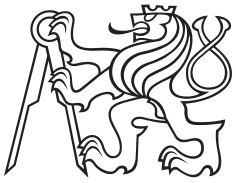
Master Thesis



Czech Technical University in Prague

F3

Faculty of Electrical Engineering
Department of Computer Graphics and Interaction

Design of Multimodal Aid for Learning Braille Alphabet

Bc. Martina Klimešová

Supervisor: Ing. Dominika Palivcová
Field of study: Open Informatics
Subfield: Human-Computer Interaction
November 2021

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Klimešová Martina** Personal ID number: **466163**

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:

Design of multimodal aid for learning braille alphabet

Master's thesis title in Czech:

Návrh multimodální pomůcky pro učení se braillova písma

Guidelines:

It is a known fact that employing multiple modalities in design, especially when designing for the visually impaired, can contribute to better usability of UIs. However, not many common aids for learning braille make use of multiple modalities. As braille literacy is dropping [1] there should be an increased effort to make learning braille more accessible and attractive as braille provides invaluable access to information for the visually impaired.
Study the principles that are used during teaching the braille alphabet, research currently used aids for learning braille and learn about the best practices from experts on the matter (teachers of braille alphabet for visually impaired).
Follow the User-Centered Design methodology [2], propose a set of designs of a multimodal aid that will support the learning process. Focus on employing olfaction as one of the modalities as olfaction can be powerful when it comes to learning and memorizing [3]. In each phase, evaluate the proposed designs with the subject matter experts or the target user audience.

Bibliography / sources:

[1] L Johnson. "The braille literacy crisis for children". In: Journal of Visual Impairment & Blindness 90.3 (1996), pp. 276–278.
[2] International Organization for Standardization.Ergonomics of Human-system Interaction: Part 210: Human-centred Design for InteractiveSystems. ISO, 2010
[3] R. M. Sullivan et al. "Olfactory memory networks: from emotional learning to social behaviors". In: Frontiers in behavioral neuroscience 9 (2015).

Name and workplace of master's thesis supervisor:

Ing. Dominika Palivcová, Department of Computer Graphics and Interaction, FEE

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

Date of master's thesis assignment: **14.09.2021** Deadline for master's thesis submission: **04.01.2022**

Assignment valid until: **19.02.2023**

Ing. Dominika Palivcová 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 her 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.

. _____ Date of assignment receipt

_____ Student's signature

Acknowledgements

I want to thank all the wonderful people for their support and help. I thank Domi for supervising. I thank Han and Paja for always being there. I thank Christine, Nasta, Tyfloservis and Tactus for their expertise and experience. I thank Jita, Terka and Dragana for pictures of bats and proofreading. And I thank my parents, myself, and the dinosaurs.

Declaration

I hereby declare that I have written the submitted thesis myself and I quoted all used sources of information in accord with Methodical instructions about ethical principles for writing academic theses.

Prague, November 29, 2021

Abstract

This thesis describes the design and development of a new multimodal learning aid for braille reading. It is based on large exploratory research of visual impairment and olfaction. The learning aid should help braille teachers introduce braille letters to complete beginners and provide an entertaining way to practice.

The visually impaired and experts on teaching braille were consulted throughout the development of the design, which is based on User-Centered Design. After many iterations, a high-fidelity prototype was built and evaluated. Based on the findings from the evaluation, the design was reworked and improved.

The main advantage of this learning aid is that it provides a different approach to learning braille compared to the available learning aids by using olfaction and the standard size of braille.

The design is focused on usability and affordability to make the learning aid accessible to everyone who wants to learn braille. Additionally, the main components of the aid were made from recycled waste materials.

A mobile application was implemented to make working with the learning aid even more engaging and interesting. This also makes the learning aid adjusted for self-studying.

Keywords: multimodality, olfaction, braille, learning aid

Supervisor: Ing. Dominika Palivcová

Abstrakt

Tato práce popisuje návrh a vývoj nové multimodální pomůcky pro výuku braillova písma. Vychází z rozsáhlého explorativního výzkumu zrakového postižení a čichu. Nová pomůcka by měla sloužit učitelům při prvním seznámení studentů s braillovým písmem a zároveň studentům poskytnout zábavnou formu procvičování při samostudiu.

Během celého vývoje jsme se soustředili především na uživatele a jeho potřeby. Návrh a vývoj byl pravidelně konzultován jak se zrakově postiženými, tak s odborníky na výuku braillova písma. Po mnoha iteracích byl sestaven a otestován high-fidelity prototyp. Na základě tohoto testování byl návrh přepracován a vylepšen.

Pomůcka představuje úplně nový a inovativní způsob výuky braillova písma, protože oproti aktuálně dostupným řešením využívá vůně jako pomůcku pro zapamatování si symbolů jednotlivých písmen. Předností je také využití standardního velikosti braillova písma, která umožnuje snadnější přechod k plynulému čtení.

Během návrhu pomůcky byl kladen důraz na použitelnost a dostupnost. Pro hlavní části pomůcky je použit recyklový odpadový materiál.

Pomůcka je doplněna mobilní aplikací, která umožnuje využití i při samostudiu a zároveň ozvláštňuje interakci s pomůckou.

Klíčová slova: multimodalita, čich, braillovo písmo, učební pomůcka

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Chapter 1

Introduction

According to braille instructors and Johnson [1], braille literacy is dropping. One of the primary reasons for this is the advancement in technology for the visually impaired. They no longer need to learn braille in order to get access to information and can rely solely on audio information. However, braille literacy is invaluable especially for visually impaired children's development. Without understanding braille, the children struggle with grammar and written text. For adults, braille literacy means gaining more independence in their daily life.

This thesis aims to create a new learning aid for introducing braille reading to complete beginners. This solution should ease the first steps of learning braille and bring fun to the whole learning experience. The entire development stands on excessive user research and User-Centered Design (see chapter 2). Throughout the design, each iteration was discussed with an expert on braille and haptic aids for educating children with visual impairment and an expert on teaching reading and writing in braille to adults. The learning aid incorporates multiple senses, mainly haptics and olfaction as olfaction can support the learning process. [2]

The thesis is composed of the following chapters:

- Chapter 2 provides the theoretical background needed for developing the learning aid.
- Chapter 3 describes the design process, iterations, and the final design.
- Chapter 4 describes how all the parts of the final design are implemented in a high-fidelity prototype.
- Chapter 5 goes over the testing and evaluation of the created prototype and all discovered issues.
- Chapter 6 discusses all of the found issues, how they can be solved and how the learning aid might be further improved in the future.
- Chapter 7 concludes the thesis and all that has been worked on.

1.1 Motivation and Goals

Potential was identified in developing an olfactory interface for the visually impaired based on recent studies of olfaction and its connection to orientation, navigation, and memorization. To validate this idea, several kinds of research were conducted over the course of a year which focused on:

- if and how olfaction is consciously used by the visually impaired,
- preferences in odors,
- which odors are connected to places and activities,
- pleasantness of common odors,
- the role of olfaction in orientation and navigation of the visually impaired,
- emotions connected to odors,
- available olfactory interfaces.

Based on the findings from the research studies, the process of learning braille characters was identified as the most suitable use case for developing a new olfactory interface.

The main goal of this thesis is to develop a new option on how to learn and teach braille reading. It should motivate the students to learn and make learning more entertaining and exciting. Braille is not just about learning the letters and special symbols. Other aspects, like keeping a good posture while reading, tracking the braille lines, or knowing the names of the dots that form the letters, are just as important and challenging to learn.

This thesis focuses on teaching braille reading as it is a necessary first step before writing. Unless the person learns at least the basics of reading braille and remembers dots representing each letter, they cannot write easily or read what they have written and check for any mistakes made. The visually impaired person will still benefit from learning to read braille even if they do not continue to learn how to write braille. They can use this knowledge to read braille labels on everyday objects like medicine packaging and elevator buttons or to mark various things they have at home (like kitchen containers).

Braille reading also provides invaluable access to information as it is an active process that improves information retention. [3] Another benefit of braille reading is that reading works in parallel with hearing. This means that the user can read and at the same time is aware of their surroundings and can interact with others and be conscious of any changes in the environment.

This thesis focuses on introducing letters to beginners, and the outcome should serve as a supportive tool for learning and teaching. By no means is the outcome meant to be a replacement for a trained braille teacher. As mentioned above, there is much more to braille than merely learning the letters. However, the letters are crucial for reading braille. Learning the letters requires students to mainly memorize the particular dots that form

each letter and train their fingertips to recognize and distinguish the letters. There are textbooks and learning aids to help with the whole learning process. However, there still seems to be a lack of learning aids that would work with more than haptics. Therefore this thesis aims to develop a new learning aid based on research and User-Centered Design that will provide a new way for beginners to learn and develop braille reading skills.

The full list of goals of this thesis is:

- Create a design of a multimodal aid for learning braille alphabet that can help introduce braille reading to beginners.
- Analyze the current learning aids used for learning braille reading.
- Analyze how various senses might improve the learning experience.
- Use User-Centered Design to propose a set of designs of a new learning aid.
- Develop a prototype based on the designs.
- Evaluate the created prototype.
- Adjust the design in line with the testing results.

Chapter 2
Analysis

The whole development of the learning aid, including analysis, follows User-Centered Design. User-Centered Design (UCD) is established in the international standard of ISO 9241-210:2019 [4]. User-Centered Design is an iterative process of designing a product. Its main focus at every moment is the user and their needs. The user is involved in the design throughout the process with research, usability testing, and so on.

This chapter analyses the current state of braille reading education. It establishes what braille is and what type of braille this thesis focuses on, and why. Then in section 2.3 there are described tools and methods used for teaching braille reading in the Czech Republic (both for adults with adventitious visual impairment and children with congenital visual impairment).

Vision is one of the vital senses that sighted people use for learning and exploring. However, vision cannot be used to learn braille by the visually impaired. Therefore, the section 2.4 describes senses (other than vision) and how they affect the learning process and memorization.

2.1 Classification of Visual Impairments

Visual impairments have several recognized categories. In Table 2.1 is the overview of the classification of visual impairments according to the World Health Organization (WHO). The visual impairment is measured by visual acuity. Visual acuity is defined as a fraction of two numbers. [5] The numerator is the distance needed to see for the visually impaired, and the denominator is the distance needed to see the same object for a person without visual impairment.

Not everybody with visual impairment needs to learn braille. Studying braille is recommended for people with total blindness, the ones who are nearly blind, or if their visual impairment is rapidly worsening. [6]

Category	Presenting distance visual acuity	
	Worse than:	**Equal to or better than:**
0 Mild or no visual impairment		6/18
1 Moderate visual impairment	6/18	6/60
2 Severe visual impairment	6/60	3/60
3 Blindness	3/60	1/60
4 Blindness	1/60	Light perception
5 Blindness	No light perception	
9	Undetermined or unspecified	

Table 2.1: Classification of visual impairments according to World Health Organization [7] (visual acuity is in meters)

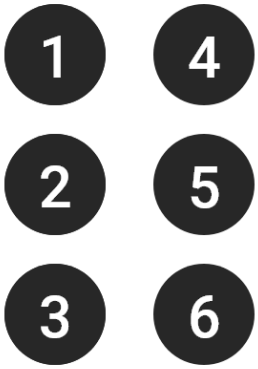

Figure 2.1: Braille character with numbered dots

2.2 Braille

Braille is a writing system developed for the blind and people with low vision. [8] A single braille character consists of a combination of 0 to 6 raised dots. Therefore there are 64 (2^6) possible characters that can be expressed, including an empty character representing a space. The dot positions are numbered from 1 to 6, as shown in Figure 2.1.

Louis Braille invented Braille in 1824 in France. [8] This writing system was officially adopted in France in 1854, after Braille's death. Before the invention of braille, embossed letters were used. Braille was inspired by an existing writing system known as night writing. [9] Night writing system was developed in France by Charles Barbier to allow the soldiers to read messages during the night without the need for light which would give away the position of the soldier. Night writing has 12 raised dots (two columns with six dots each) representing the characters. This system has the disadvantage that the characters are too large to be read with just a single touch.

Braille is still preferred over embossed letters and night writing for its

effectiveness. Studies suggest that the tactual effectiveness of the braille characters compared to embossed letters is caused by greater distinctiveness between the characters. [3]

There are two main types of braille: uncontracted and contracted. [10, p. 2] Uncontracted braille maps each letter of the word to one braille character and uses prefixes to create capital letters and numbers. Contracted braille adds special characters that represent common words. For example, instead of using three letters to write the word "can" in uncontracted braille, there is only one letter representing the whole word in contracted braille. [11] Contracted braille is used in books to save space and enable faster reading.

Braille differs across countries and languages. [12] For example, the letter w is written differently in Czech braille, Spanish braille, and Unified English Braille. These inconsistencies make it even more difficult for braille users to learn and read text in foreign languages.

This thesis focuses on the Czech uncontracted braille because uncontracted braille is the first step in learning how to read braille. The Czech braille is selected because it is used in the Czech Republic, where this thesis is created. The Czech alphabet is in Figure 2.2.

2.3 Learning Braille Reading

This section discusses various approaches used for learning braille reading. Usually, teachers specialize in teaching either children or adults but rarely both. The teaching methods have been discussed with both types of teachers, and there is a significant difference between the tools and methods used in teaching braille to children and adults. The textbooks are different as well. The learning process has also been discussed with a congenitally visually impaired braille user.

2.3.1 Specifics of Teaching Children

Each child is unique and needs a different approach to learning braille. Therefore most of the textbooks and learning tools are created for every child individually. Children are first introduced to the braille alphabet when they are about six years old. Before that, they learn and practice various skills which later help them with braille reading. According to [10, pp. 17-18] a mere exposure to braille is beneficial for the child, and braille should be introduced to the environment of the child even before they can read it. Children usually learn braille with their teacher or parent. There are not many learning activities that the child does alone.

Tactile books are a great learning aid for developing the literacy skills of children. [14] These books contain various objects, textures, and shapes children can explore and feel. The objects usually connect to a written text read by a sighted teacher or parent and braille text the child can follow together with the parent or teacher. Tactus [15] is a project in the Czech Republic that supports the creation of all kinds of tactile books and keeps a

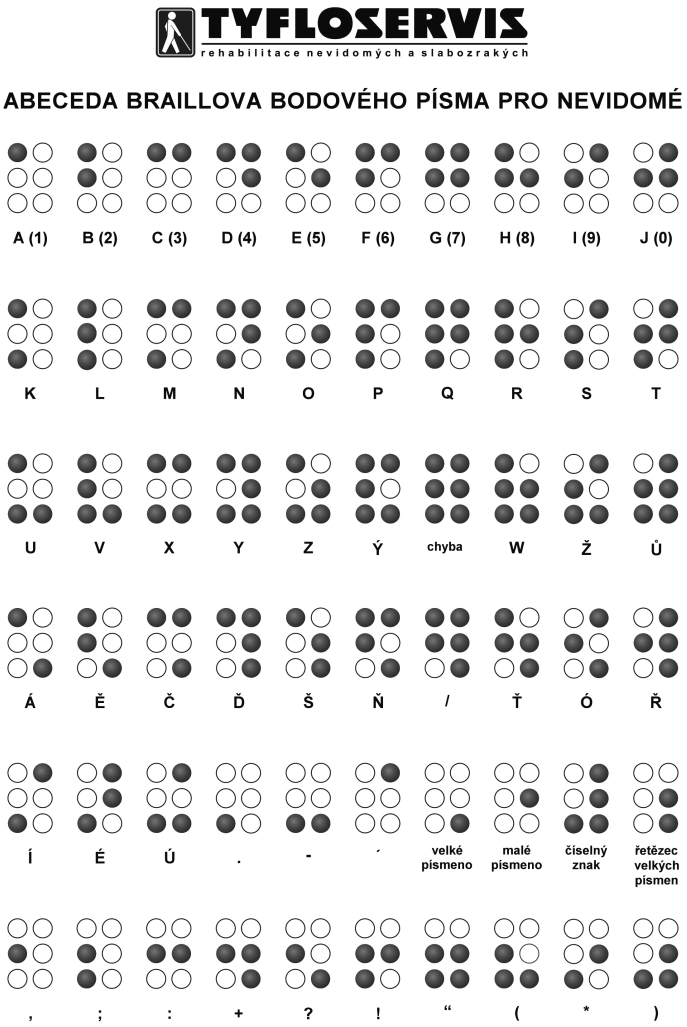

Figure 2.2: Czech braille alphabet [13]

library of tactile books. The head of the Tactus project is one of the experts with whom the development of this thesis was consulted.

Orbis Tactus [16] creates various textbooks for visually impaired children. Among these are several textbooks that focus on teaching braille. First, there is a textbook [17] that teaches pre-braille skills like correct posture, the orientation of the page, tracking the braille lines, and so on. After this, the learning should continue with a textbook [18] that introduces the children to braille letters and first words.

When the letters are introduced for the first time, they are displayed larger than the standardized size of braille and right after they are displayed in the standardized size. Children should be working with the standardized size of braille as soon as possible because the knowledge gained with bigger size of braille cannot be transferred to the standardized size as the tactile experience

is very different.

All of these textbooks are custom-made and quite expensive. They sometimes even have unique pages customized for the child with their name and other details.

2.3.2 Specifics of Teaching Adults

The specifics of teaching adults were discussed with an expert on teaching braille reading and writing to adults. This expert works at Tyfloservis [13]. Tyfloservis is a project that has supported the visually impaired in the Czech Republic since 1991. Tyfloservis offers lectures in various skills and access to information for the visually impaired to increase their independence and quality of life. One of the services that Tyfloservis in Prague offers is educating adults in braille reading and writing. They provided expertise on the whole learning process and specifics of an adult braille learner for this thesis.

Adults with adventitious visual impairment, who decide to learn braille, need to be determined because learning braille as an adult is challenging and difficult. The fingertip sensitivity that is trained and nurtured in children has not been developed for them. Also, the sensitivity to tactile stimulation lowers with age. [19] However, people with adventitious visual impairment have the benefit of knowing the alphabet, grammar, and structure of written language.

Adults use a different textbook [20] than children. This textbook uses more complex words and a direct approach to learning compared to the storytelling approach used in children's textbooks. Dignity is a crucial aspect when educating adults, and learning materials respect it. That does not mean that adults do not like games and a playful approach to learning, even though games form a smaller portion of their learning compared to children's. It is usually placed at the beginning of the learning session as a warm-up. Another difference is that adults do more exercises and tasks alone compared to children.

2.3.3 Learning Aids for Braille Reading

This section introduces some of the useful and most common toys and learning aids for braille reading that are not textbooks or tactile books mentioned above. All of them use a bigger size of braille letters and serve as an introduction to working with braille.

Alphabet board (see Figure 2.3) exists in various forms, but the main components, the braille cells representing the letters of the alphabet, are the same. The boards differ whether they have only the main letters of the alphabet or even the special characters. Other potential features may be the reliefs of the visual letters, like in Figure 2.3, or the braille letters can be removable so that they can be played with and used to form words and in other activities.

B-cube is a wooden cuboid divided into three parts. Each part can be turned and thus form all of the 64 possible combinations of the six dots. This

Figure 2.3: Alphabet board with braille letters and reliefs of visual letters

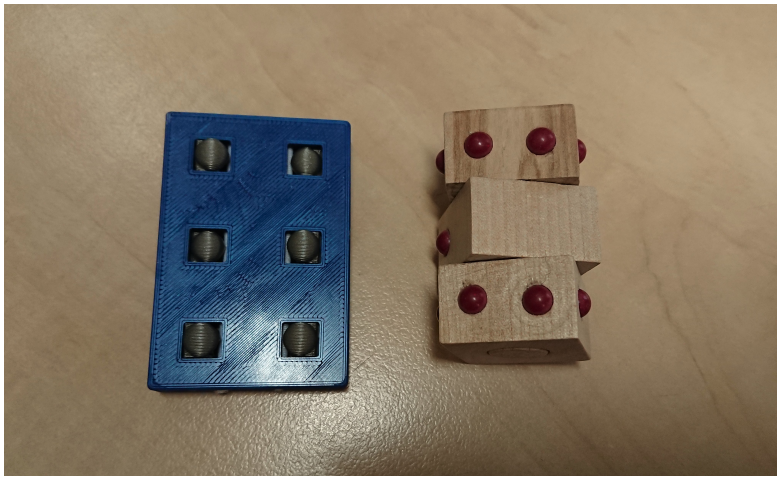

Figure 2.4: Two learning aids for braille reading, on the left is Rychlý šestibod and on the right is B-cube

system is useful because the dots and parts of the cube cannot be separated and therefore cannot be lost. B-cube is presented in Figure2.4.

Rychlý šestibod (see Figure 2.4) is a new 3D printed learning aid. It is a thinner cuboid compared to the B-cube and consists of six raised dots that can be pushed inside the cuboid. This way any of the braille characters can be created. The dots can be raised again by pushing on them from the other side of the cuboid. This system is efficient because the dots can be easily changed, and the dots cannot fall out and get lost.

All of these learning aids are invaluable during the learning process. However, there are not that many options and therefore it still makes sense to try and develop a new learning aid. This idea is supported by the braille teachers that welcome any new tool that would make the learning process more exciting and enjoyable.

2.4 Senses and Learning

The visually impaired cannot rely on vision to learn braille and have to gain all of the information through other senses. This section focuses on the various senses and their connection to the learning process and memorization to understand how the senses can be used to develop a new learning aid for braille reading.

Senses detect and respond to stimuli. [21] For humans, the most important senses are light senses, which include vision, mechanical senses, which include touch and hearing, and chemical senses, which include taste and smell.

2.4.1 Mechanical Senses

Hearing and haptics are mechanical senses. Hearing together with sight are the most used senses in human-computer interaction. [22] Haptics (sense of touch) is being used more and more in human-computer interaction. [22] Some of the tactile sensations are: vibrations, pressure, temperature, wetness, pain, and others.

Haptics combine information gained from multiple sensors located all over the body - in skin, muscles, tendons, and joints. [23, pp. 135-136] Haptics play a vital role in the life of the visually impaired, from reading braille to orientating and navigating using the white cane. It is essential for exploring and interacting with the physical environment. Haptic information is obtained mainly by hands and feet. The gained information about the surroundings can substitute information that sighted people mostly perceive from vision.

There is a difference in the use and perception of haptics among the sighted, people with adventitious visual impairment, and people with congenital visual impairment. [3] Studies suggest that there are even differences in brain organization between people with adventitious and congenital visual impairment. There are also differences in sensitivity of the fingertips of sighted individuals and congenitally visually impaired braille readers, which is mainly caused by experience and training.

2.4.2 Gustation

Gustation, the sense of taste, is rarely used and not widely researched in human-computer interaction. [24] Taste, same as olfaction, is a chemical sense which makes it so challenging to produce digitally. Taste has five basic taste sensations: sweet, salty, sour, bitter, and umami. There is a connection between taste and emotions where sweet taste is associated with positive experiences and the others with negative experiences.

There is a difference between taste and flavour. [22] Taste is a part of flavour together with other senses, mainly olfaction. Flavour is more often experienced than taste alone.

2.4.3 Olfaction

Olfaction, the sense of smell, is a unique and a more complex sense. Olfaction is still not fully understood and presents many unsolved challenges like the creation of odors, classification of odors, and general lack of research. [25] Therefore, olfaction is scarcely used in human-computer interaction. However, olfaction has several unique characteristics that might be invaluable if incorporated well into the interface.

Compared to vision, which has four kinds of receptors, olfaction has about a thousand different kinds of receptors. [26, p. 50] Therefore, creating a structure describing all odors is increasingly more complex than the existing ones for vision, which uses 3-dimensional space. The lack of a universal and precise description of odor complicates its research. The number of stimuli that can be discriminated by olfaction is significantly higher than the number of stimuli that can be discriminated by vision or hearing. [27]

Olfaction is also exceptional among the other senses because of its direct connection to the amygdala and hippocampus (parts of the brain that control emotions and memories). [28] Olfaction is closely related to memories, and it can stimulate and help during memorization. [25] Odors serve as contextual retrieval cues for all kinds of memories [25], and they also trigger retrieval of the mental representation of the source of the odor. [29] Olfaction can be invaluable when visual and auditory perception cannot be used, such as in the case of mines where the stench gas emergency alert system is used. [25]

The use of olfaction in user interfaces has some known disadvantages:

- Olfaction is a poor choice to use with quickly and often changing information. [26, p. 60]
- Odor lingers after its emission so it can affect new odors. [25]
- Some odors tend to be perceived as a combination, whereas some remain as two distinct odors even when smelled together. When using multiple odors at the same time, one needs to test if they combine or not. [26, p. 52]
- When selecting concrete odors and their intensity, we must keep in mind that sensitivity and positive or negative associations with odors are individual and culturally dependent. [26, p. 60]

The perception of odor is very individual. Research has shown that humans can safely differentiate about four levels of intensity of the odor. The levels can be described as none, weak, moderate and strong. However, the perception of the strength of odor is very individual. What one determines as weak is strong for the other. Using only the intensity of odor for conveying information is therefore risky. [26, p. 52] Furthermore, the same odor with a different level of intensity can be perceived as a completely different odor. [25] The perception of odor can differ even with the same person on different days. [28]

Identification and naming odors can be challenging for people. The difference in skill of scent identification among people is partly due to the lack of experience with using olfaction consciously. [25] Untrained people can identify between 15 and 32 scents and when trained, the number increases up to 60. [25]

Another issue is the identification of odors. [30, pp. 32-38] During a study about odor identification, participants struggled to recognize and name common odors. This can be caused by poorly learned associations. However, even the connection between well learnt odors and their names is often impaired. Participant's performance can be significantly improved by first introducing the odors and naming the odors correctly before the testing phase.

Olfaction is challenging to use in human-computer interaction. On the other hand, it brings many benefits like the stimulation of memorization. Identification and naming of the odors can be improved with training and by working more with olfaction.

2.4.4 Conclusion

Olfaction is the primary sense that this thesis focuses on, as olfaction has a great potential for supporting the memorization of braille letters and bringing something new and different to the available learning aids. By definition of how braille works, haptics form a significant part in learning braille reading, therefore, special attention should be paid to it.

Hearing is a sense commonly used in designs for the visually impaired and should also be considered during the design and development. Gustation is rarely used in interfaces for the visually impaired and does not provide as clear benefits for learning as olfaction does, therefore, it will not be the focus for now.

Chapter 3

Design

Chapter 2 establishes the theoretical background needed for the development of a new learning aid for braille reading using olfaction. Following desired key characteristics were identified from desk research and consultation with two experts on teaching braille, one from Tyfloservis [13] specialized in teaching adults and one from Tactus [15] specialized in teaching children. The new learning aid should:

- be an introduction of braille letters to complete beginners,
- use olfaction to support memorization,
- be affordable,
- be practical and easy to manipulate.

Complete beginners are selected as the target group. This means both children with congenital visual impairment and others with adventitious visual impairment. Complete beginners are selected as the target group because, according to braille instructors, and Johnson [1], braille literacy is dropping. There is a need for new learning methods and aids to make learning braille easier and more attractive as it is a valuable skill for the visually impaired.

Braille letters are selected because it is the first thing introduced to braille students after pre-braille skills like developing tactile skills. Learning braille reading is a challenging process as any learning and anything that might ease it is worth creating.

Olfaction, based on desk research, can ease the memorization of braille letters. Olfaction is an underrated sense and, therefore, also less trained. Using olfaction in teaching braille could even have the positive side effect of training olfactory skills.

Affordability is an important factor. Various learning aids for braille are often custom-made. This makes them very expensive and inaccessible. The developed learning aid should aim to be as affordable as possible.

Usability is another important factor, especially when working with scents that could potentially spill and contaminate their surroundings or small parts like the caps of the bottles that can be lost easily. The learning aid needs to be easy to manipulate and foremost safe to use.

3.1 Questions to be Solved by Design

Questions to be solved by design are created based on desk research in chapter 2 and identified key characteristics above. These questions are:

1. Material and size
   a. How big should braille characters be?
   b. What materials should be used to represent the braille characters?
2. Didactics
   a. Which braille characters should be used?
   b. What learning activities can be done with the learning aid?
3. Olfaction
   a. Which scents to use?
   b. How to use scents to be safe from contaminating their surroundings?
   c. How to ensure scents will last?
   d. How to map scents to braille letters?
   e. Which senses, other than olfaction, should be used?
   f. How to use the selected senses?
4. Affordability
   a. Which materials can be used to lower the price of the learning aid?
5. Usability
   a. Which components should be used to ensure easy manipulation?

3.2 Design Process

During the design process, each iteration was consulted with experts on teaching braille reading (one expert on teaching children and one on teaching adults). These consultations helped with the didactic correctness of the learning aid. This thesis aims to create a learning aid that will support the teachers and textbooks, not replace them.

The design process starts with many sketches and low-fidelity prototypes. The design moves to high-fidelity prototypes only when all ideas are exhausted, concepts are consulted, and no new issues arise. All high-fidelity prototypes are tested during the iterations, and only when no new issues are found, is the high-fidelity prototype polished and larger usability testing is conducted.

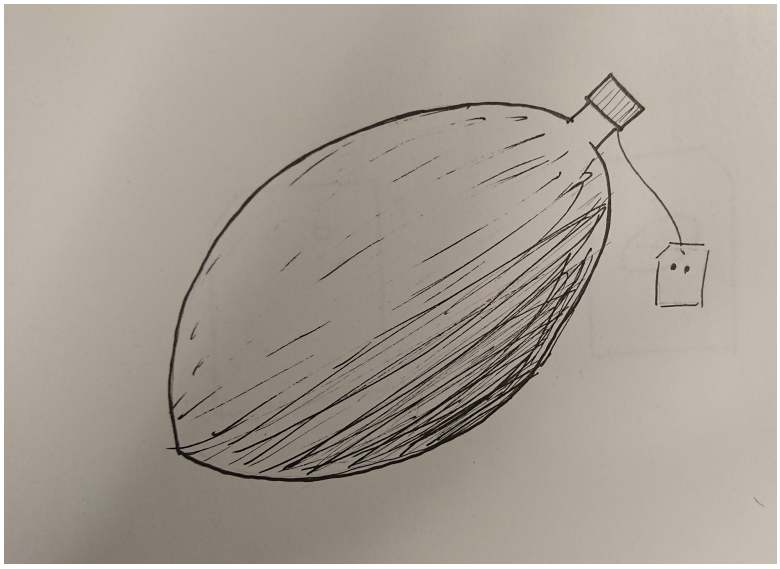

Figure 3.1: Sketch of the first iteration

3.2.1 Iterations

Iteration 1

The first iteration of the design was to create a 3D object for each letter. This 3D object would represent the selected scent starting with the same letter. For example, for letter L and the selected scent of lemon, the selected shape would be lemon. The sketch of the first iteration is in Figure 3.1.

This iteration has several issues:

- The stored scent has a high leakage potential from the non-standardized container.
- Selecting the best size of the 3D object is problematic, and experts are quite sceptical towards this design. There are options of realistic, enlarged, or decreased size, and each has issues with being too difficult to recognize by touch only. Also, storing so many objects is problematic.
- Same issues as with the size are with using the full volume, volume cut in half, or relief pictures.
- Location and orientation of the braille character are the main issues of this design. Learning braille letters is the main goal of the learning aid, and there is no place on the 3D object that would satisfy all the needs for interchangeable orientation and correct hand posture.
- The price of this design with a non-standardized container might be high.

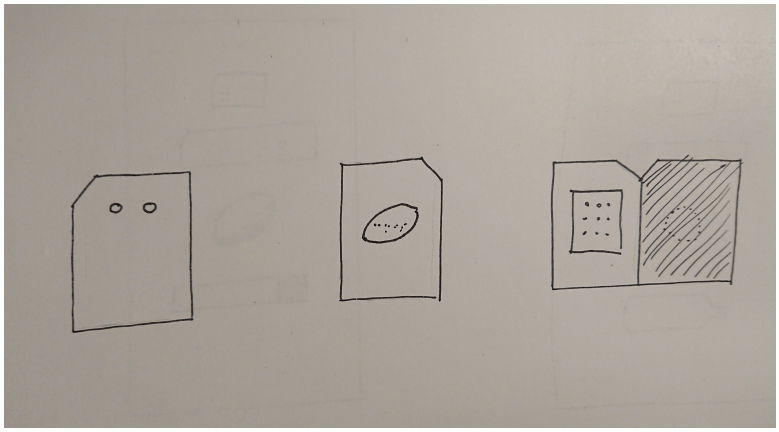

Figure 3.2: Sketch of the second iteration

Iteration 2

The next iteration is a book-like design. On the front page is the braille letter larger than the standardized size. On the back is a relief picture representing the scent and name of the scent in braille. Inside the book, there is a pocket with the scent on the one side and a sound module on the other. When opened, the book plays prepared audio stating the name of the letter and scent. The sketch of the second iteration is in Figure 3.2.

This iteration has several issues:

- The scent is almost impossible to seal inside the book. It can leak easily and affect its surroundings. The book would have to be custom-made and very sturdy, and therefore expensive.
- During the interaction with the book, the scent can get on the user's hands by accident and thus contaminate other books, mix with other scents and irritate the user.
- The played sound, whenever the book is opened, can be irritating after a while.
- The book's minimal size is determined by the size of the sound module.
- There is not much interactivity and options on how to use the aid in various educational activities.

Iteration 3

The next iteration is focused on interactivity, fully using the senses and adaptability for various learning activities. This iteration is a card-like design with many removable elements. These elements would connect to the card with magnets for easy manipulation. The use of magnets was chosen based on the recommendation from experts. These elements are:

- small flask with scent,
- shape representing the scent,

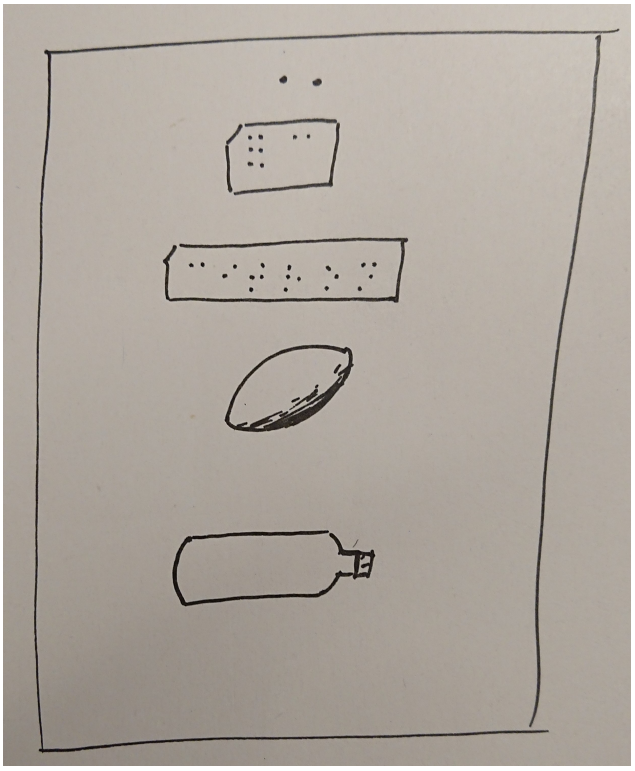

Figure 3.3: Sketch of the third iteration

- label with braille letter and braille character with all six dots (this allows the student to compare the characters and feel which dots are missing in the letter),
- label with the name of the scent in braille.

The card still has one permanent braille letter on it so that the user can identify where all of the elements belong. The sketch of the third iteration is in Figure 3.3.

This iteration has the following issues:

- There are too many elements. Working with this aid in class would be too cumbersome.
- Too many small elements that can get lost easily.

Iteration 4

The next iteration lowers the number of elements to make the design more usable and focused. This design still uses a card with attachable elements. However, now the card has no permanent element, and there are only three attachable elements: flask with scent, shape representing the scent, and label with the name of the scent in braille. The sketch of the fourth iteration is in Figure 3.4.

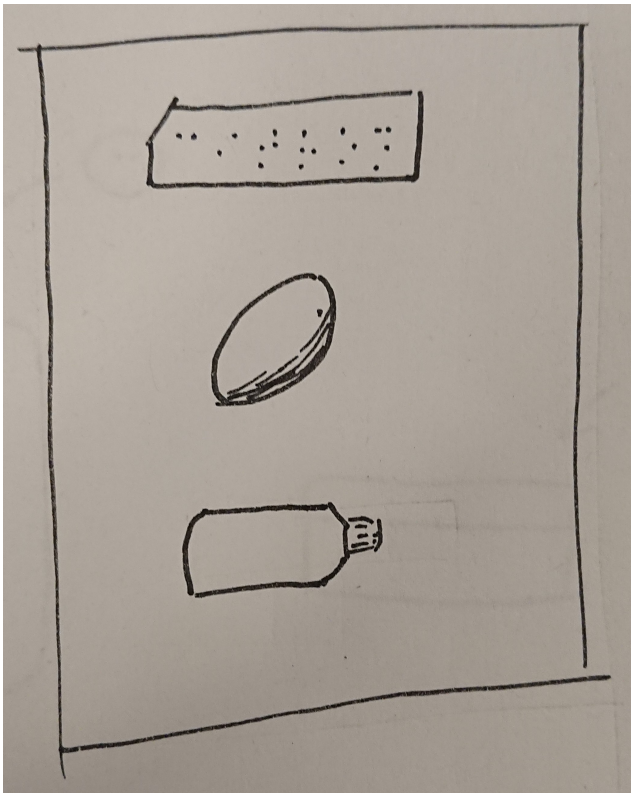

Figure 3.4: Sketch of the fourth iteration

Issues of this design are:

- Selecting the size and volume of the objects to be recognizable is still very problematic, as in Iteration 1.
- It is difficult for students to validate that correct elements were placed together on the card.
- The objects can still get lost easily.

Iteration 5

The next iteration limits the number of elements even more. This design only has a single element: the flask with the scent and braille character on the top of the lid. The sketch of the fifth iteration is in Figure 3.5.

This design solves the issue of too many elements and is more focused. Still, this design has some issues:

- The lid of the flask can be lost easily.
- The lid needs to be big enough to fit the braille character or the name of the scent in braille. However, the bigger the lid, the easier it is to touch the scent by accident and get it on the hands.

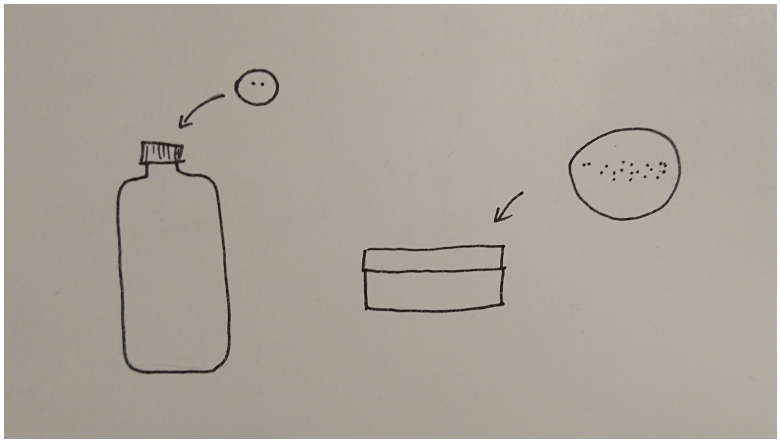

Figure 3.5: Sketch of the fifth iteration

- The correct orientation of the braille character is difficult to recognize.
- Lids can be easily switched and misplaced on a different flask.

Iteration 6

This iteration improves on the previous by changing the container from a typical round flask made out of glass used for storing scents to a cuboid plastic flask. Also, the lid is attached to the flask so that it cannot be lost, and the lid is small, so that directly touching the scent is very difficult to do by accident. Sketch of the sixth iteration is in Figure 3.6.

The flask has a braille letter bigger than the standard size on the one side and the same braille letter in the standard size on the other side. On the top of both sides of the flask there is a strip of material different for each scent. This strip helps to define the correct orientation of the flask and, therefore, the braille letter.

Even this design has some issues:

- This solution might be quite expensive because of the less traditional shape of the flask.
- Plastic is preferred over glass for safety reasons. However, this decision might affect the price as this plastic needs to be strong enough to hold the scent and not leak it and contaminate its surroundings.
- The lid needs to hold tightly to the container to prevent any contamination.
- The scent needs to be safely contained to eliminate any spillage.
- Creation of the bigger sized braille is challenging, and its use is discouraged by some experts who advocate that students should start working with the standard size of braille as soon as possible. Also, several existing aids already use bigger-sized braille (see 2.3.3).

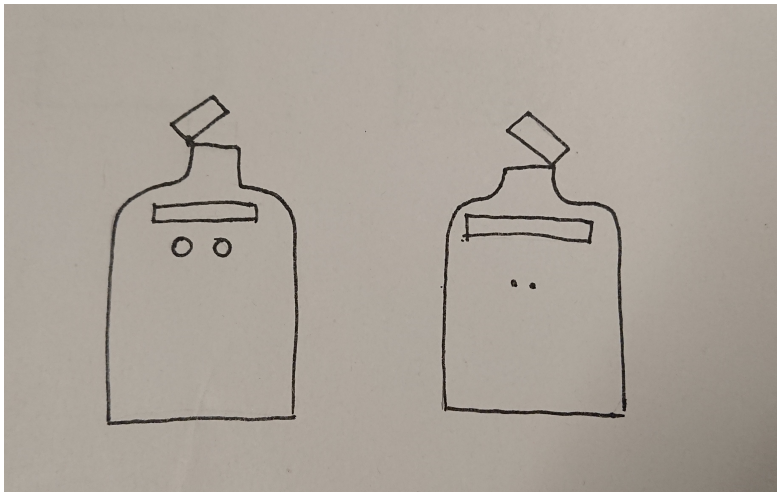

Figure 3.6: Sketch of the sixth iteration

- The material on top of the side of the box does not have a clear purpose.
- This design has low interactivity.

Iteration 7

This iteration builds upon the previous iteration and keeps the plastic cuboid flask with an attached lid. A braille character is on the one side and the same character on a removable magnetic strip is on the other side. This strip has both the braille letter and the braille character with all six dots at the beginning to define the correct orientation of the magnetic strip. This special character can also be used to determine which dots form the braille letter on the strip by comparing the two. Inside the flask there is a scent whose name starts with the same letter written on the flask. Sketch of the seventh iteration is in Figure 3.7.

This design is focused, does not have too many elements, uses olfaction to ease the memorization process, and provides intractability.

3.3 Design of Key Elements

The last iteration stands on four key elements that need to work perfectly in order for the design to be usable. These are the design of the container, usage of scents, how the scents are matched with the braille letters, and the readability and durability of the braille letters. In detail, this means:

1. Finding a cuboid flask made out of plastic with an attached lid.
2. The plastic needs to hold scent without leakage.
3. The scent needs to keep its intensity for long enough to be comfortable to use.

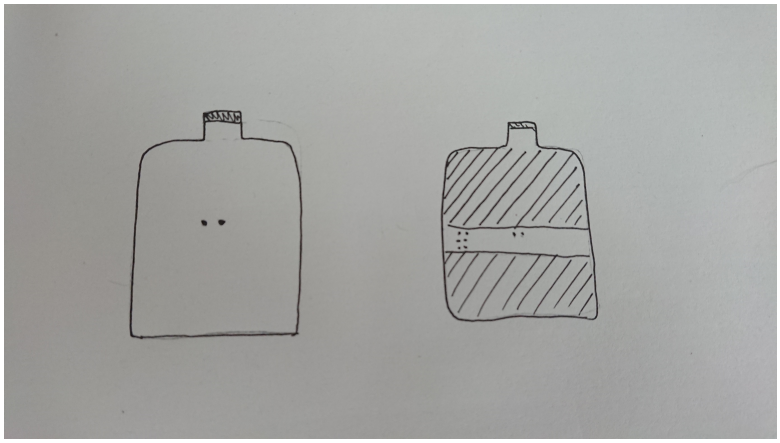

Figure 3.7: Sketch of the seventh iteration

4. Selecting the scents.
5. Minimizing the possibility of leakage of the scent.
6. Matching the scents to braille letters.
7. Looking at all options to find the one with the best performance and price.

3.3.1 Container

Finding a container that would have all of the desired qualities was not an easy task. The container needs to be:

- cuboid,
- made out of plastic resistant to odor leakage,
- right size,
- with attached lid easy to locate and open,
- sturdy enough so that the container does not open on its own.

Standard containers for odors are round, made out of glass, and the lid is not attached. Therefore they are not a good option. This type of container is on the left of Figure 3.8.

Containers for powder make-up are made out of plastic, have a second lid with small holes that would allow the scent to come through but disables direct contact with the scent. However, they are round, and the lid is not attached to the container thus, this container does not have all of the wanted characteristics. This type of container is in the middle of Figure 3.8.

Surprisingly, a Tic Tac box (see on the right of Figure 3.8) fulfills all of the wanted characteristics. It is a cuboid and made out of plastic with an attached

Figure 3.8: Analysed containers for storing the scents, original container of essential oil is on the left, container for powder make-up is in the middle, Tic Tac box is on the right

lid. Then the plastic of the Tic Tac box was tested to see how well the plastic contains the scent, and again the results were outstanding. The box contains the scent for months and does not contaminate its surroundings even when stored together with other boxes with other scents in poor conditions for the whole time (in sunlight, in a warm area, packed in a plastic bag).

Scents are usually stored in dark containers. Tic Tac boxes come in both dark and clear options. Both the dark and clear containers were tested to see which is the best option. The scents were stored both in clear containers and dark containers for weeks in poor conditions, and both proved to be effective, and no significant difference was found. Therefore both options are viable and do not influence the usability.

The lid is small, and therefore getting the scent directly onto the hand is very difficult to do by accident. Another advantage of the Tic Tac box is the low price and the fact that it is a reuse of waste material. The Tic Tac box is not waterproof, and therefore, the scent cannot be used directly in liquid form.

3.3.2 Scents

In this section the possible sources of scents are discussed together with how the scent is kept inside the container to eliminate leakage and make manipulation with the scent safe.

Source of Scents

There are not many options for a consistent and durable source of scents. The most common sources are essential oils and fragrance oils. The difference between them is that essential oils come only from natural sources, have a smaller range of scents available, and are more expensive. [31, 32] Fragrance

oils are at least partly made out of synthetic material, there is a broader range of scents available, and they are usually cheaper. All of the scents used in this thesis are either essential oils or fragrance oils.

Three brands of scents were tested: Phytos [33], Saloos [34], and Kozák Svitavy [35]. The scent is selected from the available options based on which one feels most like the scent it is supposed to smell like. This was done by testing each scent with at least three people and selecting the scent that the majority chose. The brand Kozák Svitavy is the most affordable of the three brands, but its products did not get chosen because they did not smell as good as the other brands. Both Saloos and Phytos offer a wide range of scents, and Saloos was usually the preferred option, but the difference in preference between Saloos and Phytos was not as big compared to Kozák Svitavy. For the usability testing (see chapter 5) three scents (coconut, lavender, eucalyptus) are from Saloos and two (pineapple and rose) are from Phytos.

Safekeeping of Scents

The direct use of liquid scents could easily lead to leakage, contamination, and difficult manipulation. To handle this issue, wood shavings are used as a medium that stores the scent. The wood absorbs the liquid scent and then emits it. The scent of the wood itself is not strong enough to affect the added scent, there is no longer a risk that any liquid would be spilled, and unless the wood is touched directly, it does not contaminate its surroundings.

Wood shavings are chosen over pieces of wood (see Figure 3.9) because it is a reuse of waste material. They do not make any sound once placed inside a container, soak the liquid quickly, and have a larger surface that can emit the scent. However, pieces of wood were also tested, and except for more difficult manipulation and longer soaking, there are no grave reasons not to use pieces of wood if they are more accessible than wood shavings.

There is no need to use a precise amount of the scent to soak the wood shavings because each wood and amount of wood shavings soak different amounts of scent. It is enough to put the wood shavings inside the container, add a couple of drops of the scent and wait until the liquid soaks into the wood. There is always an option to add more if the scent is not strong enough.

3.3.3 Matching the Scents and Braille Letters

The scents are matched to braille letters so that the name of the scent begins with the same letter. In Table 3.1 is an overview of all letters and scents that are matched with them. All of these scents are available as fragrance or essential oils. Only the letter W and Q have no matching scent starting with these letters in Czech. Also, the Czech letter CH is not included because the Czech braille alphabet forms it from letters C and H.

Some letters have more than one scent starting with the letter. The most common scent and the most different one from the other selected scents is then selected to represent the letter.

Figure 3.9: Example of wood shavings on the left and pieces of wood on the right

All of the scents have been selected so that if gustation is ever considered to be added, foods, drinks, or sweets connected to the scents can be found.

3.3.4 Braille

There are several available options on how a braille letter can be printed. These are:

- printed on paper,
- printed on a plastic sheet,
- printed with a special label maker for braille.

The possible options were discussed with the experts, and the label maker was chosen as the best option. Paper is the best for advanced readers of braille and has low durability. Plastic is better for beginners and has better durability compared to paper. However, braille labels are also made out of plastic and are the most durable. Therefore, they were recommended as the best option by experts.

3.4 Final Design

This section describes the final design in detail so that it can be implemented. This design is based on the seventh iteration described in 3.2.1 and the design of the key elements described in 3.3.

First, the Tic Tac box is emptied, and the stickers are removed. Afterward, the magnet is glued to the side of the Tic Tac box. Then the irremovable braille letter label is glued to the box on the other side without the magnet. The other label with the braille character with six dots and braille letter is glued to a magnet and placed on the side of the box fully covered with a magnet. Then the wood shavings are placed inside the Tic Tac box, and the

A	ananas	pineapple
B	banán	banana
C	citron	lemon
D	datle	date
E	eukalyptus	eucalyptus
F	fík	fig
G	grep	grapefruit
H	hruška	pear
I	ibišek	hibiscus
J	jahoda	strawberry
K	kokos	coconut
L	levandule	lavender
M	meloun	melon
N	nektarinka	nectarine
O	ořech	nut
P	perník	gingerbread
Q		
R	růže	rose
S	skořice	cinnamon
T	třešeň	cherry
U	uhel	charcoal
V	vanilka	vanilla
W		
X	xylitol	xylitol
Y	yuzu	yuzu
Z	zázvor	ginger

Table 3.1: Mapping of letters to scents

scent is added. Both of the narrower sides of the box feature a small label with the written name of the scent for the sighted people. A sketch of the design is in Figure 3.10.

The boxes can be used on their own or with a special construction. This keeps the boxes in the horizontal position so that reading can be easier and in a more proper position. The front side of the construction is also magnetic so that the removable magnetic labels from the boxes can be placed here. A sketch of this construction is in Figure 3.11.

This design can be further improved by having an audio output for each box that states the name of the letter and the name of the scent of the specific box. This can be done by placing a mark on each box (like QR code, AR target, or NFC tag) and then having a device that can read the mark and play the audio.

This design has three primary educational activities:

1. Recalling the name of the letter by smelling the scent and touching the braille letter.

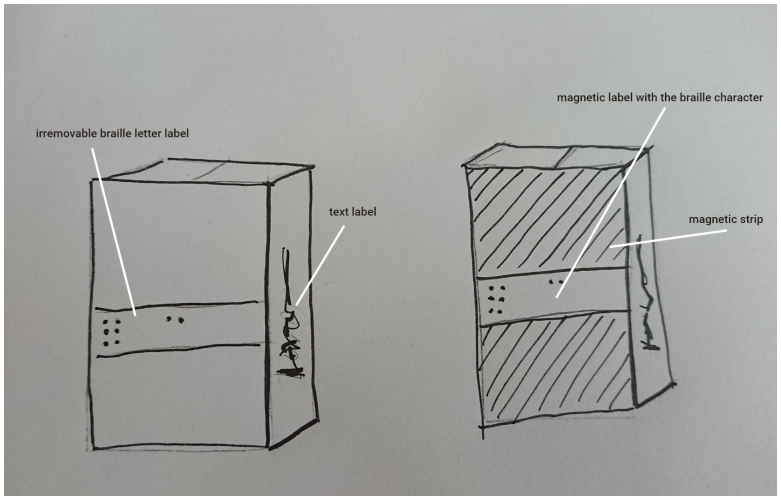

Figure 3.10: Sketch of the final design

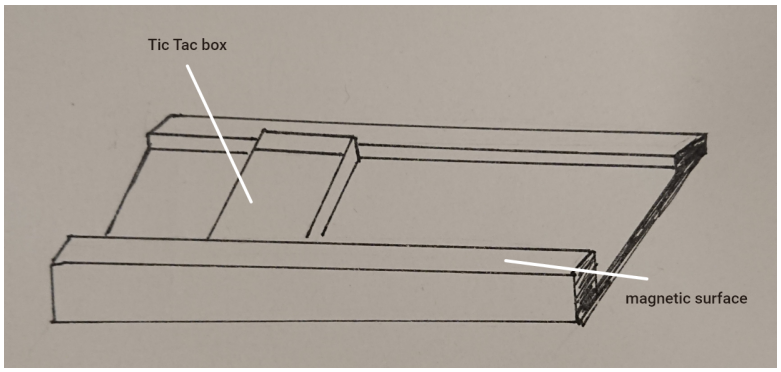

Figure 3.11: Sketch of the construction for keeping the boxes in horizontal position

2. Removing the magnetic braille letters from several boxes and then matching them back to the correct box by touching the braille letter on the box.

3. Removing the magnetic braille letters from several boxes and then matching them back to the correct box only by smelling the scent, recalling the name of the scent, and finding the first letter of the name of the scent among the removed magnetic labels.

Chapter 4

Implementation

This chapter describes the implementation of the final design in detail (see 3.4) so that it can serve as a guide for those who would like to build this learning aid by themselves at home to learn and practice braille by themselves or for their children and family. First, the creation of the boxes representing the braille letters is discussed as this is the main and most important part of the solution. Then the construction that can be used to keep the boxes in a secured position is described. Afterward, the possible audio output and its implementation are discussed.

4.1 Boxes

This section focuses on the creation of the boxes representing the braille letters. First, the five Tic Tac boxes were emptied and the stickers removed. Then the self-adhesive magnetic strip was added on one side. Here it is essential to place the magnet in the correct orientation as this will determine the final strength of the magnet. This orientation can be determined by simply trying to connect two small pieces together. Then text labels were added to the sides of the box.

Next, the braille labels were created. A special braille label maker was used for this. Each label has a special braille character with all six dots followed by a space and then the braille letter. One label is then stuck directly onto the box with double-sided tape. Another is stuck to a small piece of magnet. This magnet forms a magnetic label that can be put on the magnetic side of the box.

Now the wood shavings were placed inside the boxes. Several drops of a scent were added on top of the wood shavings. Boxes were then stored vertically overnight so that the wood could soak up the scent. After this, the boxes were finished. The finished boxes are in Figure 4.1 and 4.2.

Special attention throughout the implementation was paid to corners. Each corner, from magnetic strips to labels, was rounded. This was achieved either by using scissors or a nail file. All the corners were rounded so that the users would feel safe while interacting with the design.

Altogether five boxes were created. These boxes represent the letters l, a, k, e, and r. These letters were chosen because these are the first five letters

Figure 4.1: Detail of the finished boxes

Figure 4.2: Five boxes representing the braille letters l, a, k, e, and r

learned by adult students of braille. The scents for these five letters are lavender, pineapple, coconut, eucalyptus, and rose. For a complete overview of the mapping of scents to letters see 3.1.

4.2 Construction for the Boxes

To help ensure proper posture and easy manipulation, a special construction was created. This construction is not needed for working with the learning aid. However, it provides a stable working space. This construction was created as a model for 3D printers with Autodesk Fusion 360 [36] and it can be seen in Figures 4.3, 4.4 and 4.5.

This construction has two raised sides, and boxes can be placed between them. Once inside, the box is in a stable horizontal position and does not move. This allows the users to read the braille comfortably and motivates the

Figure 4.3: Construction for the boxes

Figure 4.4: Construction for the boxes with three boxes

proper posture. Inside the construction is a foam strip that keeps the boxes stable and makes the manipulation easier. The front side of the construction has a magnetic strip on top, so magnetic labels with braille can also be placed here. The backside of the construction is lower than the front so that the boxes can be easily removed.

Figure 4.5: Construction for the boxes with three boxes and labels on magnetic strip below them

4.3 Audio Output

As stated in 3.4, the design can be further improved by having an audio output for each box with the name of the letter and name of the scent. This is not a key element of the design and will not be fully implemented until the concept is verified by user testing.

This section describes the selected mark on the boxes for the audio output, the implementation for the usability testing which verifies the concept, and the full implementation.

4.3.1 Mark for Audio Output

Various options of marks have been considered and QR code has been selected as the best one as it is cheap, quick to prototype, and already used by other interfaces for the visually impaired like BlindShell [37] (a special phone for the visually impaired).

The QR code is unique for each box and leads to text with the name of the letter and scent (for example, "L for lavender") but does not provide the audio output. The audio output is created separately with a built-in Windows 10 screen-reading application, and an audio editor and recorder called Audacity [38]. Audio output for each box is created and will be used during the evaluation (see section 5.2.2).

The QR code was placed above the label with a braille letter (see Figure 4.1) as here it should not interfere with regular interaction with the design. The size of the QR code target is 2x2 cm as this is the smallest recommended size [39]. The boxes are quite small so bigger targets might interfere with the use of the design.

4.3.2 Implementation of the Audio Output for Evaluation

This audio output feature will be represented with a QR code and a QR code reader on the phone for now. Based on the discussion with several visually impaired people, the preferred operating system for phones is iOS for its built-in accessibility support. However, not everybody can afford this type of phone or prefers other types like Android or BlindShell [37] (a special phone for the visually impaired). For now, the feature will be tested with the iOS system. However, if the feature is to be fully implemented, more platforms than iOS should be targeted as well.

A QR reader will be used for detecting and recognizing the QR codes. *QR Reader* [40] was selected as its base features are free. Among these features is Batch Scan which enables the users to scan as many QR codes as they wish without having to interact with the application, which significantly simplifies the interaction for the visually impaired users and is closest to the wanted user experience. Also, this application recognizes the QR codes faster than the built-in recognition of QR codes in the iOS Camera.

4.3.3 Implementation of the Application for Audio Output

The evaluation (see 5.2.4) suggests that such an application will improve the user experience and therefore should be created. Several issues have been identified by the evaluation and solutions were proposed for them (see 6.3).

The main issue was that some participants had trouble scanning the QR codes with the phone. It was difficult for them to get the phone to the right position to scan the QR code. This raised the question of whether a different approach should be taken to the boxes' audio output, which would be more comfortable for the users.

However, due to the benefits of QR codes, it has been decided against using a different approach. Even though QR codes may not be the best solution for the visually impaired, it is a solution used by other tools for the visually impaired, it is common, and it is affordable. Even BlindShell [37], a phone created for the visually impaired, uses QR codes and a QR scanner for tagging objects. Therefore this skill is important and valuable for the visually impaired to learn. With this learning aid, users can practice and become more comfortable using QR codes while learning braille.

Design

Based on the findings from the evaluation, the design of the application is quite simple and clear. The key features of this application are simplicity of use, scanning QR codes with text, and haptic and audio feedback.

The application should wait for a QR code to be scanned immediately after it is opened. Once the QR code is scanned, the phone gives haptic feedback in the form of vibration, and then the text of the QR code is displayed on the screen, and the audio output is played. Afterward, the application waits for

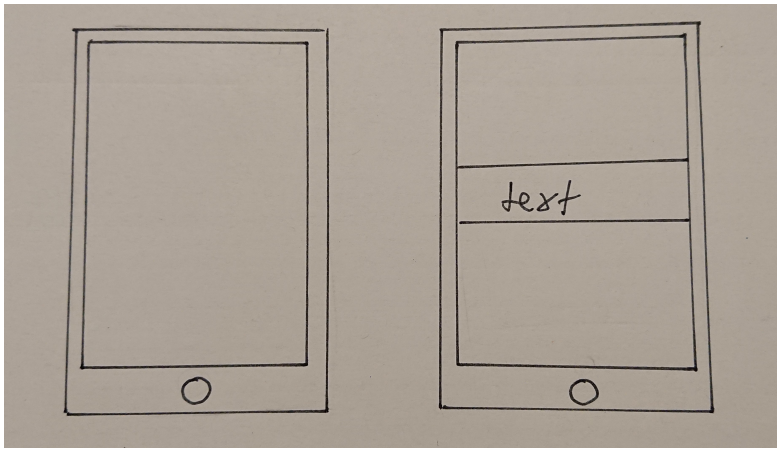

Figure 4.6: Sketch of the application for audio output

another QR code to be scanned. The sketch of the application is in Figure 4.6.

The application needs to work on iOS devices as this system is preferred by the visually impaired for its built in accessibility support. However, it would be better if the application also worked on Android devices as not everybody can afford or prefers iOS devices.

Audio

Choosing the actual audio for the audio output is complicated. After the consultation with the visually impaired braille student, it is clear that the first choice was not ideal. There are many options of voices for text to speech readers and also their speed settings. Considering that using text to speech is a very useful skill for the visually impaired, it has been decided that the application will not have its own audio output but will display the text in a way that the screen reader of the phone will read out loud. This enables the user to use their preferred setting of the text to speech software. This also means that if the text of the QR code is changed, nothing in the application needs to be adjusted.

Implementation

There are various approaches to implementing a mobile application where the main ones are native applications, hybrid applications, and Progressive Web Application (PWA). [41, 42] Native applications are platform-specific, and there would have to be two different implementations in different languages, one for iOS and one for Android. PWA applications might not work as well on iOS as on Android, and since iOS is the preferred system for this designm PWA is not used. Hybrid applications use web technologies to build cross-platform applications, so the application needs to be implemented only once for both platforms. Some minor adjustments might be needed for each platform, and the performance might not be as good as of the native

Figure 4.7: Screenshot from the application with scanned QR code and displayed text "r for rose"

applications, but for the purposes of this design, hybrid approach is selected as it is faster to develop and easier to maintain compared to a native application.

The application was implemented using Ionic Framework [43] (version 5.5.2) and Angular [44] (version 12.1.1). Ionic was chosen because it provides cross-platform development for both iOS and Android, is open source, and is free to use. Angular is a JavaScript framework written in TypeScript.

The base of the project is automatically generated. Homepage was added where the main logic of the application is. The application was implemented based on the design description above. The application waits for a QR code to be scanned, then it provides haptic feedback once the code is recognized and the text of the QR code is displayed on the screen. If the screen reader is on, it reads the displayed text out loud. The application is afterward ready to scan another QR code. In case the user wants the application to repeat the text all they have to do is tap anywhere on the screen. A QR Scanner plugin [45] was used for the QR code recognition and a Vibration plugin [46] was used for the haptic feedback. A screenshot from the application is in Figure 4.7.

The advantage of using the screen reader is that if the learning aid is ever adapted for a different language, nothing needs to be changed in the application itself. The only thing that needs to change is the text of the QR code and the language setting of the screen reader.

The application is now offered locally as distributing it via App Store [47] or Google Play [48] would be costly.

Chapter 5

Evaluation

This chapter describes in detail the evaluation of the high-fidelity prototype of the new learning aid (for a detailed description of the prototype, see chapter 4). The prototype was evaluated with both a visually impaired person skilled in reading and writing braille and blindfolded individuals without previous experience with braille.

5.1 Consultations with Experienced Braille Student

The high-fidelity prototype was consulted several times with a young student with congenital visual impairment skilled in reading and writing braille since the first years of elementary school. The goal of these consultations was to:

- learn their opinion on the learning aid as they have experienced the whole learning process of braille reading and writing,
- find usability issues,
- make sure the selected materials and shapes are not unpleasant to users with a trained sense of touch.

5.1.1 Results

Here is a list of findings obtained from the consultations of the prototype with an experienced braille student.

1. They truly enjoyed using the learning aid as it is fun and completely different from anything they used when learning braille themselves.
2. They enjoyed working with scents.
3. The selected size of braille letters, that is the standard size, is considered a great choice by the experienced braille student. They themselves had a very hard time switching from braille learning aid with bigger braille letters to the standard size, and they think it is way better to start learning the standard size as soon as possible.

4. The selected voice for the audio output is very unpopular among the visually impaired.
5. The used labels have the right size. However, the used type of label (brown) is not the best. They recommended using the green or red labels as they are the most pleasant to touch and read (the labels differ in color and the roughness of the surface).
6. The letter A on the labels is too subtle and should be reprinted. This is due to a faulty label maker used to make the labels, and for future development, another label maker should be used.
7. The boxes and the construction are easy to use and manipulate. The simple manipulation was also supported by the familiar shape of the Tic Tac boxes.
8. The student and their father, who was present during the consultations, immediately started interacting together with the learning aid. This supports the idea that this aid can also serve as a way to learn and interact with other sighted members of the family and friends.

5.2 Usability Testing

This section describes the usability testing conducted with the blindfolded participants. First, the participants' characteristics and demographics are discussed, then the evaluation of audio output is introduced and the procedure of the testing described. Afterward, the results from the usability testing are presented.

5.2.1 Participants

The target group of the learning aid is visually impaired beginners of braille reading. This means either small children with congenital visual impairment (around five years old) or people with adventitious visual impairment.

Working with such small children is challenging as it is difficult for them to remain calm for long enough for the purposes of the testing. Moreover, not only do they need to agree to participate but also an agreement from parents is necessary. Working with this group would be time-consuming and complicated.

Working with people with adventitious visual impairment that do not know braille is also complicated as it means that they have lost sight recently and are still coming to terms with the situation. Therefore, this testing might be harmful to their mental health. Another option is people with adventitious visual impairment who lost sight several years ago but have not started learning braille yet but were already able to process the loss. This target group is very difficult to find.

For these reasons, the testing was conducted with blindfolded people with no visual and olfactory impairment and no previous experience with braille.

These participants are not in danger of being harmed by the testing and there is no significant difference between blindfolded individuals and people with adventitious visual impairment in the ability to learn braille that would discredit the usability testing.

The participants for the usability testing were screened based on the following criteria:

- participants have no previous experience with learning braille,
- participants have no visual and olfactory impairment,
- participants are adults between 18 and 65 years old.

The usability testing was conducted with 11 participants. These participants were:

- Five man and six women.
- The average age is 27.
- Two participants have learning disabilities.
- Two participants had a stuffy nose.
- One participant has lowered sensitivity in fingertips due to eczema.

5.2.2 Evaluation of Audio Output

At this point, the audio output feature (see 4.3) is not fully implemented as we do not know if this feature is useful, and developing it might be unproductive in the end. The Wizard of Oz [49] testing will be used to validate this feature.

The user will use a phone which can detect a QR code and display correct text for each box stating the name of the letter and scent. However, there is no audio output. The audio part will be played by the moderator of the testing from another device. This device has five prepared audio files, one for each box. Once the phone used by the participant detects the QR code and displays the text, the moderator plays the correct audio file.

With this method, the feature can be validated without having it fully implemented and can prevent possible inefficacy.

5.2.3 Procedure

Three research questions were established for this testing, and used to create a session guide. These research questions are:

1. What usability issues does the prototype have?
2. How pleasant is the learning process with the design?
3. How many braille characters do users remember after learning with the design?

Figure 5.1: Setup of the usability testing of the high-fidelity prototype

During the testing session, the high-fidelity prototype, phone, and laptop, which recorded the session, were in front of the participant. The moderator used another phone to play the appropriate audio file. The setup of the usability testing is in Figure 5.1.

The participants had five tasks:

1. Explore the learning aid with just one box placed inside the construction and describe its elements.
2. Explore the learning aid again when a new box is added. Determine the letters and scents of the boxes and which box is new and which is the original.
3. Match labels with braille letters to correct boxes when there are more labels than boxes.
4. Match labels with braille letters to correct boxes when there are more boxes than labels.
5. Separate boxes that are new and that were encountered in the previous tasks.

In the post-test interview, the participants were asked questions to find out:

- how enjoyable their experience with learning braille using the new aid was,
- how enjoyable it was working with scents,

- which letters and scents they remember encountering while working with the learning aid.

Four days after the usability testing, the participants are asked to write down letters and scents encountered during the testing and draw the braille letters. This evaluates the recall of information learnt while working with the prototype. During the usability testing, participants were not informed that there would be another task after four days to limit any additional learning and practicing from the participants.

The usability testing was first piloted to test the session guide and establish the expected time for one session, which is 40 minutes.

5.2.4 Results

This section describes the complete results from the usability testing. It is divided into a list of issues, list of findings, evaluation of quantitative data from the first part of the usability testing, and evaluation of the second part of the testing after four days focused on long-term learning effects.

Identified Issues

During the usability testing, no severe usability issues were found, only minor issues. Here is the full list of issues from the usability testing:

1. The personal preference of scents was wide. One participant disliked the scent of lavender, others disliked the scent of pineapple or roses. However, this does not negatively affect the memorization as participants remembered the disliked scents and the connected braille letters even better than the rest.
2. Some participants were unsure whether the boxes are placed inside the construction properly because of the asymmetry of the edges of the construction. They also expected some clicking noise when the boxes were placed correctly.
3. Three participants had issues with scanning the QR codes. Then they all came to the same technique of placing the phone's camera at the QR code and then slowly moving the phone away. This approach worked well. Even though these participants struggled with scanning the codes, they still said that they enjoyed the assurance the phone provided.
4. Participants disliked how artificially some scents smelled. This was mentioned mainly with the scent of pineapple and sometimes coconut.
5. Participants put the magnetic labels on the front of the boxes, which is not magnetic.
6. For most participants, the most unpleasant part was the beginning of working with the learning aid. They disliked the uncertainty and unfamiliarity.

7. It was difficult for participants to name the scents. They felt that the scents were familiar but had a hard time recalling its name. They disliked the feeling of uncertainty.
8. The perception of the intensity of the scents differed a lot among the participants. The participants mentioned that it is more a specific characteristic of the scents. For example, eucalyptus is a more intense smell compared to the scent of pineapple.
9. The scent of eucalyptus was often mistaken for peppermint or mint at first.
10. The letter K was not clearly pronounced by the recording of the screen-reading application.

Identified Findings

During the usability testing interesting findings were identified. Here is the full list of interesting findings from the usability testing:

1. All participants mentioned that working with the learning aid was fun.
2. Four participants mentioned enjoying working with the learning aid so much that they would like to continue learning with it in their free time.
3. Once participants recognized the familiar shape of a Tic Tac box, manipulation became easy and natural.
4. Participants liked the construction for the boxes as it kept all the boxes in one place. Some participants took the boxes out and did not place them back, and then they were not sure where the boxes were so next time, they made sure to return them to the construction.
5. Two participants that have learning difficulties especially enjoyed learning with this learning aid. Learning this way felt easy and fun for them.
6. Participants felt that they could not rely on olfaction, but then they were surprised and proud when they successfully recognized the scents.
7. When participants were trying to recognize and name the new scents, they eliminated the options that started with the same letter as some of the previous boxes.
8. The lid of the Tic Tac box determines the orientation of the box well.
9. Participants liked using the phone to check the name of the scent as then they felt certain of what the name of the scent is.
10. Participants used the name of the scents to refer to the boxes and letters.
11. Participants mentioned they liked the feeling of exploration while working with the scents.

12. Some participants enjoyed placing the magnetic labels to the correct boxes the most.
13. Participants liked the haptic feedback when the phone detected the QR code.
14. Three participants mentioned they would like to have coffee beans available while working with the learning as a way to clean and refresh their sense of smell.
15. Participants preferred to call the construction for the boxes as a stand.
16. Participants enjoyed trying to recognize and name the scents once they realized they could use the phone to check the correct answer.
17. Participants were unsure how the scent connects to the letter at first, but after the phone read the QR code, the connection was clear to all participants.
18. The scents reminded the participants of scents used in toilets, bathrooms, or cosmetics.
19. The letter R was perceived as the most difficult to recognize just by touch.
20. Participants mentioned that they tried to visualize how the braille letters looked.
21. One participant mentioned that they like that the boxes do not make any noise as that would be very distracting for them.
22. One participant mentioned using the braille character with six dots as a reference to compare which dots are missing in the braille letter, which is exactly how this special character is supposed to be used for learning braille.

Results from Quantitative Data

During the first part of the usability testing participants were asked several questions from which quantitative data was collected. The results are:

- All participants evaluated learning braille with the new learning aid as very enjoyable.
- After the usability testing and post-test interview the participants were asked which letters they could recall encountering today. Ten out of eleven participants recalled all of the letters and one recalled four out of five.
- Then the participants were asked which scents they recall encountering today. All eleven participants recalled all of the scents used, even the participant who forgot one of the letters.

- As the last thing participants were shown the magnetic labels with braille letters and were asked to name the letters. Six participants out of eleven named all five letters correctly. Six named correctly L, A, K (the letters used in all of the tasks) and were unsure about which is E and R as these two letters were only in the last task, and they did not pay attention to them. However, they knew which two labels must be E and R, they just were not sure which is which.

- On average participants evaluated working with scents as enjoyable. The average is 1,82 where 1 is very enjoyable, 5 is not enjoyable at all. Only one participant rated working with scents as not enjoyable because of the scent of lavender which they hated.

- When asked to rate the strength of the scents on a scale from 1 (very weak) to 5 (very strong), the participants could not decide on one number because the strength differed between the scents. They viewed the strength of the scent mainly as a characteristic of the scent. For example, eucalyptus was often perceived as very strong and pineapple as weak.

Results of Long-term Learning Effects

Second part of the testing was focused on the long-term learning effects. After four days, the participants were contacted again and asked to write down letters and scents encountered during the testing and draw the braille letters that correspond to it. During the usability testing, participants were not informed that there would be another task after four days to limit any additional learning and practicing from the participants. Data was collected from ten participants, one did not participate in the second part of the testing. The results are:

- Nine participants out of ten recalled all of the names of the letters and scents. One participant forgot the letter E and the scent of eucalyptus.

- On average, participants recalled four braille letters out of five.

- On average, participants matched four braille letters and their names correctly out of five.

- One participant had no problem recalling all of the names of the scents and the shape of the braille letters.

- Two participants had everything correctly but forgot a space between the two dots representing the letter K.

- None of the ten participants had problem recalling the names and braille letters of A and L.

- Six out of ten participants correctly had the letters L, A, and K.

- Seven participants had trouble with the letter E and R. These letters appeared only in the last task.
- Four participants were able to draw all of the braille letters correctly, five participants recalled four braille letters correctly, and one participant recalled two braille letters correctly.
- Two participants matched all five braille letters and their names correctly. Three participants matched correctly four letters, three participants matched three letters, and two participants matched two letters correctly.
- Two participants switched the braille characters of letters K and E. Both braille letters K and E have only two dots, and the rest of the letters has either more or fewer dots, and they are therefore similar.

5.2.5 Summary of Results

Overall, the evaluation of the learning aid was a great success. No major usability issue was found, and there are many interesting insights that will lead to the improvement of the learning aid. All participants viewed the experience as enjoyable and fun. Participants have recalled most of the braille letters they worked with and all scents and letters (except for one participant out of ten who could not recall one name of the letter and scent) even days after working with the learning aid for approximately 30 minutes.

The audio output was successfully evaluated without it being implemented yet. The evaluation outcome is that such an application would benefit the user experience and should be implemented.

Chapter 6

Discussion

No severe usability issues were identified during the evaluation of the high-fidelity prototype in chapter 5. However, there are several findings from the evaluation that can help improve the user experience of the learning aid. This chapter describes all changes introduced to the various parts of the design of the learning aid to improve it based on the findings from the evaluation.

6.1 Improved Design of the Boxes

Based on these findings, several improvements have been introduced to the design of the boxes. Here is the list of issues connected to the design of the boxes that have been identified and the proposed solution for them:

- **Issue:** Participants put the magnetic labels on the front of the boxes, which is not magnetic.
  - **Solution:** Both sides of the box are now magnetic to allow the user to place the magnetic labels on the front side as well. Having the label so close to the label on the box helps the users to compare the braille letters on the labels more easily. The QR code will be added to the back of the box as well to allow the user to scan the box without having to worry if the front is facing up. The new design is in Figure 6.1.
- **Issue:** Three participants mentioned they would like to have coffee beans available while working with the learning as a way to clean and refresh their sense of smell.
  - **Solution:** Based on a study [50] coffee beans seem to have no real refreshing properties on olfaction. Even though coffee beans do not have a proven effect on refreshing olfaction, it is still worth considering adding them to the design as three out of eleven participants mentioned them. This concept is also supported by perfumeries that have coffee beans available for their customers to refresh olfaction regardless of their refreshing property being proven or not.

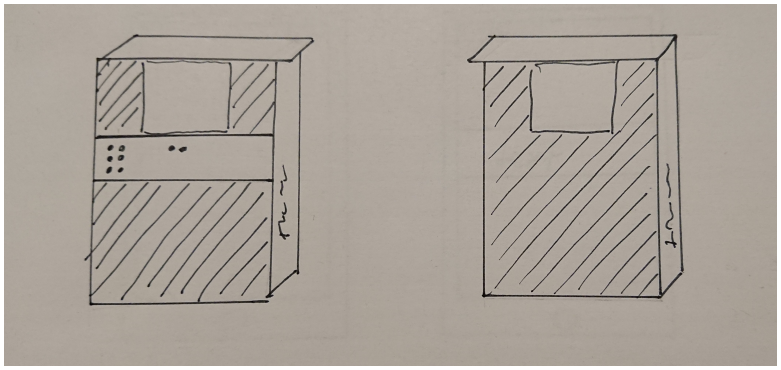

Figure 6.1: Sketch of the improved design of the boxes

- A new type of box is added. This box has coffee beans inside and is there to support the feeling of refreshing the users' olfaction. This box is easily distinguishable from the rest as the coffee beans inside a box make a sound when picked up. This box does not have braille labels on top only the magnetic strip on both sides and QR code with the text "coffee beans".

- **Issue:** The used labels have the right size. However, the used type of label (brown) is not the best. Experienced braille student recommended using the green or red labels as they are less rough compared to the used label and are the most pleasant to touch and read.
  - **Solution:** The labels with braille letters need to be reprinted on either red or green labels. These labels are the most pleasant for reading, as recommended by the experienced braille student.

- **Issue:** The letter A on the labels is too subtle and should be reprinted.
  - **Solution:** This is due to a faulty label maker used to make the labels. The labels have to be printed with a different label maker.

6.2 Improved Design of the Construction for the Boxes

Several issues connected to the design of the construction for the boxes have been identified, but overall, participants liked the construction for the boxes and found it very useful. Here is a list of identified issues:

- **Issue:** Some participants were unsure whether the boxes are placed inside the construction properly because of the asymmetry of the edges of the construction. They also expected some clicking noise when the boxes were placed correctly.

  - **Solution:** Once the participants realized that one edge of the construction is shorter than the other, the manipulation was easy and pleasant. Making the construction symmetrical or keeping the boxes more securely in any way would make manipulation with the boxes and construction more difficult. Therefore, the design of the construction for the boxes remains unchanged. However, the asymmetrical shape of the construction should be well communicated to the users to avoid confusion.

- **Issue:** Participants preferred to call the construction for the boxes as a stand.

  - **Solution:** The construction should be renamed to stand.

An alternative that can be used to the construction for the boxes is a simple metal sheet. The boxes and labels can be attached to the sheet by the magnetic side. Manipulation with it is not as comfortable as with the construction, but it is another option how to work with the learning aid.

6.3 Improved Design of Audio Output

The audio output has been evaluated by the method Wizard of Oz. Therefore, it has been evaluated without being implemented and its potential usefulness has been assessed. The evaluation suggests that such an application will improve the user experience.

The following list of issues connected to the audio output has been identified:

- **Issue:** The selected voice for the audio output is very unpopular among the visually impaired.

  - **Solution:** This issue is solved by not having a prerecorded audio but letting the screen reader read a displayed text. This way everybody can choose their preferred voice and settings.

- **Issue:** The letter K was not clearly pronounced by the recording of the screen-reading application.

  - **Solution:** This again is solved by using the screen reader and the preferred setting of the user.

- **Issue:** Three participants had issues with scanning the QR codes. Then they came to the same technique of placing the phone's camera at the QR code and then slowly moving the phone away. This approach worked well. Even though these participants struggled with scanning the codes they still said that they enjoyed the assurance the phone provided.

- **Solution:** It has been decided against using a different approach. Even though QR codes are not the best solution for the visually impaired, it is a solution used by other tools for the visually impaired, it is common, and it is affordable. Even BlindShell [37], a phone created for the visually impaired, uses QR codes and a QR scanner for tagging objects. Therefore this skill is important and valuable for the visually impaired to learn. With this learning aid, users can practice and become more comfortable using QR codes while learning braille.

Chapter 7

Conclusion

The development of the learning aid described in this thesis took almost two years. It started with large exploratory research into olfaction and visual impairment. With this research, the use case of using olfaction to learn braille was identified. The development continued with user-centered design and countless consultations with experts and users of braille. The main focus throughout the development was always the user.

After many iterations, a lot of research and evaluation of various components of the learning aid, a final design was created, and a high-fidelity prototype was built. This prototype was then evaluated by eleven participants and a young student with congenital visual impairment skilled in reading and writing braille since the first years of elementary school. Based on the findings from the evaluation, the design was reworked.

A mobile application was implemented for both iOS and Android to make working with the learning aid even more exciting and interesting. This also makes the learning aid adjusted for self-studying and practicing without a teacher.

The developed learning aid is ready to be used by the braille teachers or at home by the users to practice braille reading either alone or with family and friends.

Learning braille is challenging and requires patience and determination, especially from people with adventitious visual impairment. Anything that can make learning braille easier and more fun is needed, and that is exactly what this learning aid tries to support.

There is nothing like this new learning aid available for learning braille. Current learning aids usually use a bigger size of braille, which makes the transition to the standard size of braille very difficult, and are often expensive. This learning aid uses the standard size of braille and its main components are made from recycled waste materials.

7.1 Future Work

There are many ways how the learning aid can be further improved and extended in the future:

- The entire alphabet can be created.
  - The high-fidelity prototype had five braille letters with five boxes representing these letters. More letters and boxes can be added to extend what users can learn and do with this learning aid. A complete list of letters and scents is already prepared (see 3.1).
- More magnetic labels can be added.
  - Various magnetic labels can be added to offer new activities and increase the challenge for more advanced students of braille.
  - Adding labels with words teaches the students to recognize the braille letters when they are surrounded by other letters which is challenging at first.
  - The first labels that should be added are the names of the scents. The users then can match these labels to the corresponding boxes. At first, by recognizing the first letter of the word and matching it to the letter which is written on the box. Later they can read the whole word and match it to the boxes based solely on the name of the scent.
  - Users can also sort and match the labels to the boxes by starting with a particular letter, containing the letter, not containing the letter, or ending with the letter.
  - Personalized magnetic labels can be added, such as the name of the user.
- The learning aid can be adjusted to other languages.
  - At this moment the learning aid is only in the Czech language. To adjust it to a different language, the selected scents need to be exchanged and the QR codes need to be adjusted so that the text is in the selected language. Nothing needs to be changed in the application as the audio output is provided by the screen reader, which can be set to a different language.
- A game using the learning aid can be created.
  - A game using this learning aid can further improve the experience and provide even more entertainment and reasons for the user to practice.

- The game can use the phone to give tasks to the user and validate their answers.
- QR codes can be used for interaction with the game like having a QR code to start a particular part of the game.
- The game does not necessarily need to use technology. It can be a board game and focus on collaboration between the braille student and their family or friends.

- Gustation can be further researched and considered to be added to the learning aid.
  - Each of the selected scents (see 3.1) has some sort of food or drink connected to it, therefore gustation can be considered.
  - Gustation might provide another modality and entertaining element to the experience.

Appendix A

Research Plan and Session Guide for Usability Testing

A.1 Research questions

- RQ1: What usability issues does the prototype have?
- RQ2: How pleasant is the learning process with the design?
- RQ3: How many braille characters do users remember after learning with the design?

A.2 Participants

- N=10
- men 50 %
- women 50 %
- no olfactory impairment
- no visual impairment
- has no previous experience with braille

A.3 Screener

- How old are you?
  - Target: <18, 65>
- What gender do you identify as?
  - Target: 50 % man, 50 % woman
- Do you suffer from any visual, hearing, or smell impairment?

- Target: No

- Do you have any experience with learning or reading braille?
  - Target: No

A.4 Session Guide

Welcome + Ice Breaking

Introduction

Today we are going to test a new aid for learning braille. Braille is a written language that the visually impaired use to write and read.

Our session will last for about 45 minutes. Throughout the session, please say your thoughts and what you are trying to do at the moment aloud.

This aid is created for visually impaired people without previous experience with braille. Is it OK for you to wear a blindfold for this session to simulate that?

Recording Agreement

This session will be recorded for later anonymization and analysis. Only I and my supervisor will have access to the recording. Is this OK for you? Can we start recording?

Thank you. I will ask you again after the recording starts so that the agreement is recorded.

Start recording

Now I ask you again if it is OK for you to record our session?

To simulate the visual impairment is it OK for you to put on the blindfold for this session now?

Blindfold

Task 1

Box with 'L' is put into the container, the braille character faces up.

Each box represents one letter that is written on the box. Before each letter is a special braille character followed by a space. This character is here just to tell you where the beginning is.

Like here (*show example label*).

Each box can be opened at the top to smell a scent that is inside. These boxes are placed inside a container. The boxes can be removed from it and put back again.

Throughout the session remember to speak out loud anything that's on your mind and what you are trying to do.

Your first task is to explore the box. You can remove it from the construction, open and smell its scent, feel what all is on the box. Describe out loud what you sense with your fingers.

Now try to locate the braille character and describe how it looks according to what you feel. Try to smell the scent. Does it smell familiar to you? Can you name the smell? How do you think it is connected to the letter?

Above the braille letter is a mark. If you point the camera of a smartphone at it the smartphone reads out loud the name of the letter and scent. The application is already open and the phone is ready to be used.

Use the smartphone to read the name of the letter and scent.

Task 2

Box with 'A' is added before 'L' box.

Your next task is to explore these boxes. Describe out loud what you sense with your fingers.

What letters do they represent? What scents do they represent? Which box is the original one and which box is new?

Task 3

Add labels with 'L', 'K' and 'A'.

Now on the side of the container are 3 labels with braille letters. Put the label to the box representing the same braille letter. One label will not be used.

Match the labels and the boxes.

What is the name of the letter and the scent of the two boxes?

Task 4

Remove 'K' label and add 'K' box. All boxes now face up with the magnetic side in order 'L', 'K', 'A'.

Now there are only 2 labels and 3 boxes. Try and match the correct labels directly onto the boxes. One box will not have a label.

Match the labels and the boxes.

What is the name of the letter and the scent of the boxes?

Task 5

Add 'E' and 'R' boxes. Remove the labels. Boxes face up with braille letter sides. The order of boxes is 'L', 'E', 'A', 'K', 'R'.

Now there are 5 boxes. Put aside all of the boxes that you have not encountered today.

Put aside all boxes with new letters.

Now for each box you kept, say the letter and scent it represents. Then check this with the smartphone.

Say the letter and scent of the box. Check this with the smartphone.

Now for the new boxes you put aside, try to name the scent it represents. Then check this with the smartphone.

Say the name of the scent of the new boxes. Check this with the smartphone.

A.5 Post-test Interview

- How enjoyable did you find learning braille today?
  - 1 to 5 Likert scale (1 very enjoyable, 5 not enjoyable at all)
- Which part was the most enjoyable?
- Which part was the least enjoyable?

- How enjoyable was working with the scents?
  - 1 to 5 Likert scale (1 very enjoyable, 5 not enjoyable at all)
- How did you find the strength of the scents?
  - 1 to 5 Likert scale (1 very weak, 3 just right, 5 very strong)
- Which letters do you remember encountering today?
- Which scents do you remember encountering today?
- Now look at these braille labels. What are the names of the braille letters?

A.6 Follow Up

After 4 days from the testing the participants are asked to write down letters and scents encountered during the testing and draw the braille letters.

Appendix B

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