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Faculty of Electrical Engineering
Department of Computer Graphics and Interaction

Master's Thesis

New applications of tactile modules for individuals with vision impairments

Bc. Kryštof Woldřich
Open Informatics, Human-Computer Interaction

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Supervisor: Ing. Miroslav Macík, Ph.D

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Woldřich Kryštof** Personal ID number: **466201**

Faculty / Institute: **Faculty of Electrical Engineering**

Department / Institute: **Department of Computer Graphics and Interaction**

Study program: **Open Informatics**

Specialisation: **Human-Computer Interaction**

II. Master's thesis details

Master's thesis title in English:

New applications of tactile modules for individuals with vision impairments

Master's thesis title in Czech:

Nové způsoby využití hmatových modulů pro osoby se zrakovým postižením

Guidelines:

Individuals with vision impairments have specific problems and needs, especially from the perspective of spatial orientation and interaction with technologies. Research related to this target user group is a long-term topic at a research group at the Department of Computer Graphics and Interaction. One of its products is an interactive modular map of rooms. This solution could be potentially used in other scenarios involving tactile interaction.

Analyze current research related to the topic of support of individuals with severe vision impairment, including research conducted at the DCGI [1-4]. Focus on methods and approaches involving tactile interaction. Conduct user research into the target user group. Design use-case concepts of interactive modular tactile maps for other purposes (i.e., learning Braille script, interactive games, etc.). Using the User-Centered Design [5] method, design a set of solutions that will benefit the user group of individuals with severe vision impairment. Implement a set of prototypes that will allow evaluation of practical usability and utility. Evaluate the prototypes with representatives of the target user audience.

Bibliography / sources:

[1] Macik, M. (2018). Cognitive aspects of spatial orientation. Acta Polytechnica Hungarica, 15(5), 149-167.

[2] Gintner, V., Macik, M., & Mikovec, Z. (2019, September). Perception of tactile symbols by visually impaired older adults. In IFIP Conference on Human-Computer Interaction (pp. 325-334). Springer, Cham.

[3] Palivcová, D., Macík, M., & Míkovec, Z. (2020, April). Interactive tactile map as a tool for building spatial knowledge of visually impaired older adults. In Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1-9).

[4] Macik, M., Ivanic, T., & Treml, L. (2021, August). Interactive Modular Tactile Maps of Rooms for Older Adults with Vision Impairments. In IFIP Conference on Human-Computer Interaction (pp. 321-330). Springer, Cham.

[5] DIS, ISO. (2009). 9241-210: 2010. Ergonomics of human system interaction-Part 210: Human-centred design for interactive systems.

Name and workplace of master's thesis supervisor:

Ing. Miroslav Macík, Ph.D. Department of Computer Graphics and Interaction

Name and workplace of second master's thesis supervisor or consultant:

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Ing. Miroslav Macík, Ph.D.
Supervisor's signature

Head of department's signature

prof. Mgr. Petr Páta, Ph.D.
Dean's signature

III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt

Student's signature

Acknowledgement / Declaration

I would like to thank my supervisor, Ing. Miroslav Macík, Ph.D., for his patience, valuable advice and encouragement.

I also could not have undertaken this journey without Lukáš Treml, who generously provided knowledge and expertise.

Thanks should also go to Jan Příborský for his feedback.

Lastly, I'd like to mention my family for supporting me during my studies.

I declare that this thesis was composed by myself, and I quoted all used sources of information in accord with Methodical instructions about ethical principles for writing academic theses.

Prague, May 20, 2022

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Abstrakt / Abstract

Na Katedře počítačové grafiky a interakce na FEL ČVUT probíhá vývoj interaktivní hmatové modulární mapy interiérů. Tato diplomová práce představuje rozšíření pro nové účely, které je založené na stejné základní elektronické desce. Provedli jsme analýzu mnoha pomůcek, které lidé se zrakovým postižením používají. Nejprve jsme se zaměřili na pomůcky pro výuku a později na volno časové pomůcky a kompenzační nástroje. Analýza nám ukázala chybějící produkty mezi jednoduchými analogovými pomůckami a specializovanými elektronickými nástroji.

Za použití iterativního návrhového procesu UCD jsme vytvořili rozšiřující desku nazvanou Braillův dvoj modul. Poslední iterace má skvělou hmatovou odezvu s dvěma plnýma Braillovo šesti body navrchu. Tento vhodně navržený modul nám umožňuje kombinovat výuku Braillova písma a pexeso, které pomáhá s procvičováním látky. Dále jsme připravili mnoho zábavných herních balíčků. Nejoblíbenější mezi účastníky experimentu byly známé české hlasy. Krom zmíněných, modul lze také použít k simulaci vysílačky pro nevidomé.

Hlavní reakcí na interakci hmatem je převod textu na hlasovou syntézu, jejíž kvalita byla zásadní pro náš projekt.

S lidmi spadajícími do naší cílové skupiny jsme provedli experiment použitelnosti. Začali jsme s podskupinou aktivních nevidomých dospělých. Podle výsledků řešení splňuje zadané požadavky. A až na drobné vady jsme sbírali mnoho nápadů na nové funkce a vylepšení.

Klíčová slova: Haptic Tiles, Braillovo písmo, Pexeso, škola hrou, zrakové postižením, interakční design

Překlad titulu: Nové způsoby využití hmatových modulů pro osoby se zrakovým postižením

An interactive tactile modular map of an interior is being developed at the Department of Computer Graphics and Interaction at the CTU FEE. This thesis presents an extension beyond maps using the same baseboard electronics. We have analysed a broad range of aids that individuals with vision impairments use. At first, we focused on education, and later we moved to entertainment and life-enhancing tools. Based on our findings, we have seen a gap between simple physical tools and specialised electronic gadgets.

Following the iterative design process of UCD, we have created an extension board called Double Braille Module. The latest iteration has excellent tactile feedback and two Braille six-dots on the top. This one well-crafted module lets us combine Braille education and a Memory game that helps with the practice. Furthermore, we prepared many more game data sets for the users. Participants' favourites were the Famous Czech voices. Lastly, this module is a talking signs system simulator.

The primary response to a touch interaction is text to speech voice synthetisation, which quality was crucial for the project.

We have conducted a usability experiment with members of the target groups. We started with part of vision-impaired active adults. Evaluation indicates that our solution fulfils the requirements, and besides minor errors, we collected only future enhancements.

Keywords: Haptic Tiles, Braille, Memory game, edutainment, vision impairment, interaction design

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Chapter 1
Introduction

In the beginning, we state our motivation for this project. Why are we focusing on individuals with vision impairments? What could be the benefits of extending an already existing solution, and why this solution seems like a good base? We introduce directions we believe are suitable for being the new ways of using the Haptic Tiles baseboard, Figure 1.2.

We briefly describe our goals and expectations of the thesis results. We aim to analyse the topic, design new hardware, implement software to connect the original baseboard with the new extension and conduct a usability experiment with visually impaired individuals.

Lastly, we outline the methodology and processes of our work that we will use to achieve the mentioned goals and fulfil our expectations.

1.1 Motivation

The amount of individuals with visual impairments over the years is growing. The International Agency for the Prevention of Blindness (IAPB)[1] estimates that 1.1 billion people were vision impaired in 2020. Out of this, 338 million people were severely vision impaired, and of that 43 million were blind. Future prediction points towards 535 million severely vision impaired individuals and from that 61 million blind by 2050. Full research data is available in [1]. And historic data for comparison shows Figure 1.1.

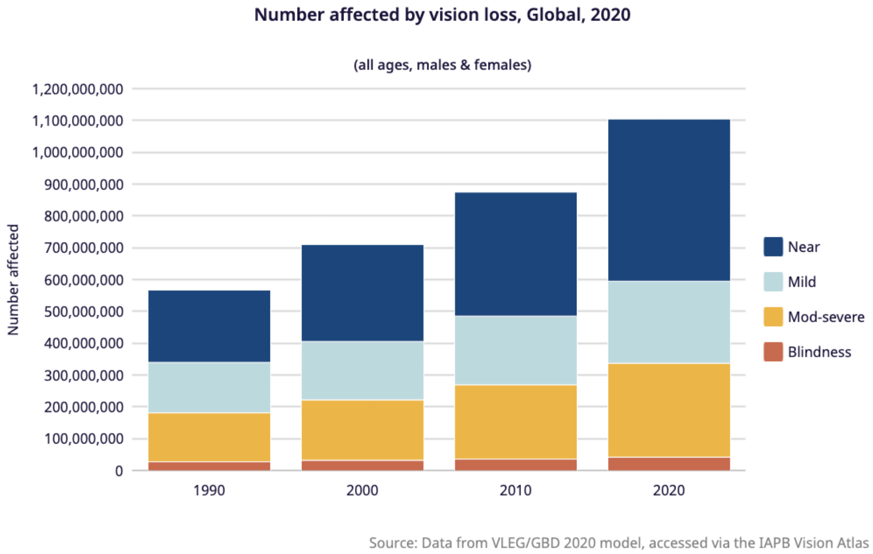

Figure 1.1. Number affected by vision loss, Global, 2020, Source[2], [1]

[1] https://www.iapb.org/

[2] https://www.iapb.org/learn/vision-atlas/magnitude-and-projections/global/

When we focus on the Czech Republic in 2020, there were 402 thousand severely vision impaired individuals, and out of that 66 thousand were younger than 50 years old. This data from [1] is also presented in online info-graphic[3].

"In many regions, the scale and approach of existing service delivery are insufficient to meet current population needs, let alone the projected increases in vision loss by 2050." says IAPB in their future projections[4] with the estimated increase to 1.7 billion individuals with visual impairments by 2050.

Previous research in the field of HCI and visually impaired individuals at CTU resulted in a haptic interactive map called Haptic Tiles. As the name suggests, connected tiles are the map's base that creates a surface of any shape. That creates a scaled-down representation of a room. A user can furnish the room using 3D printed parts. When the user moves, they can remodel the map into the new environment.

We want to extend the functionalities of this product more, as we see a lot of potential use cases using the map baseboards, see Figure 1.2. The inner boards' communication and connection to a computer are already designed and tested. We will analyse existing tools, aids for the visually impaired and games that the people play or could play if adjusted. Based on the analysis, we will create prototypes of extensions for the Tiles to bring new functionalities.

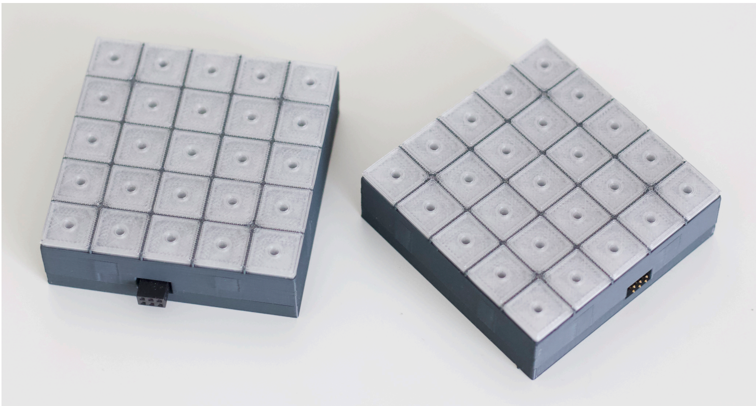

Figure 1.2. Empty unconnected Haptic Tiles boards.

1.2 Goals

We will search for possibilities where the Haptic Tiles extension could help with education, entertainment or combination edutainment. We move to design, prototyping, testing, and implementation when we find such an option. Particular goals are specified in the following list.

Goal 1.1 Analyse current related research, tools, and aids for individuals with severe vision impairments. Focus on the method and approaches involving tactile interaction. Select possible results for designing a new solution as an extension to the Haptic Tiles.

Goal 1.2 Design a set of solutions that will benefit the user group of individuals with severe vision impairments using UCD [2]. Both extension physical appearance and software to control it.

Goal 1.3 Evaluate the prototypes with representatives of the target user audience.

[3] https://www.iapb.org/learn/vision-atlas/magnitude-and-projections/countries/czech-republic/

[4] https://www.iapb.org/learn/vision-atlas/magnitude-and-projections/

1.3 Methodology

Our design process follows user-centred design guidelines, UCD, as described in [2]. Nevertheless, the ISO standard is not our only source. We also use the information from [3] as the following description of design by David Benyon, "Design is a creative process concerned with bringing about something new. It is a social activity with social consequences. It is about conscious change and communication between designers and the people who will use the system."

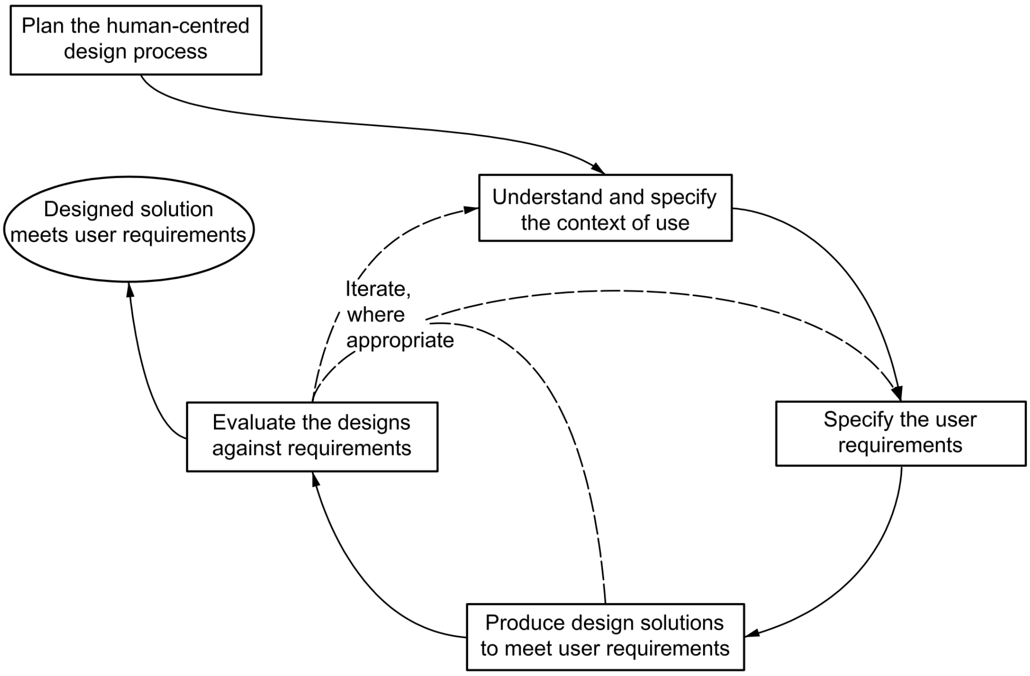

Figure 1.3. Interdependence of human-centred design activities from [2], page 11.

Our approach to the UCD loop is to iterate every week, a full two weeks, in case of more extensive changes or some unexpected issues. We meet mainly in person since we work with a physical product, and touch is crucial for the loop evaluation.

Chapter 2
Analysis

This chapter focuses on analysing existing education aids, practical live aids, and technological aids. The first section, named Edutainment, focuses on common aids used in Braille education, practical everyday life tools and desk games. The last-mentioned we hope to transform into a new edutainment aid. The second section focused on related technologies, which we can use as inspiration during our design process.

2.1 Edutainment

As individuals without any visual impairments, first, we analysed what is there to learn besides the obvious to us. Therefore, we discussed our topic with a teacher of people with lost or decreased vision. As an individual with visual impairments, he has excellent insight into the topic and showed us many possible use cases. We would not be able to discover some of them as a person without their specific needs.

Although many educational use cases can be gamified, some are purely entertainment and leisure activities. Mainly we have in mind desk games where the most significant obstacle seems to be the replacement of the visual aspects. Another helpful area is one-person games that users can play on their own.

2.1.1 Braille code

We would like to include Braille in this project because it is a fast [4] and popular [5] system that anyone can find at many public facilities. As with any alphabet, it can be used for reading and writing. Furthermore, there can be many forms of learning, from single letter recognition to writing paragraphs.

One letter written in braille consists of six points ordered from top to bottom, left to right, in two columns and three rows. That could be represented by a similar matrix of six buttons on the Haptic Tiles board. A person could learn individual letters in the following way. A computer connected to the board would explain the placement of the given letter's braille points, and the user would press the corresponding buttons. The computer would say if the point is part of the letter or not on the press. Additional information would be given on a repetitive press—for example, a sequence number of the given point. An LED can illuminate the point to be pressed to complete a letter for individuals with partial but not complete vision loss. During a test phase, users could be given a letter, and then they would have to press only the valid points. In case of a wrong move, a computer would announce that, and they would have to start over. A more challenging level of the test phase could be pressing the points in the correct order.

Table 2.1 summarises what we can do with the current Tiles baseboard and what could we create with a completely new solution. Currently, we can create a Braille extension module with one or two braille six-dots or eight-dots as buttons and write software that will teach users Braille. If we create a new board, we could implement radical atoms, and the board could also be used for reading.

Current solution	New solution
Buttons design Learning and test software	Radical atoms interface for reading

Table 2.1. Comparison of the current and the future options in learning Braille code.

2.1.2 Braille writing with slate and stylus

Writing braille could be trained using Stylus and Slate method [6], also called "Pražská tabulka", where users push mirrored braille symbols into a paper. In the case of Haptic Tiles, the users could push the stylus into the board holes. A connected computer can read what the user is writing for self-check purposes or can guide beginners in how to mirror given symbols.

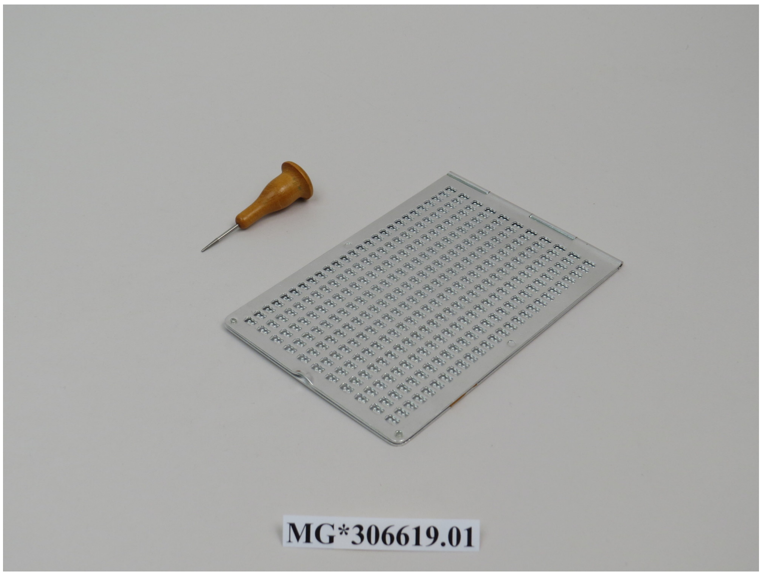

Figure 2.1. Tylor Micro-Braille Slate with Stylus[1]

Table 2.2 summarises what can we do with the current Tiles baseboard and what can we do with a completely new solution. With the current board, we can design a stylus reminding the actual one used with the writing slate, and the board will be simulating the slate. The software will check users and guide them to learn to write Braille characters mirrored as they have to do it on the actual slate. If we design a completely new solution, the board could also be used for reading the written text.

Current solution	New solution
Stylus design Self-learning and writing software	Radical atoms interface for reading written text

Table 2.2. Comparison of the current and the future options in learning Braille writing.

[1] https://americanhistory.si.edu/collections/search/object/nmah_737561

2.1.3 Braille cube

Braille cube is a tool for learning and practising braille. The cube body is divided into three rotating parts. Each part has four sides with none, one on the left, one on the right and two braille points—this way, any braille symbol can be created.

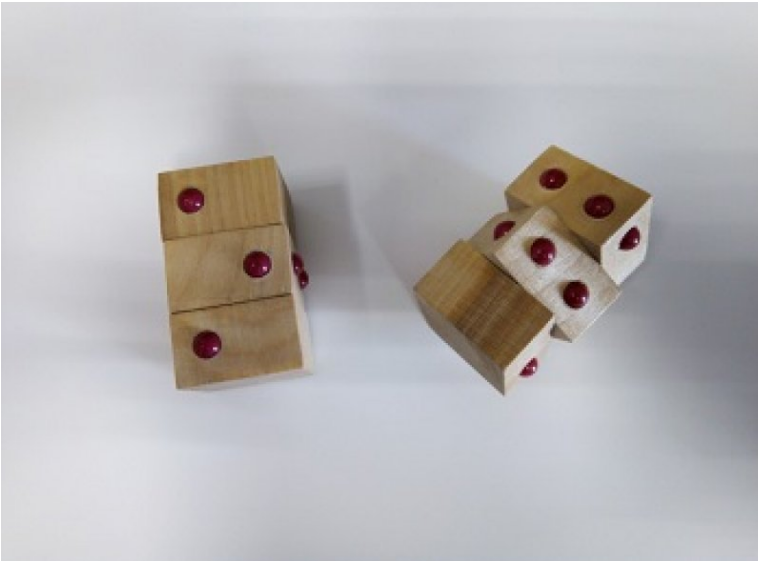

Figure 2.2. Braille cube made out of light colored wood with red points. Source[2]

Table 2.2 summarises how we can simulate the functions of a Braille cube using the current solution and what we could do with a completely new solution. We can currently use a board with Braile six-dots and software to subsidise the inability to hide dots. We could change the raised dots and be closer to the original cube idea with the new solution.

Current solution	New solution
Buttons design	Radical atoms
Checking software	

Table 2.3. Comparison of the current and the future options in virtual Braille cube.

2.1.4 Braille six-buttons keyboard

Another method of writing is a braille keyboard consisting of two blocks, one row with three buttons and a spacebar in the middle underneath. This keyboard could work in two modes, practice and memory. In the practice mode, a connected computer plays each written sound. In memory mode, the written text will be saved and can be played on request.

Braille writing on a regular computer keyboard uses keys S, D, F and J, K, and L to write points 3, 2, 1 and 4, 5, 6 respectively [7]. A spacebar works as intended. This mapping of braille is natural since J and F have an anchor point [8], a small bump at the bottom of a key for correct hand placement.

[2] https://www.tyflopomucky.cz/praha/pomucky-pro-vyuku-psani/1220-B-kostka-drevena.html

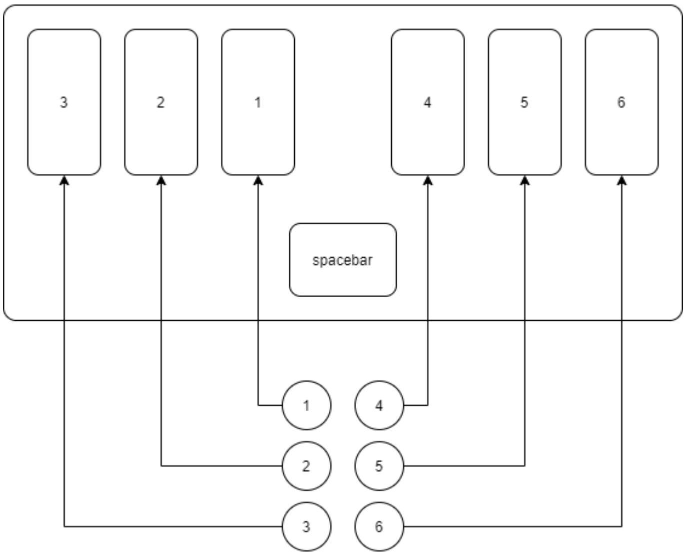

Figure 2.3. Braille keyboard with 6 buttons and spacebar underneath.

Current solution	New solution
Buttons design Self-learning and writing software	-

Table 2.4. Comparison of the current and the future options in learning Braille writing.

Table 2.4 summarises how we can use the current Tiles baseboard and that we do not need any new solution to create a Braille keyboard. We can create an extension module board with buttons spaced as Figure 2.3 shows and software that will process the input as writing on a keyboard.

2.1.5 Audio ATM Training

As of November 2021, only two banks have ATMs with an audio interface [9]. For many others, while having the physical audio output available, the software on the machines is missing.

Using an ATM with an alternative audio interface differs from standard usage in multiple steps. The ways split already when approaching the machine, even before any banking related interaction.

First, the user has to locate an audio jack for his headphones. The connector is usually located on the right side of the ATM under the insert of a banking card. It is on the right from the ATM's keypad in some cases. The presence of the connector does not mean audio interaction is available in the machine software. In many cases, the software does not change its behaviour based on connected headphones, and the only audio output is a two-tone chine announcing a successful or failed operation. If the ATM software supports the audio interface right after headphones are inserted, the user will hear a voice guiding him/her to insert his/her banking card into the slot.

A rounded metal volume button on the right side of the connector is located, which usually has three levels. From observation, there is no level indication when changing the volume. Therefore a user only hears the change when the ATM communicates with him/her.

Now is the actual time for controlling the ATM and making some banking operations. Right away, when the headphones are connected, the UI on the ATM's screen changes.

It turns from a rich graphic to plain text and single colour background. The text is a numbered list of operations like withdrawing money, cancelling the transaction etc [10]. The actual process of these operations is more or less the same as for the regular rich graphic interface. Therefore we will not go too much into detail about it here. Nevertheless, we will focus on how to interact with this interface since the ATM does not offer any explanation.

Every standard ATM machine has a four by four keypad with a number block on the left and control buttons on the right of the block. The numbers are assigned from left to right, top to bottom, and one to nine. A zero is placed in the last row in the middle. The * and # sometimes are included, but the keys surrounding the zero are usually blank. Control buttons consist of Cancel, Repair and Confirm. The order is usually just as mentioned. The placement is from top to bottom with minor differences with Confirm. Sometimes it is placed at the bottom, leaving one empty button above it.

Figure 2.4. ATM Keypad with headphones jack and control buttons above. Source[3]

The user presses a number of the given option from the list to select the mentioned list items. Control buttons on the right side work precisely as their names suggest, plus the audio guidance emphasises their action. For example, by sentence *"Press Confirm to continue or input PIN and press Confirm."*

Table 2.5 summarises that we can do ATM simulation without designing a completely new solution. An ATM keypad module and software can extend the current Tiles boards to simulate ATM behaviour.

[3] https://unsplash.com/photos/TA5DYQ3Pvi8

Current solution	New solution
ATM keyboard design	
Simulation software	

Table 2.5. Comparison of the current and the future options in ATM simulation.

2.1.6 Talking signs system (TSS)

Talking signs system in short TSS, in Czech known under the name "vysílačka pro nevidomé" shortened as VPN, not to be confused with virtual private network VPN, is an aid for outside orientation in public spaces for individuals with visual impairments. A user has pocketable battery-powered radio remote control which can activate audio beacons in their surroundings. These beacons are strategically placed at public transport stops, inside public transport vehicles, at entrances to buildings, escalators, information boards, traffic signs and other places.

The remote control mainly activates a prerecorded audio sequence that helps the users to navigate to the beacon and so to a place marked this way. However, in public transport, it informs the driver about the boarding or exit of an individual with visual impairments at the next stop, the same way a stop button works inside or outside of the vehicle. At the traffic light, it activates an audio signalisation.

In Czech republic the beacons and remotes are being made by APEX® spol. s r. o. in Jesenice and by Elvos s.r.o. in Bílovice nad Svitavou.

The commonly used remote control has six buttons in two columns and three rows. It looks like an enlarged Braille six-point, as Figure 2.5 shows. However, the numbering differs from the Braille system. Version integrated into a white cane[4] has only 3 buttons in 1 column, as displayed on the right in Figure 2.5. However, since this version is the newest and only made by one of the manufacturers, we will focus on the original solution in the further description.

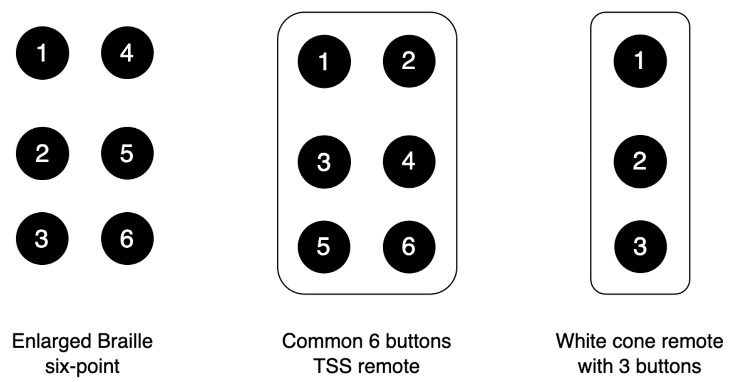

Figure 2.5. Comparison Braille six-point numbering with common TSS remote and white cone integrated remote.

The following description of features is a combination of information from the official website of the United Organization of the Blind and Visually Impaired of the Czech Republic [11], know under shortcut SONS, APEX manufacturer official description [12] and Elvos documentation [13].

The list describes older [5], and more used six buttons model of the TSS remote.

[4] http://www.apex-jesenice.cz/tyfloset10.php?lang=cz
[5] http://www.apex-jesenice.cz/tyfloset1.php?lang=cz

- **Button No. 1** Starts welcome audio track and base voice phrases of the audio beacon.
  Short press – One-time playback
  Long press – Two minutes of repeated playback. Any button press cancels it.
- **Button No. 2** Starts extended voice phrases of the audio beacon. For example, the state of machines like escalators, elevators or lifts, or opening times of offices and others.
- **Button No. 3** Starts voice information about public transport vehicle and its end stop.
- **Button No. 4** Announce boarding or exit of an individual with visual impairments to or from the public transport vehicle. Supports trams, busses and metro. The button also extends a platform for a more accessible entrance or exit in supported vehicles. The buttons call in a porter or security guard at public service buildings.
- **Button No. 5** Starts audio signalisation in a traffic light at pedestrian roads or rail crossings.
- **Button No. 6** Start voice output of information board at public transport stops or activates keyboard at some general information boards with voice output.
- **Hold buttons No. 5 and 6** Changes between Czech, Slovak and European Union frequencies.

Long press buttons No. 2 to 6 auto repeats the signal emits.

Implementation of the TSS simulator does not require any new development. It can be done entirely using the current baseboard design as the remote consist of only buttons. Table 2.6 shows what needs to be prepared using the current solution and highlights that there is no new solution.

Current solution	New solution
Buttons design	
Simulator software	

Table 2.6. Comparison of the current and the future options in learning Braille writing.

2.1.7 Reversi

“According to Whitehill, Reversi is a British antecedent for the game of Othello.” [14] It is a game of two-player Black and White, trying to obtain as many discs as possible. The discs are two coloured coins, black and white. The game board is an eight by eight matrix with numbered rows and alphabetically named columns from “a” to “h”. To gain more disc, players are enclosing their opponents. Captured discs are switched to the colour of the player who captured them. The figure 2.6 shows common field names on the left, respective Reversi fields names in the middle and the initial game state on the right.

A plain buttons version of this game should be pretty simple to transform for HapticsTiles. It will rely heavily on software implementation, which informs users or takes action in the game based on button click.

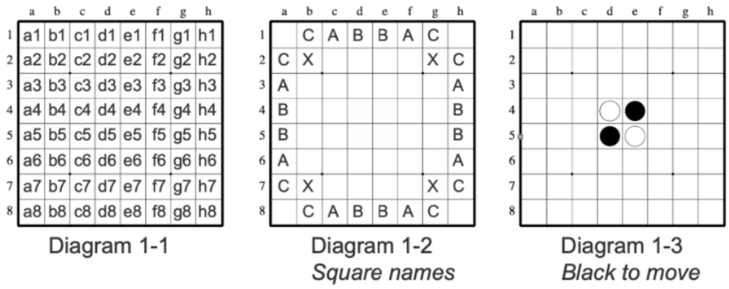

Figure 2.6. Reversi playing game field diagram, 1 to 8 rows, a to h columns. Source [15]

Current solution	**New solution**
Button design Game software (Two players, Computer opponent)	Radical atoms

Table 2.7. Comparison of the current and the future options in learning Braille writing.

Table 2.7 summarises how we can design a Reversi game alternative using the current Tiles baseboard. We can create an extension module with buttons and software to keep the game's state. That could be relatively inefficient for the users, but it would work. If we design a new solution, we can implement radical atoms, which will keep the game's state.

2.1.8 Battleship

The game itself is a well-known position war-themed two-player strategy. By [16] the first phase starts with placing the limited number of battleships into the sea, meaning the game board. The second and longer-lasting phase is the battle. When players during an attack are calling positions, and the opponents are defending by calling hit or miss positions.

Current solution	**New solution**
Hit and miss objects to place on board Rows and columns dividers Game software (Two players, Computer opponent)	Radical atoms

Table 2.8. Comparison of the current and the future options in learning writing.

Table 2.8 summarises how we can implement the Battleships game using the current Tiles baseboard. We can create 3D printed models of ships that the users will place on the map. That will work the same as the maps are designed today. We will create some extension grid guides for more effortless operation. The software will keep the game's state and record hits and misses. If we design a new solution, the radical atoms can implement a physical display of the game's state. Therefore, users will feel it if they hit or miss instead of hearing the information.

2.1.9 Memory game

A desk game called Memory game, “Pexeso” in Czech, has one objective match all items on the board. The classic version of this game has an amount of items to be matched that can be placed in a square. That is so a square can be created of all the items. The items typically are pictures printed on square pieces of paper. Every picture is twice in the stack. The game can be played by one player. Their objective would be to match all items. If more players are involved then the player with the most matches wins.

The game is similar to the rest in its default state, unplayable for individuals with visual impairments. We can change the objective from matching visuals to matching audio or feel to touch, like vibrations.

We found a memory game adaptation for individuals with visual impairments. Where they are using a computer game and connected vibration gamepad. Players are using one pad to navigate the playing field, and when they select an item, they can feel a specific vibration sequence. The problem with this approach was the players’ imagination of the field. Therefore, the researchers who conducted the experiment created a Haptic model using which the player could imagine what the playing field looked like—more about the process written in article [17].

We could implement the game using the current Tiles boards by creating an extension module with a button representing the items to be matched. Given the boards and placement of the microswitches, the items will not be in a traditional square layout. Nevertheless, we do not think that it is important. Therefore we only keep the objective to match all items, but we will change the placement. We will only keep in mind the number of items to have pairs. For example, to fill the board as possible, we can have 24 items and 12 pairs and leave the middle button to make a blank space on the module.

As summarised in Table 2.9, we need a button board module and software implementation with the current design. If we would like to use a touch more than to feel the playing field and press buttons, we could design a new baseboard using the idea of the radical atom and implement matching vibrations and sensing matched using it.

Current solution	New solution
Buttons board Game software	Radical atoms

Table 2.9. Comparison of the current and the future options of a memory game implementation.

2.2 Supporting technology analysis

In this section, we summarise related technologies, both related aids we can take inspiration from and tools we can use to create the future solution.

2.2.1 Radical atoms

Hiroshi Ishii has been a researcher at MIT Media Lab since 1995. His work Radical Atoms and Tangible Bits focuses on connecting the digital and physical worlds. The goal is to create a human-friendly interface that changes based on the digital input. This interface can have many forms and can be created from many materials. One of the examples is piston moved cuboids which can be used in both artistic and scientific directions. As briefly described by MIT News in [18]. The figure 2.7 shows human scale pistons moving a solid red ball on its surface.

Sized down versions of these cuboids, Radical Atoms, could be an excellent interface for individuals with visual impairments. Also, it could be another feedback function of the Haptic Tiles Board besides sound and LED, which are implemented in the current version, in more detail described in [19].

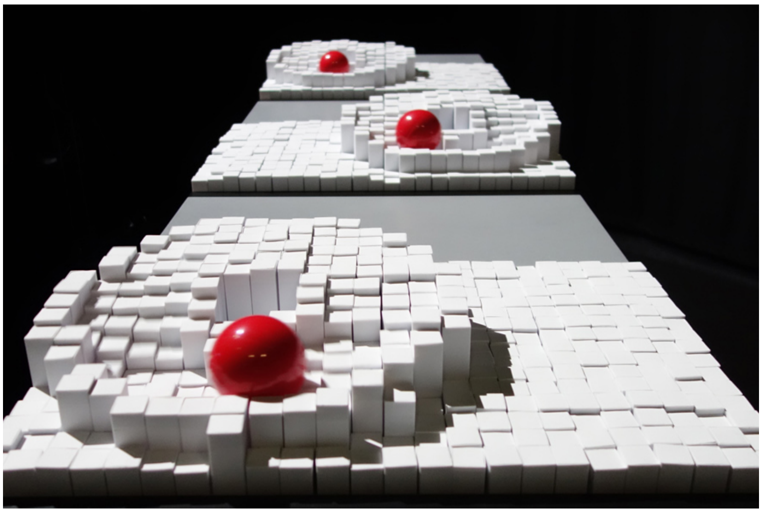

Figure 2.7. Radical atoms in human scale, white pistons moving red balls. Source[6]

2.2.2 Hable keyboard

This product is a snap-on controller for any smartphone, enabling users to type and control the device as described in its promotional material [20]. The device is equipped with six braille points and two additional function keys, as can be seen in figure 2.8, which can serve any purpose like spacebar, enter, scroll up and down, go back and forward and many more. Additional features can be set up using an application on a connected mobile device.

Figure 2.8. Hable keyboard on a white table. Source[7]

2.2.3 BrailleTooth

BrailleTooth is a 3D printed phone case with a braille keyboard at the back. This project was created in 2015 at 3D Printathon at Brandeis University. The purpose of

[6] 2012 Tangible Media Group / MIT Media Lab
[7] https://www.iamhable.com/blog/6-shortcuts-to-work-more-efficiently-with-your-hable-one

this event was to use 3D printing technology for social justice. Therefore Jason Powell came up with the idea of a 3D printed keyboard phone case for individuals with visual impairments as he describes the project in [21] and shows on figure 2.9

The keyboard is very similar to the previously mentioned. However, it is less refined with an unknown state of the internal electronics and software, which was promised to be open-sourced but the project ended before that happened. The only part released to the public is the 3D model of the case.

Figure 2.9. BrailleTooth cases, 3D printed prototypes, iPhone 5 case on the left, Samsung Galaxy S3 on the right. Source[8]

2.2.4 OSKAR

Another smartphone snap-on braille keyboard by Johannes Střelka-Petz from TU Vienna. Compared to the other solution, this is completely open-sourced and available at [9]. The keyboard consists of six braille points and two modifier keys. The keyboard was based on German standard DIN 32 982, but due to this standard obsolescent, the keyboard was programmed with newer Erich Schmid's 8 Keys Braille standard, as the author explains in [22] and shows in figure 2.10.

[8] https://www.thingiverse.com/thing:1049237

[9] https://gitlab.com/teamoskar

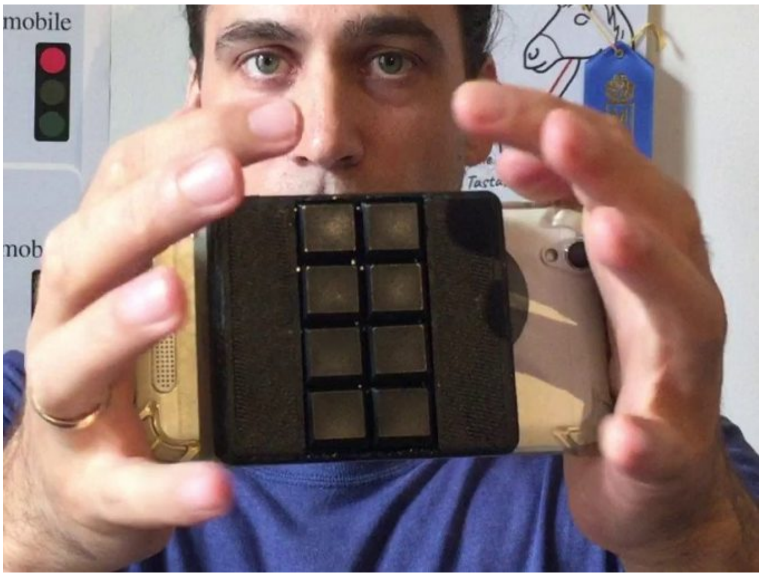

Figure 2.10. OSKAR braille keyboard on the back of an Android smartphone. Source[10]

2.2.5 Liblouis

Liblouis is an open-source bundle of libraries for translation to and from braille and formatting braille, states the [23]. Its core is written in C. However, it is meant to be used with high-level programming languages using binding libraries. Those exist, for example, for Python, Java or Javascript[11] (Both browser and Node.JS). The translation output is Unicode encoded braille characters as described by ISO 11548-1. Characters code the braille block from U+2800 to U+28FF. Details can be found in the official Unicode chart table[12]. Another exciting resource the Liblouis community created is a collection of braille specifications which includes standards from around the globe.

2.3 Analysis conclusion

There are quite a lot of products in various stages of development aiming to help individuals with visual impairments. Some are available as finished off the shelf products, like the Hable smartphone keyboard designed in the Netherlands. Many are in various stages of development, like keyboard attachment OSCAR from Austria. Furthermore, some only got to the prototype phase, like the BrailleTooth keyboard 3D printed phone case from the USA.

Both OSCAR and BrailleTooth are using 3D printing techniques to create prototypes of their keyboards. That is the right technology for the case since the second-mentioned project was developed and assembled in 24 hours, lasting a 3D printing hackathon. Therefore the time from sketch to physical mockup will be a matter of minutes, and it will be easy to develop new solutions iteratively.

Even though Hable and BrailleTooth are using two-tone designs with white buttons on dark grey and black boards, they are all facing away from the user; therefore, they only can be used to recognise which button is which. This is mainly caused by the case or snap-on design that aims to be used on the back of the phone. Some individuals

[10] https://innovationorigins.com/en/mobile-braille-keyboard-available-as-open-source
[11] https://github.com/liblouis/liblouis-js
[12] https://www.unicode.org/charts/PDF/U2800.pdf

with visual impairments could still use contrasting colours to recognise the buttons if they were facing them.

All of the mentioned braille typing solutions solve how to type, assuming the user already knows the code. Even learning tools like Braille cube require some knowledge to be helpful. There are missing tools in between that require no or low level of knowledge and can be used for learning or practising users' skills in understanding braille code.

Chapter 3
Design

We are proposing a solution based on the analysis from Chapter 2. It supports Braille education, TSS simulation and Memory Game. All these applications should be able to work with one well-designed module. The goal is to develop a touch interaction solution in the context of multimodal interaction. It is an interactive edutainment aid that can help all age categories. It tries to bridge the gap between simple tools like Braille Cube and pure practical products like Hable and other Braille input tools. It doesn't need to be a device operated by the user with visual impairments alone since the aim is to be used during education lessons.

3.1 Actors

This subsection will describe actors who will interact with the designed system. This includes the final user, lecturer, and researcher, as each has different specific needs.

- *User*
  is a individual with severe visual impairments who will be the end receiver of the edutainment experience of the designed tool.
- *Lecturer*
  is a person helping the User with the experience, preparing a computer, the tools, and controlling the software. It can also be referred to as a teacher or helper.
- *Researcher*
  is a person in need of deeper knowledge of User performance. They want to compare measurable metrics to different Users or track User, comparing the metric between different runs.

3.2 Requirements

Following functional and non-functional requirements are the results of analysis from chapter 2 and supporting technologies from 2.2. They reflect the needs of the specified actors from 3.1.

3.2.1 Functional requirements

Following functional requirements are marked using *FR X.Y*, where *FR* is a shortcut for functional requirement and X is a number of the current chapter and Y is the sequence number of the requirement. This notation is used throughout the document to refer back to the requirements.

The following set of requirements considers the physical aspects of the tool.

FR 3.1. The system enables User to control the experience using Braille points like controls, meaning two by three matrix or matrices that will resemble Braille symbols.

FR 3.2. The system gives User a tactile response to their actions which corresponds with the audio from FR 3.5.

FR 3.3. The system enables Lecturer and Researcher to start and end the experience for User.

The next set of requirements is considering the software properties of the tool.

FR 3.4. The system enables User to practice braille symbols. The system will give feedback to User if the given Braille point is part of the practised character or not.

FR 3.5. The system gives User audio response to its actions, corresponding with the tactile feedback form FR 3.2.

FR 3.6. The system gives User audio information about the application/game/practice state.

FR 3.7. The system gives Researcher data about User performance during the experience. The data includes information about:

- data mapping to the buttons
- recordings of button presses
- state of the experience after each button press

FR 3.8. The system gives data to Researcher in both human and machine-friendly forms. For example, format JSON, YAML or XML.

3.2.2 Non-functional requirements

Following non-functional requirements are marked using *NFR X.Y*, where *NFR* is a shortcut for non-functional requirement and X is a number of the current chapter and Y is the sequence number of the requirement. This notation is used throughout the document to refer back to the requirements.

NFR 3.9. The system should be easy to clean. For example, wipe with a wet cloth after use.

NFR 3.10. The system should be comfortable to touch, with no sharp edges and no misleading bumps.

3.3 Use cases

The diagram in Figure 3.1 shows all use cases based on requirements from section 3.2 and actors described in section 3.1. The general use cases are *Control*, *Start*, *Stop experience*. These are generalizations of specific applications, referred to as experience, like Learn *Braille numbering*, *Practice Braille characters*, *Play Memory Game* and *Practice TSS*. The same applies to *Retrieve log data*, where the specific cases are *Retrieve Memory Game log* and *Retrieve Braille character practice log*. These are only two in the diagram to show that not all the applications offer logs. Also, not in all cases, logs would be meaningful. Lastly, *Clean board* is an independent use case because it's not tied to any software application.

Besides generalization the diagram 3.1 shows a dependency relationship between *Start experience* and *Control experience*. This expresses that User can only control an experience that Lecturer has started. Similarly, Researcher can only retrieve logs from an experience that has started but doesn't have to be finished. For example, a game can be too long for User to finish, but data about the current state was already logged.

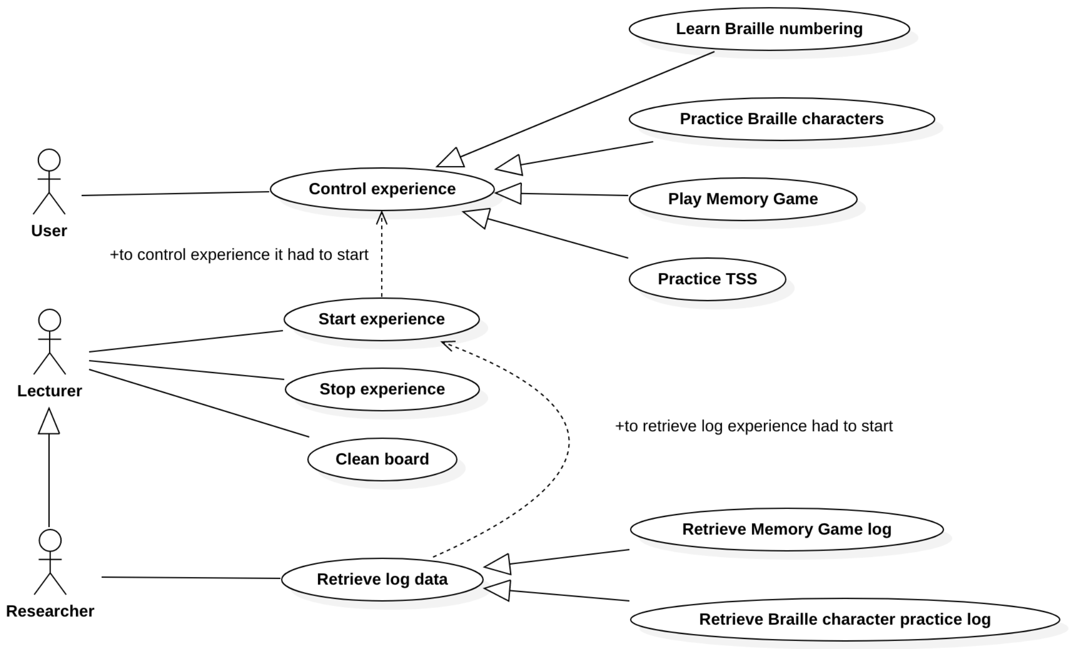

Figure 3.1. Use case diagram

3.4 Input button design

The controls need to be thought through well because it will be the only physical interaction with the user. Buttons are interactive and might be the right way to represent braille code. It also enables us to record and respond to the interaction. Every button would resemble a point in the braille code symbol. Based on the analysis and observation of the button designs we keep the following in mind:

What can a button do?

- Be pressed
- Vibrate

How can a button feel?

- Soft to press
- Hard to press
- Can't be pressed

What can a button activate?

- Audio
- Vibration
- Change of its feel

3.5 Extension board mockups

As physical interaction is one of the most important aspects of this project, the sketch phase was very short, and more emphasis was given to the design of material, shape and tactility.

One of the first mockups was a braille six-point symbol that could be used for writing only. Wooden sticks placed in the button openings on the top of the board represent points of the braille symbols. The top of the board, including the sticks, is covered by a clear tape to ensure safety during testing and also to make the material more smooth to touch, as Figure 3.2 shows.

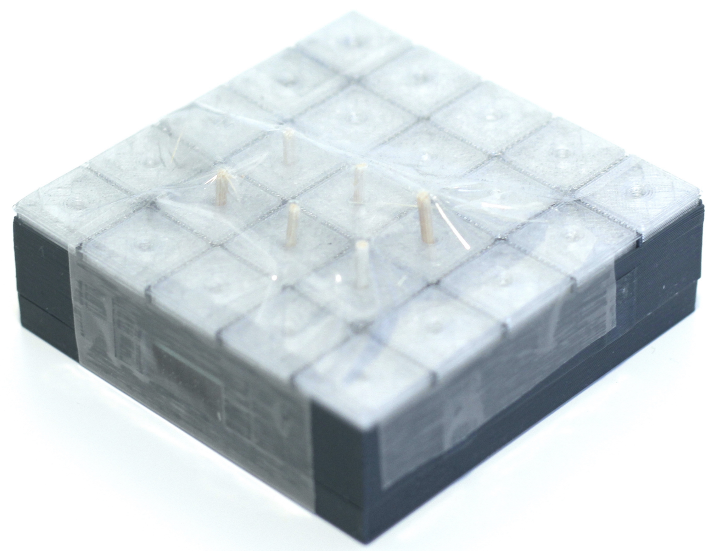

Figure 3.2. First mockup of braille six-point for writing.

3.6 First iteration

The next picture shows a mockup of Reversi's gameplay. Two players have different lengths of sticks representing the original game's disks. There are two possible ways to recreate this game for players with visual impairments.

Imagine the sticks as 3D printed movable disks designed to be easy to place, grab and recognize for the opposite player. This way, the users can play the same way as in the original game. It requires fine motor skills, also known as manual dexterity, as described in [24], in hands to move and place the disk. But the target users mostly lack these skills, as mentioned in [25]. The same applies to scanning the paying field, which requires a lot of memorization using only touch sense. This is because it's not possible to feel more than a few disks at a time compared to users with eyesight who can see the whole playing board.

The other way to play the game would be using three staged buttons, representing the empty point when it is flush with the board, player one while pushed slightly above the surface and player two while fully extended. While easy to mock using wooden sticks, this solution requires many mechanical changes to the baseboard, which is not part of this project's scope since the focus is on extensions and not remodelling the original board. The figure 3.3 shows on the left the mocked extension on top of the Haptic Tiles board and on the right the bottom of the extension.

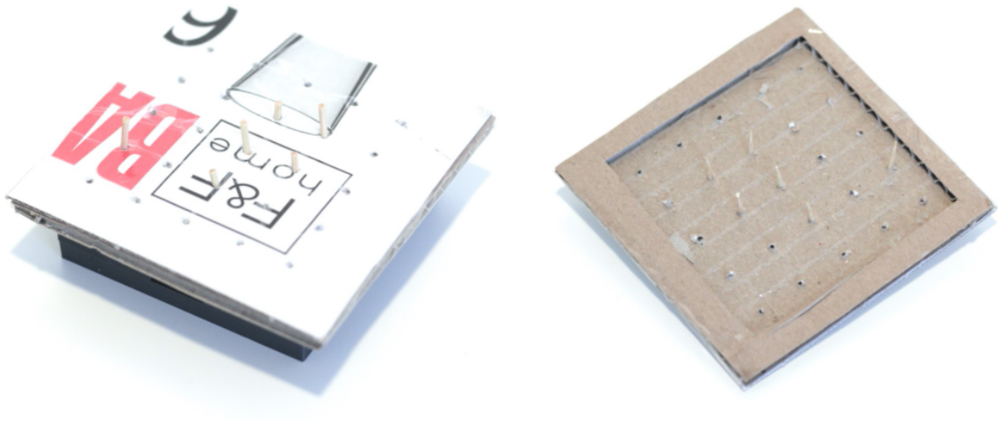

Figure 3.3. Mockup of multi stage buttons (in this case for a game Reversi)

The first mockup doesn't have an overview table because of its low fidelity and no resemblance to the final materials compared to the rest of the mockups, which use the potentially final materials.

3.7 Second iteration

The 3D printed mockup buttons were inspired by a spring-loaded buttons experiment by Marc Schömann, published on his personal Instagram account [1]. STL files for printing were published by the website HackDay [2] and are available to download from the articles' Google Drive link.

The first 3D buttons mockup has rounded buttons standing above the baseboard surface. These buttons are connected by a 3D printed spring mentioned above. Due to hard edges and more than 1 mm overhangs, it needs to be printed as 3 separate pieces, baseboard, spring and button. To assemble the mockup PETG compatible adhesive is needed. Figure 3.4 shows detail of the bottom assembly on the left and the top of the buttons on the right.

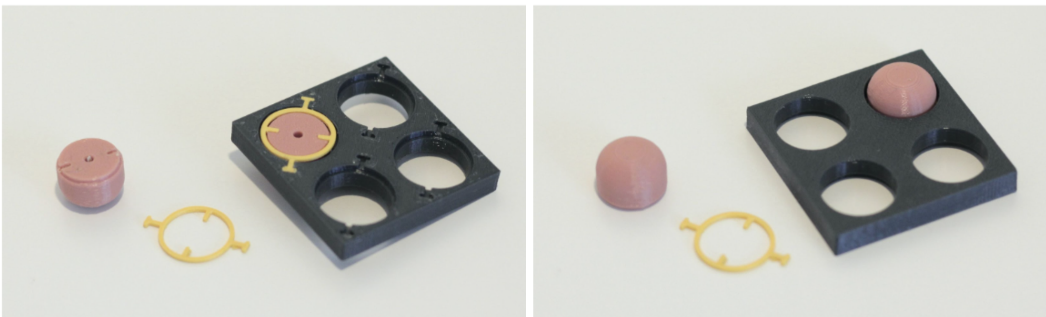

Figure 3.4. Mockup 1 3D printed bottom on the left, top on the right.

The spring of this mockup is weak, and a user can press the buttons by accident. This is not ideal since it's necessary first to look around and feel the board before use. These mockups' baseboard corners are sharp and therefore uncomfortable for a user and need to be treated in the next iteration. There are also only small sides around the buttons to rest a user's hand. Lastly, the spacing between buttons does not correspond

[1] https://www.instagram.com/p/BypbXyjohMr
[2] https://hackaday.com/2019/07/06/3d-printed-buttons-printed-as-a-single-unit

to the Czech braille norm[3]. The button and space should be approximately the same size, but this first mockup has buttons about twice the size of the space, as shown in Figure 3.5.

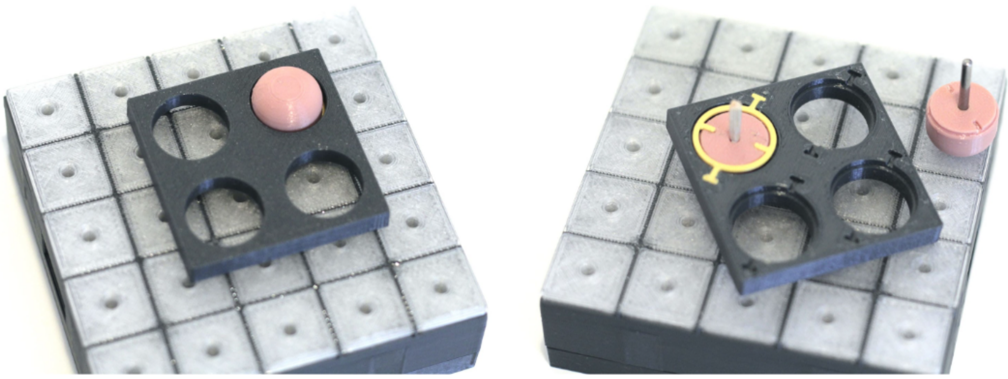

Figure 3.5. Mockup 1 3D printed size comparison on the left, bottom with wooden and metal rods on the right.

Table 3.1 shows positives and negatives about the second iteration mockup. Our goal is to remove mentioned negatives in the next iteration and keep all positives if possible. Not all the solutions can only remove cons. Some bring a new set of cons that will need to be tackled in future iterations. Some will change current pros into cons as we are looking for the optimal trade-off.

Pros	Cons
Smooth surface	Requires assembly and adhesive
Two tones	Too soft spring
	Oversized (in general and button height)

Table 3.1. Second iteration overview.

3.8 Third iteration

The second 3D printed mockup is scaled correctly; therefore, the size of one button block is the same as the size of the one block on the Haptic Tiles board. It is possible to print it as a one-piece that includes the button, spring and baseboard. To make this possible, all the overhangs from the previous iteration have been transformed into negative slopes, see Figure 3.6, which still overhang, but now the material supports itself during the printing process; therefore, it does not start sagging down.

As a side effect, these negative slopes prevent the button from sliding against the wall of the baseboard and creating stutters during a press.

[3] `https://www.sons.cz/Braillovo-pismo-v-CR-zakladni-informace-P4002991.html`

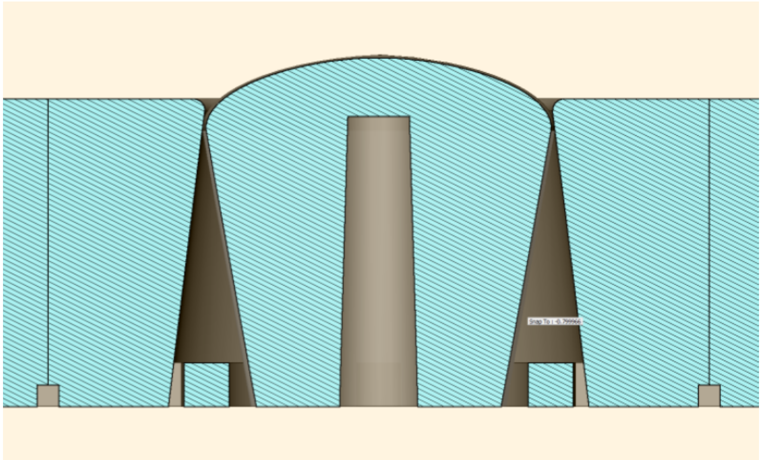

Figure 3.6. Cut away the view through the middle of the button, revealing the internal structure of the extension board mockup.

The spring is firm enough not to be pressed by accident when looking around with a hand. The spring attaches only using two points to the baseboard and two others to the button. The force to move the button in any direction is approximately the same. Therefore, a user can't feel how the button is attached. The spring is visible in Figure 3.7, both without a metal rod on the left and with it on the right.

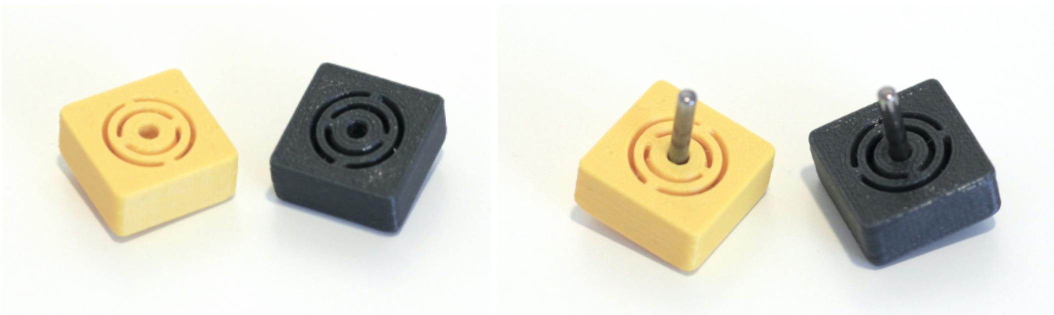

Figure 3.7. Bottom of the mockup 2 buttons showing the one-piece print, two empty buttons on the left and buttons with the metal rods on the right.

The button shape changed from completely rounded to an ellipse shape that still feels round to the touch. The top of the button, the ellipse, is now only 1 millimetre above the surface of the baseboard. This is still high enough to be recognized by touch but low enough to glide with fingers over the whole board. The spacing is also correct, and the buttons are the same size to the touch as the space in between them. The actual size of the button is bigger because it ends under the surface of the baseboard, as seen in the figure 3.6.

Straight out of the 3D printer, this second mockup is ready to be used with one imperfection on the surface of the button. The 3D printing nozzle leaves burrs; see detail on the right side of Figure 3.8, which can be removed using a knife or sandpaper.

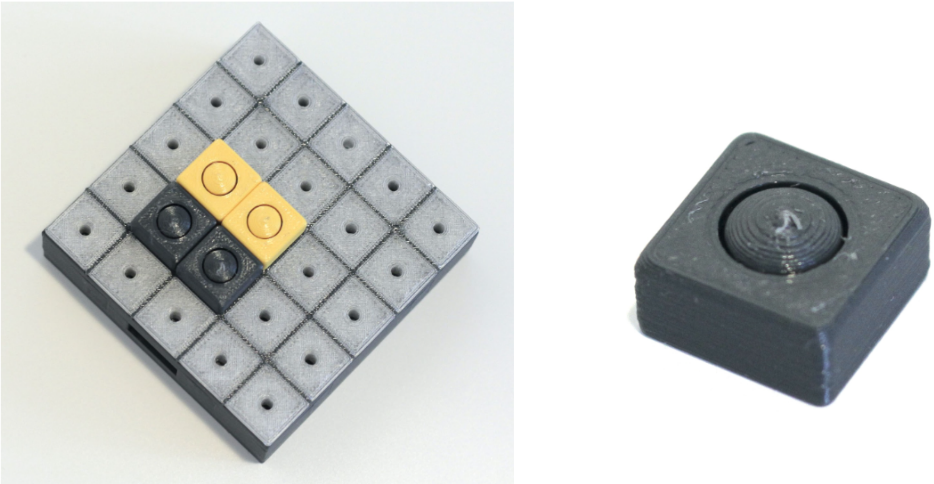

Figure 3.8. Array of 4 mockups buttons on the original Haptic Tiles board on the left, detail of one button on the right.

We printed a full board module with two braille six-point symbols during the third iteration. Work name of this extension is "Double Braille Module". Besides the button and spring design, an important part of the module is its connection to the board. That needs to serve two purposes. One, it should correctly space the extension and the board surface for the spring to move and buttons to be pressed. Second, it should ensure a stable connection of the module to the base block. The extension should not move, rattle, or fall off in the best case.

Our first solution for this connection is a matrix grid that uses friction to hold the base and the extension together. This grid tightly fits into the grooves separating buttons on the surface of the base; see left of Figure 3.9. Similar grooves are at the bottom of our module. The height of this mash ensures correct spacing between the extension and the base for the spring movement, as shown on the right of 3.9.

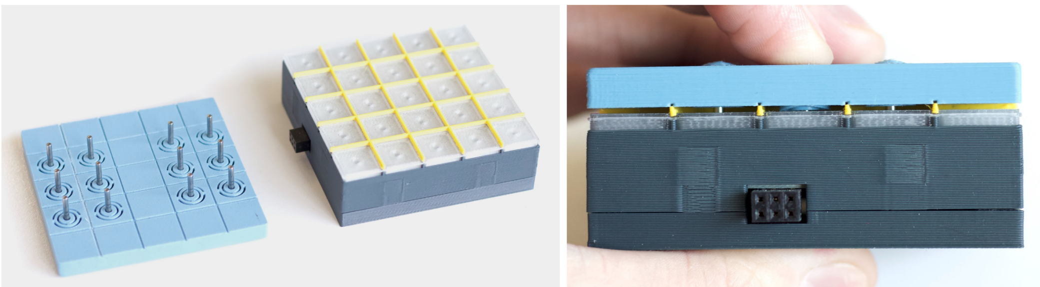

Figure 3.9. Connect grid place on the baseboard and Double Braille Module on the left, pressed button showing flexing spring on the right.

Table 3.2 shows positives and negatives about the third iteration mockup. Compared to the second iteration, we fixed the spring strength but lost a smooth surface and two-colour design. The two-colour variant can be achieved by cutting the model into two pieces, a button and board, and printing it using a multi-colour 3D printer. We can smooth the rough top surface using 3D printer head ironing or chemical smoothing. An important advantage of this version is the one-piece printing. It saves time, labour and makes mass production very feasible. But only in case when the rough top is not an issue or can be treated with the same efficiency, during the print or in high volumes.

After testing the buttons integrated into the full Double Braille Module. We discovered the force to move buttons is too high. The button can be pressed, but due to the high force of the haptic response, the distinct click at the end of the press is missing. The second problem is that using the buttons is tiring after a few seconds.

The connection grid holds the module nicely in place but doesn't have enough friction in the module grooves to hold it in. Figure 3.9, on the right, shows how the grid doesn't fully enter the grooves.

Pros	Cons
One piece print	Rough surface
Correct size	One color
Solid spring	
	Insecure connection
	Rough sides
	Missing white space
	Surface imperfections
	Mushy press feedback

Table 3.2. Third iteration overview.

Newly discovered cons are displayed in Table 3.2 under the last dividing line. Namely, not strong enough connections of the module to the board, rough sides caused by the connection grid, missing white space on the sides of the Braille symbols, on the left of the left one and right of the right one, and surface imperfections caused by the 3D printer.

3.9 Fourth iteration

This iteration's main focus is removing new imperfections which arose when we assembled Double Braille Module. We removed three out of four of the new cons. The last *insecure connection* is still present. Although we adjusted the dimensions to create a better fit with enough friction to hold the module firmly in place, it doesn't work for upside-down situations. But since that is not the primary way to use the module, this con has a low priority during the mockup phase.

Figure 3.10. Detail of Spacer Blocks with the connectors on the left, assembled module with the spacer on the right.

The rough side created by the connection grid is removed. The grid is now smaller, and the module doesn't have cutouts on the sides, as Figure 3.10 shows. This solution doesn't change the stability of the module on the board, but it improves the surface smoothness and creates a feeling of a one-piece when the module is firmly attached.

We didn't change its dimensions compared to the base to keep the system modular and universal for future versions and different modules. We created the white space using extra side pieces. These can be placed in between and at the sides. The current version uses only the six-pin connector to hold it in place. The small knobs and grooves, see Figure 3.10 at the top of the sides, ensure better alignment and connection to the main module, Figure 3.10 shows the whole assembly. As mentioned previously, until magnets are in place, the connectors alone are a fragile connection between the sides and the baseboard.

The surface imperfections from the previous iteration were removed partially. The module surface process called ironing helped smooth the top layer lines. We repeated the same process for the top of the buttons to remove burrs. We added a small flat surface to the top to make this possible. The result was disappointing. Nothing changed. At the same time as the ironing, we also turned on variable layer printing. This, in theory, should make the curves of the buttons more smooth, but the results are not noticeable nor measurable in our case. To the touch, the buttons feel rough, but as we discovered later in the experiments, in the section Finding evaluation 4.5, it's not a problem for users and some even like it for its distinct feel.

To summarize the changes of the fourth iteration, only one of the new cons of the previous mockup was not removed, an insecure connection to the base. Smooth sides of the module, smooth surface of the top of the module and distinct button press feedback are all solved and moved to the pros columns of the overview table 3.3.

Pros	Cons
One piece print	Rough surface
Correct size	One color
Solid spring	Insecure connection
Smooth sides	
Space on the sides	
Smooth surface	
Distinct press feedback	

Table 3.3. Fourth iteration overview.

3.10 Future ideas

Future development will mainly depend on the module usage and feedback after longer and more intensive use. This assumes that we fix *insecure connection* con. Both the *rough surface* and *one colour* didn't show as a problem to our users, based on the experiment described in Chapter 4. But since the mentioned cons have potential shortcomings, we will describe what those are, how we could prevent them and what would be their implications. The following list is not just theory. We have a mockup, see Figure 3.11, prepared using the proposed solutions, but in its current state, it's not better than the latest fourth iteration 3.9. Therefore we left it as a future idea due to time restrictions and unsure benefits due to the significantly more complicated manufacturing process. List of the cons solution proposal:

- *Insecure connection.* To solve this, an updated 3D model is needed. The current solution doesn't have the magnet pockets needed for a stronger connection. We would use magnets, as they showed a feasible, strong enough solution when connecting the boards without extensions, described in [19].
- *One colour.* To solve this issue, only a 3D Printer using automatic filament switching is needed. We already have a 3D model that is cut into multiple parts enabling multi-filament, multi-colour print.
- *Rough surface of the buttons.* This is to be seen in long-term usage. From the experiment 4, it comes as a positive. A problem could be dirt and debris slowly building up on the buttons. A smoother surface could make cleaning easier and the buildup slower. One solution is chemical smoothing, but it complicates manufacturing. Another solution is to use a resin printer for buttons and then glue multiple pieces together, which is also a manufacturing complication but involves less dangerous processes.

Example of future mockup shows Figure 3.11. This is a not working mockup. It shows coloured buttons, which could be either chemically smoothed or printed using resin later on. This model is glued using commonly available cyanoacrylate quick glue.

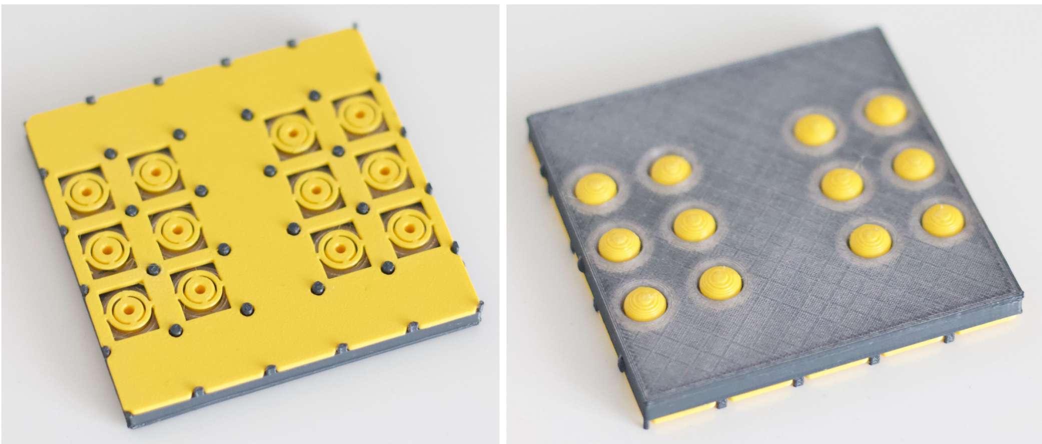

Figure 3.11. Future iteration idea created using multiple glued pieces, multi-colored with seen-thought filament.

To see what material would be an option for the smoothing, we constructed solvents and filaments compatibility table 3.4 based on the article [26] and on the article focusing on PETG [27].

Filament	Solvent
ABS, ASA	acetone
PLA	none
PVB	isopropanol (IPA)
PETG	dichloromethane, methyl ethyl ketone (MEK), toluene, and cyclohexanone

Table 3.4. Smoothing solvents and filaments compatibility.

A smooth surface doesn't only bring subjectively nicer looks, but it will be also beneficial for the practical use of the extension boards. The new smooth surface will be easier to clean, as more described in [28] and disinfect as debris won't catch in small grooves caused by the 3D printing process.

Chapter 4
Usability experiment

This chapter covers the design, process and results of performed usability experiment of the latest iteration 3.9 of the board and its companies software closely described in Chapter 5.

4.1 Research questions, experiment goals

This part focuses on the first evaluation with more representatives of the target user audience. However, we were able to continuously assess essential aspects of the design thanks to cooperation with a team member that also deals with vision impairments. The generalisation of the following findings is limited do the relatively low number of participants and the qualitative nature of the used evaluation method.

- Verify concept usability in different application scenarios (education, entertainment).
- Identify interaction problems related to the physical prototype, low-end software implementation (firmware) and high-end application implementation (Braille education, Memory game).
- Is the form of exercise considered entertaining (subjective, small number of participants)?
- Is the game entertaining for adults (subjective, depends on the game data set)?
- How difficult is finding a match using logical similarities (categorise, possible vs impossible)?
- Does the new solution bring anything new compared to already existing tools (known by the participants)?

4.2 Target group, screening

We target individuals with visual impairments, from low vision to completely blind. We can categorise these people based on their vision level for better orientation and our tool's application. More in detail, we will describe the categories in the following lists.

Vision levels

- Severe low vision (Category 2 and 3 by [29])
- Practical blindness (Category 4 by [29])
- Complete blindness (Category 5 by [29])

Software-based categories

- Children to 6 years old.

  We target elementary knowledge practice, for example, animal noises, in this group.
- People from 7 years old.

Teenagers, adults, and elderly around 70 years old. We focus on edutainment lecture extensions and on free time entertainment activities.

- Elderly at an advanced age.

  People from the specified categories can use our aid for memory training and cognitive functions practice.

Our defined screening would have at least one participant representing each category. But the following is the minimum for concluding the experiment is valid.

We are aiming for a younger target group in the first experiment. We expect a lower probability of visual impairments caused by higher age.

- Participant minimal count: 5
- Visual impairments extent
  - Sever low vision (1-2)
  - Practical blindness (0-4)
  - Complete blindness (1-4)
- Visual impairments duration
  - Since birth (1-4)
  - Minimum 5 years (1-4)
  - Less than 5 years (0-2)
- Gender
  - Male (1-5)
  - Female (1-5)
  - Other (0-2)
- Age
  - 18-39 (2-4)
  - 40-60 (2-4)

The overview of people participating in the following experiment shows Table 4.1. More specific information about visual impairments and their lengths are summarised in Table 4.2. In total, we had 6 participants, primarily females and one male. We tried to contact more males, who fit our target group, but none of them was available to meet with us for various reasons, mainly due to their location far from Prague.

P. ID	Gender	Age	Education	Note
1	Female	25	High school	University student
2	Female	36	Bachelor	Writer, Journalist
3	Female	48	Bachelor	Journalist
4	Female	32	High school	Social worker
5	Female	40	Music school	Artist, Music teacher
6	Male	37	Music school	Artist, IT lecturer

Table 4.1. Participants demographic overview.

In the last year of her studies, participant 1 is a university student and is currently writing a bachelor's thesis. Her visual impairments are categorised as practical blindness and has been the same her whole life. She learned Braille in elementary school, where they used various learning tools to make Braille system closer for children to understand.

Participant 2 is a book writer specialising in books for children. She lost her sight at five years due to a severe illness, and her current state of vision is practical blindness.

She learned Braille in elementary school. After grammar school, she decided to study journalism at a university.

Participant 3 is a journalist and lecturer. She studied journalism at a university. She has struggled with her sight since the day she was born. She has never undertaken special education for individuals with visual impairments and never learned or used braille. Her current eye's visual strength is 20 dioptries and is stable after surgery five years ago.

Participant 4 is employed as a social worker, helping and teaching other visually impaired people. Her current state is in the category of completely blind. She has learned Braille system as an adult and now uses it daily but only for writing.

P. ID	Vision category	Note
1	Practically blind	From birth
2	Practically blind	From 5 years old
3	Sever low vision	From birth
4	Completely blind	Last 6 years
5	Completely blind	From birth
6	Completely blind	From birth

Table 4.2. Participants vision impairments overview.

Participant 5 is an artist, music teacher and mother of a toddler daughter. She plays the piano very well. She can use both single hand and two hand Picht's typewriters. She is a fan of Braille system and likes to use it. She loves "Prague slate".

Participant 6 is a musician and singer but also an IT enthusiast. His Music school-leaving exam included playing accordion, singing and music theory. His knowledge of Braille is broad, and it includes regular alphabet and music notes. He uses it only for writing on his smartphone.

4.3 Interview scenario

This section consists of the interview scenario overview. All the questions we will ask the participants are marked with Q X.Y, where the X represents the chapter number in this document and Y is a sequence number of the question.

We will open the interview with an introduction, a quick informal briefing about how will we proceed and informal small talk to make the participant feel comfortable.

We will focus on the participant's visual impairments and knowledge of Braille in the first group of questions.

Q 4.1. Could you describe your visual impairments? How is it categorised?
Q 4.2. How did your impairments develop? For how long is it in its latest state?

Q 4.3. How would you describe your knowledge of Braille?
Q 4.4. How often do you use Braille?
Q 4.5. How did you learn Braille? At what age? Using what education aids?

We will follow questions 4.1–4.5 with formal introduction of our education aid prototype and included software.

"Today, we will be testing education and entertainment aid created by a block of two Braille symbols. These blocks can be connected into a long line. But for the testing, we will stick with only one of them. Braille points are buttons with haptic response, but the solution is heavily dependent on its connection to a computer, where the appropriate software evaluates a user input. The software examples we will experiment with today are Braille Numbering, Braille Characters Education, Memory Game and Talking Signs System Simulator."

After or during the introduction, the participant will get familiar with the tested tool. We are mainly interested in the feel of the Braille points, their size, spacing within the character and in-between the characters, shape and other physical characteristics of the board.

Q 4.6. How do you feel about the buttons? How do they resemble Braille?
Q 4.7. How would you describe a button press feedback?

Braille Numbering application aims to introduce the Braille numbering system to complete beginners.

Q 4.8. What are your thoughts about the Braille Numbering software?

Braille Character Education application goal is to exercise Braille characters. The prerequisite is that the user has been already introduced to the letters. It's possible to use the software without previous knowledge, but it's not intended to be used like that.

Q 4.9. What are your thoughts about the Braille Character Education software?

In the next part of the interview, we will describe the concept of the Memory Game application and explain using an example.

"Our memory game is special because you don't search for the exact same items to match, but you look for the match based on the logical similarities. For example "BMW" car brand is made in "Germany". Other examples are matching voice with a persons' name, audio with an animal name, date with the historic event."

Depending on the participant, we will try the following data sets.

- Animals sounds aimed at kids.
- Famous voices aimed at adults
  The voices are Czech mainstream people known through generations.
- Braille characters, aimed at people that know Braille by heart.
  The goal is to match a Latin letter to a Braille expression as a sequence of numbers.

Q 4.10. How would you recap your game?
Q 4.11. How do you feel about the board size and the number of items to match?
Q 4.12. Could you describe the after press audio guidance?

Question 4.10–4.12 will repeat after each game because we are concerned that the answers can also vary with different data.

The last application to experiment with will be the Talking Signs System Simulator. With participants who know it well, we can observe if the simulator behaves as they expect actual TSS to work. And on the other side, for participants who don't know it, we can observe if the simulator helps to understand the purpose and functions of TSS.

Q 4.13. How do you feel about the controls?
Q 4.14. Could you describe the accuracy of the descriptions of the functions?

After the last application, we will follow up with a conclusion and informal debriefing. In the end, we will again ask questions 4.6 and 4.7 to observe if the prototyped solution is suitable for course/class use, which lasts approximately the same as our interview.

4.4 Programmatically collected data

Besides video recording, verbal communication and notes that were taken by the interviewer, we were able to record participants' behaviour using the software. We saved the meaning of the buttons at the current moment and in what order the buttons were pressed. In the later stage of the experiment, we also added a timestamp of the press. The goal of the recordings was to use them for evaluation and comparison with our notes, notes from the participants, and further statistical use, which could reveal some new information.

Data was saved in JSON format. Listing 4.1 shows an example of memory game mapping. The array indexes represent the Braille symbols points. For example, index "0" is a point "1" of the first Braille symbol and index "6" is a point "1" of the second symbol.

```
[ "feet", "arm", "foot", "chodidla", "noha", "paže",
  "chodidlo", "tělo", "body", "leg", "hand", "ruka" ]
```

Listing 4.1. Example of data set mapped to the game board.

Data to buttons mapping is saved right after the software generates it. The file name is ISO format timestamp and `.board.json` postfix.

Users' behaviour is saved as a combination of "keydown" actions, and the game moves array. Actions show what the user pressed and when it happened. The moves show what items were assigned together, an example of which shows Listing 4.2.

```
{ "keyDownHistory": [
    { "key": "hand", "timestamp": "2022-03-30T08:31:44.208Z" },
    { "key": "body", "timestamp": "2022-03-30T08:31:46.366Z" },
    { "key": "hand", "timestamp": "2022-03-30T08:31:49.478Z" },
    { "key": "arm", "timestamp": "2022-03-30T08:31:50.854Z" }
  ],
  "moves": [
    [ "hand", "body" ],
    [ "hand", "arm" ]
  ] }
```

Listing 4.2. Example of a game moves history.

Game history data are saved to a file after every key down event. This ensures that data are not lost, even in the case of an unfinished game. These data can't be used for restoring the game state. Their purpose is purely to log user behaviour. The file name is ISO format timestamp and `.json` postfix.

4.5 Findings evaluation

Different metrics have been collected during usability experiments based on the various software applications. In general, we recorded completion as binary Yes or No values with every task. Other common values were the number of mistakes or mistakes before a first correct hit. The list below shows an overview of the metrics for all the tasks.

- Task completion

  100 % of participants completed Braille Education Tasks

  50 % of participants completed the Memory Game assignment
  100 % of participants completed TSS Tasks
- Number of errors (median)
  0 errors for Braille Education Tasks
  7 errors from all the Memory Game assignment
- Number of errors before first correct hit (median)
  0 errors for Braille Education Tasks
  2 errors from all the Memory Game assignment

Both errors measuring are not applicable for the TSS Task because participants can't make a mistake. The tool only informs about TSS functionalities.

Based on the number of errors, or to be precise, the lack thereof, we can conclude the Braille education software was not confusing for the participants. Both newcomers and experienced users of Braille could complete a given letter.

In the memory game part of the experiment, other measures were added. This task is more complex, and knowing participants' behaviour could lead to further development and ensure a more seamless and entertaining experience. Therefore values describing total tried pairs and a number of the matched values were followed. The following list gives an overview of both finished and abandoned games. Values are calculated from Table 4.3.

- Median total number of pairs across the data sets is 9.
  Finished 13 / Abandoned 5
- Median amount of matched pairs is 2.
  Finished 6 / Abandoned 1

We can see that the participants who abandoned the game made almost half of the effort as the ones finishing the game. With the half effort, they only found one correct match. The reason could be an inefficient game strategy shown in section 4.6.

The following list contains critical findings common to all software applications.

- All participants would like to have the option to break the audio guidance at the moment when they understand and want to move on.
  For Participants 1 and 2, it could be why they haven't finished any Memory Game. For the same reason, Participant 5 probably only finished one game.
  The same applies to Braille Education, where people who know the assigned letter are generally faster and don't need to wait for the whole number to be pronounced.

- All participants would appreciate an option to speed up the audio voice.
  Many of them use smartphones with screen readers and have the voice speed set to a fast.

- As we tried to guide our participants as little as possible to discover their natural ways. We know that our audio guidance needs a more precise and larger volume of information to be sufficient with very little or no additional help.

If we categorised our current participants' group, they would be experts. That explains many findings regarding speed mentioned here and in the detailed finding in subsection 4.5.2 and 4.5.3. It doesn't make the finding less valuable, but it directs the implementation toward adding options instead of changing the default or constant values.

4.5.1 Hardware impressions

Similarly to the interview structure, we will go through the evaluation of the experiment, and we will start with the general response to the solution's hardware.

- Distinct buttons surface structure participants overall liked.
  Participant 1 found them maybe a bit too rough. Participant 3 didn't recognise the button using remaining eyesight because of the single colour, but she recognised them quickly using touch.
- Clear tactile button feedback all participants agreed on.
  Everyone could feel it when they pressed a button. They also heard the mechanical click of the microswitch hidden under the buttons.
- Smooth surface across multiple modules all participants agreed on.
  Everyone could feel that the tool is assembled from multiple parts because of the slight movement when discovering it. Participant 4 noticed the minor groove between one of the sides and the main module.
- Clear Braille resemblance all participants saw after the first touch.
  Everyone recognised the full Braille six-point.

The following list highlights *rare but insightful comments* we collected from the participants.

- Participant 2 found the buttons a bit too stiff for her liking, both using one finger or multi-press.
- Participant 1 noted that the buttons are incredibly enlarged compared to actual Braille size. That was caused by us hiding the aid purpose from the participants till after the first impressions.
- Participant 6 mentioned how moving the connection cable from the left side of the module to the top could make the single module experience nicer. The cable would be out of the way when the user grabs the module from the sides.

4.5.2 Braille Education

In the learning part of the experiment, all the participants completed the given task of pressing all points of the selected Braille letter. But over 65 % of them received special education at a young age. All these participants first tried to press all the points at once. Participants without or with insufficient knowledge started pushing buttons in sequence compared to the rest.

We concluded that extending the software with multi-point recognition would be helpful for students with brother knowledge. This includes inpatient students and students starting to recognise the symbols more like a one-piece than a sequence of points. The audio response would not be in a random order like in the first version, but simultaneously pressed points will be repeated in ascending order. Case of multiple points from two or more Braille symbols should be evaluated as errors and followed by audio guidance to press one symbol at a time.

The following list summarises *key findings* regarding Braille Education software applications.

- The system is intuitive enough for the participants who know Braille not to make mistakes.

  People from our experiment, who know Braille, didn't make mistakes. They also pressed the points in the correct order even though it is not mandatory to complete the assignment.

- The system guides the participants who don't know Braille to complete the character they got assigned.

  We only had one participant familiar with Braille but didn't know a majority of the alphabet, Participant 3. This participant finished an assignment of unknown letters based on the voice guidance.

- The participants who know the assigned character tend to speed up and have to wait for the audio to finish.

  This was already described in detail above.

- Some participants wanted to press assigned Braille characters' dots at the same time.
  - Two of our participants started pressing the points in sequence.
  - Other two asked if they should press all points of the Braille symbol at one, as that is the way they use it on their smartphone.
  - The remaining two tried to press all the points at once.

  We purposely didn't guide the participants on approaching the assignment to observe what they would choose naturally.

- Some wanted to press the assigned letter into only one Braille symbol.

  We again didn't give the participants specific instructions. That resulted in some of them forgetting about the second Braille six-point on the right.

The following list includes rare but insightful participants' comments and our observations.

- Participant 3 didn't like the straightforward way the voice reacted to the wrong point press. The participant feels like the "Wrong!" note after pressing incorrect dots is offensive. Maybe an error buzzer sound would be sufficient, she said.

- Participant 4 thinks it could be helpful for pupils with eyesight at elementary schools during Braille's presentation.

- Participant 6 was a bit offended by how "Zuzana", the Czech voice, deals with Czech characters. For example, she can't pronounce standalone "ř" therefore, we made her say "r s háčkem", which means "r with háček", which is an accurate description of the character. Another option would be to use "eř", which the voice synthetization can pronounce easier and the participant would prefer.

4.5.3 Memory game

The Memory Game was the second software application presented to the participants. We first gave each participant a brief overview of our logical matching memory game idea and then let them play a game. We allow people to choose a data set they want to play. The reason is mainly the comfort of the participant. We didn't want anyone to feel like being examined in English or History, as those were the data sets mostly skipped by the participants.

At the beginning of our experiment, our hopes were low because the first three participants did not complete a single game. Our assumption was that the playing field is too large and difficult to memorise. The second half of the participants showed us wrong as they all completed at least one or more games. Participant 6 completed an astounding five whole games.

Table 4.3 shows measured data from the Memory Game experiments. Starting from the left, the *No.* stands for a sequence number of the game, *P. ID* for participants ID, *Data set* for the given data set, *All* for a number of tried matches, *Corr.* for a number of correctly matched items, *Err.* for a number of mismatches, *Err. b. hit* for errors before the first correct match.

The records under the divider line of Table 4.3 are excluded from the statistic as they are the only examples of given data sets in our experiment. We tried the Cars-Countries, History and Animals with Participant 6 because of his interest and also his high score of finishing all the previous games within a relatively short time and a small number of mistakes.

No.	P. ID	Data set	All	Corr.	Err.	Err. b. hit
1	1	English-Czech	9	1	8	8
2	1	Famous voices	5	2	3	1
3	1	Braille	10	1	9	4
4	2	English-Czech	14	2	12	3
5	2	Famous voices	3	1	2	2
6	2	Braille	4	2	2	0
7	3	English-Czech	10	2	8	0
8	3	Famous voices	4	1	3	0
9	4	English-Czech	13	6	7	2
10	4	Famous voices	9	6	3	2
11	4	Braille	13	6	7	5
12	5	Famous voices	16	6	10	3
13	5	Braille	5	1	4	3
14	6	Famous voices	9	6	3	2
15	6	Braille	14	6	8	4
16	6	Cars-Countries	10	6	4	1
17	6	History	12	6	6	2
18	6	Animals	12	6	6	3

Table 4.3. Measured data from Memory Game.

The following list shows *key findings* we gathered from the Memory Game experiment.

- The game is possible to finish but needs more difficulty options.

  Because half of our participants didn't finish the memory game, we can assume an option to select matches' amount in a game is necessary. For example, the simplest level can be 3 matches, 6 points. Therefore, only one Braille six-point will be used. Better players can do 6 matches which is the current size. And if someone wants, they can even use 9 or 12 with two connected modules.

  At the same time, we need to keep in mind that the first three participants came in together on the first day of testing and maybe that fact had to do something with them not finishing any game.

- The placement can't be completely random as it introduces confusing situations.

When the random items' placement puts all 6 matching items out of 12 items in total onto the one Braille six-point, the participants tend to forget that there is another one. This situation is illustrated on the left side of Figure 4.1.

Another problematic situation arises when one Braille symbol is filled mostly with items of one type, for example, only Names and the other one is filled mostly Voices examples. A situation like this is illustrated on the right side of Figure 4.1.

These cases lead to the user's frustration and most likely leaving the game.

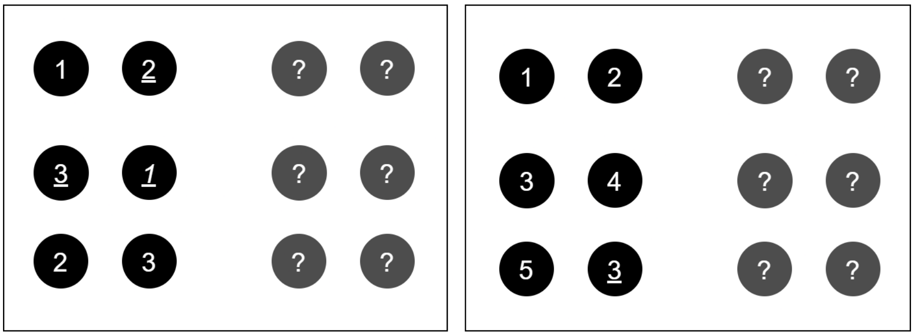

Figure 4.1. Six matching items in the left Braille symbol on the left of the figure. Mostly numbers without underscore on the left Braille symbol on the right of the figure.

Figure 4.1 show examples of confusing placement of items. For this example, we used a data set where the players should match numbers without underscores to numbers with underscores.

- The audio guidance slows the player down.

  As mentioned in the general notes at the beginning of this section, the participant had to wait till the voice finished talking to match items for which they knew the placement before or during the voice talk.

- Long phrases and audio samples.

  Based on our observation, the participants would benefit from even shorter phrases from the audio guide and shorter audio samples in the data set where applicable.

- Players are well informed about matched items.

  The participants liked the way they were informed about selecting an already matched pair. The system tells them that the current item is already matched and also to what items it's matched. They also liked saving a move when the second selected item was matched. This behaviour was based on a traditional memory game where it's also not possible to select an already matched item.

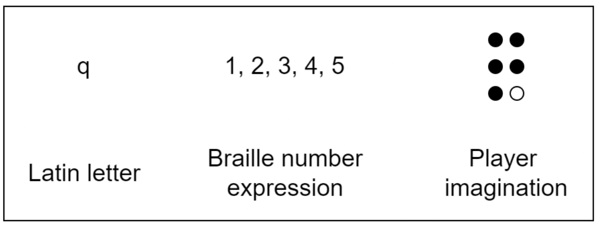

Figure 4.2. Memory Game Braille Data set example of character imagination

- The repetitive audio causes confusion in the Braille data set

  Because the Braille data set includes a lot of numbers and matching the Latin letter with the number representation requires visualising the Braille six-point. The participants get confused when they are trying to visualise the Braille character, and the guiding voice starts repeating the numbers all over. Example of letter imagination shows Figure 4.2.

- The most popular game data set was Czech famous people.
  Every participant wanted to play this data set after they heard the name, and everyone liked it, which is essential that it wasn't just about the name.

The following list includes rare but insightful participants' comments and our observations.

- Participant 1 felt frustrated about random items' placement on the board and offered a solution in the form of placement using a pattern. The game's objective would shift towards discovering the pattern and then just matching the items using the pattern.
- For Participant 2, the Braille data set would be nicer to play if the Latin letter on the left and on the right would be all the Braille characters. She would use one of the placements, which we marked as confusing when it does happen randomly, on purpose.
- Participant 4 compared our Memory Game with the BlindShell memory game, a classic example matching the same items.

4.5.4 Talking signs system

The last software application the participants got to try was a Talking signs system simulator, the easiest of the bunch. Because of the way TSS works, there are no rights and wrongs. Our goal was to observe how intuitive the controls are for the participants and what they think about the accuracy of the information and selected examples of the audio signs.

The following list shows key findings we gathered from the TSS simulator experiments.

- Although the software is missing a real chine at the start of the talking sign, the participants didn't mind it, and some even didn't mention that it is missing.
- Almost everyone mentioned that "návěští", a Czech technical term for a Traffic Light is not what they use in the daily language.
- Even though the participants were familiar with the TSS remote, almost no one knew what the number six is. After playing the example, they were pleasantly surprised.
- Number four had information about the boarding of a blind person but was missing information about a blind person leaving the public transport.
- None of the participants knew that the TSS number 4 also activates the wheelchair platform at the vehicles that support it.

The next list includes rare but insightful participants' comments and our observations.

- Participant 6 would again appreciate the ability to skip the audio with the next button press.
- Participant 6 also tried long press, but that is not implemented in the simulator.
  This feature should start playing the TSS beacon audio for 2 minutes until the time is up or the user presses any button on his TSS remote.
- Participants 2 and 3 would enjoy having the possibility to hear what the buttons should do in their actual TSS controller.

4.6 Experiment visualisation

In order to clearly represent participants' behaviour and to see differences between them, we prepared a simple graph diagram representing the double Braille extension module. The initial state is an unconnected graph with twelve vertices graphically placed to resemble the physical properties of the module.

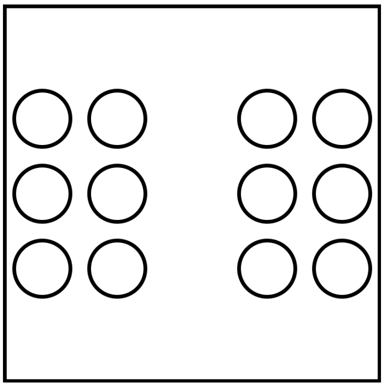

Figure 4.3. Double Braille module diagram

Every participant has to start with Braille Education software before moving on to the Memory Game. Participants' behaviour can be observed using network graphs where nodes represent buttons on the board, including their placement. There are no connections as, during this education exercise, we are following only the pressed buttons, and there are no relevant connections between them.

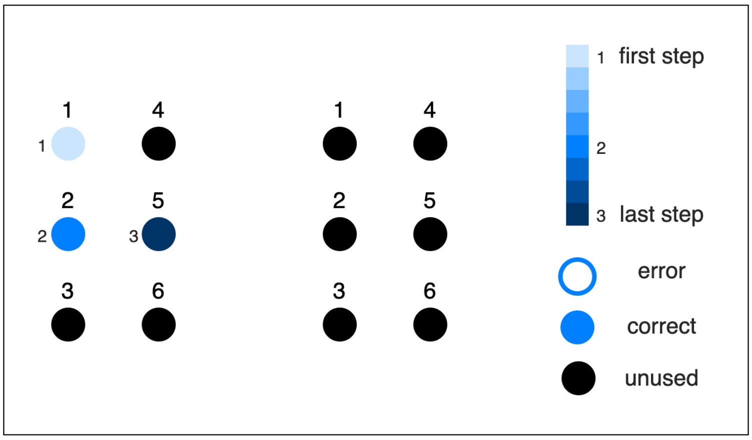

Figure 4.4. Braille Character Education, Participant 1, lower case "h"

As the figure 4.4 shows, Participant 1 pressed all the correct points, filled with a shade of blue. Besides not making a mistake, the pressed points are also in the correct order, which is not a requirement for completing the task. The order is marked using an intensity of the blue colour and numbering labels next to the points. Based on the experiment observation, Participant 1 just imagined the number sequence representing the lower case letter "h" and started the exercise. This behaviour matches precisely with our expectations for a person familiar with Braille.

To help process and observe patterns in data collected from the memory game, we use a graph diagram showing buttons as black circle points placed the same as on the actual physical board. Connections between points represent game moves done by a participant. As the game rules enforce a selection of two items for comparison, there is a natural order from the first selected to the second selected item. Therefore connections are oriented, and the end of a line encodes match or mismatch information using an arrow or slash icon. Similarly to the figure 4.4, we use colour intensity and label to express the order of participants' moves.

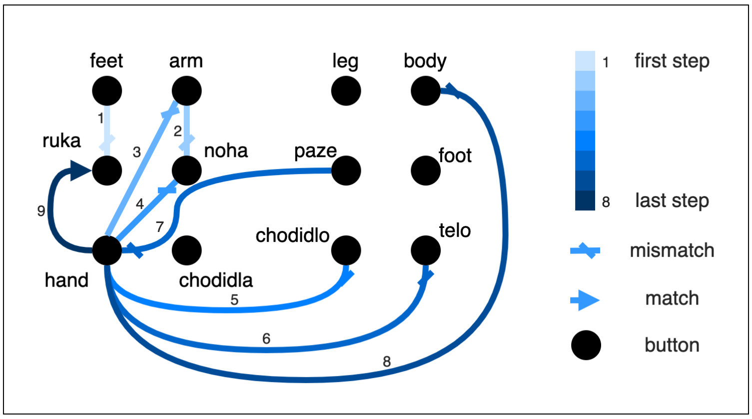

Figure 4.5. Memory Game, Participant 1, English-Czech

Figure 4.5 shows the unfinished English-Czech memory game of Participant 1. The game started on the left side with a sequence search of the game board. As the participant tried twice assigning the "hand" to non-matching items, "arm" and "noha", we suggested looking into the other symbol on the board. From that moment, we can see an arbitrary focus on getting the match for "hand". After 6 mistakes, Participant 1 found the match in the first symbol. Although happy from the match, the frustration of the participant was too high, so we moved on to the next game data set.

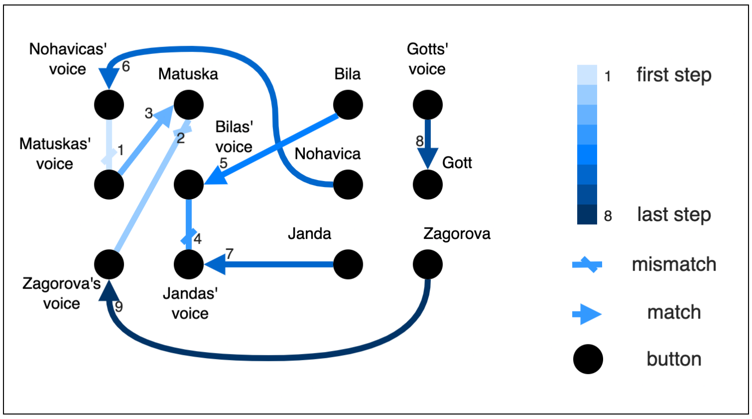

Figure 4.6. Memory Game, Participant 6, Czech famous voices

Figure 4.6 shows a game of Participant 6, who chose a very different strategy from the previous showed Participant 1, Figure 4.4. Participant 6 finished a game of the same size in the same amount of tries as Participant 1 matched one item. Comparing the two diagrams, Figure 4.6 and Figure 4.4, we can see that both started in the top left corner, the left Braille six-point, and moved forward in a top-down, left-right direction. However, Participant 6 continued this movement even if the match was unsuccessful and only returned when he found a potential match to an item discovered earlier. Compared to that, Participant 1 was trying to find a match to one item she focused on, "hand".

4.7 Conclusion

The system in the tested version seems to be working well, and a lecturer or researcher can use it while working with an individual with visual impairments. Our experiment supplied enough information to answer our questions and brought many ideas for new options making the system universal for different kinds of users. Answers to the question are in the following list.

- Verify concept usability in different application scenarios (education, entertainment)

  We only had one participant to verify Braille learning, but she, Participant 3, managed to learn a new Braille character without a problem. Others passed the application only as a practice of letters they know well.

  The experiment showed that all the prepared applications are usable by the participants. Many of them expressed joy when playing the Memory Game, and some of them also learned new things. For example, Participant 6 when trying the Cars-Countries data set. We watched participants smile and enjoy the Famous-Voices data set. It was our most popular one.

  The TSS simulator surprised some participants because they didn't know all the functionalities even after many years of use.

  Therefore we agree that the applications fulfil our expectations of both education and entertainment.

- Identify interaction problems related to the physical prototype, low-end software implementation (firmware) and high-end application implementation (Braille education, Memory game)

  The physical prototype surprised us since there were no major problems or complaints from the participants. They liked the feel of the material and the haptic feedback. Problems that we expected, rough buttons and multi-part design, showed to be only minor issues.

  There were no issues with the low-level communication. Everything worked as expected.

  The application implementations have a lot of options to extend their functionality. But the only major issue was the inability to break the audio guide when a participant wanted to proceed with the application. We suspect this issue appeared mainly due to our younger participants group, who is used to this behaviour on their smartphones.

- Is the form of exercise considered entertaining? (subjective, small number of participants)

  For half of our participants, the current version of the Memory Game wasn't as entertaining as we expected since they hadn't finished a single game. One of the problems we discovered is that not everyone enjoys the concept of the memory game, and some were just tired of the inability to speed up the game. Although everyone said they liked the game, there was a clear difference between the two halves.

  The other half of our participants enjoy the game a lot. They finished multiple games, some even 5 different games in a row.

  As we showed in Figure 4.6 and Figure 4.4, some participants got frustrated with no successful matches and quit the game. Others in the same amount of steps finished the whole game.

- Is the game entertaining for adults (subjective, depends on the game data set)?

  None of the participants seemed offended by the game data set we offered. Everyone smiled and sparked joy when listening to the Famous-Voices set.

- How difficult is finding a match using logical similarities (categorise, possible vs impossible)?

  Some participants seemed unsure in the beginning, but everyone got it after the first example that the application tells a player at the beginning of a game.

  The most confusing was the Braille data set, where the objective is assigning a Latin letter to a numerical representation of Braille. An example of this for easier imagination is in Figure 4.2.

- Does the new solution brings anything new compared to already existing tools (known by the participants)?

  Participant 4 mentioned BlindShell 2, which also introduced a memory game on their phones. Their version is a standard memory game, where the objective is to match the same items. The playing field is the classic button phone keyboard.

  Everyone else doesn't know anything similar to our product.

Chapter 5
Implementation

This chapter provides detail into the software implementation, reasons why we selected given software stack and how does the deployment architecture looks like. The applications are separate console tools, controlled mainly by the connected Haptic Tile board. This solution provides a large amount of flexibility and therefore we could focus on developing a friendly audio interface. The console input is used only for prototype debugging, each of the applications can be started by clicking an icon in a production environment. Applications' code base is shared and ensures plug and play connectivity with the Haptic Tiles board and audio interaction, this includes text to speech and audio files playback.

5.1 Used technologies

The software stack primarily reflects the needs of the product as defined in the previous chapters. The second parameter of choosing the right technologies has already defined communication with the baseboard that we wanted to keep. Since using the same firmware ensures compatibility with the original Haptic Tiles and the newly developed extensions.

Node.JS We were looking for a quick, efficient way to prototype our application. Therefore we looked into high-level, not strongly typed programming languages. High-level because it ensures that we can focus on our business logic instead of solving technical problems. Not strongly typed because we value flexibility more than the code robustness. Our prototype, and the final product, are not mission-critical software. Therefore we can sacrifice the benefits of typed languages.

We had a few requirements for the chosen language coming from the base solution we are building on and some coming from our research and future vision. The following list summarises the requirements.

- Ability to communicate over Serial Port. Because that is the only interface, the baseboard has to connect to a computer.
- Display UI. It's unnecessary for the prototype development, but the final product will need UI. And choosing a prototyping language unable to produce UI could be a tremendous slowdown in development.
- It can play audio or control an external player and synthesise voice or control external voice synthetization. In general, it has an interface for controlling external processes.
- Multi-platform and runs on Windows. We wanted the multi-platform ability for the development and prototyping convenience and independence of the production environment of the original project, which runs on Windows.
- It's a language we are familiar with as developers. That is why the main decision was Python or JavaScript.

After evaluating all the requirements above, we choose Node.JS because it can communicate well over Serial Port using its C++ addons as described in [30] and [31]. It can display UI using chromium webview as described in [32]. It's multi-platform, and we are familiar with the technology from previous projects.

Say.JS This is a Node.JS library that supplies one universal interface for speech synthesis on Windows, macOS and Linux. On Windows, it works by default with Microsoft Speech API[1], on macOS with Say CLI Tool[2] and on Linux with Festival. More about the tool is described in [33].

Node SerialPort This library supplies C++ implementation of Serial Port communication for Windows, macOS and Linux. And creates one universal interface for usage in JavaScript, as described in their documentation [31].

Commander.JS This is a CLI UI library for parsing command-line options, as described in [34], which we decided to use since the main goal of the implementation is the interface for visually impaired end users. Therefore a command-line interface is sufficient to start the application.

5.2 Deployment architecture

The final product can be used in two ways, as an accessory that needs to be connected to a computer or as a standalone unit that will include a small form factor single board computer, like Raspberry Pi, Orange Pi or others. In both cases, the computer parts need to be equipped with an audio interface capable of spoken word playback.

Figure 5.1 shows generalised deployment architecture starting on the left with a Computer Unit followed by the Haptic Tiles Main board connected to the computer and at the end Haptic Tiles Secondary Board representing ability to chain multiple boards in a row. The following list describes individual components of the diagram.

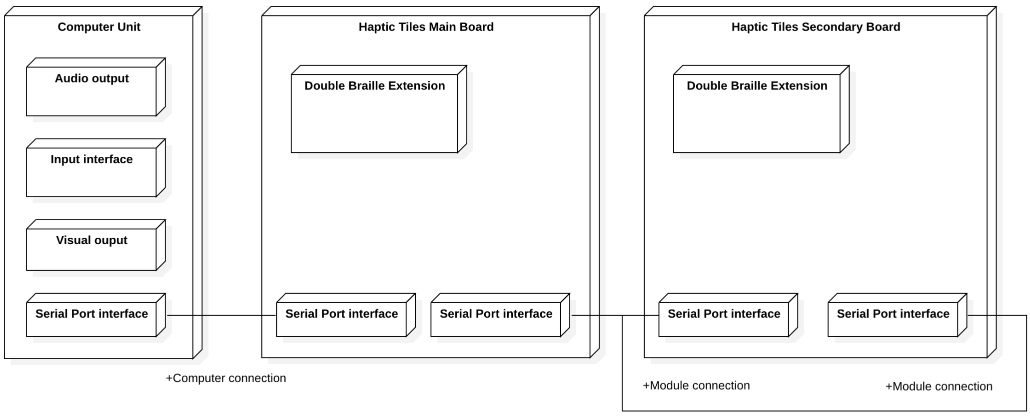

Figure 5.1. Deployment diagram

- Computer Unit is the main machine running the software. It can be a single board computer or regular PC. It needs to be equipped with an Audio Interface, either with speaker or headphones. Serial Port interface is needed for the communication and powering the Haptic Tiles. Visual output is optional since the application doesn't

[1] https://docs.microsoft.com/en-us/previous-versions/windows/desktop/ms723627(v=vs.85)
[2] https://ss64.com/osx/say.html

have any UI at the moment. Input interface represent either button or keyboard of PC that can be used to start the application.

- Haptic Tiles Main Board is the baseboard connected to the Computer Unit. It has a Double Braille Extension module on it.
- Haptic Tiles Secondary Board shows how extra boards can be connected to the main board to create a row for writing or bigger block for memory game.

5.3 Software architecture

The project heavily relays on many layers of abstraction. From object representation of the physical parts of the baseboard and the extensions modules to software parts like an audio player. Aggregation structure is described in Figure 5.2.

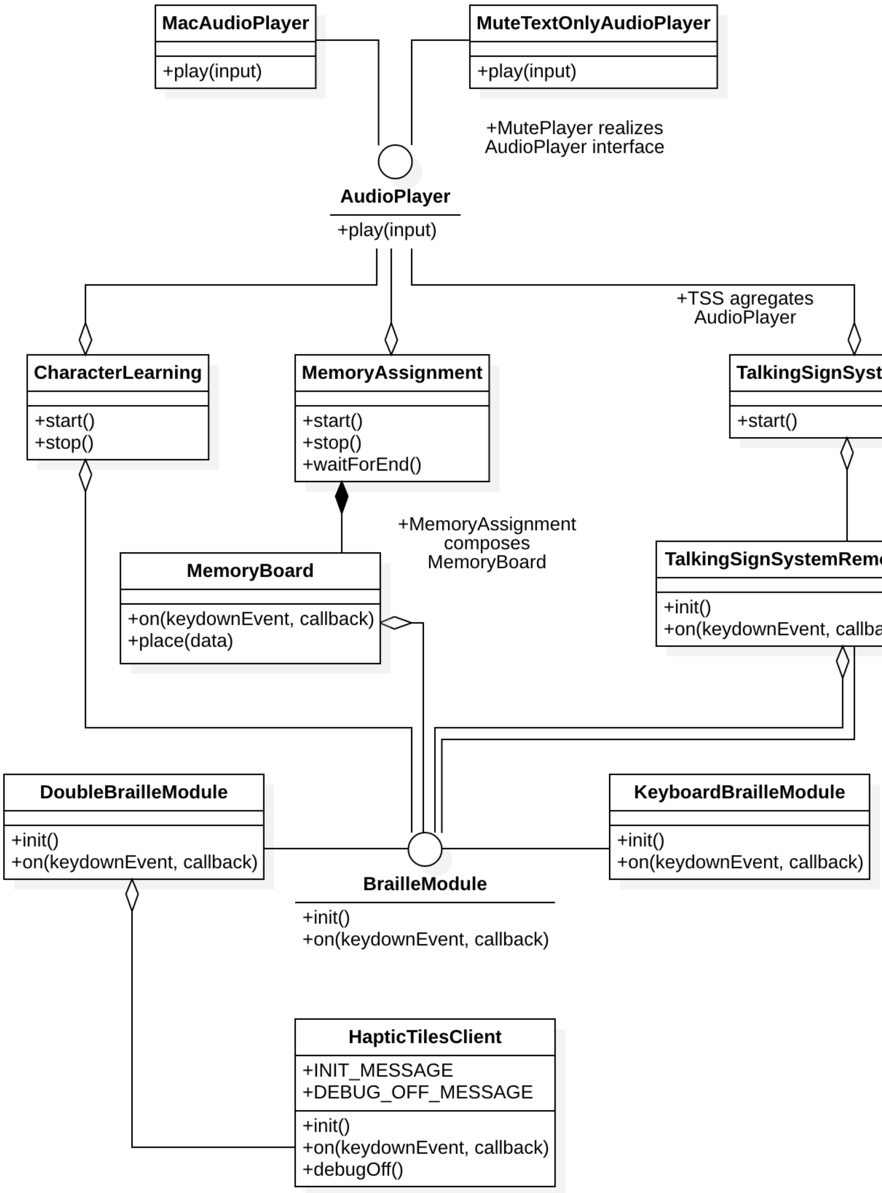

Figure 5.2. Class diagram

Figure 5.2 shows the structure of the software. It focuses on the key classes and leaves out technical details like factory classes, data loading helpers and classes for testing. The three implemented software applications, used in the usability experiment in Chapter 4, are in the middle of the diagram. For them to work they all need instances of a class implementing `AudioPlayer` and `BrailleModule`.

`AudioPlayer` implementations can play both text input, by transforming it into a speech, and audio files from a file path. Text to speech can be either plain string, then default voice is used, or language and dialect can be specified. `MuteTextOnlyAudioPlayer` is an implementation which prints all audio into a console, which is useful during development.

`CharacterLearning` on start method call prompts the user, Lecturer or Researcher from Chapter 4, to select a Latin character from a loaded data set. Then in waits for the User to fill in the letter in Braille. After successful fill the user is prompt to choose a new letter. This loop repeats until the user quits the application.

`MemoryAsignment` on start loads the selected data set. It creates `MemoryBoard`, which places the data on to the virtual board which is representing the physical `DoubleBrailleModule` and calls back the `MemoryAssignment` when an item on the board is selected, pressed by the player. `MemoryAssigment` keeps state of the game and check for matches when two items are selected. At the end it announces a win and stops.

`TalkingSignSystem` on start wait for user input and based on it plays an information about it functionalities. On it's creations it expect to receive an instance of `TalkingSignSystemRemote`, which is responsible for mapping the `BrailModule` buttons to TSS numbering.

```
{
    "symbol": 0,
    "braille": 1
}
```

Listing 5.1. Example of BrailleModule "keydown" event data.

`BrailleModule` interface represents any Braille module that can be connected to the baseboard. It is implemented by `KeyboardBrailleModule`, which is simple computer keyboard module simulation for development purpose. `DoubleBrailleModule` implements actual physical extension module. It maps Haptic Tiles button to one or more Braille symbols, depending on the physical setup. Example of first Braille symbol dot number one press shows Listing 5.1.

```
{
    "tile": 0,
    "button": {
        "row": 1,
        "column": 0
    }
}
```

Listing 5.2. Example of HapticTilesClient "keydown" event data.

`HapticTilesClient` implements the Serial port communication with the Haptic Tiles baseboard. It supports hot reconnect, which is useful when the cable get pulled out of the baseboard or the application starts before the board is plugged in. It emits raw “keydown” events with the button location information, example of which shows Listing 5.2.

5.4 Input data

All of the applications are generic and the input data can be prepared using a simple structure saved in common human friendly format `JSON`.

Character learning input data set is a `JSON` object mapping from phonetic transcription to Braille number expression. Good transcription is important for the voice synthetisation to pronounce the text clear and as close to human voice as possible. The Braille expression must be sequence of numbers from 1 to 6 separated with dots if multiple Braille symbols are needed. Example of our Czech alphabet data set shows Listing 5.3.

```
{
    "vykřičník": "235",
    "malé písmeno. - prefix": "5",
    "malé písmeno. a": "1",
    "malé písmeno. b. s přehláskou": "1.15",
    "písmeno. G": "6.1245"
}
```

Listing 5.3. Example of Character learning data set.

Memory game data set have multiple options how to construct a game data set. Simple text only games can be saved as array of arrays of two strings, representing two matching items, as shows Listing 5.4. Amount of matches is not limited, if the game board is smaller only the first n of matches is used for the game.

```
[
    [ "29.9.1938", "Mnichovská zrada" ],
    [ "rok 1968", "Pražské jaro" ]
]
```

Listing 5.4. Example of simple text based Memory Game data set.

In case of audio files or specified language, the matches are represented by an array of two objects, as shows Listing /ref[object_game_data_set]. The item object has required fields `value` and `type`. Optional fields are `key` and `language`. If `key` is used it must be unique for the whole data set. If it’s missing value of `value` is used instead. Therefore if all values are unique `key` can be omitted for convenience when creating the data set. Allowed values and overview of the item object structure shows Table 5.1

Filed	Type	Required	Note
key	string	No	Optional, unique
value	string	Yes	text, file path
type	string	Yes	sound, voice
language	string	No	en-us, cs-cz

Table 5.1. Memory game item object overview.

```
[
    [
        {
            "key": "gott_sound",
            "value": "gott.m4a",
            "type": "sound"
        },
        {
            "value": "Karel Gott",
            "type": "voice",
            "language": "cs-cz"
        }
    ]
]
```

Listing 5.5. Example of Memory Game with specified language and audio file.

TSS doesn't have any input data at the moment, because the information is not changing too often.

5.5 CLI Interface

All the application can be started from one command line tool using different commands and options combinations. The current state is in the Listing 5.6, which shows printed overview using `--help` option on the root command.

```
$ ./src/index.js --help
Usage: haptic-tiles-extensions [options] [command]

HapticTiles extensions cli testing tool

Options:
  -V, --version                output the version number
  -h, --help                   display help for command

Commands:
  tss [options]                Run TalkingSignSystem Numbering Education
  char-education [options]     Run Character Education
  memorize-game [options]      Run Memorize-Assigning Game
  braille-numbering [options]  Run Braille Numbering to get user fami...
  help [command]               display help for command
```

Listing 5.6. Example of help overview on the root command.

The applications can be started in debug mode using environment variable `DEBUG`, as showed in Listing 5.7. Besides debugging this mode can be also used as verbose version of the applications. This is useful for checking what buttons are the users pressing for example.

```
$ DEBUG="HapticTilesExtensions:*" ./src/index.js tss
```

Listing 5.7. Example of running the TSS in debug mode.

Chapter 6
Conclusion

In this thesis, we have presented an analysis of currently used aids for individuals with vision impairments and desk games requiring vision to play, which we considered transforming into interactive blind games variants. Further from the analysis, we selected games and aids that were the base for our Haptic Tiles extensions. As the Tiles were interactive haptic maps, they offered a valuable technical base for our edutainment solutions. Next, we have introduced the Double Braille Module extension, accompanied by three software solutions. Braille Character education software, Memory game and Talking signs system simulator. We implemented the applications, conducted a usability experiment with the target group and processed the outcomes. All three applications were successful with minor changes and many future features and additions. All the participants would have liked to have this tool when they were learning Braille, and they would like to have it home now to play the Memory Game. In the following paragraphs, we will describe the fulfilment of the goals defined in the introduction chapter of this document.

6.1 Goals fulfilment

In the following text, we describe the level of fulfilment of particular goals set in Section Goals 1.2. Goals' numbering is the same as the introduction, and the goals' text is repeated for clarity.

Goal 1.1 *Analyse current related research, tools, and aids for individuals with severe vision impairments. Focus on the method and approaches involving tactile interaction. Select feasible results for designing a new solution as an extension to the Haptic Tiles.*

Braille aids we analysed lack immediate feedback or check. They are simple tools aiming for training Braille character combinations 2.1.3 or writing tools 2.1.2. The combination of electronic board and mechanism of these tools was one of the selected directions. ATM with an audio interface 2.1.5 has a specific interface for individuals with vision impairments, which we could simulate. However, we were unsure of the usefulness compared to the other analysed tools. TSS 2.1.6 is an important help for individual orientation in a city but can be complicated to explain without a live example. Desk games are hard or impossible to play without vision, and the challenge was to replace the sense with another to make a game playable and, more importantly, enjoyable. The Braille phone keyboards all missed any education step and focused on fast and comfortable typing. Here we saw a gap between the physical aid without feedback and full solutions for writing.

To design the solution, we looked at already existing solutions. First at Radical atoms 2.2.1, which could enable the users to feel different states of game items based on piston height, but mechanical complexity at the scale of the Tiles baseboard is a project on its own. We decided to design a solution using buttons and focus more on the audio feedback.

Goal 1.2 *Design and implement a set of solutions that will benefit the user group of individuals with severe vision impairments using UCD [2]. Both extension physical appearance and software to control it.*

First, we created a set of cardboard mockups 3.6 to experiment with different interaction approaches. Buttons were the only feasible options, as any freely movable parts would be too difficult to operate for the users.

As buttons showed as the primary building block of the extension module, we started our design loop with a simple one-button design. We focused on tactile response, button surface feel, and manufacturing simplicity. After a few iterations, we created an ellipsoid-shaped button top that feels like a half-sphere to the touch. That was important since the buttons represent enlarged Braille dots. We further developed the Double Braille module 3.9, an extension to the Tiles with two Braille six-dots. Although we still were unsure about the rough surface of the buttons, we decided to start the usability experiment with this version.

In terms of used technologies for implementation, they fit the purpose. We want to use some actual voice recording in the future or try AI-generated voice synthetisation since it should be more natural than the current "Zuzana" version.

Goal 1.3 *Evaluate the prototypes with representatives of the target user audience.*

The usability experiment 4 had five essential parts, introduction briefing, Braille education, Memory game, TSS simulator and debriefing. We had six participants 4.1 with an average age of 36 years old and the oldest participant of 48 years old. They all were familiar with braille and could write and read. Only one participant did not know braille. Therefore first application experiment with Braille education turned into Braille practice, and we were mainly observing how people approached the software and comparing it with our assumptions. Some participants wanted to press all dots of the Braille symbol at once. Others forgot to move on to the next symbol. These are important notes for our instructions that we did not give to the participant because we wanted to observe the participants' behaviour.

In the beginning, the Memory Game seemed too tricky since none of the first three participants did finish the whole game. They chose a lousy strategy and were impatient and therefore failed but still liked the game. The following three participants all finished at least one whole game, and the last one even five games in a row. The favourite data set was famous voices. Based on the finding, we will make multiple levels with different amounts of items to match. We will add the ability to stop the audio guide by continuing the game and making minor adjustments to the guide's voice.

TSS simulator was a success. Everyone like how simply it explains what the system does. Some participants would like this guidance even at their actual TSS remote because they do not remember all the functionalities. The only adjustment to this application is the change in phrases that were too technical or did not use the terms of individuals with vision impairments.

In conclusion, we did not discover any fatal flaws in the current prototype, only minor mistakes that we will repair with all the new features that the experiment revealed.

6.2 Future development

We want to continue with usability experiments because the current group of participants represent only a part of the target group. Only active adults. We want to focus more on the elderly, where the tool can have a more significant impact on their quality of life. Moreover, it can also help to train their cognitive capabilities. Also, we would like to do some tests with younger individuals with vision impairments to observe if the system works for them, as we have a data set ready with animal sounds for kids. We did not get to experiment with mentioned groups due to time constraints both from our and the participants' sides.

We want to proceed with the multiple part module that can deliver smoother buttons using Resin printing the buttons part. That would be especially useful in cases where cleaning the rough buttons will be difficult. We will need to compare if the complicated manufacturing model benefits outweigh the simple one-piece print of the current solution.

If the research and places, where the solution will be used, will support it, we will add a standalone unit with a microcomputer that will connect to the extension board. Therefore no computer connection will be needed.

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Appendix A
CD Structure

All the model files, photos and other materials created during this thesis are included on the CD at the back cover of this document.

The following list describes the root structure of the CD.

`thesis.pdf`	This document in PDF version.
`thesis-tex.zip`	Source files of this document in TEX.
`application.zip`	Latest version of the application source code.
`repository.zip`	Archive of the repository[1].
`experiment`	Data logs collected during the usability experiment.
`photos`	High resolution pictures of the prototype.
`model`	3D model source files[2] and STLs.

[1] https://gitlab.fel.cvut.cz/woldrkry/haptic-tiles-extensions

[2] https://myhub.autodesk360.com/ue2a727f5/g/projects/20200820324962401/data/dXJuOmFkc2sud2lwcHJvZDpmcy5mb2xkZXI6Y28ucUhuTnBqQ2pTeXlCblk0cjBNelhndw==

Appendix B
Acronyms

This attachment explains shortcuts and terms used in this document.

ABS	Acrylonitrile butadiene styrene
ASA	Acrylonitrile styrene acrylate
CLI	Command-line interface
DIN	Deutsches Institut für Normung (German Institute for Standardization)
FR	Functional requirements
HCI	Human computer interaction
IAPB	International Agency for the Prevention of Blindness
IPA	Isopropanol
ISO	International Organization for Standardization
MEK	Methyl ethyl ketone
NFR	Non-functional requirements
PETG	Polyethylene terephthalate glycol
PLA	Polylactic acid
PVB	Polyvinyl butyral
SONS	Sjednocená organizace nevidomých a slabozrakých České republiky (United Organization of the Blind and Visually Impaired of the Czech Republic)
STL	Standard Tessellation Language file format
TSS	Talking signs system
TUW	Technische Universität Wien (Vienna University of Technology)
UCD	User centered design
VPN	Vysilačka pro nevidomé (Transmitter for vision-impaired)

Appendix C
Interview transcripts

This appendix contains the interview transcripts of all usability experiments' participants from Chapter 4. An important note is that the first three participants were interviewed in the same session.

C.1 Participant 1

Social-demographic profile. The participant is a university student in the last year of her studies and currently writing a bachelor's thesis. Her visual impairments are categorised as practical blindness and is the same her whole life. She learned Braille in elementary school, where they used various learning tools, making the Braille system closer for children to understand.

Interview transcript. We started the interview with a few questions about general information about the participant, their eyesight and their knowledge of Braille. In response to the first question about the state of their vision, the participant categorised it as practical blindness and specified the concrete problem as *retinopathy of prematurity.* That partially answers the following question about how long are the vision limitations lasting. To confirm, we asked, and the state has not changed since birth.

The next set of questions is oriented on Braille and participants' experience with it. The participant learned Braille in the third grade of elementary school. In the school, they used multiple learning tools. A cube with push in dots, Braille typewriter Picht, wooded slates with cylinders to insert as braille dots. The last, we asked a question about the self-evaluation of Braille's knowledge. The participant can read a regular text and some basic mathematical symbols, equal, brackets, and others she encountered during elementary and grammar school. She read only one book in Braille. She is not actively using Braille in favour of audio outputs. She thinks she should be practising it more. Maybe for the future, when she wants to read books to kids.

Hardware first impressions. The next set of questions is about our tool, its purpose and hands-on with the prepared software. When we were describing the tested tool and what it can do, the participant started to look at it. There were no comments at first, but after a few seconds, she noticed it is not all in one piece. That is due to the modularity of the tool. *"Is there a reason why there are four Braille characters?"* We explained more about the size of the blocks and how it is possible to connect multiple of them in a row. *"The buttons are a bit rough"* was the main first impression of the buttons. The participant appreciates that buttons are easy to distinguish from the surface. In comparison with real Braille characters, the participant mentions the larger scale, using the words *"a lot, a lot larger"*, but confirms that it still resembles Braille well. *Side note, these are the hardware first impressions, no software applications involved.* With a button press, the participant recognises success based on the audible sound. She tried to press a Braille character using multiple symbols at once. Quickly after, she comments on the fact is probably not for fast typing or using both hands. We have confirmed that the assumed use case is one finger. The participant would instead use the Picht style buttons at the bottom of a braille display for fast typing.

Braille numbering application. In the next part of the interview, we started with the software applications testing. First, we have started with plain Braille numbering system education. At first, we had to clarify it is purely about the indices, no letters, no characters. Only one button is pressed at a time. After a few presses, we continued on to the next application since the participant knows reading braille well, and there was no need to learn the indices.

Characters education. At the beginning of this section, we tried to be more specific about the purpose of the application to avoid misunderstandings. However, at the same time, we realised we could not be too strict because that would compromise the experiments' findings. We selected lower case "h" from the Czech braille alphabet for the experiment. Before starting, the question from the participant was, *"Should I press the character at once or in a sequence?"*. After confirming the use of sequence, she quickly pressed every button needed, 1, 2 and 5. Moreover, she commented *"That's good for learning! Especially when you encounter Braille later on."*. The participant tried what happens during multiple buttons press. The first registered by the software has been taken. Since the participant knows Braille, we instructed them to press the wrong dot to see their reaction to the software behaviour. The reply was *"Nice!"*. The participant liked this application and could imagine using it during her learning process in the past.

Memory game. The next software application to try is a memory game with a twist instead of searching for the same objects. The goal is to search and match based on logical similarities, like a car brand and a country, like a person's voice and name. The first question was, how does it work, *"Do you write it down?"*. No, it is based on pressing the buttons. There are six combinations on the one block of the tool. The shape and placement of the button do not matter for this application. Under each dot is something hidden, and the goal is to press first and press second and see if they match.

First, we started with English-Czech body parts. After the game started, the participant said, *"Now I need to understand which dot is hiding what and the logic behind it."* After the first press "feet" she stopped and said *"Okay, and now what?"*. Meaning where she should look, we think. The second press was "ruka" and said *"Okay, I know, it will be next to it."*. Furthermore, she pressed another dot, thinking she was still looking for a pair for the "feet". When she heard "arm" she said *"Hasn't said it wrong."*. At this moment, our worries were confirmed. There is a miss understanding of how the game works. We have explained, and we continued. The participant sounded worried about where to look for the matching pairs. We ensured her the placement was random and that she could freely search through all buttons. She was still attached to the idea of finding logic in it. When a mismatch occurred, it was clear that the information was not necessary to hear. She said *"Yeah, yeah, I know!"*. After two mistakes, We realised she looked only in the first Braille character. After that was mentioned, she realised it was purely about trying places out and memorising where things were placed. During pronouncing "body", it was not well understood by the participant. We clarified. The participant thought that the more you play, the easier it gets; therefore, we explained that there is a new order with each run.

We left this game unfinished. We saw that it would be a relief for the participant. We started a new game with the famous Czech voice thinking this could be more interesting for the participant. Soon after the start, the participant again mentioned that she did not like the guessing part. In this game, the successful match happened right the second time, which clearly brought joy to the participant. Again as in the previous game, the participant wanted to press a button, but the system wasn't yet listening for input. The change in the game data made the participant more engaged with the game. She searched more, commenting on the voice, not even minding the announcements about the mismatches. The participant underestimated her input to the game logic, thinking it might not be the game for her personally, but could be pleasant for others.

Latest, we've tried matching Braille to the Czech alphabet. After showing an example, the participant showed interest in the game. She thought she would have to write the letter in Braille but was also okay with searching for them like in the previous games. As the previous times, the participant tried to press a button before the system was listening. The participant wanted confirmation. *"Do I look for any possible letter from the mentioned braille character dots or the one that is specified by all the dots?"* Also, the same has been omitting the second Braille character, therefore quickly getting to the point of feeling like there is no match. We have asked what the participant thinks about the mismatch announcement. She has felt about it rather negative. In this last game, it was for her more confusing than helpful. She has thought maybe just half of the amount to match would be enough. Before moving on to the last software application, we have talked about the possibilities of bringing logic to the placement. Meaning instead of random, some pattern would be used, and the game's objective would be to find the pattern. Since matching it afterwards would be simple and fast.

Talking sign system. First, we explained how the Talking sign system application works. That any of the two Braille characters can be used and that there is a sequence of how to get different information from the application. Starting from the number explanation to a complete example from the real world. The participant understood the controls without a problem and liked the explanation and examples. She has found it very intuitive and great for learning TSS for newcomers. The participant mentioned her frustration in a place where TSS is not implemented or is implemented partially or wrong.

Debriefing, last thoughts. The speed of the voice could be a bit faster, so it does not get boring, and the application feels more prompt. Also, the mismatch repeating, especially during the Braille matching game, could be shortened to only "Incorrect.". In the games, she dislikes the randomness part. Should could imagine some help, where to look for the matching pair. The participant likes the character learning and does not feel a need to press all dots at once. The tactile feedback of the buttons feels to her fine even after half an hour of clicking the buttons.

C.2 Participant 2

Social-demographic profile. The participant is a book writer specialising in books for children. She lost her sight at five years due to a severe illness, and her current state of vision is practical blindness. She learned Braille in elementary school. After grammar school, she decided to study journalism at a university.

Interview transcript. We started the interview with a few questions about general information about the participant, their eyesight and their knowledge of Braille. Based on the categorisation by her eye doctor, the participant is practically blind. Her right eye does not see anything, and the left one has 8 % of vision remaining. The loss of sight happened to the participant after an illness at the age of 5 years old.

To a question about the usage of Braille, the participant replied that she doesn't use Braille almost at all for reading. But she uses it day to day for writing on her smartphone. She learned Braille at elementary school, where they used several tools to help with her education. For example, wooden chickens placed in two columns and three rows represent one braille character's dots. These chickens are folding to the side when a dot (a chicken) is not in the character the tool should represent at the moment. Another too the participant mentioned was a wooden sheet with metal rods that they could push in to represent the Braille dots. Evaluation of her knowledge of Braille, the participant said reading was not good, about 15 to 20 characters per minute. But writing is not a problem for her. Sometimes she switches up similar characters in Czech "z" and "ž" or "ě" and "é". She concluded that about 95 % of characters are not a problem. The participant is not familiar with basic maths symbols like "+", "-", "=", etc.

Hardware first impressions. We started the next set of questions with a brief overview of the prototype and its functions. The participant right away noticed the large size compared to standard Braille. Right after that, she commented on the spacing of the two columns being too close, but also she mentioned that she did not know how it would be used yet.

The buttons felt a bit too stiff to the participant on the first try. She was using multiple fingers. We guided her to use only one and repeat the experiment. Even after that, it still felt the same.

Braille numbering application. First, we explained what the software about is. The participant tried it, and everything went without a problem. After noting that two quick sequence presses could be a problem, the participant tried it and succeeded.

Characters education. Since the participant was familiar with Braille numbering, we quickly moved on to the characters' education. We again explained a bit about the software and chose a letter for the participant to try after that. First, we selected "ú". The participant first tried to press all the dots at once, and after the software only replied "3", she tried again. Then we intervened and explained that it needed to be done in a sequence. Then she completed the letter, and only once the software did not register press because it was still playing the audio.

Memory game. In the next part of the interview, we explained how the memory game works and how things are assigned based on logical similarities. We started with the English-Czech data set. The participant was searching only in the left Braille symbol. After a moment, when the participant went through all the dots in the one character, we guided her to search also in the right symbol. During the search, the participant looked like she did not mind the repetitive information about matches and mismatches. She always waited till the end of the voice note and then continued searching. After a while, she commented with a smile *"I'm totally lost."*. After a while, we decided to continue with the interview and asked about the repetitive notes. The participant finds it adequate for the game.

After the questions, we moved on to the famous voices data set. The participant asked if the game was the same and if she was looking for a voice and name. We confirmed and added a note that it could be in both Braille symbols. The participant felt being slowed down by the game because right when she knew the correct answer, she needed to wait till the end of the audio track. But the audio notes about the wrong or correct matches were fine, she said.

Lastly, we tried the Braille to a Latin letter matching. We explained that all the numbers mentioned must be used in the Braille character we are looking for. The repetition of the Braille characters expressed as a sequence of numbers started to be confusing for the participant, she said. Because it is long and much information. Both to keep in mind and also to listen to the audio notes. She said, *"It could be simpler if the left Braille symbol had Latin letters and the other has the numbers."*. In the end, she said that she would enjoy playing these games.

Talking sign system. In the end, we explained the TSS system and how controls work. After a few clicks, the participant said, *"Yaay, I would need this, I still don't remember what is what on the TSS controller."*. She only uses numbers 1 and 3, and when she needs to open a door or get off the public transport, she presses number 5. But that is the activation of the acoustic signalisation at traffic signs.

Debriefing, last thoughts. In the end, we asked again about the feedback and feel of the buttons. Now they felt less hard to press, and also because she used only one finger, it was more comfortable. But she still mentioned that pressing multiple points would be difficult. Since the participant didn't mention anything about the build quality and multiple pieces, I asked at the end about it. She noticed the seam between the mainboard and the sides, but it was nothing distracting or uncomfortable.

C.3 Participant 3

Social-demographic profile. The participant is a journalist and lecturer and studied journalism at a university. She has struggled with her sight since the day she was born. She never undertook special education for individuals with vision impairments and never learned or used braille. Her current eye's visual strength is 20 dioptries and is stable after surgery five years ago.

Interview transcript. We started the interview with a few questions about general information about the participant, their eyesight and their knowledge of Braille. The participant has a left eye with vision but without a working lens. Therefore without glasses, she can see only colourful smudges. She has one long-distance glasses with about 10 meters fixed focus point. At that distance, she can see relative sharp. The glasses are about 14 dioptries, and her own eye is about 10 dioptries. She has also reading glasses with 20 dioptries for a distance of about 15 to 20 centimetres. The participant had a period when she was completely blind. The complications with a vision came after 35 years old, and now she is 48 years old. She did not go to any particular school or have any courses regarding visual impairments. The things she knows are only from self-learning. The current vision state is the same about 5 years after surgery.

The participant does not use Braille and has never learned it. Therefore I skipped the questions about it.

Hardware first impressions. We started the next set of questions with a brief overview of the prototype and its functions. The participant sees the block as just one flat slate. She cannot recognise the buttons, mainly because of the similar colour to the surroundings. She can see the space between buttons and the main board using the reading glasses. She also feels the attached side block and the spaces there but can see them only with the reading glasses. She likes that the buttons are easily recognisable and have different structures than the surface around.

Braille numbering application. First, we explained what the software about is. The participant tried to press a few dots, and then she asked if she could use both of the Braille symbols. She mentioned that it would be handier for her to use only one of her arms. To which we explained that it is possible. She noted that it would be needed to use two hands because of the two symbols. At this point, the participant also mentioned that she can hear only with her right ear and sees only with her left eye. So it isn't very easy to combine these senses. The senses are not working intuitively. It needs more processing by the brain.

Characters education. The participant does not know the Braille system, so first, we chose the letter "a" to clarify how the software works. First, we guided the participant that the Braille character would be on the left one on the board. After the simple letter, we chose "ú" as a more complex character that the participant does not know. The participant pressed all the dots until all the correct ones were selected. Immediately after selecting all correct ones, she said the numbers containing the letter, which seconds after the system confirmed it was right. The participant feels like the "Wrong!" note after pressing incorrect dots is a bit offensive. Maybe an error buzzer sound would be sufficient, she said. Also, the whole word felt too long to pronounce.

Memory game. The participant does not know the Braille system, so first, we chose the letter "a" to clarify how the software works. First, we guided the participant that the Braille character would be on the left one on the board. After the simple letter, we chose "ú" as a more complex character that the participant does not know. The participant pressed all the dots until all the correct ones were selected. Immediately after selecting all correct ones, she said the numbers containing the letter, which seconds after the system confirmed it was right. The participant feels like the "Wrong!" note after pressing incorrect dots is a bit offensive. Maybe an error buzzer sound would be sufficient, she said. Also, the entire word felt too long to pronounce.

Next, we moved on to the famous voices data set. For the first time, the participant runs into the issue of wanting to click when the software is still playing audio. The participant feels that after a while the audio notes can be too long and would be nice to be able to quit them earlier.

Since the participant doesn't know Braille system and the last game with assigning Braille is for people knowing it very well, we skipped this part.

Talking sign system. In the end, we tried the TSS demo. The participant is familiar with the system and uses it in her day to day life. She does not have trouble remembering the function used frequently but appreciates the possibility of hearing what the buttons should do. The participant would enjoy having this in her actual TSS controller. But for that, the audio description should be shorter and in more human language.

Debriefing, last thoughts. The participant thinks the buttons are OK. She had not noticed any trouble with the pressure or recognising when the button was pressed. She compares it to a bubble foil wrap because of the size and how pressing the buttons feels.

C.4 Participant 4

Social-demographic profile. The participant is employed as a social worker, helping and teaching other individuals with vision impairments. Her own current state is in the category of completely blind. She has learned the Braille system as an adult and now uses it daily but only for writing.

Interview transcript. We started the interview with a few questions about general information about the participant, their eyesight and their knowledge of Braille. The current state of the visual impairments is in the category of complete blindness with no vision in the right eye and the remaining bits of light in the left eye. The state is not changing the past 8 and a half years. Before that, from her childhood, her eyesight was better, in the category of low vision. It was changing during the years but always in the same range. The participant knows the Braille system. She started learning after her complete vision was lost in her first year. The course she took was about half a year. The participant does not use Braille a lot, admits. She would rate her reading speed on the level of first-year elementary school pupils. But she uses it for writing every day on her smartphone. One of the reading use cases is the names of medication or food. The participant finds it nice and help full when she encounters Braille, but she would not read a book in it. A teacher brought a plate with knobs representing enlarged braille symbols during the Braille course. Another tool she used during learning was a Braille cube, also known as a B cube. That was all. The participant rated her knowledge as essential, with only letters and numbers and no math or music symbols.

Hardware first impressions. We started following part of the interview with a general description of the project and the prototype that we will test. The first question of the participant was “Can I dissemble it?”. We confirmed that the tools are meant to be in one piece to be used. The next reaction was “Oh, these are buttons.”. Next, she noticed one of the gaps between modules but was pleased that she could not feel the rest. The participant recognised the button press without any further comments. The participant likes that the buttons are easily distinguishable from the board. Her only concern was too little spacing between buttons of a Braille symbol on the board. But that did not show to be a problem later on. She likes the height and prefers the latest prototype compared to the previous, where buttons are only 1 mm above the surface.

Braille numbering application. First, we started with Braille symbols numbering to familiarise the participant with software and audio response. At this moment, the participant realised that the board had two Braille letters. As confirmed in the previous comment, little spacing does not make sense. After the first press, the participant asked, “What happens when multiple points are pressed”. We explained that the software would react to one of the points randomly. The participant also tried to rotate the board upside down. She likes that the points stay, so she knows that the board is upside down. She also mentions that the instructions can specify having the cable on the left or having the cable on the top. Therefore it is not in the way. She thinks this could be a product even for self-learners if the controlling software were adjusted.

Characters education. We selected lowercase “h” to be used in the exercise. The participant immediately tried to press all the points at once, but the software recognised only one. The reason why she tried to press all the points at once was a habit of typing on the smartphone. We suggested not to worry and continue in sequence to complete the letter. She asked if the order mattered. We confirmed it does not. The participant encountered an issue with not having her press recognised because the audio was still running. Another letter was lowercase “l”. Before leaving the education topic, we tried uppercase “G” so the participant could experience working with both of the Braille symbols. She completed the task without a problem. The participant thinks it could be helpful for pupils with eyesight at elementary schools during the Braille presentation.

Memory game. First, we explained different available game data sets and how the memory game works. The board is just a blind map. The Braille symbols do not have meaning in the game. The participant mentioned BlindShell[3] version 2, where one of the games is a regular memory game. This project was also developed here at CTU[4]. After that, we started with the English data set. The participant right away tried what happens when she presses the same item multiple times. She likes that the system tells

[3] https://www.blindshell.com
[4] https://dspace.cvut.cz/handle/10467/23743

her what was is the item again and that it is not counted as a mismatch. She finds it funny how the system guides her and tells her to try again. She also appreciates that the system knows and tells if the file was already matched. The participant got one time a bit confused about what should belong together but successfully finished the game. She started in the left Braille symbol, but she moved to the right one before getting looped in it and continued the game.

The participant expressed worries about knowing all the voices, but right after hearing the first voice. She realised this would be a lot of fun. The audio examples were sometimes a bit too long, especially when she needed to wait so that she could select known items. She would like to have a Czech band called “Kabát” in the data set.

We tried the Braille to Latin letters data set in the last game. The participant first thought that the goal was to select Latin letters and then write them in Braille. This game was more difficult for the participant, but she decided to finish it. She would like some statistics at the end of the game for self-competition purposes. She can also imagine beginners playing the Braille data set with some help, like a plastic map Latin letter to Braille.

Talking sign system. At last, we explained the TSS simulator software. The participant compared her “VPN02”, Czech made TSS version 2, to the tested board. The actual TSS remote is a bit bigger than our board. She very much likes it. When pressing number 4, she would also add information about exiting public transport. She would use a better term for traffic light than Czech “návěstí”. Even if the examples stayed only using voice synthetisation, she would like it.

Debriefing, last thoughts. After the experiment, the participant finds the material and build of the board still nice to touch. She appreciates the rounded shape and rough surface of the buttons. She also thinks this is a nice alternative for training touch of beginners compared to a bag of lentils, which is the standard now.

C.5 Participant 5

Social-demographic profile. The participant is a musician and mother of a toddler daughter. She plays the piano very well. She can use both single hand and two hand Picht’s typewriters. She is a fan of the Braille system and likes to use it. She loves “Prague slate”.

Interview transcript. We started the interview with a few questions about general information about the participant, their eyesight and their knowledge of Braille. The participant is from the category of completely blind people. She uses Braille daily. She is a big fan of it and thinks it ensures her independence and better life quality. She can read fluent and fast. She knows both math symbols and music notes in Braille. *“I think if people are not using Braille, their knowledge of Czech slowly gets weak. People will forget how to use correct punctuation.”* she said. She like modern technology and uses, for example “PenFriend” to mark spices in her kitchen. But she still keeps the old Braille labels and finds them maybe almost better, especially when the “PanFriend” is nowhere to be found.

The participant does not use Braille for writing on her phone because she can comfortably rest her hands in position for writing. She uses Picht’s Braille typewriter for writing music notes. She studied music. She used two hands Picht’s typewriter in elementary school, but she can also use the right-hand version. It just takes a moment for her to get used to it. The participant also knows how to use Braille writing slate, known as “Prague slate”. She said, *“I love Prague slate!”*. She sometimes struggles with using the slate in the right orientation when writing a diary, so the written text goes from left to right. She also uses Braille for memorising long texts. Besides Braille, the participants use a computer to communicate "with the World" and write using a computer keyboard. If she had a friend, who knew Braille only, she would not mind using Braille exclusively.

Hardware first impressions. Before we finished the description of our tool, the participant started exterminating the board. She said with a smile, "Oh, it feels like Philips screw heads!". Right after that, she recognised two full six points of Braille characters. The participant compared the points enlargement to a printed vocabulary that she remembers from the first grade of elementary school. This vocabulary was created using PVC foil.

Braille numbering application. We explained what the application is about. The participant recognised voice synthetization "Zuzana" immediately after the first button press. She said "Zuzana is everywhere.". She likes "Eliska" for longer texts, but she knows "Zuzana" software is fast and "Eliska" is slower.

Characters education. We did not have to explain much for the second application, because the participant asked about possibilities to write Braille letters during the previous example. We have tried the lower case letter "h" participant promptly pressed all the necessary points and clapped her hand at the end, with a comment that she really liked it. Next we tried upper case "G", before writing the participant asked if she should use the upper case prefix, point six. During this experiment, she tried to write the whole letter into the left character on the board. We guided her to move to the second one after writing the prefix. During the experiment the participant press wasn't registered only once. She again mentioned how she likes it because of her huge interest in Braille. She mentioned sometimes she can be a bit judgmental to people who don't know Braille system. To her, it is like reading with eyes. At last, we tried the Czech letter "ň", and the participant finished the exercise without making a mistake.

Memory game. Before starting the game, we explained to the participant our idea and how to match items. Due to time constraints, we skipped the usual English data set and started with the Czech famous voices. The first question from the participant was: if the left Braille symbol is "names" and the other is "voices". During the game, we once needed to clarify that it is necessary to wait till the end of the audio sequence. The participant was dedicated, and even though she got lost towards the end, she finished the game successfully. The participant appreciated the chosen voices and voice examples.

Next, we started the memory game with the Braille data set. We asked the participant about the repetitive audio guidance. She thinks it slows her down. Mainly because it throws her mind off the search for a match. She also does not want to wait for the audio's end. We left this game unfinished because of the time, and we wanted to try the TSS simulator.

Talking sign system. We started with an explanation of the sequence controls of the simulator. Then the participant tried it and had no complaints about it. She knows TSS very well therefore she tried a few buttons, and everything was as expected.

Debriefing, last thoughts. We started with an explanation of the sequence controls of the simulator. Then the participant tried it and had no complaints about it. She knows TSS very well. Therefore, she tried a few buttons, and everything was as expected.

C.6 Participant 6

Social-demographic profile. The participant is a musician and singer but also an IT enthusiast. His Music school-leaving exam included playing accordion, singing and music theory. His knowledge of Braille is broad. It includes a regular alphabet but also music notes. He uses it only for writing on his smartphone.

Interview transcript. We started the interview with an informal briefing, and later on, we transitioned into the experiment. In the beginning, we talked about the current state of eyesight of the participant. He is completely blind from birth. After that, we talked about his studies and knowledge of Braille. He uses Braille very little for reading nowadays, maybe in an elevator, but he used it a lot during his studies. Therefore he knows it well and thinks every blind person should know Braille. He says *"Everyone listens to the audio and thinks, what do I need Braille for? But what happens during a blackout?"*. He also mentioned how blind people without Braille forget grammar. His knowledge of Braille is based on his music school education. But besides Braille, he also learned to use "black-print"[5] letters. In his studies, they used relief exercise books. To this day, he is still excited to read, for example, a car's license plate. Lukas added that this was very useful for using "Oktakon", a silent reading machine, wherein one hand camera recorded text. On the other hand, a person can feel the letter displayed using tiny needles. In general, this device was used for the 3D visualisation of the camera vision. The participant used to read books like this, and it is a pity that kids now miss the Latin letters completely in their education.

Hardware first impressions. After the general information talk, we moved on to the first impressions. We did not explain the use of the tool yet. The participant immediately noticed that the tool is made out of multiple connected parts. He asked about the blank spaces on the sides. We explained that they keep the spacing when multiple modules are connected. His first thought on the material was wood. Therefore we explained its 3D printed plastic. We also explained why there is a baseboard on which the Braille symbols are placed. We check that the participant can feel when the buttons are pressed.

Braille numbering application. As a first software example, we tried Braille numbering. We choose this mainly to make the participant familiar with the audio response of our tool. He pressed a few points in both Braille symbols on the board. The fact that the software behaves the same on both symbols was clear to him.

Characters education. Quickly after that, we explained how the Braille education software would work. We will select the letter the participant will have to press points that the letter is made out of. Before we started the software, Participant asked if the press should be in sequence or all the points at once. He was asking because of this smartphone experience. We started with the letter lowercase "r". Right after the third press, the participant encountered the issue of ignoring input during audio playback. Otherwise, he did not make a mistake. That was expected based on his experience with Braille. He thinks this would be perfect for people who are learning Braille or do not know what Braille is. He thinks some people are afraid that they won't be able to feel Braille. But that doesn't mean that they won't need it for writing. Next, we tried uppercase "G". We explained that on the left symbol would be a prefix and on the right one the letter. After a successful finish, the participant was curious and wanted to try to make a mistake on purpose. He was happy about the software's response telling him this point was wrong. After that, we returned to the same letter again, so he

[5] This is an expression used by individuals with vision impairments for Latin alphabet.

could explore more. The participant was a bit confused about the repetitive press of a correct point. The software only repeats the number, but he would like some additional information. The only thing he does not like is the wait for the audio to end. Lukas asked if the participant used both hand. He uses only right because that's how he reads Braille and is used to it. Then we talk more about how to make the audio faster. The participant would prefer that the audio ends when he presses another point. The participant also thinks that the audio started a bit late after the press.

Memory game. Next, we move to the game. First, we explained the concept of matching items based on logical similarities. And also that the Braille symbols don't have any meaning in the game. We introduced what game data sets are available to try.

We started with Famous Voices. We ensured the participant that the placement was random and that not even we knew where a correct match was. The participant was deeply focused on the game and proceeded systematically. He mentioned that again it would be nice if he could stop the voice and speed up the game that way. After a first match, he tried how the software reacts to a press of an already matched item. There was one audio sample in which the participant didn't know the person's name at first, but he figured it out later on in the game. The participant liked that in case of a miss-match with an already matched item, the first chosen item stays selected. The game ended in quite a short time because of the good strategy. The participants enjoyed it a lot.

Next, we selected the Cars data set. The participant was excited about Cars initially, but he thought he would struggle when he learned that the goal is to match a country to a brand. The participant did not understand "Lancia". The voice synthesizer did mispronounce it.

After two games, we returned to Braille, now with the Braille game data set. We explained what the game was about and that we expected it to be more complicated than the previous one. The participant did not like how the Czech "Zuzana" voice deals with Czech special characters' pronunciation. But he understood what she said. In one match, the participant thought there was a mistake in the game, but soon after, he realised that he mistook "s" with "q". Although the participant initially thought the game would not be more complicated than the others, he admitted that it was complicated during the game. He said *"I didn't know what 2, 4, 5, 6 is. I thought that was a mistake because it's a number. But when I imagined the points, it was clear."*. This last data set is heavy on the users' imagination, but the participant thinks good imagination is important for individuals with vision impairments.

Talking sign system. As a last software application example, we tried the TSS simulator. The participant does not actively use TSS for 2 years but still remembers some of its functionalities. The participant would again appreciate the ability to skip the audio with the next button press. He was curious and pleasingly surprised about button number six. The participant also tried long press, but that is not implemented in the simulator.

Debriefing, last thoughts. Because the participant liked the game, we tried our new history data set at the end. He finished it as all the other previous games. For fun, he also primarily tried animal sounds for kids' users.

The participant thinks the aid is great for beginners, all age categories, kids in elementary schools, and people who lost their eyesight at an older age. We asked if the participant as a musician would find the aid useful for practising music hearing in music schools. He would find helpful a memory game with a tone and audio sample of the tone for general music education. For tuners would not be ideal as they cannot use absolute hearing. He would also imagine matching instruments' names and sounds.