate reduces significantly if the touchpoint is more than five. If we differentiate between the normal press and the hard press, there are a total of 20 inputs with just tap. Besides, if we consider the double-tap, the total interaction has increased to 30. For sliding interaction, there are only two directions: distal slide (sliding toward the fingertip) or proximal slide (sliding toward the thumb) on the volar side or on the radial side of the finger. From the listing, the total interaction that we can have for thumb-to-index tapping and sliding is 34 possible interactions.

The above listings are just basic interactions between the thumb and the

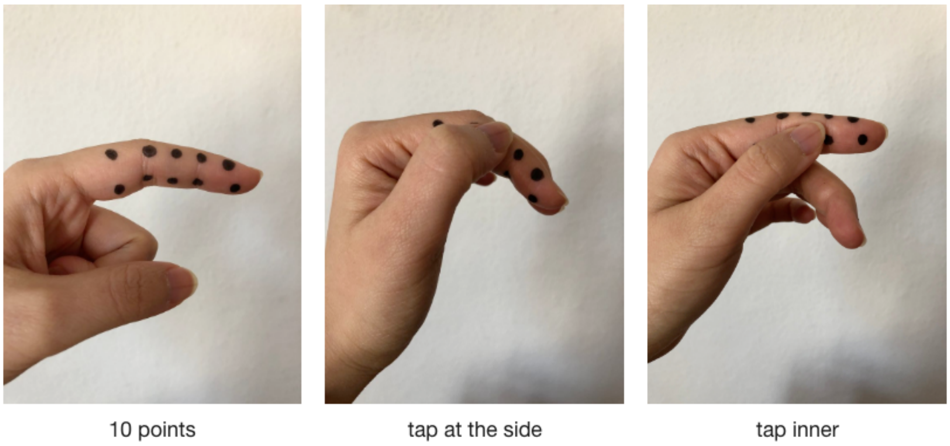


Figure 3.1: Illustration for 5 touch points on the radial and volar sides of the index (2 touch points are at the joints of the finger segment, 3 touch points are at the middle of each segment) **finger and touch interaction between the thumb and the index finger**

index, there are some other interactions that these two fingers can perform. For example, Huang et al. [2016] has enabled a more complicated interaction that is stroke gesture recognition, or Tsukada and Yasumura [2004] can recognize bending or rotating of the index finger. These can be another source of inputs. This exploration has proved that thumb-to-index interaction is capable to create many inputs that can be used in different applications. For this reason, a wearable device can be designed for the index finger to be used as an input option for daily contexts.

3.2 Practical Application

This section investigates the practical application of the single-hand thumb-to-index input interface. Assuming that the input interface satisfies the condition of wearable devices and can recognize many of the interactions listed in the previous section, it may be useful for enabling multitasking and controlling smart-home devices, or to be used as in input device in AR/VR, or even helping disabled people control computer system. These applications will be explained in the following sections.

3.2.1 Multitasking and Controlling Smart Home Device

Thumb-to-index interactions have great potential for supporting multitasking. Taking an example of the iPad, Apple is trying to make the iPad as powerful as the laptop with the new iPadOS14 that enables the iPad to work with a mouse and keyboard. It is popular that people often use their iPad with the keyboard but it seems to redundant to use the iPad with a mouse that supports the left and right-click. The iPad works fine without a mouse or a keyboard, but it will be more powerful to incorporate these input devices, for example, performing shortcut can only be done with a keyboard. However, carrying the iPad around with these accessories will lose the cutting edge of the mobility of the iPad. The wearable thumb-to-index interface can be an alternative option. Let take a specific application of the digital artist that uses an iPad to draw. On the laptop, they can set their shortcut to bring up the function at any time, but on the iPad, they need to locate the position of that function and tap on it. The device can help the artist solve this problem by allowing them to set the shortcut for the tap position. The artist can use their dominant hand to draw and wear the device on the other hand, so when they want to access the feature while drawing, the other hand can simultaneously trigger the function by eye-free tapping without interrupting the main task. The secondary input from finger gesture can help to speed up the workflow of the artist.

With the capability to recognize sliding interaction, one of its prominent applications should dedicate to controlling the music player while traveling. Those who love listening to music while commuting or exercising often invests in a Bluetooth headphone so they are free to leave their phone in the bag or in the pocket. However, they still need to open the bag to take the phone if they want to adjust the volume or change replay the song. In a crowded environment like the train station or on the bus, this exposes the thread of dropping the phone, having a pickpocket, or forgetting the phone. Instead, they can use the thumb-to-index interface for controlling the player. In winter, this could be worst if you wear a winter glove. It often happens that people take out the glove to use their mobile phones and lose one glove. Thumb-to-index interface can be a solution for using a mobile phone in the mobility context. The device can be worn outside the glove, so the user can easily access the control for the mobile phone. For example, people can read the news on their phones and use the device to scroll up or down the page without taking out the glove. For the above scenarios, this wearable device is an ideal option for mobility input.

Your home devices are getting smarter with the new innovation in technology, the device now has access to the internet and can connect with each other via Bluetooth or Wifi. The smart device can be controlled by an app on the smartphone or it will have a separate remote control. Tsukada and Yasumura [2004] also proposed the finger input interface that sends the infrared signal to the appliance receiver for initiating the connection and then using the finger gesture to control it. The approach seems to be complicated in the context of today in which everything can connect to each other easily with Bluetooth. However, it is a potential solution to use thumb-to-index gestures for controlling smart home appliances such as the light, heater, or speaker. This interface can be an option to replace the remote control which is often lost somewhere. With the wearable interface attached to the index finger, people can access control at any time with the minimum effort.

3.2.2 Input for AR/VR

As mentioned in the research Whitmire et al. [2017], there is an unmet need for input methods that are expressive, subtle, and portable that can enable broader use of head-mounted computing devices. For this reason, Whitmire et al. [2017] used a glove-based approach to build Digitouch for text input in VR. However, the vision-based approach is more advanced in creating emerging experience in the virtual world. With the progress in vision technology, future HMD will be equipped with a powerful camera to detect hand gestures and provides input for the system, but it is more difficult to detect micro hand gestures. The hand gestures are intuitive to manipulate concrete concepts such as drag and drop, but it is hard to conceive the abstract concepts that people have been familiar with using the two-dimension laptop such as right-click or double click the mouse. The thumb-to-index interface can play the role of a mouse in virtual space, for example, tap, double-tap, or hard press will enable more input options for VR/AR applications.

3.2.3 Input for disabled people

Supporting people with one-hand availability is the primary motivation for the single-hand thumb-to-index interface. This group of people faces many difficulties in daily life interaction, and it is even more challenging for interaction with the computer system. With this concern, the interface concept is trying to address the practical aspect of the interaction in daily context. The first case study is about the usage of the smartwatch. According to the recent development of wearable devices, a smartwatch today has many powerful features besides checking the time. For example, people can make a call, make the payment, check messages, or tracking the health data, etc. Payment with the smartwatch is easy, they just need to move their wrist wearing the watch near to the payment reader and everything is done. Imaging one person with one-hand disabled going for groceries, he has to carry many things with his hand when checking out, the cashier tells him the money, he has to put all the stuff down to find his wallet, tries to open, and takes the money out with just one hand. The whole process would be much faster for normal people than for the disabled one. With the watch wearing on his wrist, he can pay the money as fast as others. However, the remaining problem is that smartwatch also requires two hands to control and navigate since it receives input via touchscreen and the physical button. For this reason, the thumb-to-index interaction interface poses huge potential in supporting disabled people to access innovative technology that sometimes is exclusive for the majority.

Another group of disabled people that may find the interface helpful is the visual impairment group. This group depends a lot on haptic and audio feedback to perceive the surrounding environment. The finger gesture interface can play as an assistive device to help them easily control the smart device in their house. The interface should work together with audio feedback, for example, a Bluetooth earphone or a speaker. With this setup, blind people can use the digital system on the way, for example, when someone calls to their phone, they can tap on the device wearing on the finger to pick up the phone and listen via the Bluetooth earphone. There are some potential applications of the tactile input interface for shortsighted people that require more research. However, the interface for this group must prioritize tactile feedbacks since it is an important factor deciding the success of the interaction.

3.3 Prototype

3.3.1 Prototype Experiment

The first approach for building a prototype is using electronic textiles. A piece of Velostat fabric was chosen because it is able to detect touch pressure by changing its resistance. This behaviour can be applied to detect both tapping and sliding interaction. For tapping, I cut the fabric to the size of one part of the finger and measure the change in resistance when pressing. Unfortunately, there is a huge delay between the stimulus and the response. When pressing, the resistance does not change immediately, and when releasing, it also takes some time to recover to previous state. Sometimes, the material was unable to go back to the previous state. For these reasons, this approach did not work for building a working prototype.

The original idea is to separate tapping and sliding: tap buttons at the volar side and sliding at the radial side of the index finger. Therefore, a touch sensor was considered for recognising tapping input. The sensors are as small as the finger. It is very sensitive, so it often gives the wrong input, for example, the thumb has not touched the sensor surface, but the sensor has already sent a signal to the system. Even though it is quite small, it requires many wiring that makes the prototype redundant.

Besides, Huang et al. [2016]'s technique of using the hall sensor to detect thumb-to-index interaction was implemented to detect sliding. The approach adopted a magnetic tracking method, a magnetic was attached on the thumb and a hall sensor on the index finger. After experimenting and processing the input from the hall sensors, I was able to perform the sliding, but it was not stable at all. Every time restarting the system, the threshold changed and the magnitude was not consistent for each test. It was unable to figure out the problem or the method to improve its performance, therefore, I ended up finding another sensor that enables accurate touch detection.

3.3.2 Force-sensing linear potentiometers

A potentiometer is a three-terminal resistor that has two terminals connect to both end of the resistor and the third terminal connects to a sliding contact controlling the output resistance. This mechanism enables the output resistance and voltage to be adjustable. A force-sensing linear potentiometer (FSLP) can change its resistance and output voltage based on the magnitude and location of the force applied on the strip. For these properties, an FSLP strip can read the user's touch pressure as well as the touch position on the strip.

In this project, an FSLP 1.4"x 0.4" strip was chosen for the purpose of implementing the interaction and evaluating the concept in a practical scenario. A photo and setup instruction for the device are described in Figure 3.2. More technical details can be found on the product website.

The device provides input for the pressure and the position value, so it still needs to process and map these data for a specific interaction, for example, tapping left or tapping right. At first, I would like to set 5 buttons for the device in which 2 big arrows are two buttons, then the middle point of the strip

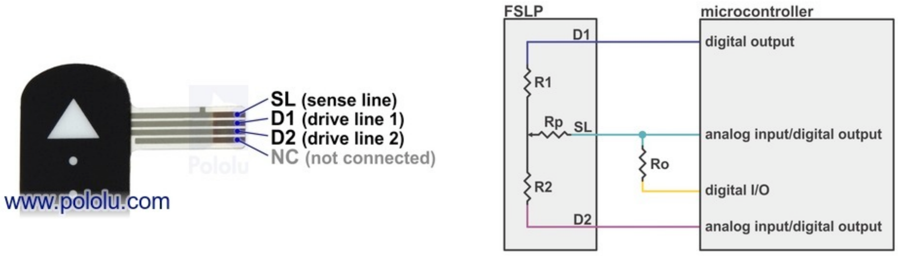


Figure 3.2: Technical details of Force-sensing linear potentiometer, *borrowed from pololu.com website*

is the third button, the fourth and fifth are the positions that are between the middle point and the arrow button. To know what should be the threshold value, I conducted an experiment with the physical device that I have to know how many touch area the device can detect accurately. For each target area on the device, 100 touches are recorded and plotted in Figure 3.3. For different positions, the sensor provides different results: higher value on the left and decrease toward the right. From the experiment result, the middle position may cause a higher error rate for making the decision of the interaction. For this reason, I decided to have only four separated touching areas.

Besides, I also conducted another experiment for investigating the pressure for each tap by performing hard-press for 150 times and normal press for 150 times. The result is displayed in Figure 3.4. The first box-plot represents the hard-press result and the second box-plot shows normal pressing values. From Figure 3.4, hard press interaction creates a larger range of input values. Pressing interaction often has the start and the end in which the finger starts to put pressure on the surface and then release the finger from the surface, the pressure will gradually increase, reach the peak, and then reduce. Since the device record the data in a discrete manner, the value recorded include all phase of the pressing. From this analysis, the hard press is not accurate in this situation, therefore, only normal tap and sliding are implemented for the user study. The result of this experiment is used to improve the accuracy of the sliding interaction.

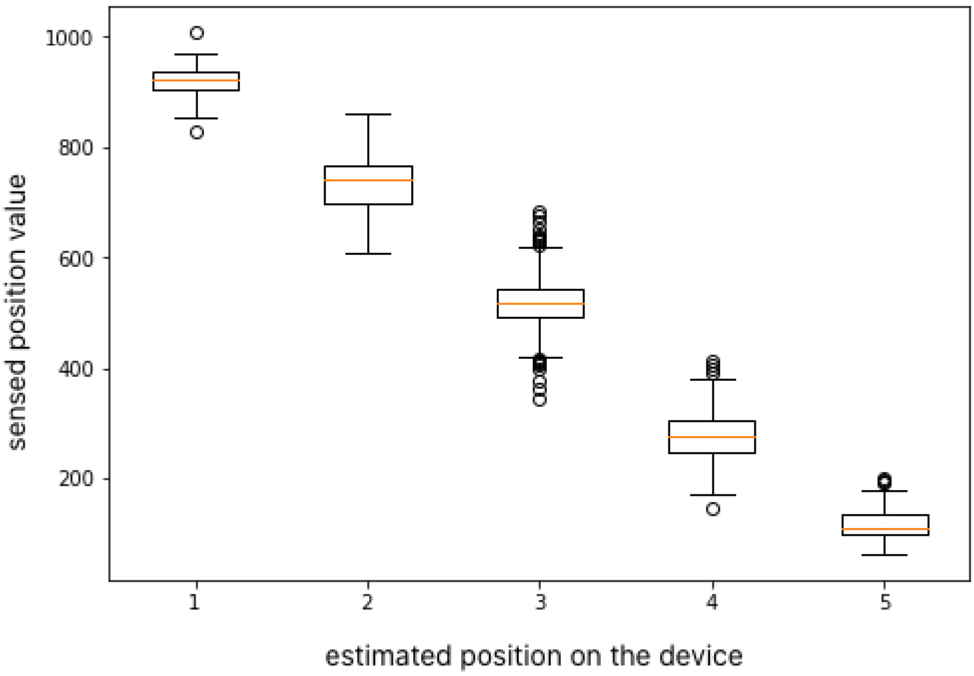


Figure 3.3: Position value sensed by the potentiometer when tapping at 5 designed touch areas on the device surface

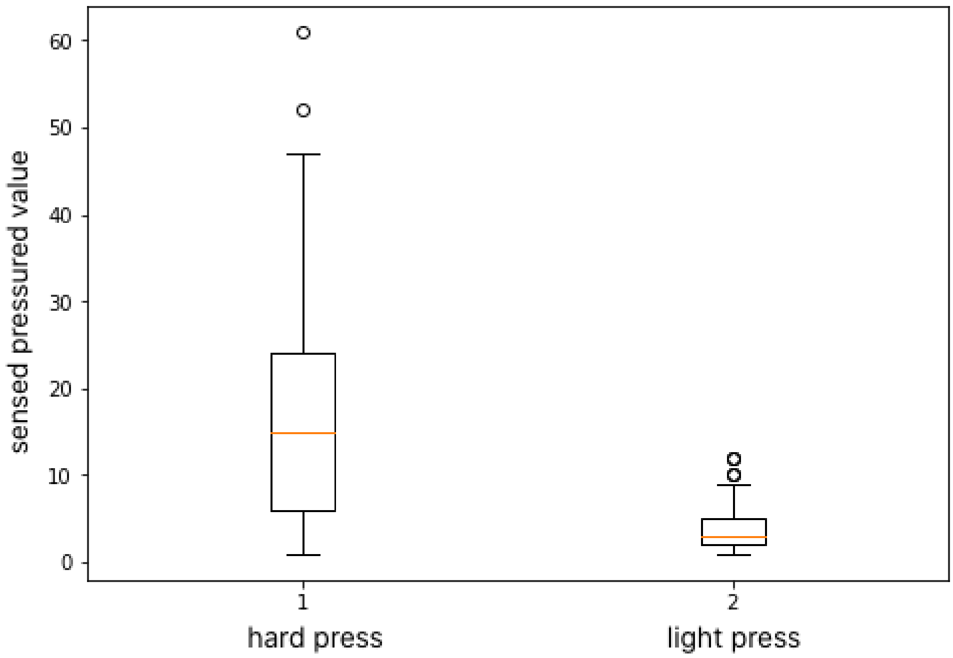


Figure 3.4: Pressured value sensed by the potentiometer when trying hard press and light press

Chapter 4

Application Implementation

4.1 Context of use

To evaluate the concept in practice, I came up with a use case and conducted a usability study. A smartwatch seems to be a practical device that can work with the prototype. By observation, people who use a smartwatch need both hands to control the watch, one hand to wear the watch, and the other hand to perform the interaction. In this case, thumb-to-index interaction can be a solution for private single hand input for the smartwatch. The user can wear the input device on the same hand wearing the watch, so they have the other hand free for other tasks. Besides, this is also an input option enabling the disabled user to use a smartwatch. In the upcoming evaluation, it will focus on this context of use and also try to compare this type of input to the normal touch input on the screen.

After consideration, I decided to use Apple smartwatch for this project due to its popularity as well as its familiarity since I am an iOS user. Firstly, it is necessary to develop a solution for connecting the sensor device to the smartwatch so it can read the input data from the device. Then, it also requires to build a separate application within the smartwatch since the Apple watch does not support outsider input. To compare the interaction between our device and smartwatch, an application is built to mimic the watch's basic interface and interaction.

4.2 Technical Implementation

4.2.1 Arduino Bluetooth Module

There are two options for wireless communication which are Wifi and Bluetooth. After researching the difference between the two technology, Bluetooth is chosen for this project as it is fast and affordable, and Bluetooth Low Energy (BLE) technology is also supported by Apple's device.

Bluetooth Low Energy is commonly used by recent electronic devices due to its optimization for low-energy consumption. The traditional form of Bluetooth or "Bluetooth Classic" does not work with the some recent mobile devices, especially Apple devices, therefore, I had to carefully choose the correct hardware for implementation.

I ended up using the HM-10 BLE module for transmitting the sensing signal from the potentiometer to other devices. The implemented schematic is shown in Figure 4.1.

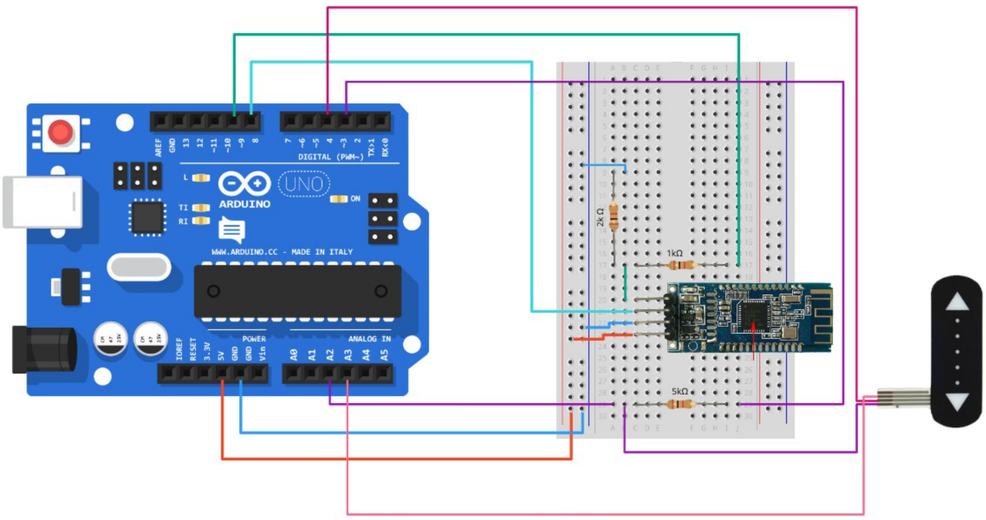


Figure 4.1: Arduino with BLE & FSLP Schematic

4.2.2 System Setup

The application system includes input device, which is able to recognise thumb-to-index interactions, an iPhone, and an Apple smartwatch. The input device has the setup as in Figure 4.1 which comprise a force sensing linear potentiometer (FSLP), Hm-10 BLE module and Arduino board.

Input signal from the sensor device is sent to the iPhone via Bluetooth Low Energy. On the transmitter side, Arduino provides a *library* to support sending the data to central device which is the iPhone in this case. On the receiver side, the iPhone can receive signal from other peripheral device with the help of *Corebluetooth*.

Communication between the smartwatch and the input device has to go through the iPhone since it is convenient to implement two-way communication between an iOS app and its paired watchOS app using *WatchConnectivity*. For this reason, an iPhone app and a watch app were developed so these two apps can pair with each other to receive and transfer the data. The iPhone app receives the signal from the input device and sends it to the watch. With the help of the iPhone app, input data from Arduino as well as touch interaction on the watch will be captured and stored inside the smartphone as .csv files.

Chapter 5

User Study

5.1 Study Overview

5.1.1 Participants

A total of ten participants, five males and five females, were recruited with convenience for the experiment. All the participants are students aged 20 to 35. They are all right-handed and are not a smartwatch user. The participants were asked to select their preferred time via the Doodle link. The time slots for the experiment were allocated from 4 pm to 9 pm to avoid the summer heat. The whole session took about 40 minutes to almost an hour.

The experiment was conducted with the lab setup. During the pandemic period, two large windows of the room were opened for good air ventilation in the 22 sqm room.

5.1.2 Procedures

The study includes two parts. The first part is Interaction Training which aims to give the participants time to familiarise themselves with the device and the interaction that they are going to perform in the main experiment. For the training session, the participants only need to wear the device on the index finger and perform the interaction as instructed. A detailed explanation of this part will be elaborated in section 5.2.1 Interaction Training.

The second part is the Main Experiment which requires the participants to perform the selection tasks with the smartwatch under three different conditions. The participants are requested to wear the smartwatch on their left hand. In the first condition, they uses the thumb-to-index interaction to per-

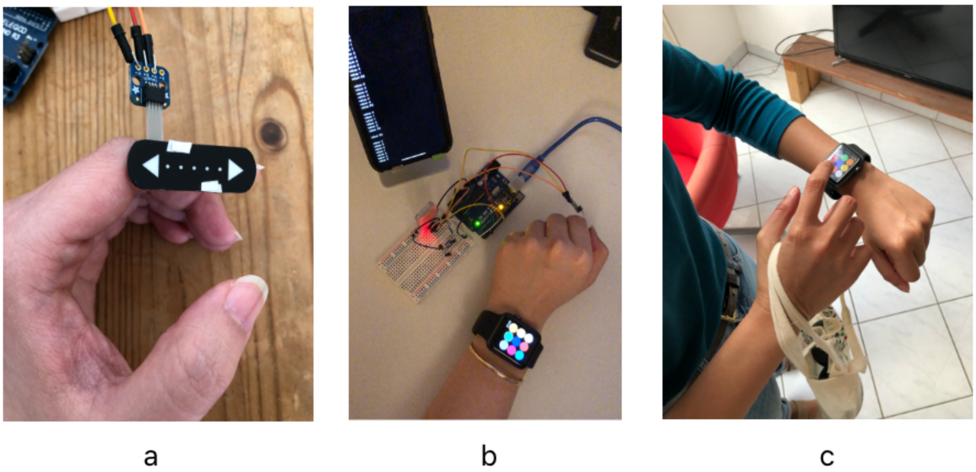


Figure 5.1: a) Input device with 2 tape marks indicating up and down area - b) smartwatch setup with mobile, Arduino and input device - c) Carrying the bag constraint while performing selection task with two hands

form single hand selection with the smartwatch. In the second condition, they performs the selection task with both hands and constraint, it means the participants carrying a bag on their right hand and also using the right-hand finger to tap on the touchscreen of the watch. The third condition is performing the task with both hands and without any constraint. Section 5.2.3 will describe the experiment in detail.

A pilot test for the main experiment suggested to have some tactile feedback for the touch positions in the middle. Figure 5.1-a shows the device with two tape marks to indicate tapping regions in between.

A full document prepared for the study can be found in Appendix A. The procedures of the whole study includes the following steps:

1. Read safety instruction for Covid-19
2. Briefing about the thesis
3. Sign consent form
4. **Part 1: Interaction Training**
5. **Part 2: Main Experiment** - Selection Task with three different conditions (1) *thumb-to-index single-hand input* (2) *two hands with constraint* Figure 5.1-c (3) *two hands without constraint.* The order for three condition is randomised.

6. Fill in the survey

5.1.3 Apparatus

The hardwares are chosen to build the input prototype includes: Elegoo Basic Starter Kit with R3 Atmega328P Microcontroller Board; DSD Tech HM 10 Bluetooth 4.0 BLE iBeacon UART Module with 4 Pin Base Board; Pololu Force-Sensing Linear Potentiometer: 1.4"x0.4" Strip. For accuracy test, the prototype is connected to my Macbook and is programmed by Arduino ver 1.8.13. When the device sends input signal, Arduino's terminal will print out feedback on the screen.

In the task performance experiment, I use the Apple watch and the iPhone together with the Arduino prototype. The app on iPhone and Watch is developed with Xcode using Swift. These devices connect to each other via Bluetooth. Besides, I also prepare a 3kg bag for the participant to carry while perform the two-hand experiment with constraint, and a double-sided tape to stick the device on the participant's finger.

5.2 Experiment design

5.2.1 Interaction Training

In this part, the participants have an opportunity to learn about the interaction and get the impression of the interface's behavior. Based on the experience, they can adjust the expectation to minimize the error in the upcoming main experiment in which they need to perform the selection task. One example behavior of the interface worth noticing is that it may take a while for the system to receive and display feedback of the user's interaction. The delay is less than half a second, but it is enough to be noticeable, especially when the user performs sliding interaction. For this, the participants need to perform their interaction with caution to ensure that the system has received the input.

The participants are required to perform six basic different interactions. Four of them are tapping on four different areas on the device, and the other two are distal sliding (sliding toward the tip of the finger) and proximal sliding (sliding toward the thumb). For each interaction, the participants have to repeat it until the system has recorded 15 correct inputs. Fault recognition will be counted as an error, so the total number of interactions will be 15 correct

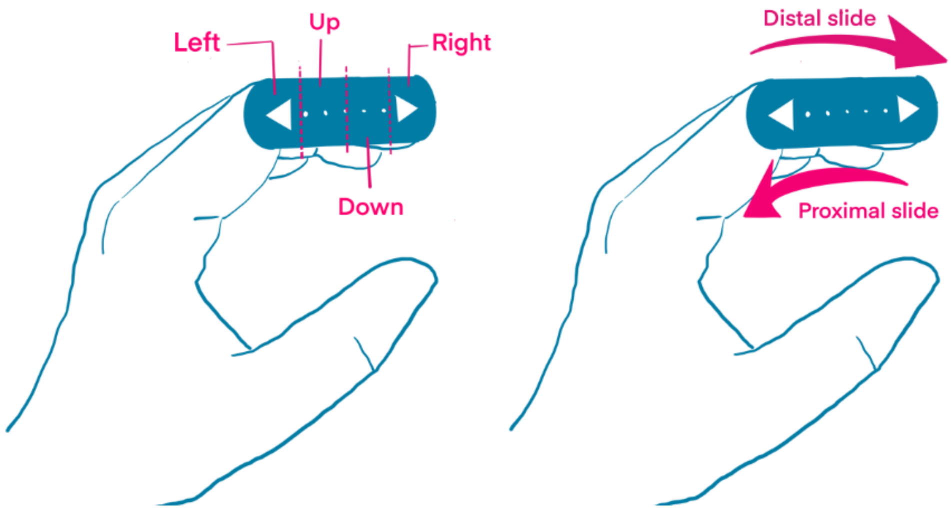


Figure 5.2: Training Interactions: Four tapping regions (left, up, down, right) **and two directional slides**

inputs plus the error inputs (if any).

Figure 5.2 demonstrates the six interactions that the participants have to perform. As they will use left hand in the main experiment, the training session also focus on the thumb-to-index interaction on the left hand. Therefore, naming the touch position, left and right, is based on the direction of the left hand, and up and down, is based on the interaction in the main experiment.

The participants are requested to correctly perform the interaction 15 times. This requirement can be clarified by taking an example. The task is to tap on the first position of the device, which is also represented by Left or Back, 15 times. The screen provides feedback with counting numbers every time it receives the input of the first position. If the participants tap on the other areas, it will show an error. The participants can stop when the counting number reaches the value of 15. There are some cases that the participant has tapped 15 times, but due to the system delay, the feedback only shows 14 times, and sometimes, the participant taps on the other area without noticing.

5.2.2 Main Experiment: Interface design

Since the Apple devices do not allow other devices to control the main menu of the system, a simple app was built for the purpose of the user study. The app mimics the menu and the basic interface of the watch apps. The watch interface typically has three main layouts: grid view, list view, and text display view. Therefore, the implemented interface also includes three main screens as shown in Figure 5.3. The first screen with a grid layout that represents the main menu, the second screen with a list layout that represents different options, and the third screen with content.

The participants have to perform the requested task: selecting the items on the first screen to open the second screen, then selecting the items on the second screen to go to the third screen. After that, the participants need to go back to the first screen. While they perform the task, the system captures their interaction as well as the completed time.

Figure 5.3: Interface design for the app - Screen 01: display circle items in grid view, select the circle to open screen 02 - **Screen 02**: display row item in list view, select the item to open screen 03 - **Screen 03**: display the text content

5.2.3 Main Experiment: Selection Task

In the main experiment, the participants wear the watch on their left hand and perform the selection task as instructed. The selection task is selecting items on the first screen (Screen 01) to open the second screen and selecting items on the second screen (Screen 02) to open the third screen and going back to the first screen to start the selection process again. The instruction can be summarised as follow:

- Navigate and select the circle item on Screen 01 to go to Screen 02
- Navigate and select the item on Screen 02 to go to Screen 03

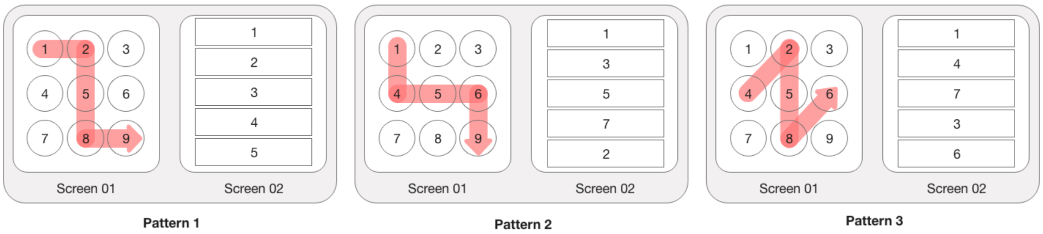


Figure 5.4: Selection patterns for Screen 01 and 02

Table 5.1: Interpretation of selecting pattern 2

	Screen 1	Screen 02	Screen 03	Screen 02
1	select circle at position 1	select item 1	Back	Back
2	select circle at position 4	select item 3	Back	Back
3	select circle at position 5	select item 5	Back	Back
4	select circle at position 6	select item 7	Back	Back
5	select circle at position 9	select item 2	Back	Back

- From Screen 03, back to Screen 02
- From Screen 02, back to Screen 01

The participants need to repeat these steps 5 times to complete one session. What to select on Screen 01 and Screen 02 are defined by the pattern described in Figure 5.4. Then, they will need to repeat the task for two more sessions, each has a different selecting pattern.

How to interpret the selection patterns: For one session, the participant needs to repeat the selection item on screen 01 and screen 02 five times. For this, one pattern in Figure 5.4 will include two screens (Screen 01 and Screen 02), each screen has 5 items noted. Taking pattern two as an example, the interpretation for the figure is described in Table 5.1, noting that the participant needs to navigate to that item before selecting.

The purpose of having three defined patterns instead of randomizing is to reduce the cognition load for the user as they need to spend effort on locating the item to select. It is easy to memorize the pattern on the first screen with the red highlighted path. One the second screen, the order of selecting items is increased by 1, 2, and 3 respectively to patterns 1, 2, and 3. By controlling the selection order, it is also easier to compare between different interaction conditions: one-handed vs two-handed vs two-handed with constraint. Besides, having three different patterns can also suggest if the pattern has a significant impact on the performance.

5.2.4 Main Experiment: Thumb-to-index interaction

There are three different conditions for the selection task: single hand, two hands with constraint and two hands without constraints. In the condition of single hand, the participants need to use the thumb-to-index interface to perform the task. This section will describe the interaction that the user can perform to complete the task while using thumb-to-index interaction.

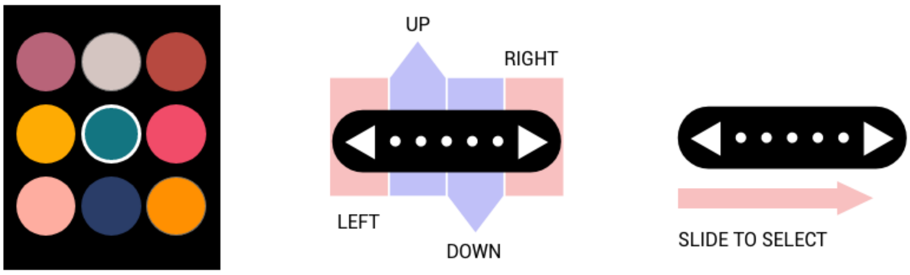


Figure 5.5: Screen 01: tap on different area of the device to navigate to the desired item and use distal slide for selection

Screen 01: The first screen (Figure 5.5) shows a 3x3 grid of 9 colorful circles. The user can tap *Left* - *Right* - *Up* - *Down* on the device to navigate to the desired circle, use *Distal Slide* - slide toward the finger tip to select the circle, and the app will bring up the second screen.

Screen 02: On the second screen (Figure 5.6), the interface shows a list view of 7 items. The user can tap *Up, Down,* or using *Slide* interaction to navigate to the item row. The length and direction of the slide will determine the number of rows that the pointer will go up or down. For example, if the user slides from this side of the device to the other end, the pointer will jump down or up 3 rows depending on the sliding direction. On this screen, the user can press *Left (Back)* to go back to the Screen 01, and press *Right (Enter)* to go to the Screen 03.

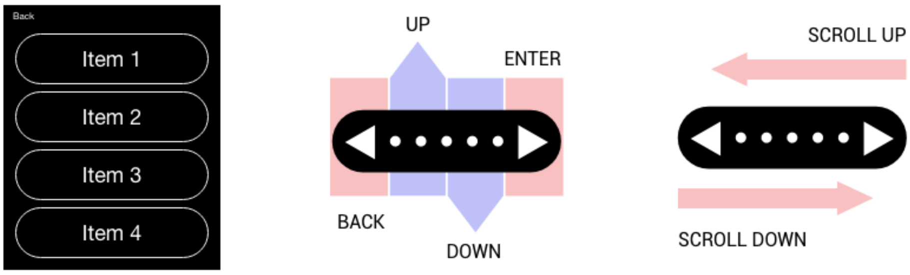


Figure 5.6: Screen 02: tap *up, down* to navigate to the desired item or *slide* to navigate multiple rows at once, tap *Enter* to go to Screen 03 or tap **Back** to go back to previous screen

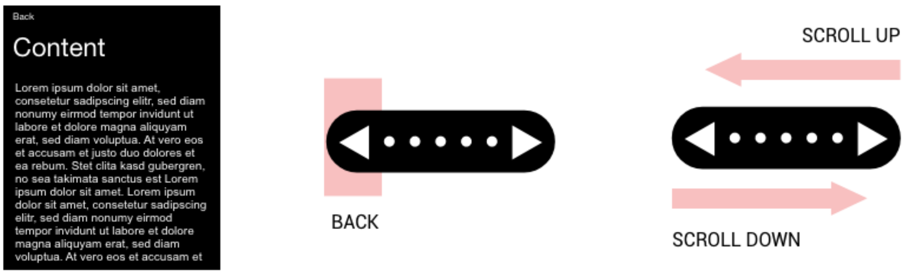


Figure 5.7: Screen 03: display text - tap Back to go to previous screen

Screen 03: The third screen (Figure 5.7) just simply display some text content, the user can *Slide* to scroll down the view, and press *Left (Back)* to go back to the second screen.

5.3 Study Findings

This section includes the findings from three parts: the interaction training, the main experiment, and the survey after all experiments.

5.3.1 Interaction Training

Table 5.2 shows the average completion time for each interaction and total errors that all of the participants made during the training session. Since the participant wears the device on their left hand, the position of Left, Up, Down, Right will be placed in order toward the index's fingertip as in Figure 5.2. Comparing the four tapping interactions: Left, Right, Up, and Down, tapping at the Right position has the shortest completion time and the lowest number of errors. Tapping Left has the second-lowest error but has a longer completion time comparing to Right, Up, and Down. Both tapping Left and Right provides low error because the tapping positions are at two sides of the device, which are easy to locate without looking at it because the participant have to pay attention to the feedback on the laptop' screen. Also, between Left and Right position, the Right position which is near the fingertip position is more comfortable to reach based on the research of Huang et al. [2016] that explains why it has the best performance result. Tapping at the Left position has a longer completion time comparing to others because of two reasons. The main reason is the participant perform this interaction first, so due to the learning effect, they perform the interaction better in later task. The second reason is mentioned above, the Left position is not so comfortable for tapping.

Table 5.2: Performance result of interaction training

	Completion time in second(s)	SD	Total Errors
Left	10.9	5.4	7
Right	8.3	3.2	0
Up	9.5	4.8	19
Down	10.4	5.5	19
Distal slide	22.3	6.6	20
Proximal slide	18.3	3.3	1

For tapping at the Up and Down position, both interactions have a similar error value that are higher than the other tapping interactions. This is due to the difficulty of locating the tapping position since they are in the middle of the device and there is no tactile boundary to notify the participant if they are in the correct position. It is also noted an outlier for this session. One participant had made 9 errors (out of 19) for tapping at the Up position and 12 errors (out of 19) for tapping at the Down position.

Sliding interaction is the most challenging interaction because the user should not leave their hand out of the sensing surface and the interaction should be slow enough to be recognized by the system. Sometimes, when the user lifts their finger at the end of the sliding, the system can interpret as sliding and tapping. For this problem, some delay is added to avoid adding extra tapping input. However, it slowers the response time of the system. Besides, the prototype is a low-value device, its performance can not compare with other commercial devices that can detect accurately and respond quickly. However, the participant expect the device to perform as similar to those commercial devices that they use daily. Therefore, during the training session, some tried to slide quickly at the beginning, and the system missed out on these interactions or interpreted them as errors. The participant need to figure out by themselves how to perform sliding so that the system can recognize the interaction. To my surprise, proximal sliding, which starts from the fingertip and moves toward the thumb, is more comfortable and accurate, according to the participant's feedback, as well as the experiment result. This suggests that the proximal sliding on the index finger is more exceptional than the distal slide. This finding can be a good guidance for the future design of micro hand interaction in applications.

5.3.2 Main Experiment Result

Table 5.3 shows the average completion time of the participants for three conditions. As expected, one-handed interaction using the thumb-to-index interface takes the longest time which is 94.2 seconds. Two-handed with constraint and without constraint has equivalent completion time which are 31.1 and 29.7 seconds respectively. Carrying the weight slows down the completion time a few seconds, but it does not have a significant impact on the task performance. Overall, task performance with just one hand takes three times longer than doing the task with both hands.

Table 5.3: Result of task performance

Average completion time in second(s)		
	Completion time(s)	SD
One-handed	94.2	18
Two-handed with constraints	31.1	5.5
Two-handed	29.7	4.2

I applied a one-way repeated measures ANOVA (Greenhouse-Geisser corrected) and observed considerable differences in task completion times between the three types of interaction (one-handed, two-handed, two-handed with constraints) (F(1.112, 10.0)= 139.1, $p < .001$, $\eta 2$: 0.9). Post hoc testing was carried out using the Bonferroni technique and revealed significant differences between the one-handed condition (M: 94.2 seconds, SD: 18.0) and both two-handed forms of interaction (with constraints: M: 31.1 seconds, SD: 5.5; without constraints: M: 29.7 seconds, SD: 4.2) ($p < .001$). Completion times between the two-handed conditions did not differ.

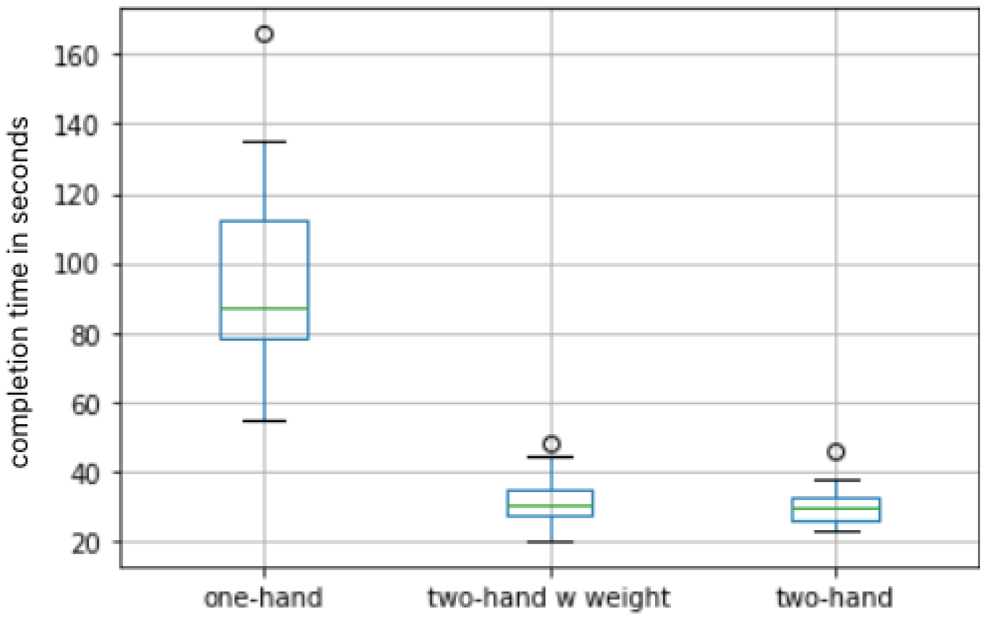


Figure 5.8: Box-plot charts demonstrate completion time between three conditions

Figure 5.8 shows the distribution of performance data for three different conditions. Each box-plot represents 30 recorded data across patterns. From the chart, there are outliers for all three conditions. Since the volume of the data set is not sufficient, it is uncertain that this behavior will apply for a larger set of data. From my prediction, outliers can happen for one-handed interaction but will be diminished for the two-handed condition if we do the experiment with a larger population. The main reason that supports this prediction comes from the current shape of the box-plot. The performance of participants in the two-handed condition are more consistent than in the one-handed condition. And if we comparing between two-handed and two-handed with constraint, it is noticeable from the figure that interaction with two hands available is even more reliable and steady.

Table 5.4: The number of interactions to complete selection task

No. of interaction inputs for each selection pattern					
	Pttn 1	Pttn 2	Pttn 3	Avg Inputs	SD
One-handed	49.8	59.8	56	55.2	12.5
Two-handed with constraint	23.7	24.3	25.8	24.6	1.2
Two-handed	23.7	25.4	25.9	25	1.0

Table 5.4 has summarised the number of interaction input for each pattern across three conditions. In one-handed condition, the minimum interaction one need to complete the selection task for pattern 01, pattern 02, and pattern 03 are 34, 37, and 47 respectively. The patterns were intentionally designed with increasing difficulty in terms of interactions and cognition load, so in theory, the number of interactions and completion time in pattern 03 should larger than pattern 02, and the recorded value in pattern 02 should larger than pattern 01 in one-handed condition. However, the value from Table 5.4 shows that pattern 01 has the least number of interaction. Total average input in one-handed condition is 55.2 interactions which is 1.4 times the average minimum value of input interaction.

Taking a closer look at the two-handed condition tasks, the number of interaction inputs for each pattern changes as predicted, inputs in the pattern 01 is less than pattern 02 ($23.7 < 24.3$ (with constraints), $23.7 < 25.4$), and pattern 02 is less than pattern 03 ($24.3 < 25.8$ (with constraints), $25.4 < 25.9$). This behavior does not apply for one-handed interaction with the thumb-to-index interface. The minimum interaction requires to complete the task in two-handed condition is 22. For this, in two-handed condition, the average input from the experiment (24.5 and 25 interactions) is almost identical (1.1 times) with the minimum interaction.

In one-handed condition, pattern 02 has the highest number of inputs but not pattern 03. There is some potential explanation for this. The first reason is the random fault interaction that the participant made during the task, for example, when the participant slide to select (1st screen) or scroll down (2nd screen), the system recorded as tapping left which led to wrong behavior and the participant had to go back to the previous state which also added more interactions. The second reason may come from the possible interaction options on the second screen. For example, if the participant had to select an item that needs to navigate down such as item 7, instead of tapping down 7 times, the participant can slide right to jump 3 rows at a time so they were able to reach item 7 with just two interactions. The option for navigation can influence the number of interactions recorded.

5.3.3 Survey Result

The survey can be found in Appendix A. The first question asks how they rate the accuracy of the interface. In the scale from 1 to 5, the participants rate the accuracy of tapping and sliding interaction **4.1** over 5 and **2.9** over 5 respectively with 5 means very accurate. All participants expect the accuracy level as similar to other commercial devices, regardless this is a prototype. Improving accuracy can improve the user experience as well as their performance.

In the main experiment with selection task, the participants are asked to rate the cognition load for three selection patterns Figure 5.4 on how difficult it is for them to locate what to navigate and select on the screen. With 5 is the highest cognition load, the result is **1.2** over 5, **2.3** over 5, and **2.4** over 5 respectively for pattern 01, 02, and 03. The rating is equivalent to their actual performance result.

With 5 is the highest difficulty level, the participants also need to rate how difficult it is for each interaction condition. The average ratings are **3.5** over 5, **2.8** over 5, and **1.4** over 5 for one-handed, two-handed with constraint, and two-handed without constraint. Even though the participants vote two-handed with the constraint to be more difficult, the difficulty does not seem to have a lot of impact on their performance.

All participants are asked to rate the practical level of the of the concept. The average result is **3.1** over 5. They also need to answer an open question about which application and situation they find thumb-to-index interface useful. Since this is an open question, the participants are free to list out their ideas, some answer in detail while some just simply write the keywords, for example, multitasking. Their ideas can be similar with other participants or unique. The list below summarises their ideas and is arranged by popularity which means more participants suggested this application.

- used for disabled people or in the scenario that only one hand is available. There are 7 participants suggested this scenario.
- to control the audio system. There are 5 participants suggested this scenario.
- used as an alternative for mouse/keyboard for mobility scenario, for example, on the bus or train. There are 4 participants suggested this scenario.
- For each of these scenarios, there are 3 participants suggested (1) to control TV or other home devices from a distance such as light, speaker, etc. (2) to support multitasking (3) to support driving
- For each of these scenarios, there are 2 participants suggested: (1) presentation control (2) when the touchscreen is broken.
- Only one mentioned about these applications, (1) send dangered message (2) vision disable - feedback from tactile

Most of the application has been covered in the section 3.2. Applications for VR and AR is not recognised by the participants. Sending S.O.S messages is an interesting concept since the interaction is subtle, and easily accessible at any time unlike mobile phone.

Chapter 6

Discussion

6.1 Experiment Results

The length of the device matches the length of the two segments of the index finger: the distal and middle segment. The participants had to perform the eye-free tapping on the four touch-points located on the device surface. From the feedback of the participants during the experiment session, they found it difficult to locate the two positions in between without a clear tactile feedback. Similar to the work from Huang et al. [2016] which suggested 5 buttons layout for the index finger, this study also suggest a maximum of four touch points in the first two segment of the index finger. People may have no problem identifying the fifth touch point if it is located at proximal segment. However, if we only consider the interaction for the first two segments: distal and middle which are also the comfort areas, a maximum of four touch points is recommended to ensure the accuracy of eye-free tapping.

In the beginning, I have the hypothesis that males will perform worse than females since they have bigger hand and fat fingers which may cause difficulty when targeting a small touch area. However, this hypothesis is proven to be invalid based on the performance results of the training session. The result from the main experiment is not considered because it is affected by other factors such as cognition load. In the interaction training part, participants were asked to repeat an interaction as fast and accurately as possible and this process requires minimal cognition load. A summary of their performance split by gender group is shown in Table 6.1. In general, the male group took less time to complete the task, except for the distal slide, this group took significantly more time and also made more errors. In contrast, the female group took longer completion time but has a higher accuracy rate. While performing an interaction, it is often a trade-off between speed and accuracy. For distal

Table 6.1: Performance results for the accuracy test breaking down by gender

	Time in seconds		Total errors	
	female	male	female	male
Left	11.3	10.6	3	4
Right	8.8	7.8	0	0
Up	10.5	8.5	5	14
Down	11.6	9.1	6	13
Distal slide	17.8	26.7	4	16
Proximal slide	18.4	18.2	0	1

slide, female shows a much better performance in terms of speed and accuracy, this is due to the nature of the interaction. Participants must slide slow enough for the system to recognize, however, if it is too slow, the system may interpret as different interactions such as slide and tap, and in this case, the tap will be recorded as an error. So the difference in the two groups simply because of their priority of speed or accuracy, which is not relevant to the hand and finger size. This also suggests that four finger layout for the two segments of the finger applies for both gender which have quite different hand size.

Since the result for task performance with one hand depends heavily on the accuracy of the device, future works can improve the algorithm to process the input data. Besides, one can also improve the gesture design for controlling the watch. In the experiment, distal slide, sliding toward the tip of the finger, was designed for selecting the item on the first screen. However, participants had difficulty performing this interaction as observed in the training session. Therefore, replacing distal slide with proximal slide will improve the performance results of the selection task. One problem that had not been fixed during the experiment is the off-time of the smartwatch. Since the watch is designed to save energy, its screen will auto off after a few seconds. This is not a problem when the participant uses both hands to control the watch, but when they use the device, the watch did not receive any touch interaction and off their screen after a while. The participant had to turn their wrist to on the screen again. This issue also cause annoyance to some participants and impact their performance. By fixing these adversities, one can expect a better performance than the current result. It is important noting that the performance will get better through time and practice.

6.2 Design of the device

The sensor device used in this study is small and lightweight compared to other devices in the glove-based approach. The participants did not have any complaints about the comfortability of the device while performing the experiment. Since the device was attached to the finger by double-tape, the participants were free to adjust the position of the device on their index finger. While the majority put the device more toward the tip of the finger which covers the middle and distal segments, a few put it nearer to the thumb which covers proximal and middle segments. This is not aligned with the comfort zone mentioned in Huang et al. [2016]. The main explanation for this behavior is the size of the index finger. The female participant has a small hand and since the hand's anatomy that makes the finger's diameter reduces toward the tip, putting the device on the proximal segment provides more support for the pressing. Males group who have a thick finger put the device on the middle and distal segment of the index. When it comes to the design for the ideal device, it should consider the thickness support for the pressing, so the user regardless hand' size can wear it on the comfort zone of the finger.

It also recommended by some of the participants to have tactile and haptic feedback for the device. First, even though they can locate the position they should tap without looking at it, it is easier to locate the position at the boundary and it is more challenging to target the position in the middle. When the user touches the area that they should tap, it will be more helpful if there some tactile feedback that they can feel. In the experiment, I added the two marks on the middle area with sticky tape at the edge to notify the pressing area, Figure 5.1 a, this helped the participant a little bit, but there was still a problem. Instead of pressing in the middle of the stripe where the sensor works best, they pressed on the edge where the mark was. I did not stick the mark in the middle because it would affect the sliding interaction. Along with this, some expected to have haptic feedback when they press on the device since this is eye-free, the sense of touch is very crucial. They were expecting a bouncing feedback which was similar to press a button. Even though, the participant successfully controlling the watch without looking at the input device for where to press, adding tactile and haptic feedback can significantly increase their confidence of interacting with the device. A faster and more accurate sensing device with appropriate tactile and haptic feedback, the device will be easily adopted by the public.

Besides, some also suggest to have the device bendable so they can bend their finger a little since when using the current sensor device they had to make it straight for accurate input. This brings up another challenge for technology.

6.3 Technology Challenges

Satisfy the condition of a wearable device is the first challenge of the input interface. The interface will be worn on the index finger which the interaction area is on the radial side. The main criteria for the design include comfortability and accuracy. For comfortability, this means the user can bend their finger and move their finger freely without constraint, and the device will not interfere with other actions of the hand. The interface should be simple, compact that the user can wear daily like a watch or neckless. The user should be able to feel the touch interface with tactile marks indicating different tapping areas which helps increase accuracy when performing eye-free interaction with the device.

Ideally, the interface should have to capability to recognize as many thumb-to-index interactions as possible. These interactions include tapping, pressing, double-tapping, sliding, and finger bending. If the device can sense the direction of the index finger. If the finger is in a horizontal position or vertical position as in the figure, the sliding can map to a vertical scroll or horizontal scroll of the application.

Besides, the interface should have a great mechanism to switch connections between different applications as the concept of the interface is to replace different types of control in the house and also support multitasking for different computer systems. For this, visual or audio feedback should be implemented to inform the user which system the device is connecting to. Visual feedback can be an LED light on the interface or it can be a small display to show the information, and with audio feedback, the interface will tell the user which application has been connected.

The above challenges provide some suggestions for future work. With more advanced implementation, the interface can move away from the prototype phase and can be evaluated in a real-life situation. It can be a new assistive wearable device that enables people to interact with the ubiquitous screen.

Chapter 7

Conclusion

The study provides another investigation of the thumb-to-index interface from a pragmatic point of view. Instead of focusing on the volar side of the fingers like other researches, the interface pays more attention to the radial side of the index finger. In the first part, the study focuses on the concept and possible application of the interface. The second part conduct a user study for the prototype which can recognise tapping at four positions and sliding. The training section proves proximal slide is easier to perform and tapping on two sides of the device is more accurate. The eye-free single-hand interaction with the smartwatch is one of the practical applications of the interface. While looking at the screen of the watch on our wrist, interacting with the radial side of the index is easier due to the hand's anatomy. Despite some limitations in analyzing the input data, the participants are able to complete the task on the smartwatch with just one hand using the thumb-to-index interface. On the average, the total time to complete the task with single hand is triple the time to complete the task with both hands. With the improvement in implementing the prototype and more practicing with the interaction, there is a high chance that the performance will be better.

The work has elaborated on many practical applications of the interface that can be implemented with the available technology such as Bluetooth and the internet of things. Besides the prominent application in controlling the audio system, smart home appliances and multitasking, the interface is also an input option for VR/AR implementation. Moreover, it can be a potential assistive technology to help bringing the computer system nearer to the disabled people.

Appendix A

Experiment Procedures & Safety Instruction

A practical approach for thumb-index gesture as input for ubiquitous screen

Bauhaus-Universität Weimar

Date ____ /____ /2020 Time: ___________

Name ____ Gender ○ Male ○ Female ○ NA

Contact method: ____

Age ______________ Handedness ○ Left ○ Right

Experiment Procedures

- ☐ Read safety instruction
- ☐ Sign consent form
- ☐ Part 1: Learn basic gestures
- ☐ Part 2: one-hand interaction
- ☐ Part 3: two-hand interaction without constraint
- ☐ Part 4: two-hand interaction with constraint

The order of part 2, 3, 4 will be randomised.

Randomised order _________________________

A practical approach for thumb-index gesture
as input for ubiquitous screen

Bauhaus-Universität Weimar

Consent Form 2020

Voluntary Nature of the Study/Confidentiality

Participation in this study is entirely voluntary. You may refuse to continue at any point without giving reasons. You may ask the researchers any questions about the research and the study. You may decide not to answer our questions or ask for your data to be withdrawn.

Your names will never be connected to the research results; a pseudonym will be used for identification purposes. Information that would make it possible to identify any participant will not be included in any sort of report, or disclosed outside the project unless explicitly granted – below you can choose whether we for instance may utilise any pictures where you may be recognised.

Consent to Participate

I, ____agree to participate in this project.

I have had the purposes of the study explained to me.
I have been given the opportunity to ask questions about the study and have had these answered satisfactorily.
I have been informed that I may refuse to participate at any point by simply saying so.
I have been assured that my confidentiality will be protected.
I agree that the information that I provide can be used for educational or research purposes, including publication, with my personal data being handled confidentially (privacy).

I ○ do
○ do not agree that still images of myself can be used in presentations and publications, which may appear online

I understand that if I have any concerns or difficulties I can contact:

Yen Dang, yena.dng@gmail.com

Signed ____Date________/2020

A practical approach for thumb-index gesture
as input for ubiquitous screen

Bauhaus-Universität Weimar

Part 1 - Basic Gestures

Task 1: See the image for the design of the interaction.

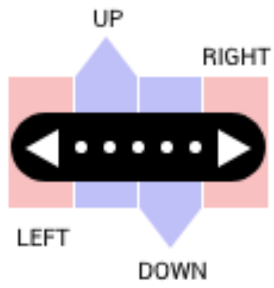
For each interaction, please repeat 15 times.

☐ tap Left 15 times

☐ tap Right 15 times

☐ tap Up 15 times

☐ tap Down 15 times

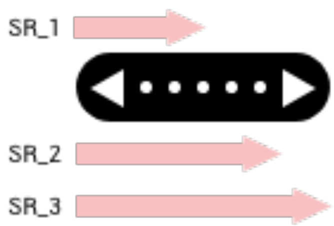


Basic tap

Task 2: Sliding to the right with 3 differences of distance

For each interaction, please repeat 15 times.

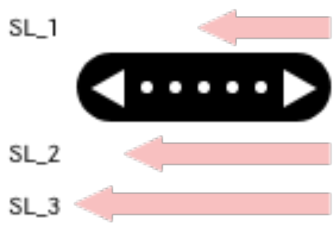
☐ Slide Right - 15 times



Task 3: Sliding to the left with 3 differences of distance

For each interaction, please repeat 15 times.

☐ Slide Left - 15 times

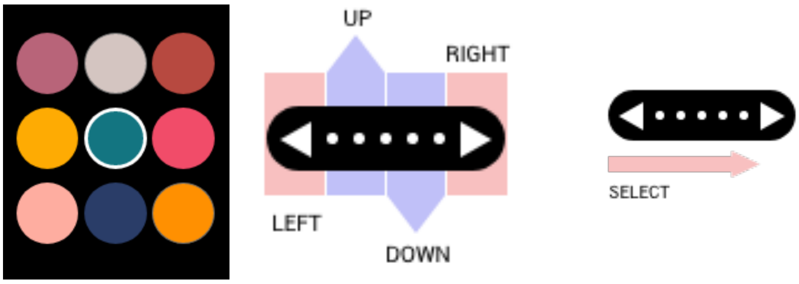


A practical approach for thumb-index gesture as input for ubiquitous screen

Bauhaus-Universität Weimar

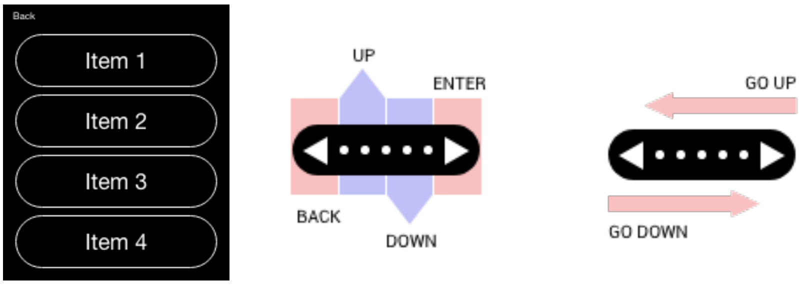
Part 2, 3, 4 - Screen Interaction Design

Screen 1: Tap LEFT - RIGHT - UP - DOWN to navigate the circle that you need to select. Use slide right gesture to select the circle and bring up Screen 2.



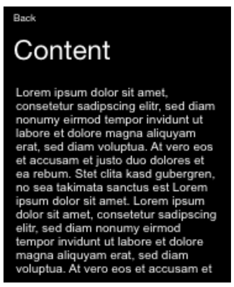
Screen 2: Tap UP - DOWN or using slide to navigate to the row. Slide right_2 to go down 2 rows; slide right 3 to go down 3 rows; Slide left_2 to go up 2 rows; Slide left_3 to go up 3 rows;

Tap LEFT to go back to previous screen and tap Right to bring up Screen 3.



Screen 3: Tap LEFT to go back to previous screen

Participant needs to perform these tasks:
- navigate and select the circle on screen 1
- navigate and select the item on screen 2
- from screen 3, back to screen 2
- from screen 2, back to screen 1
- navigate and select another circle again, repeat this flow for 5 times to finish 1 session, there will be a total of 3 sessions



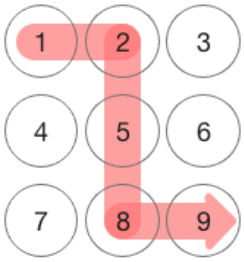
Screen 3

A practical approach for thumb-index gesture as input for ubiquitous screen

Bauhaus-Universität Weimar

Part 2, 3, 4 - Interaction Pattern

Repetition 1

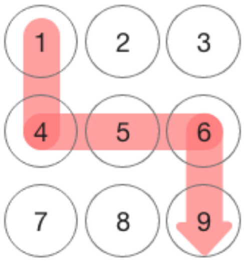


Screen 1

1
2
3
4
5

Screen 2

Repetition 2

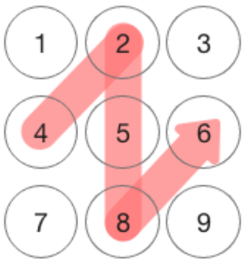


Screen 1

1
3
5
7
2

Screen 2

Repetition 3



Screen 1

1
4
7
3
6

Screen 2

A practical approach for thumb-index gesture
as input for ubiquitous screen

Bauhaus-
Universität
Weimar

Survey Question

1. How do you rate the accuracy level of the device?

Tapping

not accurate ◯ ◯ ◯ ◯ ◯ very accurate

Sliding

not accurate ◯ ◯ ◯ ◯ ◯ very accurate

2. How do you rate the cognition load when trying to identify which item on screen that you need to select?
   (a) Pattern 1

easy ◯ ◯ ◯ ◯ ◯ hard

   (b) Pattern 2

easy ◯ ◯ ◯ ◯ ◯ hard

   (c) Pattern 3

easy ◯ ◯ ◯ ◯ ◯ hard

3. How do you rate the difficulty level for each part?
   (a) Part 2: one-hand interaction

easy ◯ ◯ ◯ ◯ ◯ hard

   (b) Part 3: two-hand interaction without constraint

easy ◯ ◯ ◯ ◯ ◯ hard

(c) Part 4: two-hand interaction with constraint

easy ○ ○ ○ ○ ○ hard

4. How do you rate the practical aspect of the device?

low ○ ○ ○ ○ ○ high

5. The interaction can be use as input for ubiquitous screen such as google glass, watch, speaker, etc … Can you name 3 situations in which this thumb-index interaction will be helpful?

Safety Instruction

Due to the current situation of Covid-19, participants in the study are requested to practice the following instructions.

1. Researcher and participants should wear mask when talking and interact with each other. Participant can remove the mask while there is no communication.

2. Participants should wash hand before and after the experiments. Disinfection liquid is provided by the researcher.

3. The researcher will clean the device and equipment after the participant finishes their experiment.

4. The participant needs to provide their name and contact method, in case someone gets infected, others will be updated about the situation. The researcher will keep this information for two weeks.

Bibliography

Daniel Ashbrook, Patrick Baudisch, and Sean White. Nenya: subtle and eyes-free mobile input with a magnetically-tracked finger ring. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2043–2046, 2011. 2.2.2

Liwei Chan, Rong-Hao Liang, Ming-Chang Tsai, Kai-Yin Cheng, Chao-Huai Su, Mike Y Chen, Wen-Huang Cheng, and Bing-Yu Chen. Fingerpad: private and subtle interaction using fingertips. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*, pages 255–260, 2013. 2.2, 2.2.2

Pragati Garg, Naveen Aggarwal, and Sanjeev Sofat. Vision based hand gesture recognition. *World academy of science, engineering and technology*, 49(1): 972–977, 2009. 2.2, 2.2.3

Chris Harrison and Scott E Hudson. Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology*, pages 121–124, 2009. 2.2.2

Da-Yuan Huang, Liwei Chan, Shuo Yang, Fan Wang, Rong-Hao Liang, De-Nian Yang, Yi-Ping Hung, and Bing-Yu Chen. Digitspace: Designing thumb-to-fingers touch interfaces for one-handed and eyes-free interactions. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 1526–1537, 2016. 2.1, 2.1, 2.2, 2.2.2, 3.1, 3.1, 3.3.1, 5.3.1, 6.1, 6.2

Amy K Karlson, Benjamin B Bederson, and Jose L Contreras-Vidal. Studies in one-handed mobile design: Habit, desire and agility. In *Proc. 4th ERCIM Workshop User Interfaces All (UI4ALL)*, pages 1–10. Citeseer, 2006. 1

Li-Chieh Kuo, Haw-Yen Chiu, Cheung-Wen Chang, Hsiu-Yun Hsu, and Yun-Nien Sun. Functional workspace for precision manipulation between thumb and fingers in normal hands. *Journal of electromyography and kinesiology*, 19(5):829–839, 2009. 1

Roberto Maiocchi and Barbara Pernici. Directing an animated scene with autonomous actors. *The Visual Computer*, 6(6):359–371, 1990. 2.2.3

Carsten Mehring, Falko Kuester, Kunal Deep Singh, and Michelle Chen. Kitty: Keyboard independent touch typing in vr. In *IEEE Virtual Reality 2004*, pages 243–244. IEEE, 2004. 2.2.1

Mohamed Soliman, Franziska Mueller, Lena Hegemann, Joan Sol Roo, Christian Theobalt, and Jürgen Steimle. Fingerinput: Capturing expressive single-hand thumb-to-finger microgestures. In *Proceedings of the 2018 ACM International Conference on Interactive Surfaces and Spaces*, pages 177–187, 2018. 2.1, 2.1, 2.2.3, 3.1

Koji Tsukada and Michiaki Yasumura. Ubi-finger: A simple gesture input device for mobile and ubiquitous environment. *Journal of Asian Information, Science and Life (AISL)*, 2(2):111–120, 2004. 2.2.1, 3.1, 3.2.1

Eric Whitmire, Mohit Jain, Divye Jain, Greg Nelson, Ravi Karkar, Shwetak Patel, and Mayank Goel. Digitouch: Reconfigurable thumb-to-finger input and text entry on head-mounted displays. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 1(3):1–21, 2017. 2.2.1, 3.2.2

Sang Ho Yoon, Ke Huo, and Karthik Ramani. Plex: finger-worn textile sensor for mobile interaction during activities. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication*, pages 191–194, 2014. 2.2.1

Sang Ho Yoon, Ke Huo, Vinh P Nguyen, and Karthik Ramani. Timmi: Finger-worn textile input device with multimodal sensing in mobile interaction. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 269–272, 2015. 2.2.1