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Pengible: Designing an Active Pen-Shaped Tangible

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Media Computing Group
Prof. Dr. Jan Borchers
Computer Science Department
RWTH Aachen University

by
Rene Niewianda

Thesis advisor:
Prof. Dr. Jan Borchers

Second examiner:
Prof. Dr. Ulrik Schroeder

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Niewianda, Rene — 346905

Name, Vorname — Matrikelnummer

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Abstract

Touchscreens have become an indispensable part of today's everyday life. However, different areas on these screens are difficult to distinguish if the user is not looking directly at them. Tangibles have proven to be a solution to this problem as they serve as haptic control elements for the user that can easily be distinguished from the rest of the touchscreen. Such Tangibles are often used on large tabletop touchscreens and are mostly designed to be held in place or to be moved around on the touchscreen. These Tangibles occlude the view of the screen below them, which makes precise tasks difficult. Due to this fact, such tangibles cannot be used for drawing and writing tasks.

As a solution to this, we present the Pengible: A pen-shaped Tangible which is equipped with additional functions such as a vibration motor and a multi-colour LED. The new Tangible design scales the previous PERC Tangible electronics down and ports them to the ATmega328. This microcontroller, which is also used in Arduino Unos, significantly simplifies programming and extending the Pengible.

To improve the design of the Pengible, we conducted a user study. In this study, the subjects were given a simple drawing task. After having finished this, they were asked to provide feedback on the Pengible in general and its functions. In addition, we measured the time the test subjects took to react to the individual feedback modalities of the Pengible during this drawing task. The examined feedback options were *vibration front*, *vibration back*, *LED front* and *LED back*. The study showed that users reacted faster to *vibration front* and *LED back*, but the options *LED front* and *vibration front* were rated to be more comfortable.

Überblick

Touchscreens sind im heutigen Alltag nicht mehr wegzudenken. Allerdings sind auf ihnen verschiedene Bereiche nur schwer zu unterscheiden, wenn der Benutzer sie nicht direkt ansieht. Als Lösung für dieses Problem haben sich Tangibles bewährt, da diese für den Nutzer ein haptisches Bedienelement sind, das sich leicht vom restlichen Touchscreen unterscheiden lässt. Solche Tangibles werden häufig auf großen Tabletop-Touchscreens verwendet und sind meist dazu entworfen worden auf diesem stehen gelassen oder umherbewegt zu werden. Dabei verdecken diese Tangibles die Sicht auf den Bildschirm unter ihnen, was ein präzises Arbeiten erschwert. Durch diesen Umstand können solche Tangibles nicht für Zeichen- und Schreibaufgaben verwendet werden.

Um dem Abhilfe zu schaffen präsentieren wir das Pengible: Ein Tangible in Form eines Stiftes, welches mit zusätzlichen Funktionen wie einem Vibrationsmotor und einer Vielfarb-LED ausgestattet ist. Das neue Design verkleinert die bisherige PERC Tangible Elektronik und portiert diese auf den ATmega328. Dieser auch in Arduino Unos verwendete Microcontroller vereinfacht das Programmieren und Erweitern des Pengibles erheblich.

Um das Design des Pengibles weiter zu verbessern, haben wir eine Nutzerstudie durchgeführt. In dieser Studie haben die Probanden eine einfache Zeichenaufgabe erhalten. Nachdem diese erledigt war sollten die Probanden Feedback zum Pengible im Allgemeinen und zu dessen Funktionen geben. Zusätzlich stoppten wir die Zeit, die die Probanden benötigten, um während der Zeichenaufgabe auf die verschiedenen Feedback-Möglichkeiten des Pengibles zu reagieren. Die untersuchten Feedback-Möglichkeiten waren *Vibration vorne*, *Vibration hinten*, *LED vorne* und *LED hinten*. Die Studie zeigte, dass die Nutzer am schnellsten auf *Vibration vorne* und *LED hinten* reagierten, allerdings wurden die Feedback Möglichkeiten *LED vorne* und *Vibration vorne* als angenehmer empfunden.

Acknowledgements

First of all, I would like to thank Prof. Dr. Borchers and Prof. Dr. Schroeder for examining this thesis.

Secondly, I want to thank my family and friends who supported my during this thesis. Especially, I would like to thank Jennifer Witham, Tim Hildmann, René Schäfer and Frederik Menke for their support and advice.

Lastly, I want to thank my supervisor Christian Cherek for his help and feedback.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in coloured boxes.

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Definition:
Excursus

The whole thesis is written in British English.

For reasons of politeness, unidentified third persons are described in male form.

Chapter 1

Introduction

Touchscreens are ubiquitous in our everyday life, whether as small smartphone-screens, big wall-mounted information displays or as tabletop screens. However, most touchscreens give little to no haptic feedback when using them. This issue proves to be especially tricky when they are operated eyes-free. Tangibles, which are commonly used on tabletop touchscreens, are one option to address this issue since they have proven to increase one's performance when operating touchscreens [Voelker et al., 2015b, Weiss et al., 2009]. Tangibles provide something tactile on these otherwise flat screens. To further strengthen the recognizability of different Tangibles, their outer shape can be altered to adapt to various tasks. This makes the distinction between objects on the screen even simpler.

Tangibles improve eyes-free operation of touchscreens

To make Tangibles even more customizable, their internal electronics can be changed and extended. That way, Tangibles can be adapted for many different usages. For example, these advanced Tangibles can support active feedback, including sound and light [van Huysduynen et al., 2016]. Or, they can provide new input methods like rotary knobs [Voelker et al., 2015b]. Some Tangibles can even be used as off-screen controllers like the 3D Object Manipulation Tangible proposed by Asselborn [2018], which can be rotated by the user to control the object displayed on the screen. This way of manipulating the on-screen object proved to be more intuitive, especially for beginners. To

Tangibles provide new input and feedback options

Tangibles need a framework to function correctly

function properly, Tangibles need a unique framework to communicate with any touch-device. For this purpose, we use the Multitouch-Kit (MTK), a software framework built for tabletop-touchscreens [Linden, 2015]. The MTK mostly supports all-purpose Tangibles, which are slightly modified versions of PERCs [Voelker et al., 2015a] that are not specialized for specific types of input.

Current Tangible design is unfit for writing and drawing tasks

Tasks like writing and drawing are hard to accomplish using these all-purpose Tangibles since they are designed to be placed onto the touchscreen or as complete off-screen controllers, rather than to be held and moved continuously by the user. The design of these Tangibles makes it difficult to precisely perceive the Tangibles exact touchpoints because the screen is occluded by the Tangible itself. Furthermore, these Tangibles have three touchpoints instead of one, which are needed for the Tangible to be recognised by the screen. This design makes it even harder to draw with them.

Pengible as new writing and drawing Tangible

Since we are using the MTK for our Tangibles, the user can only use his finger or the already mentioned Tangible types to draw. Considering that Tangibles have proven to increase one's precision [Voelker et al., 2015b] and that using something similar to a pen could drastically increase the comfortability, especially for longer tasks, a specialized Tangible would be the better choice. Due to the MTKs unique architecture, most commercially available pens for precise touch input cannot be used as an alternative. Therefore, a completely new Tangible design is needed to fill this gap. To provide such a Tangible, this thesis has two goals: One goal is to design and evaluate a pen-shaped Tangible, named the Pengible, which allows intuitive drawing and writing on the touchscreen. The other goal is to remodel and simplify the current tangible electronics to make it easier to develop new Tangibles or extend existing ones.

Thesis outline

In the second chapter we will take a look at related work concerning the influence of handwriting on the learning process, Tangibles in general and already commercially successful pen-shaped input devices. This will be followed by a detailed description of the Tangible alteration process in the third chapter, including the difficulties that we encountered during the development process. The experimental design and results of the user study are presented in the fourth chapter. The focus of this study was the evaluation of the general design and the ideal position for the LED and the built-in vibration motor. In the fifth chapter of this thesis, we will provide our conclusions and suggestions for future work concerning the Pengible.

Chapter 2

Related Work

Overview

To build a pen-shaped Tangible, a few theoretical foundations need to be considered. Firstly, what are the benefits of using a pen over a keyboard, especially when learning? Secondly, a look upon the Tangible research itself must be taken. How do they work? In which context can they be used? Thirdly, which pen-shaped devices are already commercially available that can also provide sound, vibration or other feedback which will also be the main features of the Pengible? These commercial products are used as input devices for computers, too. Since these devices are already established and tested, their concepts can be used to determine some core characteristics of electronic pens. What can be adapted, and what will not work for the Pengible?

2.1 The Influence of Handwriting on the Learning Process

Manipulation of tools is crucial for cognitive development

When writing digitally, keyboards or similar tools are the most common input devices. But when it comes to learning, the haptic elements of handwriting are of great importance. Mangen and Velay [2010] state that the manipulation of tools and tangible objects with our hands plays a crucial role in the process of cognitive development and learning. The pen that is used for writing with our hands can be considered as such a tool.

Writing supports the learning process

In their experiment, Naka and Naoi [1995] showed that graphic forms can be remembered more easily when written down multiple times than by reading alone. Similar results were observed by Longcamp et al. [2005], who compared the effects of handwriting and typing on the recognition of letters. They tested children from ages two to four, with the result that the older children showed a significant improvement in the recognition task when the letters were learned by writing them by hand.

Figure 2.1: The components of the Character Alive system. [Fan et al., 2019]

Character Alive provides an analog and digital learning environment

To utilise this phenomenon, Fan et al. [2019] designed Character Alive, a Tangible reading and writing system. Character Alive was designed to help dyslexic children improve their reading and writing skills. It consists of a tablet equipped with a camera and several 3D-printed cards (see figure 2.1). To guide the user during practice, grooves that resemble Chinese characters and letters are printed onto these cards. The tasks and explanations are displayed on the tablet and have to be performed using the 3D cards. Displayed explanations include but are not limited to drawing animations of the characters and dynamic colour cues. By using the camera, the system can detect if a task was finished successfully and can provide help and feedback if needed. However, a study to investigate the actual impact on learning performance was not conducted.

2.2 Tangibles

Tactile and haptic feedback have proven to be useful to the user, especially when working with touch-displays. Weiss et al. [2009] proposed a set of acrylic and silicone widgets as an input modality for a digital guest-book. These Tangibles can be operated blindly, which increases the user-friendliness by allowing the user to look around while using them.[Voelker et al., 2015b, Weiss et al., 2009] Tangibles can be divided into two classes, passive and active Tangibles: passive Tangibles contain no electronic parts while active Tangibles can contain complex circuitry that can be used for more enhanced interactions and feedback.

Difference between active and passive Tangibles

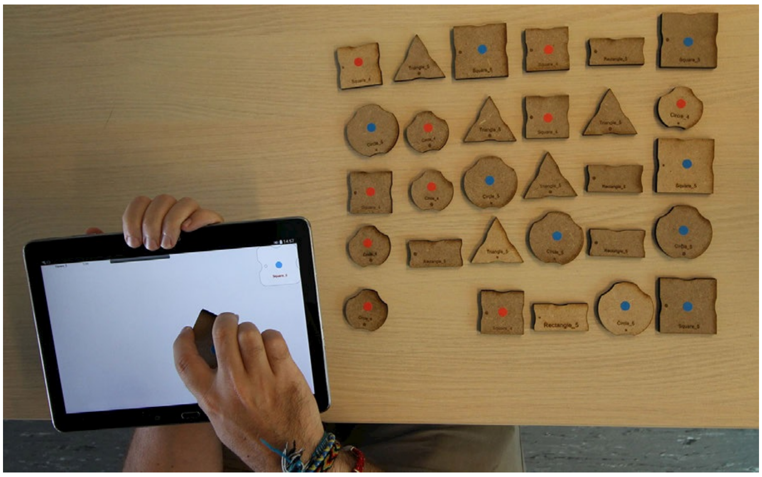

Figure 2.2: All different types of Touchtokens. The indents on the edges encourage the different grip positions.[Morales González et al., 2016]

TouchTokens enforce grip patterns

The simplest passive Tangibles are the TouchTokens [Morales González et al., 2016], which are small wooden or acrylic cutouts with notches for the user's fingers (see figure 2.2). These tokens enforce specific grip patterns that are recognised by the computer. The action associated with the pattern is not predefined. Therefore, every app can choose its own implementation. Morales González et al. [2016] mention shortcuts and games as possible applications.

Figure 2.3: PUC widgets on an iPad: a transparent Bridge PUC (left) and a Ring PUC (center). The clip to permanently ground a touch point and override the iPad's adaptive filter can be seen on the right. [Voelker et al., 2013]

PUCs use the touchscreens own capacity to be recognised

These Tangibles always require a person to hold or touch them to be recognised. One of the first Tangibles that addressed this issue was the PUC (Passive Untouched Capacitive widgets) developed by Voelker et al. [2013]. Modern touchscreens use changes in capacitance to recognise touches. Therefore, an object must provide a certain capacitance to produce a touch-point. Since the small PUCs cannot provide sufficient capacitative charge by themselves, they utilise the capacitative coupling between two areas on the display. This is possible because not all areas of the screen are active at once and the areas that are not currently active are connected to ground. The "Bridge" PUC shown in figure 2.3 is an example of this concept and features two interconnected contacts that can be placed simultaneously onto the touchscreen.

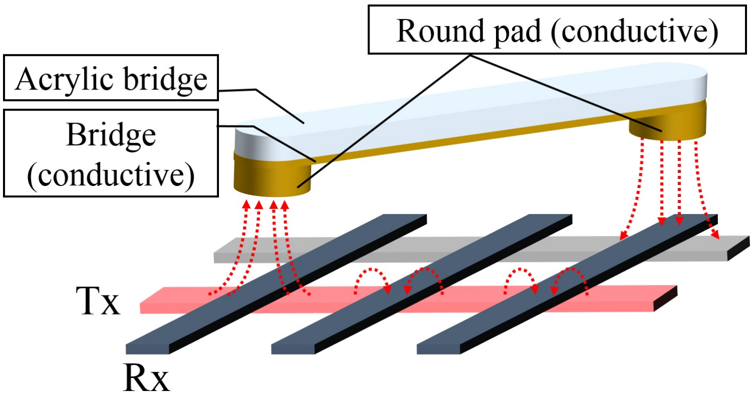

Figure 2.4: Basic concept of a Bridge marker. Red connections indicate capacitive coupling between marker and electrodes. [Voelker et al., 2013]

PUCs need three Touchpoints to be recognised reliably

Due to the structure of the touchscreen, the active areas are always arranged in horizontal and vertical lines. Therefore, no capacitance is provided between two points that are located on the same active line (see figure 2.4). To be recognised consistantly a Tangible needs at least three interconnected touchpoints. The ring PUC in figure 2.3 is an example for this concept.

”permanent touch” prevents PUCs from being filtered by the Touchscreen

Figure 2.3 also shows a third PUC: the clip. This PUC was added to prevent the noise reduction algorithm on older tablets like the iPads 1 to 3 from filtering the touchpoints of the other PUCs. It simply provides a ”permanent touch”, a touchpoint that is connected to the aluminium back of the iPad.

PERCs are active tangibles

PERCs, (Persistently Trackable Tangibles on Capacitive Multi-Touch Displays) designed by Voelker et al. [2015a], are a more advanced version of the PUC concept. In contrast to PUCs, PERCs are active tangibles. In other words, PERCs feature additional circuitry. These include but are not limited to a field sensor and a Bluetooth-element. The PERCs general design can be seen in figure 2.5.

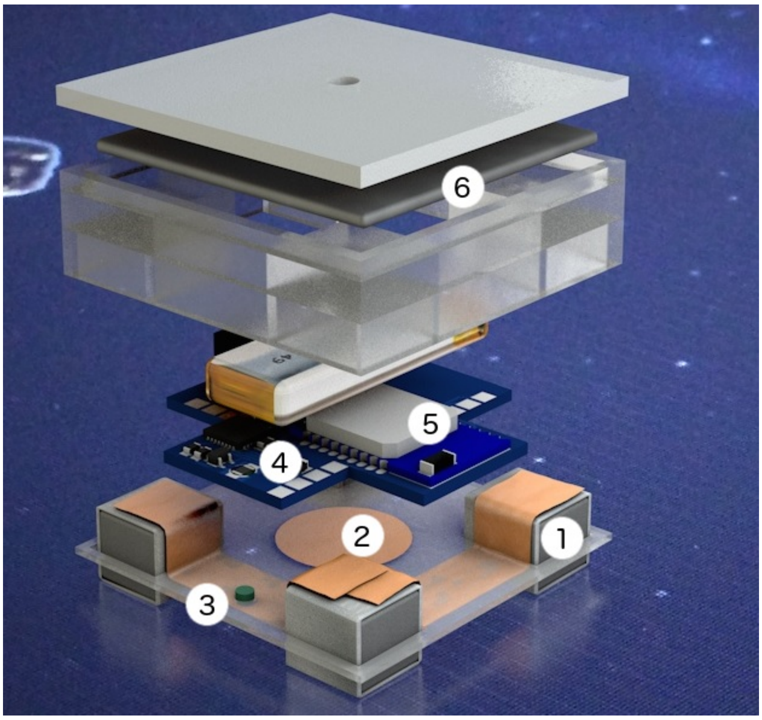

Figure 2.5: The six main components of a PERC tangible: (1) marker pattern, (2) field sensor, (3) light sensor, (4) micro controller, (5) Bluetooth element, and (6) lead plate. [Voelker et al., 2015a]

PERCs can be tracked and identified by the computer

One disadvantage of the PUC is the fact that a set of touchpoints cannot be assigned to a specific Tangible, especially when the Tangible was lifted from the screen at any point. The PERCs solve this problem by utilizing the previously mentioned three touchpoint strategy of the "Ring" PUC and a field sensor. The field sensor can detect when the tangible is placed onto the touchscreen, which triggers a Bluetooth Low Energy-message (BLE-message) to a computer which is connected to the screen. Now the computer can connect to the Tangible that sent the message to the touchpoints that where detected in the same time frame the BLE-message was received. This assignment is handled by the Multitouch-Kit (MTK) [Linden, 2015], a framework developed especially for those Tangibles. Additionally, the MTK provides utility methods like connecting touchpoints to traces and Bluetooth communication to the Tangibles.

The PERCs also feature a light sensor which used to support the surface detection of the Tangible, but was removed in later versions. Additionally, a LED, a vibration motor and a buzzer were added, which can be controlled via BLE-messages. The latest version of the PERCs served as the basis for the Pengible.

LED, vibration motor and buzzer were added to the PERC

2.3 Electronic Pens

There are many different, commercially available types of electronic pens which can in general be divided into two groups: One group consists of pens that determine their position on a non-electronic surface like paper and can digitize these inputs to give feedback accordingly. Examples for these type of pens are the Livescribe Smartpen [Livescribe, 2010] and the Tiptoi [tip]. The other group consists of pens that can be used directly as input devices for computers or tablets, like the Apple Pencil [App, b]. In the following section, these solutions are presented and discussed.

Two different groups of electronic pens

2.3.1 The Livescribe Platform

The Livescribe Platform is a product bundle developed and published by Livescribe [liv, a]. This bundle features the Livescribe^{TM} Smartpen and Livescribe^{TM} Dot Paper [Livescribe, 2010]. The main feature of the Livescribe products is the ability to digitize one's handwriting and convert these notes into files. Moreover, the user can add notes via voice input while writing. The Smartpen also offers a speaker and an Organic Light-Emitting Diode (OLED) display to give live feedback to the user (see figure 2.6).

Livescribe Smartpens can digitize handwriting

In order to function correctly, the Smartpen needs the Livescribe^{TM} Dot Paper, a special paper which is covered with a unique microdot pattern developed by Anoto [ano]. The pen uses the built-in camera and the dot pattern to determine its position on the paper. There are also special types of this pattern to encode so-called paper controls, as seen in figure 2.7. These controls are areas on the paper

Microdot pattern serves as orientation

that trigger special actions. Since there are no buttons on the Smartpen itself except for the power switch, this is the only way to access most of the pen's functions.

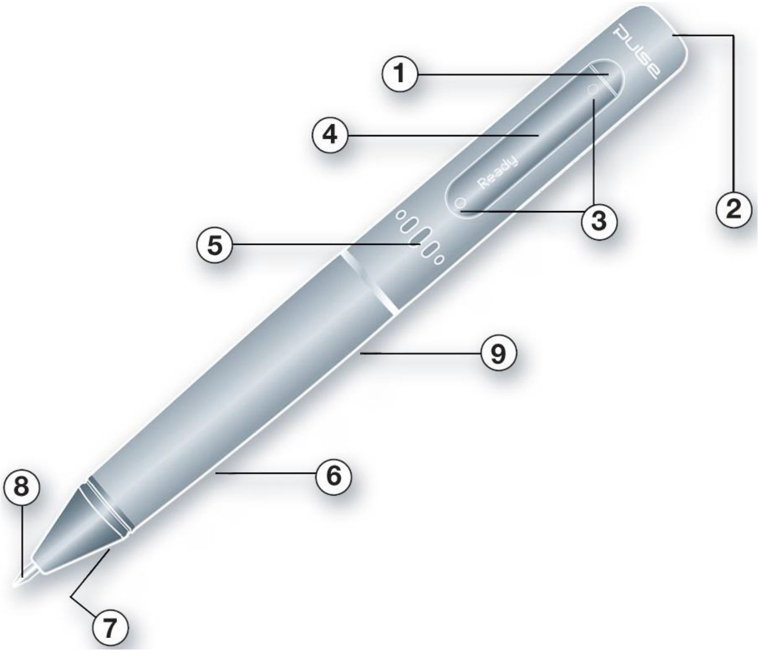

Figure 2.6: The Livescribe Smartpen: (1) Power button, (2) Stereo headset jack with an external microphone input, (3) Built-in microphone, (4) OLED display, (5) Built-in monophonic speaker, (6) USB connector, (7) Infrared camera, (8) Removable ink cartridge and (9) Rechargeable lithium battery (non-removable) [Livescribe, 2010]

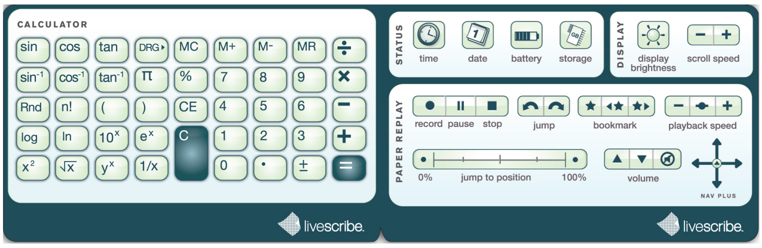

Figure 2.7: Paper Controls for a Calculator (Liv)

To allow third-party developers to develop apps for the Livescribe platform, the Livescribe SDK was published in 2009 [liv, b]. However, the Livescribe developer program was discontinued on the 29th of July in 2011 after three years. Since then almost no documentation has been published for the general public and the old documentations have also been deleted from the Livescribe website as well [liv, c].

Almost no documentation on the Livescribe SDK

The discontinuation and the fact that the pen does not work on touchscreens made this Smartpen not eligible to be used as a Tangible or to be modified into one.

2.3.2 Tiptoi

The Tiptoi (see figure 2.8) is a playful learning pen made by Ravensburger [rav]. The Tiptoi requires special books, where children can tap the pages to trigger events. These events are purely audio feedback which includes fitting sounds, short explanations and even small games like searching an object on the page.

Tiptoi can record and play audio

Since there is no official documentation available, the pen was reverse-engineered by Joachim Breitner and his colleagues. A teardown of their work was presented at the Gulaschprogrammiernacht 2015 of the Chaos Computer Club in Karlsruhe [gul]. As Breitner explains in his presentation, the Tiptoi works similar to the Livescribe Smartpen, and the the key difference being how the dot pattern is used. While the Livescribe uses the uniqueness of the pattern to determine its location, the dot pattern the Tiptoi uses encodes a 16-bit value, which is processed by the pen. Furthermore, all files on the pen are encrypted, and the purpose of some parts of these encrypted files is still unclear. The process Breiter describes to alter or change those files is incredibly difficult to repeat without in-depth knowledge on most parts of the implementation of the pen.

Livescribe Smartpen and Tiptoi use a similar technology

Tiptoi cannot be modified easily

Figure 2.8: The Tiptoi pen of the third generation with audio record and replay function [tip]

Tiptoi is not compatible with touchscreens

As already mentioned for the Livescribe, the lack of proper documentation and the missing ability to be used on touchscreens disqualifies the Tiptoi to be used as a Tangible. However, the games that can be played with the Tiptoi can be used as an inspiration for future Pengible apps.

2.3.3 Wacom Intuos Pen Tablet

Figure 2.9: The Wacom Intuos Pen Tablet. This tablet is able to track its pen, which can be used as an input device for a computer. The pen has an integrated button and pressure sensor [Int]

The Wacom Intuos pen-tablet, shown in figure 2.9, is a special input device for computers produced by Wacom [Wac]. It was designed for artists to create digital art and consists of a pen and a screenless tablet, which has to be connected to the computer. To detect the position of the pen, even if the pen is not touching it directly, the tablet uses a special Electromagnetic Resonance (EMR) technology. This technology also enables the Wacom Intuos to detect up to 4086 levels of pressure. However, the pen is not connected to the tablet, and it has no built-in battery. Therefore, it cannot give any feedback [Int].

Intuos pen-tablet uses EMR to track its pen

Although the Wacom Intuos can be used as mouse input on almost every computer, the disconnection of screen and input defies the purpose of Tangibles. Furthermore, the EMR technology does not work with MTK since it uses a completely different recognition technique similarly to the one described in the Tangibles section.

EMR-touch recognition not supported by the MTK

2.3.4 Apple Pencil

Figure 2.10: The Apple Pencil 2. Generation (App [b])

Apple Pencil works and charges wirelessly

Apple [App, a] developed the Apple Pencil as an additional input device for the Apple iPad. The Apple Pencil Generation 2 (see figure 2.10) only works with the iPad Pro and the iPad Air. It features a build-in button and can detect pressure and the tilt of the pencil while writing. All interactions and the recharging of the internal battery are done fully wireless since the pencil has no external ports. [App, b]

Apple pencil is to compact to be modified

The design of the Apple Pencil makes it almost impossible to access the internal electronics without damaging the pencil in some way. Throughout the examination of the pen's design we discovered that the Pengible has to provide more space than the Apple Pencil to fit every feedback device and the electronics inside.

Chapter 3

Implementation

Overview

The design of the Pengible can be divided into four parts: The circuitry, the onboard software, the hull, and the Multitouch-Kit (MTK) software. A redesign and extension of the existing Tangible circuitry was necessary since the original boards were too big to fit into a pen-shaped device and the Pengible adds new functions to the existing Tangibles. Given the change of the circuitry, we altered the onboard software as well to accommodate the new functionalities as well. We also had to completely rewrite the onboard software because the used microchip and almost the complete architecture of the board were changed. Moreover, the new hull needed to be big enough to fit all the circuitry inside and still small enough to be used comfortably to write and draw. Lastly, we introduced the already mentioned new functionalities to the MTK, which is needed for all Tangible applications to communicate with the Tangibles.

3.1 The Pengible Circuitry

After examining the old circuit diagrams for the Tangibles, we decided to switch to another micro-controller. This switch was necessary because the old chip was not as extensible as we needed it to be, especially if we want to ex-

Circuitry was ported to the ATmega328P

tend the functions of the Pengible further in the future. We chose the ATmega328P, which is the chip used on the Arduino Uno [Ard, a]. One major benefit of this change is the large selection of predefined function libraries like the Adafruit Neopixel library[Ard, c], which we used for the WS2812 LEDs. The circuitry of the Pengible can be divided into two parts: The mainboard and the peripheral electronics.

3.1.1 The Mainboard

Board features pins for one Fieldsensor, one WS2812 LED, one vibration motor, one buzzer and one serial communication

The board used in the Pengible is a minimalistic version of the standard Arduino Uno breakout-board. An Arduino-Clone [Ard, b] made for the Fab Academy served as a model for the circuitry. Since the space inside the Pengible is very limited, we removed the unused pins. To further optimise the space taken up by the individual electronic components, they are partly layered on top of each other, as shown in figure 3.1. The current version of the board features pins for the field sensor, one WS2812 LED, one vibration motor, one buzzer and the serial ports needed for the Bluetooth communication. The buzzer pin is currently not in use due to space limitations.

HM10s serial communication cannot be used at 5V

We used a premade Hm10 Bluetooth Low Energy (BLE) module to communicate with the iMac connected to the Surface Hub. Most of the premade Hm10 modules use a 5V supply voltage, but only a 3.3V maximum Voltage for the serial communication. Our board is designed for usage with a 5V battery. Therefore, the voltage provided via the RX serial pin has to be limited to 3.3V using a voltage divider. However, if the voltage divider is used with a supply voltage lower than 5V, the serial communication may not work correctly. But the BLE module can tolerate a slightly higher voltage than 3.3V. Therefore, it is possible to use the board without the divider by connecting a standard 3.7V Lithium-Ion battery.

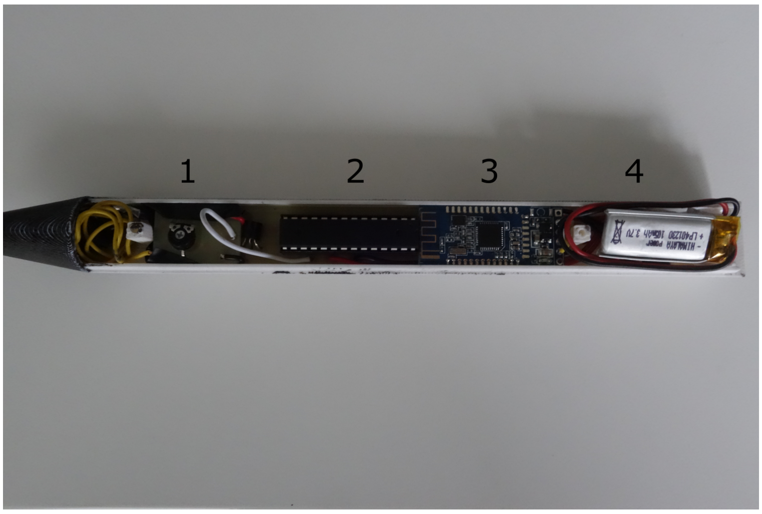

Figure 3.1: The main electronic components of the Pengible: Fieldsensor(1), Mainboard(2), Bluetooth Module(3) and Battery/LED(4)

3.1.2 Peripheral Electronics

Circuitry is split into multiple boards

Besides the mainboard there are also smaller electronic parts built into the Pengible. These parts had either to be mounted to specific spots, like the LED and the vibration motor, or to be shielded from the rest of the electronics to function properly, like the field sensor (see figure 3.1).

The field sensor needed to be shielded from other electronics

For expample, the LED and the vibration motor can be directly connected to the mainboard because the circuitry, which ensures that they work correctly, is already located there. However, the whole field sensor circuitry had to be placed into the tip of the Pengible on a completely separate board. Every other electronic part, which is placed next to it, can easily influence the signals picked up by its antenna. To reduce this influence, the vibration motor that is located in the tip of the Pengible is shielded with copper foil.

Back LED was replaced by an LED stripe

Another important factor for the placement and the design of the peripheral electronics were once again the space limitations. During the development process, the LED at the back needed to be exchanged with a part of an LED stripe, since the normal WS2812 LED took up too much space which was needed otherwise for the battery and the power switch.

3.1.3 Extensibility

Two PWM pins are not in use

As mentioned before, the mainboard of the Pengible is a minimized version of an Arduino Uno. Therefore, every electronic device that would work with an Arduino Uno can be integrated into the Pengible. Due to the minimization, the Pengible only offers four Pulse Width Modulation (PWM) pins, namely Pin 3, 9, 10 and 11 (see figure 3.2). Every other PWM pin indicated on an Arduino Uno is emulated by the Arduino Uno board. The LED and the vibration motor already occupy two out of these four pins. Therefore, only one part that needs a serial communication port can be added without removing both of these functionalities.

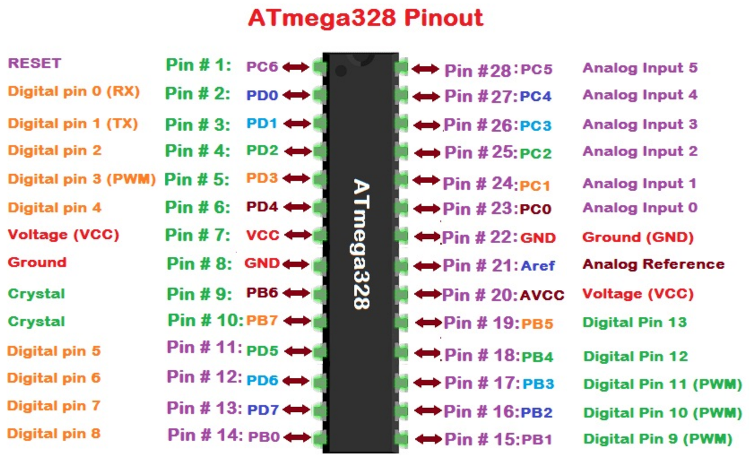

Figure 3.2: The pinout of the ATmega328 which is used in the Pengible [Atm]

3.2 The Pengible Software

The ATmega328P built into the Pengible can easily be programmed with the Arduino IDE using the special Arduino language, which is a C/C++ derivative. To program the chip it has to be plugged into an Arduino Uno board, as the Penglible itself has no build-in In-System-Programmer-pins (ISP-pins), to reduce the size of the board.

The Pengible has no ISP-pins

To communicate with the iMac and the MTK, the Pengible must send and receive specific codes shown in figure 3.3. With the implementation of the Pengible, codes for button input, vibration motors and multicoloured LEDs were added to the protocol (for more information, see chapter 3.4). This communication channel is established when the Pengible is turned on. Messages are sent via the BLE-module which can be addressed by using the native serial ports of the ATmega328P.

MTK-Bluetooth-protocol support

As long as a Bluetooth connection to the iMac is established, the Pengible software reacts to every input that starts with a "[" and ends with a "]". When such a block is received, it is checked for the correct format. If the block passes this test, it is decoded and the contained instructions are carried out.

Software performs integrity check on each received message

Due to the loop-based structure of Arduino programs, the Serial port is checked only once per loop to see if there is new data available. Additionally, if a sensor is subscribed to by the MTK, the Pengible must send the sensor's data every loop, if it had changed its value. This program flow can lead to delays, especially when many sensors are subscribed or when the checking of the sensor itself is time-consuming. In the current setup of the Pengible, this issue poses no problem, since the currently built-in sensors only produce one-bit values and the time needed to process and verify those is negligible.

Too many sensors checks can slow down the software

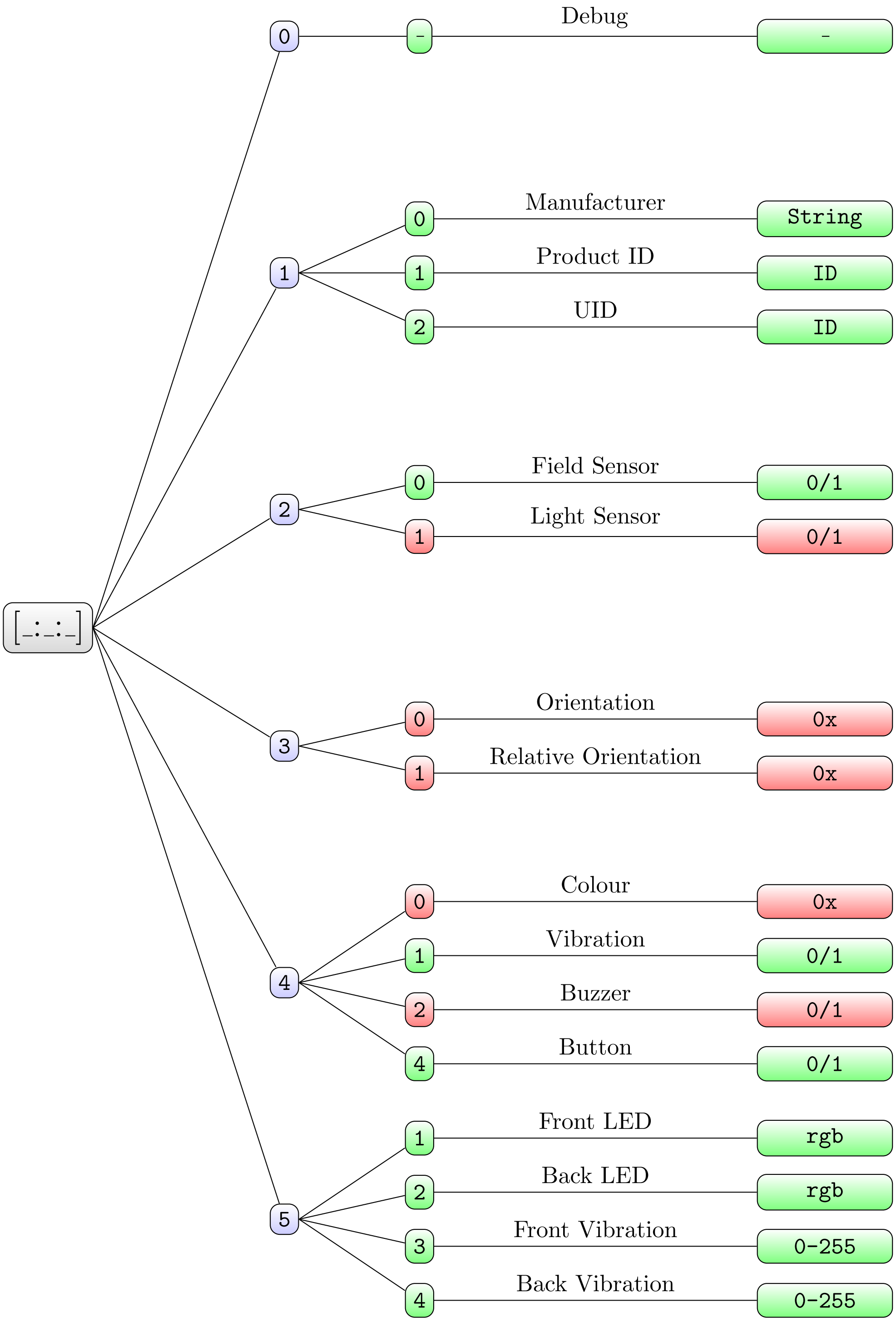

Figure 3.3: Code scheme and supported codes of the Pengible software(All green codes are currently supported by the Pengibles software, the red ones are only supported by the MTK BLE protocol. The Front LED and the Back LED were only available during the study)

3.3 The Pengible Hull

Designing and building the hull proved to be difficult with the given resources of our workshop. The final hull needed to address two major issues: The Pengible must be recognisable by the touchscreen and the hull had to be as comfortable as possible for the user when held.

The first challenge included the change from three touchpoints to only one. A Tangible needs at least two touchpoints to be recognised by the touchscreen (refer to chapter 2.2 and figure 2.4 for detailed information). To solve this problem the Pengible needed a connection to a fairly large source of capacity. Luckily the Pengible won't be left on the surface like most Tangibles. Therefore, the user's body can provide the required capacitance.

Pengible uses the users capacitance to be recognised by the touchscreen

Figure 3.4: The 3D-printed hull of the Pengible. The black parts are coated with a thin layer of graphite.

One of the first ideas to utilise the user's capacitance was to make the whole hull out of conductive material. But there were a few issues with this idea: The first one was a health issue concerning the materials we tried to use. Since our workshop does not provide tools to work with metal, we had to 3D-print the hull. Most of these conductive materials, like the Proto-Pasta filament [fil, b], contain some sort

Hull needs to be conductive

of conductive dust like carbon black, which can lead to lung diseases when inhaled [Organization et al., 2012]. The other tested material, namely the 3DXTech-ABS filament [fil, a], was to bridle to be used for the Pengible. The other concern we had with the fully conductive hull was that it might act as a Faraday cage and block or influence the field sensor or the Bluetooth signals. Furthermore, a conductive hull could produce a short circuit in the inner circuitry if there is no proper isolation. Considering these problems we decided to cover only parts of the outer surface with a conductive material. For the first version of the Pengible, which was used in the user study described in section 4, we simply used copper foil. For the final version of the Pengible, we used a graphite coating on the tip and one side of the outer hull, which can be seen in figure 3.4.

Hull was coated with graphite

Figure 3.5: The thumb indent of the Pengible.

The second issue that we needed to resolve was the ergonomics of the hull. During the design process, we shrunk the diameter of the hull multiple times to ensure that the Pengible is comfortable to use even with small hands. Another improvement we made was an indent for the thumb (see figure 3.5). To determine the best position for this indent we conducted a small study, where we handed the pen to ten right-handed people. We asked them how they would like to grab the Pengible while they can still reach the button. We used the grip that was used by 70% of the

Thumb indent for better grip

participants. One downside of the indent is that it is uncomfortable for left-handed users, but this can be addressed by mirroring the hull or removing the indent. Those small changes are easily possible since the hull can be adapted by changing the according parameters in the parametric design-file.

3.4 The Multitouchkit Integration

The integration of the Pengible into the Multitouchkit (MTK) consists of two parts: The first one is the basic integration, the second one the full integration. The basic integration only deals with the communication of the Pengible and the MTK while the full integration enables the MTK to automatically recognise and track the Pengible as a Tangible as described in section 2.2.

All new functions of the Pengible were integrated into the MTK

We did not fully integrate the Pengible since most functions of the MTK require three different touchpoints. Changing that would require us to change or rewrite most of these functions. At the moment, the Pengible needs to be manually registered, but every supported function shown in figure 3.3 can be accessed through the MTK. Since these functions are now part of the MTK, each and every other Tangible can use them as well.

Chapter 4

Evaluation

Figure 4.1: The Pengible version used in this study, equipped with two LEDs, two vibration motors and one button. (For the study the red LEDs where exchanged with multi-colour LEDs). A dent on the back lets the Pengible rest more comfortably in the hand while holding.

A study to evaluate the Pengible

We conducted this study to evaluate and improve the Pengible and its feedback modalities based on the feedback of the participants. It focuses primarily on duplicate modalities like the two LEDs shown in figure 4.1. The findings of the study will be integrated into the design of the next version of the Pengible.

4.1 Hypotheses

H1: There is no difference in recognition time between the front and back LED

H2: There is no difference in recognition time between the front and back vibration motor

H3: There is no difference in recognition time between LED and vibration feedback

Definition:
Recognition time

RECOGNITION TIME:
Time between the feedback modality is turned on and the press of the Pengibles button

4.2 Experimental Design

Pilot study to test the main study

Before conducting the study, its design was tested in a pilot study with two different participants, which were excluded from the main user study. Due to the findings in this pilot study, we changed some details like the colour of the LEDs, which was changed from red to blue, and the size of the picture the participants needed to draw. The pilot study also gave us an estimate for the time required to complete the study (approx. 40 min). The detailed experimental design is described below.

4.2.1 Environment

The drawing task was performed on a Microsoft Surface Hub 84′ which was orientated horizontally as a tabletop. The display of the Surface Hub has a screen-size of 220cmx117cm with a resolution of 3840x2160 pixels. It can detect up to 100 individual touchpoints. In the setup of this study, the table height was fixed to 97cm. The software used was executed on an iMac Pro in fullscreen resolution running at 30 fps. The study was performed in an open project space. The lights directly above the table were turned off to prevent any reflections. For all feedback modalities, the newly developed Pengible (4.1) was used.

4.2.2 Feedback Modalities

The performance of four different feedback modalities were measured in the study:

FEEDBACK-MODALITY STRENGTH:
The strength of the feedback modality is determined on a scale from 0 to 255 which resembles the ATmega328s pulse width modulation cycle length. At the value 0 the pin is always off and at 255 always on.

Definition:
Feedback-modality Strength

- LED-Front: A WS2812 LED placed on the side of the pen tip. The LED is oriented upwards when the pen is held in the right hand. For the study the colour was set to blue (0,0,0-250) with 25 equally distributed levels of brightness.
- LED-Back: A WS2812 LED placed on the back end of the Pen. For the study the colour was set to blue. (0,0,0-250) with 25 equally distributed levels of brightness.
- Vibration-Front: A vibration motor placed directly under the thumb-indent of the pen. 80-250 with 17 equally distributed levels of strength.
- Vibration-Back: A vibration motor placed inside the pen at the back end of the pen. 80-250 with 17 equally distributed levels of strength.

4.2.3 Procedure

Counterbalance with Latin square

Each feedback modality was played 4 times, i.e. 16 measurements were taken from each participant. The order in which the modalities were played was randomized, using a 16x16 Latin square (figure 4.1), to counterbalance fatigue and learning effects during the study.

1	2	4	3	3	4	2	1	1	2	4	3	3	4	2	1
2	3	1	4	4	1	3	2	2	3	1	4	4	1	3	2
3	4	2	1	1	2	4	3	3	4	2	1	1	2	4	3
4	1	3	2	2	3	1	4	4	1	3	2	2	3	1	4
1	2	4	3	3	4	2	1	1	2	4	3	3	4	2	1
2	3	1	4	4	1	3	2	2	3	1	4	4	1	3	2
3	4	2	1	1	2	4	3	3	4	2	1	1	2	4	3
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4	1	3	2	2	3	1	4	4	1	3	2	2	3	1	4
1	2	4	3	3	4	2	1	1	2	4	3	3	4	2	1
2	3	1	4	4	1	3	2	2	3	1	4	4	1	3	2
3	4	2	1	1	2	4	3	3	4	2	1	1	2	4	3
4	1	3	2	2	3	1	4	4	1	3	2	2	3	1	4

Table 4.1: Latinsquare which determines the order of the given feedback modalities: LED front(1), LED back(2), vibration front(3) and vibration back(4)

Procedure of the study

At the beginning of the study, the participant was asked to make himself familiar with the Pengible and the operation of its button. Now every feedback modality was shown to the participant. The individual feedback modality started with a strength of 0 (for the LEDs) or 80 (for the motors) and were increased over time by a value of 10 each second. The full bandwidth of the feedback modalities strengths was played at the beginning of the study, to show the participant how every mode works.

Description of core task

The core task consisted of redrawing a part of the world map (figure 4.2) which was displayed on the surface hub. While drawing, the feedback modality was active until the participant noticed it and pressed the button on the Pengible. The feedback modality started at a strength of 0 or 80

Figure 4.2: The map for the drawing task: The users had to retrace the black outlines of the map.

and was increased in strength like described above. After a random delay between 10 and 30 seconds, the next modality was played. Due to the ongoing nature of this task, no breaks were allowed during this part of the user study. After finishing this task, the participant was asked to fill out a questionnaire. The full questionnaire can be found in Appendix A.

4.2.4 Measurements

Reaction times and questionnaire

For each feedback modality the recognition time was measured. No other measurements were taken during the trials. After the participants had performed the task, they were asked to rate the feedback modalities regarding comfortability and noticeability on a five-point Lickert scale. Furthermore, the participants had the option to give additional comments about the Pengible. Additionally, their demographics were collected.

4.3 Participants

16 people participated in this study. The age ranged from 22 to 48 (M = 29.9, SD = 8) and all where right-handed. Left-handed people were excluded from the study, because the indentation on the side of the Pengible enforces a specific grip to ensure that the LED in the front points upwards and can be seen. When a left-handed user holds the Pengible, the front LED is turned downwards, which may cause differences in the recognition time. The group consisted of 3 females, 8 males, and 5 n.a. gender. Most of the participants were computer scientists or worked in a similar field.

4.4 Results

240 separate measurements

The study resulted in 256 individual time measurements from all 16 participants, 224 answered questions and additional comments by 8 users. One participant stated that he pressed the button when he heard the vibration motor and not when he felt the haptic feedback. His data was excluded from the data analysis, which resulted in 240 separate time measurements.

4.4.1 Recognition time

To determine which of the feedback modalities could be recognised the easiest and fastest, we analysed the recognition times we collected. The means and the standard deviation of the reaction time are displayed in table 4.2 and figure 4.3.

Back LED was recognised faster than front

It took the participants on average 4.2 seconds to notice the front LED and 1.2 seconds to notice the back LED. Furthermore, the reaction times regarding the front LED were spread more widely than the times of the back LED (SD-Front=8.5s, SD-Back=1.2s). Overall, the participants needed on average around 3 seconds less to notice the back LED than to notice the front one.

Feedback Modality	LED Front	LED Back	Vibration Front	Vibration Back
Mean Recognition Time	4.2s	1.2s	2.2s	6.3s
Standard Deviation	8.5s	1.2s	0.9s	2.5s
Minimum	0.5s	0.3s	0.4s	0.6s
Maximum	48.4s	6.1s	4.9s	8.9s

Table 4.2: Mean, minimum- and maximum recognition times with Standard deviations for all feedback modalities in seconds

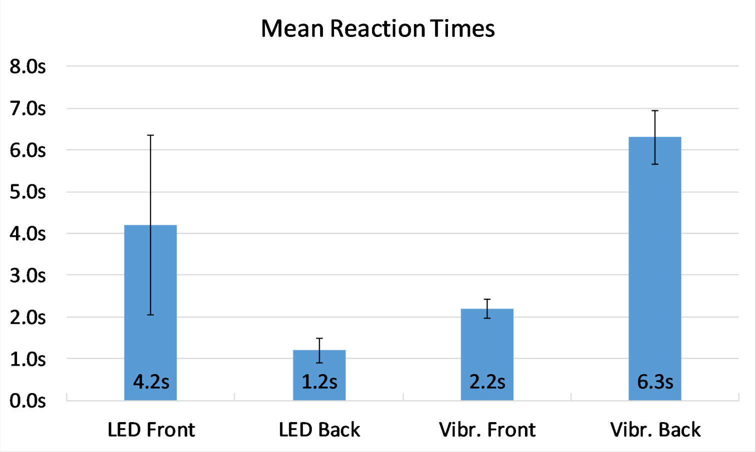

Figure 4.3: Mean recognition times and 95% confidence intervals for all feedback modalities in seconds

The average recognition time for the front vibration motor was 2.2 seconds and 6.3 seconds for the back vibration motor. The reaction times of the front motor were not as broadly scattered as the ones of the back motor (SD-Front=0.9s, SD-Back=2.5s). In this case the difference was not as big as for the front and back LED. On average the front vibration motor outperformed the back one by approximately 4 seconds.

Front vibration was recognised faster than back

Overall, the participants noticed the back LED the fastest, followed by the front vibration motor, which was noticed on average only 1 second slower than the back LED. The back vibration motor had the longest overall reaction times in this study.

Back LED was recognised fastest

4.4.2 Questionnaire

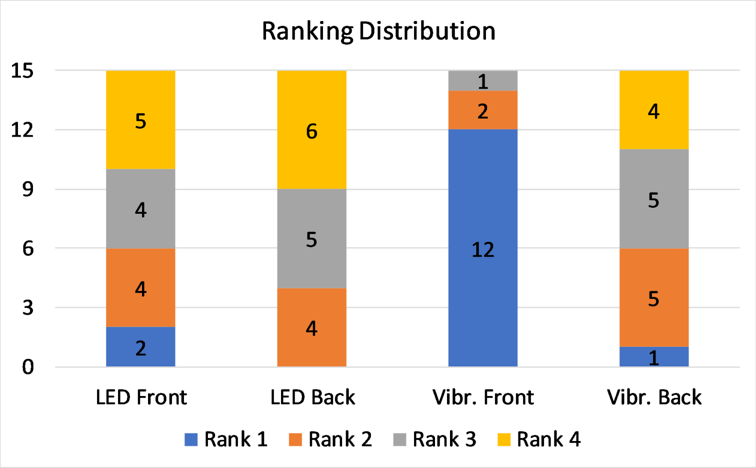

Figure 4.4: Absolute distribution of overall user ratings grouped by each feedback modality

Feedback Modality	LED Front	LED Back	Vibration Front	Vibration Back
Mean Rank	2.80	3.10	1.30	2.80
Standard Deviation	1.05	0.81	0.57	0.91

Table 4.3: Mean Rankings with Standard deviations for all feedback modalities

Front vibration was ranked best and back LED worst

The participants had to rate every feedback modality from 1 (best) to 4 (worst). The results, displayed in figure 4.4, show that two participants rated the front LED best. This feedback modality was rated second and third best by four participants each, five rated it worst. The back LED was rated best by no participant, second-best by four and third-best by five. Six participants rated it worst. The front vibration motor however, was rated best by a majority of twelve participants. Two rated it second best, one third best and no one worst. The last feedback modality, vibration motor back, was rated best by one participant, five times second and third best and four times worst.

On average the front vibration motor performed best (Mean: 1.26 SD: 0.57) and the back LED worst (Mean: 3.13 SD: 0.81) as shown in table 4.3.

Feedback Modality	LED Front Main	 SD	LED Back Mean	 SD	Vibration Front Mean	 SD	Vibration Back Mean	 SD
Comfortability	4.27	0.57	3.73	1.24	4.47	0.81	3.93	1.06
Noticeability	3.13	1.15	3.40	1.20	4.73	0.57	3.73	1.31

Table 4.4: Mean Ratings for Comfortability and Noticeability on a 5 point Likert Scale with Standard deviations for all feedback modalities (1 = strongly disagree and 5 strongly agree)

Feedback Modality	LED Main	 SD	Vibration Mean	 SD
Distinguishability	4.40	0.80	2.60	1.31

Table 4.5: Mean Ratings for Distinguishability on a 5 point Likert Scale with Standard deviations for all feedback modalities (1 = strongly disagree and 5 strongly agree)

The average results of the other questions are shown in table 4.4 and 4.5, where 5 is the highest and 1 the lowest possible rating. According to the given answers, the front vibration motor (Mean: 4.47 SD: 0.81) and the front LED (Mean: 4.27 SD: 0.57) were the most comfortable feedback modalities. The least comfortable modality was the back LED (Mean: 3.73 SD: 1.24) (see figure 4.5). In terms of noticeability, the front vibration motor (Mean: 4.73 SD: 0.57) was rated best and the front LED (Mean: 3.13 SD: 1.15) worst (see figure 4.6). In contrast to the vibration feedback (Mean: 2.6 SD: 1.31) the LED feedback (Mean: 4.4 SD: 0.8) was rated to be easier to differentiate (see figure 4.7).

Vibration front and LED front were rated most comfortable

Front vibration and back LED were rated most notiable

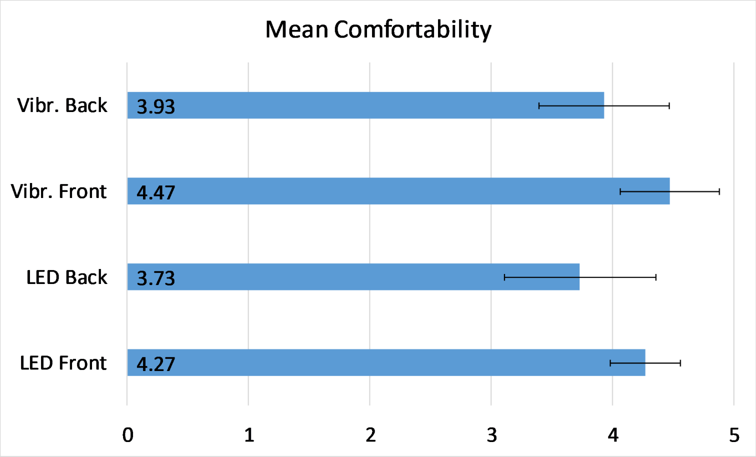

Figure 4.5: Mean Rating of perceived comfort on a 5 point Likert Scale and 95% confidence intervals for all feedback modalities (1 = strongly disagree and 5 strongly agree)

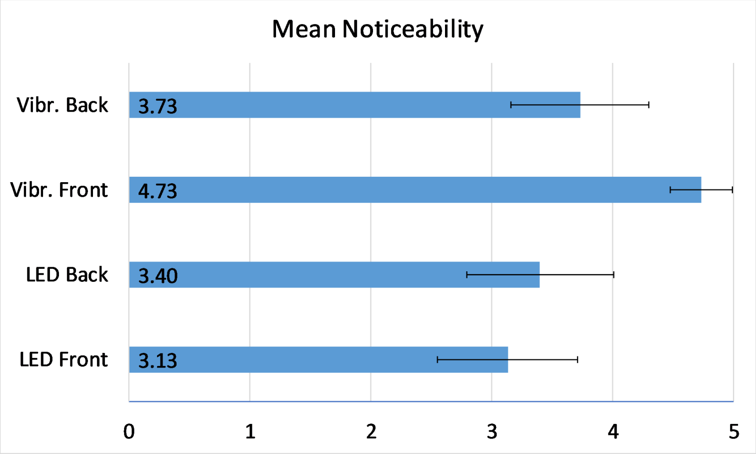

Figure 4.6: Mean Rating of noticeability on a 5 point Likert Scale and 95% confidence intervals for all feedback modalities (1 = strongly disagree and 5 strongly agree)

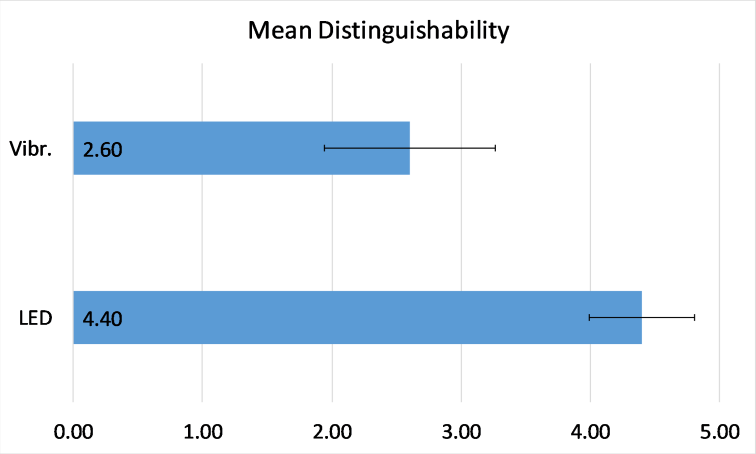

Figure 4.7: Mean rating of distinguishability on a 5 point Likert Scale and 95% confidence intervals for all feedback modalities (1 = strongly disagree and 5 strongly agree)

4.4.3 User comments

In addition to the quantitative measurements, the participants also had the opportunity to give individual comments about their experience with the Pengible and its overall design.

Three participants stated that they were blinded by the back LED, one suggested to diffuse the light. Another one advised to use bigger LEDs with lower light intensity. Four other users noted that they could not see the front LED because it was either covered by their hand or by the pen itself. They also noted that the coverage heavily depended on the drawing angle and that they sometimes had to change their grip to be able to see the LED.

Back LED was to bright

Front LED sometimes not visible

During the trial or in the questionnaire, four participants described the vibration motors as least obtrusive while drawing. The size of the pengible was also mentioned as uncomfortably big or bulky by three participants.

Vibration motors least obtrusive

4.5 Discussion

The study showed several advantages and disadvantages of the current Pengible design and its feedback modalities. When comparing both visual feedback modalities, it took the users less time to notice the back LED, but the results of the questionnaire showed that it was also the least comfortable. The reason for this could be the fact that some users stated that they were blinded by the LED. The front LED was perceived as more comfortable than the other LED, but the broad distribution of its recognition times suggests that the holding angle of the Pengible massively influences its recognisability. This was also mentioned by four participants in the comments. Another explanation why the back LED performed better than the front one could be that its uncomfortableness itself led to a fast recognition since it was more disturbing than the more comfortable front LED.

Holding angle may influence front LED recogniseability

Looking at the tactile feedback, the front vibration motor was recognised faster than the back one. The reason for this could be the placement of the fingers of the user since the indents in the surface of the Pengible enforce a specific grip. The reason for this design choice was to get the user to hold the pen in a way that the front LED is always orientated upwards. In addition to that, the front motor was mounted directly under the predicted location of the fingertips of the user. The back motor, on the other hand, was placed at the very end of the Pengible, far away from the points where the user is likely to grab. Since its easier to recognise a tactile stimulus with one's fingertips, the participants could feel the vibration on lower intensities.[Benninghoff and Drenckhahn, 2004]

Chosen grip position may favour front vibration

However, most of the users could not actively differentiate both motors from each other, which could be attributed to the fact that both were glued to the hull of the Pengible. This causes the whole Pengible to vibrate when one motor is active. Therefore, both motors mostly differed in their perceived intensity and not the actual position. As stated in the procedures section the intensity of the vibration was

Vibration motors are not easily differentiable increased with every second. So when it was noticed, the intensity of the vibration was already strong enough that the user could not differentiate between a strong back motor vibration and a weak front motor vibration.

To explain the differences in the reaction times, the task itself has to be taken into consideration as well. While performing the task, the user was heavily focused on the actual drawing. Therefore, he did not look directly at the Pengible and its LEDs. Since the vibration feedback does not depend on the user's field of view, it was recognised almost immediately even when the user did not look directly at the Pengible.

Tactile feedback better noticeable during drawing tasks

Taking all results into account we conclude that when performing a mainly visual task it is advisable to use the front vibration motor for feedback since it is easy to notice and unobtrusive. When additional feedback modalities are needed, the LED on the back of the Pengible should be used. To prevent the uncomfortable blinding effect, the usage of a diffuser is recommended.

front vibration easy to detect and unobtrusive

4.6 Resulting Changes for the Pengible

The results of this study lead to three design changes for the Pengible. Firstly, we removed the front LED and the back vibration motor since they were outperformed by their counterparts. Another cause for this removal was that we needed to save space inside the Pengible and therefore we decided to remove one feedback modality of each type. The second change was the addition of a diffuser (see figure 4.8) for the back LED to accommodate the complaints about its brightness. Lastly we were able to reduce the Pengibles circumference even further, from 25mm to 20mm (see figure 4.9), which makes it easier and more comfortable to hold the Pengible.

Front LED and Back vibration motor removed

Pengible's circumference reduced

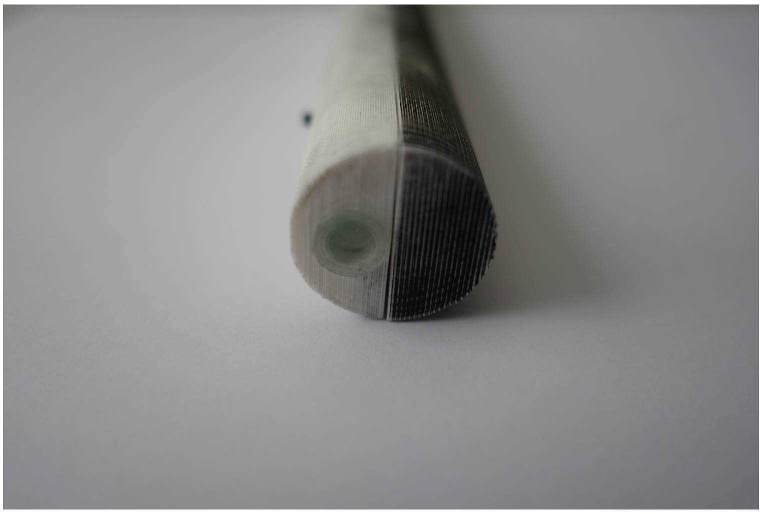

Figure 4.8: Diffuser for the back LED made from translucent material

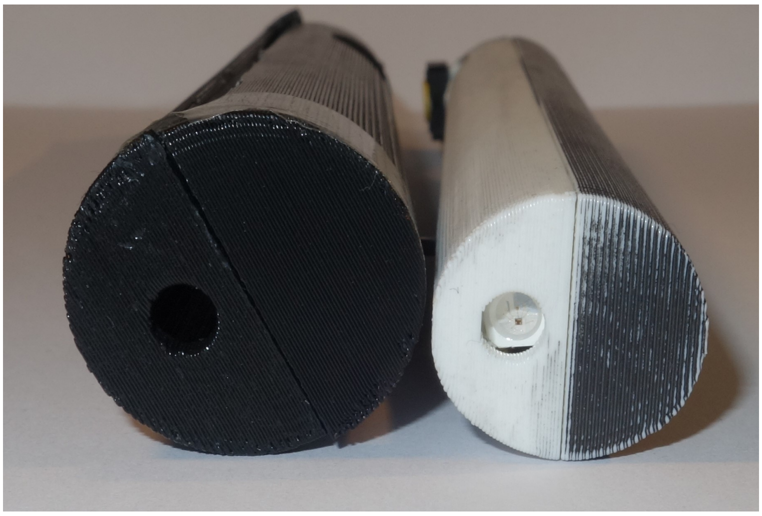

Figure 4.9: Circumference comparison between the old (left) and the new (right) Pengible hull designs

Chapter 5

Summary and Future Work

To conclude this thesis we will summarize our work on the Pengible and we will sketch out possible future work with the Pengible.

5.1 Summary and Contributions

New hard and software were designed

Throughout this thesis, we created and improved the Pengible based on the PERCs Tangible. We redesigned the soft- and hardware to work on an ATmega328P; this made the Pengible more accessible and extensible. Furthermore, we added some new functionalities to the Pengible like the multi-colour-LED and the fully controllable vibration motor. These functions were also integrated into the Mulitouchkit (MTK), which is necessary to work with each of our Tangibles.

Userstudy was conducted, and the Pengible was refined

To determine the best positions for the LED and the vibration motor, we conducted a user study. We tested: LED back, LED Front, vibration motor front and vibration motor back. The participants had to draw a specific shape, and each of the feedback modalities was triggered multiple times throughout that task. During this task, the reaction time to each feedback modality was recorded. Afterwards, the participants had to rank each feedback individually and against each other. Our measurements showed that the users preferred the LED and the vibration motor in the front. However, the measured recognition times showed that the front vibration motor and the back LED were perceived faster than the other feedback modalities.

5.2 Future Work

There are two fields of possible future work: The first field is the further development of the Pengible, the second one is the research on more possible usages of the Pengible.

5.2.1 The Pengible Hard- and Software

Further improve the Pengible

Since most electronic parts of the Pengible were handmade or prefabricated, our ability to reduce the size of these parts was limited. In a future version of the Pengible, it would be possible to further reduce the size of the individual parts by fabricating them via industrial-grade machines. Additionally, the Pengible could be extended with new Feedback modalities like a buzzer or a weight-shifting feature like the one presented by Huang et al. [2020]. Furthermore, the Pengible needs to be fully integrated into the MTK. To do so, the MTK needs to differentiate between the old three touch-point Tangibles and the new one touch-point Tangible.

5.2.2 Future Usages

Explore new applications

Writing is a vital part of learning. Therefore, learning apps for foreign languages could profit from the Pengible and its immediate and direct feedback options. But it needs to be evaluated if these types of feedback have a greater positive impact on the learning effect than the traditional methods.

Appendix A

Study Questionnaire

The following pages contain the complete questionnaire which was used in the user study.

Questionnaire

Nr:

Age:

Gender:

LED Front:

The Feedback was comfortable

Strongly disagree				Strongly agree
1	2	3	4	5

The Feedback was easy to notice

Strongly disagree				Strongly agree
1	2	3	4	5

LED Back:

The Feedback was comfortable

Strongly disagree				Strongly agree
1	2	3	4	5

The Feedback was easy to notice

Strongly disagree				Strongly agree
1	2	3	4	5

Both LED Feedbacks where easily distinguishable

Strongly disagree				Strongly agree
1	2	3	4	5

Vibration Front:

The Feedback was comfortable

Strongly disagree				Strongly agree
1	2	3	4	5

The Feedback was easy to notice

Strongly disagree				Strongly agree
1	2	3	4	5

Vibration Back:

The Feedback was comfortable

Strongly disagree				Strongly agree
1	2	3	4	5

The Feedback was easy to notice

Strongly disagree				Strongly agree
1	2	3	4	5

Both Vibration Feedbacks where easily distinguishable

Strongly disagree				Strongly agree
1	2	3	4	5

Rank the feedback (1= best)

1.

2.

3.

4.

Additional Remarks:

(About Feedback or the pen itself)

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