Faculty of Electrical Engineering
Department of Computer Graphics and Interaction

Master Thesis

Interactive tactile plans for visually impaired older adults

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Field of study: Open Informatics
Subfield: Human-Computer Interaction

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Interaktivní hmatové plány pro seniory se zrakovou vadou

Název diplomové práce anglicky:

Interactive tactile plans for visually impaired older adults

Pokyny pro vypracování:

Senioři s vážnou zrakovou vadou často žijí v pobytových zařízeních, která jim poskytují specializovanou péči. Tato uživatelská skupina má specifické problémy, potřeby a preference, zejména z hlediska orientace v prostoru, interakce s technologiemi a z hlediska trávení volného času. Proveďte analýzu dosavadních výsledků výzkumu zaměřeného na téma orientace vážně zrakově postižených v prostoru se zaměřením na osoby vyššího věku. Navažte na tento výzkum a na dosavadní výsledky výzkumu provedeného na DCGI [1-3] a na řešení popsané v užitném vzoru názvem 'Trojrozměrný model budovy určený především pro zrakově postižené uživatele' [4]. Pomocí metody User Centered Design [5] navrhněte sadu prototypů dílčích komponent interaktivního modelu budovy. Zaměřte se na interaktivní hmatové plány jednotlivých podlaží. Interakční metodu přizpůsobte schopnostem a preferencím cílové uživatelské skupiny. Navržené řešení otestujte se zástupci cílové uživatelské skupiny.

Seznam doporučené literatury:

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III. PŘEVZETÍ ZADÁNÍ

Diplomantka bere na vědomí, že je povinna vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací.
Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

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Datum převzetí zadání	Podpis studentky

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Finally, I would express my gratitude to my family for supporting me during my studies.

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, May 23, 2019

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Abstract

An interactive 3D model of the building which allows visually impaired older adults to explore the exterior of the building as well as the interior is being developed at the Department of Computer Graphics and Interaction at the CTU FEE. This thesis proposes the design of interactive tactile plans for this model tailored specifically for older adults with vision impairment. We followed the User-Centered Design methodology, and based on a comprehensive analysis of the target audience and domain, we created two generations of prototypes of the user interface. The interaction is based on tactile symbols, interactive tactile symbols, and touch-sensitive spots. We introduce route-guidance functionality, which helps users to get better spatial orientation. Qualitative evaluation with the target user audience (N = 19, mean age of participants was 85.1 years) was employed for each prototype. The results indicate the ability of our concept to create cognitive maps of the indoor environment.

Keywords: visually impaired, older adults, orientation, tactile maps, interaction design, User-Centered Design

Supervisor: Ing. Miroslav Macík, Ph.D.

Abstrakt

Na Katedře počítačové grafiky a interakce na FEL ČVUT probíhá vývoj interaktivního 3D modelu budovy pro zrakově postižené seniory, který umožňuje prozkoumání exteriéru i interiéru budovy. Cílem této diplomové práce bylo navrhnout interaktivní hmatové mapy interiéru pro tento model. Využili jsme principů User-Centered Designu a na základě analýzy cílové skupiny i aktuálně využívaných pomůcek pro zlepšování orientace zrakově postižených jsme navrhli dvě generace prototypů uživatelského rozhraní. Interakce s mapami je založena na použití hmatových značek, interaktivních hmatových značek a plošek, které reagují na dotyk. V práci je také představen speciální *route-guidance* mód mapy, který umožňuje uživatelům následovat na mapě určitou trasu. Námi navrhnuté prototypy jsme otestovali se zástupci cílové skupiny (N = 19, průměrný věk 85.1 let). Výsledky testování ukazují, že je náš koncept použitelný pro vytváření mentálního modelu prostředí.

Klíčová slova: zrakově postižení, senioři, orientace, hmatové mapy, interakční design, User-Centered design

Překlad názvu: Interaktivní hmatové plány pro seniory se zrakovou vadou

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Chapter 1

Introduction

In this chapter, we present the motivation behind our field of research – we introduce the reasons why we focus on the design of aid for enhancing the spatial orientation of visually impaired older adults. Then, we state research questions for which we aim to find answers, and we list the goals that should be covered by this thesis. Finally, we define the methodologies and the terms we use further in the thesis.

1.1 Motivation

We list the reasons that led us to the field of research dedicated to the orientation of visually impaired older adults.

Advanced age and visual impairments.
According to the report of World Health Organization [48], in 2010, there were 285 million of visually impaired people, 39 million blind and 246 million of people having low vision in the world, while the majority of both visually impaired (65 %) and blind people (82 %) is 50 years and older. Not surprisingly, the situation in the Czech Republic is pretty much the same — statistic data from 2013 (see Table 1.1) show 67 % of visually impaired people is 60 years and older. Moreover, the most frequent cause of visual impairment is a disease (more than 50 %) or elderly polymorbidity, i.e., the presence of multiple conditions at the same time (18 %), see Table 1.2. This fact correlates positively with the previous statement because, many eye diseases (cataract, refractive error, and AMD) are known to be age-related, as well as diabetes and its vision-related complication: diabetic retinopathy, from [69].

Increasing life expectancy.
Another important fact is the life expectancy increases. In 2016, the global life expectancy was 72.0 years (74.2 years for females and 69.8 years for males), and it increased by 5.5 years between 2000 and 2016, the fastest increase since the 1960s, from [39]. In 2018, life expectancy was 76.5 years for males and 82.3 years for females in the Czech Republic, and the prediction for the year

2100 indicates the life expectancy of 86,5 for men and 90.1 years for women. According to [1], the projection for the year 2050 assume 15 % of world's population will be over 65 years up from 9 % now, moreover in more-developed countries, it will be 27 % up from 18 % now.

Even though we wish the opposite, an occurrence of visual impairment is linked to an older age, and we have now greater chances to live longer. Taking this into account, there emerges an important question to answer:

How to design products for visually impaired older adults?

Quality of life and spatial orientation issues.

In general, being independent is an important aspect of one's life that contributes to maintaining a satisfactory quality of life. For visually impaired, one of the essentials of autonomy and self-respect is an ability to move freely [3]. Unfortunately, studies ([64], [35], [60]) show that visual impairment affects mobility and orientation of elderly negatively, and the results of the study from the Czech Republic [79] also indicate that orientation causes difficulties to VIPs, see Table 1.3.

Orientation and mobility training. Training of orientation and mobility (O&M) is a means of visual rehabilitation for enhancing the mobility of visually impaired that is successfully applied with older adults, as reported in [8]. However, as the elderly have tendencies to underestimate their abilities, and the majority of them gained visual impairment in an advanced age, an adaptation to new procedures for accomplishing known tasks is very challenging for them — in a qualitative study with 16 visually impaired older adults [8], 11 of them reported orientation training as the most difficult social-rehabilitation activity. Despite this, five of the participants of this study noted a skill gained by learning O&M, i. e. enhancement of their spatial orientation in the building, as their most significant achievement since they came to a specialized care home for visually impaired elderly, which is an excellent example of the importance of such activity. Importance of O&M can be further emphasized by the fact that according to [33], even sighted older adults acquire knowledge about novelty environment slower than younger individuals.

For the reasons listed above, we focus on enhancing O&M training of visually impaired older adults. Our goal is to design a new type of aid that will simplify and speed up the process of creation of a mental model of an indoor environment. We will employ an interactive 3D model of a building that will allow the user to explore individual floors within a building as well as the whole building complexly. The general idea of the model was already described in [44], and the preliminary research realized in the specialized home for visually impaired older adults Palata with the non-interactive 3D-printed haptic model of the building of the home itself indicated this is a challenging but promising approach to explore. This thesis aims to design and implement the main part of the 3D model – interactive tactile plans of individual floors.

Age category	Number of people
0 - 14	6 715
15 - 29	4 501
30 - 44	7 892
45 - 59	14 851
60 - 74	19 796
75+	48 440
Total	102 195

Table 1.1: Visually impaired people in the Czech Republic, from [79]

Cause	Number of people
Congenital	17 354
Injury	6 984
Disease	50 694
Elderly polymorbidity	18 954
Other	2 245
Unknown	5 964

Table 1.2: Causes of visual impairments in the Czech Republic, from [79]

Consequent problem	Number of selections
Orientation	12 031
Mobility	5 931
Independence	6 600
Household management	7 398
Receiving information	6 344
Communication	3 911
Eating	803
Legal capacity	511
Other	3 183

Table 1.3: Consequences of visual impairments in the Czech Republic, multiple choice, from [79]

1.2 Research questions and goals of the thesis

The thesis aims to explore the usage of interactive tactile plans of an indoor environment and describe its contribution to the acquisition of spatial cognition of visually impaired older adults in their close indoor environment.

1.2.1 Research questions

We define three research questions, for which the thesis aims to find responses.

- Research question 1:

  What is a suitable mapping of the characteristics of the environment to the 3D model?

- Research question 2:

  What are suitable interaction techniques for exploration of an indoor environment when employing the 3D model?

- Research question 3:

  Is usage of the interactive model suitable approach for creation of a mental model of space and if so, how does the 3D model help the visually impaired older adults to build a mental model of the environment?

Answers for stated questions will outline processes behind the interaction of visually impaired older adults (VIOAs) and the interactive 3D model about the creation of a mental model of a space. We also define the best practices for the creation of the interactive 3D model to present an indoor environment to VIOAs as well as visually impaired people VIPs, and researchers in the field of Human-Computer Interaction can profit from such conclusions in their further researches.

1.2.2 Goals

Regarding the research questions, we have several partial goals (denoted as G_i):

- G1: **Analyze characteristics of visually impaired older adults.** According to UCD, it is crucial to understand the target audience to provide them with suitable, usable design.
- G2: **Analyze terms related to spatial cognition and discuss spatial cognition abilities of visually impaired.** As the topic of the

thesis is focused on the design of the plan, it is necessary to be aware of the processing of spatial knowledge in humans and then mainly with people with visual impairment.

- G3: **Study the tools and techniques used for acquiring spatial cognition without vision.** The overview of currently used tools and methods may help to choose the techniques applicable to our design solution.
- G4: **Analyze the requirements for the 3D model of the building related to the creation of interactive tactile plans, and define requirements for the interactive tactile plans.** The topic of the thesis follows prior work of Macík et al., who proposed an interactive 3D model of building as a tool for enhancing spatial knowledge of visually impaired. The design of interactive plans should meet the requirements for this model and comply with the needs of the target audience as well.
- G5: **According to UCD methodology, create prototypes of the UI**. The prototypes present the intended design and allow to employ usability testing.
- G6: **Describe the implementation of the prototypes.** Documenting the implementation for future work is necessary.
- G7: **Evaluate the prototypes with the target user group.** According to UCD, evaluation with the target audience enables exposure of usability issues and allows to adjust the designed UI to the needs of the future users.

Such goals and activities corresponding with them should be covered by this thesis to deliver relevant and well-founded answers to our research questions.

1.3 Methodology and terms

In this section, we explain the methodology and the terms further used in the thesis.

1.3.1 User-Centered Design

The term *User-Centered Design (UCD)* refers to a process of design and development of a product, while in each phase of the process, the focus is on gaining a deep understanding of humans/users who will be using the product. The whole process is iterative - it is repeated until the designed solution meets the requirements of the target user group. UCD methodologies are based on international standard ISO 9241-210:2010 [18] which defines methods recommended to use during the design process. Individual phases of the UCD design process can be seen in Figure 1.1.

Figure 1.1: Phases of User-Centered Design process, from [77]

1.3.2 Usability

Usability is a qualitative attribute of a system or a product that defines how difficult it is for the user to use the user interface. By Jakob Nielsen [46], the usability consists of has five quality components:

- **Learnability.** How difficult is it for the users to accomplish a basic task the first time they use the system?
- **Efficiency.** Once users have learned the design, how quickly can they perform tasks?
- **Memorability.** When do users return to the design after a period they did not use it, how easy they will be able to use the design efficiently again?
- **Errors.** How many errors does a user make and what is their severity? How difficult is for a user to recover from a mistake?
- **Satisfaction.** How pleasant is to use the design?

1.3.3 Ability-Based Design

Ability-Based Design described in [83] is an approach of design for users with disabilities. Wobbrock states that while designing a product, the designer should ask ”What can a person do?” instead of ”What disability does a person have?”. He also empathizes the importance of automatic detection of people’s abilities and defines seven principles of ability-based design that are listed in Table 1.4.

Principle	**Description**	**Severity**
Ability	Designers will focus on ability not dis-ability, striving to leverade all that users can do.	Required
Accountability	Designers will respond to poor performance by changing systems, not users, leaving users as they are.	Required
Adaptation	Interfaces may be self-adaptive or user-adaptable to provide the best possible match to users’ abilities.	Recommended
Transparency	Interfaces may give users awareness of adaptations and the means to inspect, override, discard, revert, store, retrieve, preview, and test those adaptations.	Recommended
Performance	Systems may regard users’ performance, and may monitor, measure, model, or predict that performance.	Recommended
Context	Systems may proactively sense context and anticipate its effects on users’ abilities.	Recommended
Commodity	Systems may comprise low-cost, inexpensive, readily available commodity hardware and software.	Encouraged

Table 1.4: Principles of ability-based design, from [83]

Chapter 2
Analysis

This chapter covers the analytical phases of the UCD process. In Section 2.1, we address topics related to the target audience. The next part 2.2 presents terms related to spatial cognition in humans, and describes the spatial abilities of visually impaired. Analysis of tools used for acquiring spatial knowledge with visually impaired is found in Section 2.3. It is followed by the overview of non-visual interaction techniques employed in maps in 2.4, and in 2.5, we list the methods for implementation of maps for visually impaired. In Section 2.1.3 we describe Home Palata, as it is an institution for visually impaired older adults, which allows us to access to the representatives of our target audience, and evaluate our designs. Finally, in 2.6, we examine the groundwork of the thesis – the interactive 3D model of a building by Macík et al. [44], and we derive the requirements for the interactive tactile plans in 2.7.

2.1 Visually impaired older adults and their needs

In this section, we describe characteristics of our target user group - visually impaired older adults to understand better their needs, requirements and limitations.

2.1.1 Visual impairments and their classification

According to World Health Organization (WHO) classification [49] of visual impairments including blindness, there are two groups of visual impairments: presenting distance visual acuity and presenting near visual acuity. The complete overview of classifications of impairments by the visual acuity can be found in Table 2.1.

Category	Presenting distance visual acuity	
	Worse than:	Equal to or better than:
0 No vision impairment		6/12 5/10 (0.5) 20/40
1 Mild vision impairment	6/12 5/10 (0.5) 20/40	6/18 3/10 (0.3) 20/70
2 Moderate vision impairment	6/18 3/10 (0.3) 20/70	6/60 1/10 (0.1) 20/200
3 Severe vision impairment	6/60 1/10 (0.1) 20/200	3/60 1/20 (0.05) 20/400
4 Blindness 6 Blindness	3/60 1/20 (0.05) 20/400 No light perception	1/60* 1/50 (0.02) 5/300 (20/1200) or counts fingers at 1 metre
5 Blindness	1/60* 1/50 (0.02) 5/300 (20/1200)	Light perception
6 Blindness	No light perception	
9	Undetermined or unspecified	
Category	**Presenting near visual acuity**	
	Worse than N6 or M 0.8 with existing correction	

Table 2.1: Classification of visual impairments according to [49]: visual acuity is explained using fractions, where the numerator is the distance in meters needed for visually impaired to be able to read a letter, the denominator is required distance for a sighted person to read a letter of the same size.

2.1.2 Older adults and visual impairments

As mentioned in the Section 1.1, according to [69], many eye diseases are known to be age-related, namely: Age-related macular degeneration (AMD), cataract, diabetic retinopathy, and glaucoma. Most of these diseases do not lead to total blindness but low vision, and even with regular glasses, contact lenses, medicine or surgery, everyday tasks are still complicated to do. Older adults have to adapt themselves to different behaviors and means how to resolve routine tasks, which is very hard.

Capabilities and limitations of visually impaired older adults.

Aging brings changes to how people perceive – sensory devices are becoming less sensitive and less accurate. Macík et al. in [41] summarizes aspects of aging and their effects on the design of user interfaces:

- **Hearing:** older adults usually cannot detect very high and very low pitches. When it comes to age-related hearing loss, they require at least 90 dB loud sound, and in general, the loudness of sound notifications should be at least 10 dB above the background noise. Otherwise, they will not hear it. Despite the fact it is very easy for them to miss such notification, they play a significant role in the interaction, e.g., when using a virtual keyboard, older adults expect sound feedback after pushing a button.

- **Motor capabilities:** Studies showed that the older adults require 50 - 100 % more time for completion of a task than adults under 30 do. The difference plays mainly the time that the older adults think of their decisions; the movement time is similar to younger people.

- **Cognition:** there are higher requirements on the quality of user interface when comes to design for older adults. The first step is appropriate visual design (high contrast, clear icons, large control elements), but also information architecture and words used in the UI matter. If the UI do not present information in an understandable way, the users do not know what they should do to complete the task, they blame themselves for this, and the error rate increases significantly. In this case, an adaptation of the UI for one's personality helps.

Psychological aspects of visual impairment

In general, the vision loss is known to have a cumulative negative impact of the life of older people and negatively affect the productivity of those people, from [69]. According to [69], there are much more issues that come along with visual impairment:

- **Loss of independence for self-care, daily activities, and mobility.** As the visual capacity was a critical prerequisite of the majority of the daily tasks and behaviors, there is evidence of significantly lower everyday competence.

- **Increased risk of depression and anxiety.** Visually impaired older adults are twice more likely to have depressions or anxiety, which is related to the previous fact.

- **Decreased life expectancy.** Even in high-income countries, vision impairment is associated with a decrease of a life expectancy among older adults.

Multimorbidity/comorbidity

Multimorbidity defines as the co-occurrence of two or more chronic medical conditions in one person, from [69], and it has an undeniable impact on the everyday lives of older adults. When we look at multimorbidity from the perspective of one specific index condition (in our case eye condition), we speak of comorbidity when it comes to other accompanying diseases.

According to [69], the prevalence of multimorbidity among the aging population is almost 60 %. The comorbidity of visual impairment and other conditions is crucial, e.g.:

- Hearing loss increases the risk of social isolation. The overall psycho-social situation of those with dual sensory impairment is found worse than single impairments, and they show poorer personal health.
- Stroke can lead to coordination problems and locomotor difficulties.
- Alzheimer's disease is the most common neurodegenerative disease, and 30 % of the population 85 years and older suffer from this disease.
- Dementia is a syndrome which causes deterioration in memory, thinking, behaviour and the ability to perform everyday activities. According to [17], dementia is one of the major causes of disability and dependency among older people worldwide. As many as 7% of adults aged 60 and older suffer from dementia, from [16].

Elderly adults experience greater activity limitations and a steeper decline over time than those without visual impairment [9]. Design for such a group can be very challenging. According to [69], elderly polymorbidity affects the efficacy of channels that can replace missing or worsen visual channel – the tactile response is lower, audition ability deteriorates, and olfaction is getting worse, too. Furthermore, mental changes have an impact as well. In general, older age decreases the willingness to learn new things, which is a crucial problem in case of the loss of the vision in advanced age.

2.1.3 Home Palata

For the research purposes, we cooperate with Home Palata [52], a residential care institution for visually impaired older adults. Home Palata was founded in 1888 and from the beginning, it served as home for people with severe visual impairments. The average age of a client is 84 years, and the severity of their visual impairments spreads across all the categories of WHO classification [49]. The majority of the clients (75 %) are women.

Home Palata is a large and complex building comprised of four floors, while three of them are above the ground and accessible for the clients. The capacity of Home Palata is 133 beds, and there are about 100 employees. The grounding plan of Palata resembles number 8, see Figure 2.1, and there are 39 one-bed and 47 two-bedrooms. The indoor environment is adapted for the needs of the clients. The orientation is supported by various means, see Figure 2.2. A typical hallway has a handrail on one side, that is equipped with haptic marks that indicate a particular door next to the mark. The orientation is also enhanced by the presence of high-contrast horizontal navigation lines on the floor in each corridor.

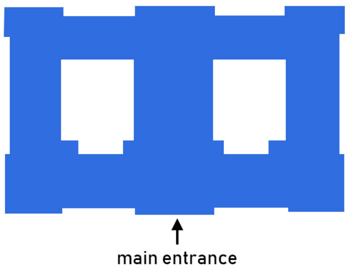

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Figure 2.1: Shape of the ground plan of Home Palata

2.1.4 Orientation and navigation of visually impaired older adults

As the clients of Home Palata (see the subsection 2.1.3 above) represent our target user group, during our preceding research activities, we analyzed their needs extensively. Macík et al. in [41] describes the results of on-site study related to the everyday life of the clients. He also describes problems with navigation and orientation in the building. We further examined issues of the clients related to orientation and navigation in semi-structured interviews conducted for subject Psychology in HCI, and we got comparable results.

Various types of landmarks help the clients to maintain orientation. For people with higher visual acuity, those can be images on the walls or the furnishings in the hallway; the clients with remaining light-perception appreciate the high-contrast navigation lines and the haptic marks on the handrail. Some clients navigate independently and without limitations, but it is more common the clients orientate and navigate themselves independently only along a few selected routes, or they avoid entirely leaving going out of their rooms alone. Our research indicated that adaptation to the environment is very difficult for the new clients: they rely on the personnel that guides them, and learning at

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Figure 2.2: A typical corridor in Home Palata. The dashed green line shows the high-contrast navigation line; the haptic orientation marks on the handrail are highlighted in the red circle. On the side of the corridor where is not located the handrail, furniture and items are placed to support the feel of the natural environment (in the picture is this zone marked by the blue overlay. From [41]

least few routes to important places is a lengthy process that lasts months. Similar results got Bělovová Dolejší from qualitative research with 16 visually impaired older adults living in a residential care facility in Brno [8].

Macík et al. [41] state that autonomous navigation improves with experience. However, it seems that for the VIOAs is still troublesome to create a correct mental model of the environment. In our preliminary research connected to the idea of the 3D model of the building (specified in Section 2.6), we printed the 3D model of the building of Home Palata, and let the clients (N=6) examine it. The majority of them was surprised by the real ground plan of the building. According to their direct experience, the shape of the floors resembled digit 8, and they believed there are no right angles.

2.2 Visual impairment and spatial cognition

This section describes the process of spatial cognition itself, and the results of researches focused on the exploration of spatial cognition of visually impaired as well.

2.2.1 Spatial Cognition and Related Terms

Talking about spatial cognition in humans, Montello [68] defines spatial cognition as the study of knowledge and beliefs in about spatial objects and events in the world. There are several important terms related to spatial cognition:

Cognitive map. Concept of *cognitive map* was developed by Tolman in [73] to refer to internally represented spatial models of the environment [68]. The synonyms for this term are: *imaginary map, mental map, environmental image, spatial image, spatial schema* and *spatial representation*, from [67]. The cognitive map includes knowledge of landmarks, route connections, and distance and direction relations; non-spatial attributes and emotional associations are stored as well, from [68]. According to O'Keefe [47], cognitive maps include at least two types of representations. The first one includes remembering a specific pathway or route to reach some target point in space. It is an efficient means for reaching some destination. However this kind of association is not very flexible, it offers low variability, and it cannot be used to derive shortcuts and alternative pathways. On the other way, the second representation stored in a cognitive map is based on maps, and it consists of knowing aspects of a topography. This representation can be adapted easily, and it is used for inferring shortcuts or alternative pathways. It can be acquired directly in the environment or by using external representations of the environment that represent topography, e.g., maps or small-scale models.

Spatial frames of reference. Spatial frames of reference are necessary to encode and to represent positions of objects in space. According to [51], we use two representations: egocentric and allocentric frames of reference. Egocentric frames define spatial information in relation to one's body, while the allocentric uses external landmarks. The work of Milner and Goodale [45] shows the importance of vision in spatial memory.

Navigation. According to Montello [68], people use spatial knowledge for *navigation* and *orientation* when travelling on Earth's surface. Term *navigation* refers to coordinated and goal-directed travel through space, and it consists of two components: *locomotion* and *wayfinding*. Locomotion is a process of guidance of oneself through the environment by using immediately available sensory information, and it does not require any internal model or cognitive map of the space. On the other hand, wayfinding is a planning and decision-making process that humans use to reach destinations that are not in the immediate sensory field, and it involves using a cognitive map of the environment. Wayfinding and locomotion tasks vary greatly in their demand in attentional capacity, that is, following a known route is much less demanding than finding a way in a new environment.

Orientation. By Montello [68] *orientation* is knowing 'where you are', although the precision of this activity varies greatly in different situations and people. Montello [68] also describes two processes involved in orientation during navigation: *recognition of external features or landmarks* and *dead reckoning*. In the majority of the cases, recognition of landmark serves as a key to internal cognitive map or external map, to access further spatial knowledge. Dead reckoning refers to a process that integrates information about movement, speed, direction and acceleration without reference to recognized features.

2.2.2 Spatial cognition of visually impaired

According to [40], there are three main theories that describe spatial cognition ability of visually impaired people:

- **Deficiency theory** presumes that due to lack of visual experience, the spatial understanding lacks completely. However, this theory is rejected by empirical results.
- **Inefficiency theory** states the spatial cognition abilities are similar to sighted people but less efficient.
- **Difference theory** assumes visually impaired people may use qualitatively different methods, but functionally comparable or equivalent to abilities of sighted people. There exist empirical results that confirm this theory, and the probable cause is that many blind people have developed highly effective spatial strategies.

For navigation, visually impaired use primarily hearing, touch, kinesthetic and olfactory stimuli. The problem is, information obtained by these senses have lower reliability than vision, and they are not able to provide continuous simultaneous sensing of multiple spatial reference objects. Because of this, the coding of spatial information of visually impaired individuals is different.

Ungar in his work [75] presents important distinctions about spatial abilities of visually impaired:

- **Near vs. far (haptic vs. locomotor) space.** The concept of *near space* refers to small-scale or manipulatory spaces – areas, that can be explored without changing the position of the body. When exploring near space with hands and arms, the location of the body provides a stable egocentric frame of reference, and the locations of the objects can be represented relative to one's body. On the other hand, term *far space* refers to medium or large scale environments in which locomotion has to be used for exploration, and the egocentric frame of reference becomes less reliable.
- **Early vs. late onset.** It is essential to distinguish between people born blind or since early in life and people who have lost their sight during

the lifetime and have therefore some visual experience. In general, the performance in spatial tasks is more similar to sighted people for late blind people.

- **Memory vs. inferential tasks.** There is a significant difference between spatial tasks that require to infer a new relation based on a direct experience and tasks that require a response based on direct experience with a spatial relation. The latter requires only simple spatial coding, while the former requires to transform coded information. Indeed, inferential tasks are more likely to be employed when testing the efficacy of acquired spatial knowledge, because they are generally more reliable when based on external coding, e.g., map-like representation of a spatial layout.

Finally, Ruggerio in [62] discuss the processing of spatial frames of reference with visually impaired. His study indicates that visual status altered the spatial processing selectively. There was a drop in the allocentric processing showed with congenital participants compared to blindfolded. On the other hand, all groups performed similarly in egocentric processing. Ruggerio presumes that the lack of vision affects allocentric but not egocentric frames of reference.

2.3 Tools and methods for enhancing the spatial cognition (without vision)

In this section, we analyze tools and methods that are currently used for enhancing spatial knowledge of visually impaired.

2.3.1 (Tactile) Maps

According to [26] and [11], maps are two-dimensional, projective, small-scale representations of an environment, presented from allocentric perspective. Maps are used for acquiring spatial knowledge successfully for centuries, although their form varies and interactivity increases.

According to [85] Zeng and Weber, there are two types of maps for visually impaired: desktop-based maps and mostly GPS-based mobile maps. Those maps use a representation of geographical features via different media, and they ensure that their features are accessible to visually impaired. This is done mainly by employing three kinds of non-visual interaction: tactile perception, acoustic perception, and by audio-haptic channels.

Tactile maps are a powerful tool for acquiring spatial information. In [30], Jacobson let students draw their mental representation of the campus they were familiar with. After that, the students had to explore a tactile map of the campus, and then redraw the map of the campus again. In comparison, the second map produced by the participants contained much more descriptions and details of the environment, and it was also closer to the actual map of the campus. Another study by Jacobson [31] compares spatial knowledge of two groups of visually impaired adults. The first group of participants had to gain spatial knowledge by walking a route with a mobility instructor. The second group, also, studies an audio-tactile map in advance. After that, both groups had to walk the route unaided. Finally, the participants were asked to draw a map of the route, and as in the previous study, the results of the second group proved to be more accurate, that is, the exploration of the map played its role. By [11], similar results got Espinosa and Ochaita [19] in a study focused on learning a new route either by direct experience, by direct experience while carrying a tactile map, or by taking the route with a verbal description of the area. Again, the tactile map served as the best means of gaining spatial knowledge.

Finally, the work of Ungar [76] shows tactile maps can help visually impaired children to create their cognitive maps, and using tactile maps; they were also better in estimating the distances between objects in space.

That is, the studies show that tactile maps are an efficient tool for mobility training of visually impaired for both familiar and unknown space.

Strategies for exploration of tactile maps

Tactile maps differ from classic maps, which allow reading spatial and other information almost simultaneously. Information from the tactile map can be acquired only sequentially, and a consequence of this can be higher demands on memory when using such kind of map. Secondly, the efficacy of the reading may depend on the chosen scanning strategy. There, Ungar [76] states that more systematic strategies are better. Witntjes in his study [82] examines approaches of visually impaired used for exploration of tactile images. They study them using three strategies:

1. Using one hand.
2. Using both hands, while a single hand moves and the other hand rests on the image.
3. Using both hands simultaneously.

The studies [82], [27] indicate that the most effective way for exploration is the second, bimanual strategy. We hope those strategies may be used when exploring tactile maps as well, as both processes (reading of tactile images and reading tactile maps) are sequential.

2.3.2 Small-scale models

Small-scale models are three-dimensional representations of an environment that represent topology. The prior work of Pickard [55], Papadopoulos [53] and Yngstorm [84] indicates employing small-scale models can enhance spatial knowledge of visually impaired, even with only a brief introduction to the model itself.

Voight and Martens in [78] suggest the usage of 3D printed small-scale models as tools for obtaining structural characteristics of the real space and recognize better the elements and their interrelationships, as well as subspaces, spatial sequences and decision-making situations (e.g., crossings of hallways) in the environment.

Finally, a recent study of Holloway [29] shows that using 3D printed models is a promising approach. In a study with 16 participants, she compared task performance, recall and user preference on tactile maps and 3D models of a park and a train station, see Figure 2.3. The results showed a strong preference for the 3D models over printed tactile maps. The performance in the tasks was also better for 3D model thanks to the use of 3D iconic symbols. When talking of recall, there was some advantage in the short-term recall, but not for long-term recall. The only issues are, all the participants were experiences tactile graphics readers. Sadly, we did not find any studies focused on the evaluation of the benefits of 3D models for people with recent vision loss.

Indeed, with the increasing popularity of 3D print as flexible and low-cost technology, small-scale models could be used more frequently, as existing researches indicate this approach is promising.

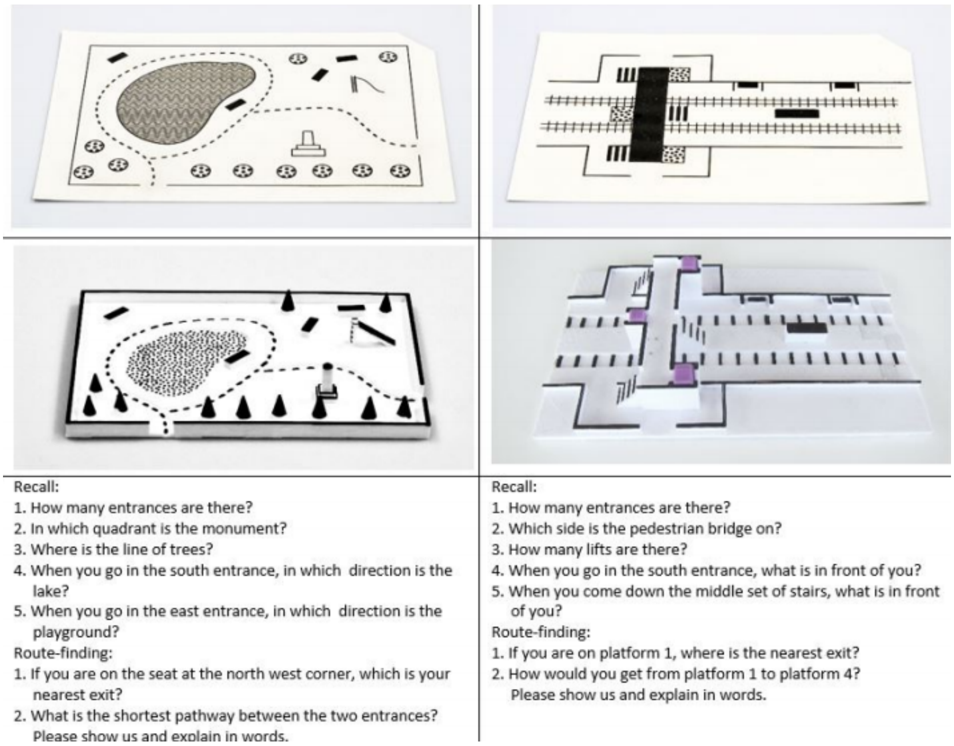

Figure 2.3: Setup of Holloway's experiment for comparison of tactile maps and 3D models, from [29]

Strategies for exploration of small-scale models

As Holloway compared exploration techniques used for exploration in tactile graphics and 3D models in [29], some similarities and differences were found. Frontmost, all the 16 participants of the study, used both hands and multiple fingers and followed features such as walls and pathways on both tactile and 3D models. The majority of the participants (13 of 16) tend to place both hands on the 3D model to get a complete overview, while only 7 participants did the same for the tactile map. Initial exploration of the small-scale model was also reported in [24].

However, there is a lack of studies addressing this topic, although it can be a useful insight both for the design of such models and mobility training methods.

2.3.3 Virtual Environments

Another approach to enhancing O&M of visually impaired is by employing virtual environments, that are explored by visually impaired using a computer or mobile devices. Exploration of the space is done by listening to verbal and non-verbal audio output, that can accurately simulate the environment and provide a sufficient amount of information. Employing this approach, it is required to design an acoustic rendering module, such as a speech synthesizer and sonification of sounds, from [85]. For example, Zhao [88], [87] uses sonification to describe patterns and trends in geographic data. According to [15], the sonification is an efficient mean for transmitting geo-referenced information, but it is not a suitable way how to access details, and it also requires heavy working memory load.

There are also projects focused on employing virtual reality, e.g. [32], [65]. Some of them use VR as an approach to O&M training, e.g., [66]. This system simulates the sounds of a real environment and allows the user to get used to it in a safe environment. The evaluation showed employing VR O&M training is less stressful than training in real-environment conditions. Another VR training system, [36], employs even more modalities for exploring the space: haptic sense (force feedback of a virtual white cane, thermal feedback as sun simulation) and auditory sense. However, the navigation in virtual space was done by the system itself, so we cannot evaluate the contribution of the system to the creation of a mental model.

Finally, gamification can be employed to make the process of learning more enjoyable. In [71], Tang proposes learning indoor environment using a mobile game, that allows the user to travel through the building's environment virtually. The primary purpose is to learn a route to a particular place. However, the evaluation itself does not examine the quality of created cognitive map of the space itself.

2.3.4 Direct modifications of the environment

When talking about indoor spaces, the orientation process can be enhanced by adjustment of the space itself. The orientation aids can be rather passive (tactile signs, high-contrast guiding elements as reported in [41]), or active. That means interaction with the environment is enabled by carrying dedicated devices (e.g., in [72]), smartphones, or it can be done without any additional equipment. For example, Macík et al. in [42] proposes a context-sensitive indoor navigation system that employs computer vision.

2.3.5 Conclusion

We examined different types and approaches to design of tools for enhancing orientation used with visually impaired. The most traditionally used tool are maps which provide mainly a tactile representation of the environment. In many studies, they proved to be powerful as they enable the creation of a mental model of an environment. However, there is a lack of studies focused on the evaluation of tactile maps for VIOAs. Next presented approach, small-scale models, can be perceived as enhanced maps by 3D iconic symbols. Small-scale models have promising results, and there are indications that the performance of users is better for small-scale models than for classic tactile map. Then we presented two utterly different approaches. The first one employs virtual reality to simulate the environment; the latter one uses direct modifications of the real environment. We suppose that VR may allow the user to build the mental model of the environment, and the enhancements in the real environment improve one's situational awareness. However, we did not find many works focused on the evaluation of acquired spatial knowledge using those methods. Based on our research, we suggest to employ tactile maps along with the usage of 3D iconic symbols for our design.

2.4 Non-visual interaction for interactive maps and 3D models

According to [40], navigation of visually impaired primarily employs hearing, touch, kinesthetic and olfactory stimuli. That is, the perception is multimodal, and different aspects of spatial knowledge may be coded using different sensory data.

Studies show that tools used for O&M training profit from multimodal interaction as well. An example given: in [11] Brock shows results of her research that compared two designs of a map for visually impaired — an interactive map that employed taction and audition, and a paper map. When comparing the results of both plans, there were no differences in acquired spatial knowledge, but the learning time was significantly shorter for the interactive one, and there was a preference of interactive map over the paper one. Valuable insight from this study is, the interactive map was accessible to a blind person with low Braille reading skills. Finally, the satisfaction for the interactive maps showed to be age-independent, while when evaluating satisfaction from the paper map, there was a significant correlation between satisfaction and braille reading experience and proportion of life with visual impairment.

In conclusion, according to [11], using multiple modalities can break down the complexity of communicated information. For this reason, we further explore interactions, that can be possibly implemented in our 3D model.

2.4.1 Haptic exploration

Haptic exploration is the most common interaction used mainly in tactile maps and 3D models. Haptic perception has been extensively studied. According to [28], exploring an object by touch requires significant cognitive effort. Also, different movements have to be used for perceiving different aspects of an object by touch: a lateral movement for texture, enclosure for global shape and contour following for exact shape, from [37].

Training plays an important role when talking about haptic exploration: the first step is to touch and scan the tactile graphic to get an overview, and then systematically explore present symbols.

2.4.2 Auditory cues

Employing audition is also a common mean for communicating an environment. Audio feedback can be used as the principal form of interaction (e.g., in virtual maps, natural-language-based navigation systems [80]), or it can enhance the experience of haptic exploration when used in tactile maps and 3D models. In this case, audio cues usually describe an environment (e.g., in [29]), but they can also provide ambient sounds of the environment (e.g., in [2]).

We further analyze the audio feedback used in combination with haptic exploration. There exist plenty of methods, e.g.:

- **Audio labels.** Holloway [29] and Giraud et al. in [24] discuss the usage of interactive audio labels — they can enhance the overall accessibility of the model, because the users are no longer forced to be Braille readers to get some additive information from the map, such as names, descriptions, etc. Moreover, the users do not need to read and memorize any legend and shift attention between the graphics and legend, labels, and so on. Various types of gestures can be implemented to activate the labels, e.g., tap, double tap (examined in [11]), but the sensitivity must be set correctly, do not trigger the audio events too often, and provide clear feedback, as mentioned in [24], [11].

- **Overlaying the tactile graphic on a touchscreen.** This approach uses, for example, Brock in [12]. Again, the choice of gesture and set sensitivity of the touchscreen plays its role. In this method, the size of the map is limited by the size of the touchscreen.

- **Stylus-based technologies.** Stylus-based technologies allow a user to get audio by touching symbols by a pen, e.g., Talking Tactile Pen [70]. This approach was demonstrated for example in [34] for exploration of a complex map. However, the user is always required to carry the pen, and as it is necessary to hold it, only one hand is left free for haptic exploration.

- **Hand tracking.** There are studies focused on employing hand-tracking to recognize user's gestures on a tactile map to play audio, e.g., [50]. However, this technique requires precise setup and also controlled conditions. Otherwise, its reliability decreases. On the other hand, the method is beneficial for analysis: in [13] Kinect camera is used to track hands to analyze strategies of exploration of an interactive tactile map.

- **Conductive tactile lines.** Brito in [10] employs conductive filament printed on an image. As the 3D-print object is touched, the corresponding audio is played, to help the user to recognize the object. As the 3D print is very flexible, this is a promising approach to examine.

2.4.3 Olfactory cues

Even though olfaction undoubtedly plays a role in the orientation process of visually impaired, there is no evidence of a user interface that uses olfactory cues to enhance O&M, and the role of olfaction in the orientation process should be further analyzed.

2.5 Methods for implementation of maps for visually impaired people

In [85] Zeng and Weber review existing approaches in maps for visually impaired. According to them, there are three most popular methods of design and implementation of desktop-based maps: paper-based maps, computer-based maps, and Braille tactile maps.

2.5.1 Paper-based maps

Paper-based maps are a traditional tool - they are portable, but unlike to computer-based maps, they are static, and they offer only tactile interaction. There are two most popular methods for implementation of the paper-based map: using microcapsule paper, and thermoforming (see examples in Figure 2.4).

- **Microcapsule paper.** Accessible maps made using microcapsule (or swell) paper are the most available for visually impaired users – it is possible to create a map online, and then pick it up in a center for visually impaired [25]. The technique prints black and white graphic onto a special microcapsule paper. Then, a device with an infrared lamp is employed to heat the paper, and dark areas are expanded upwards then. There is only one height profile of the elements, and that is probably the most significant limitation of this technique – reading and using them requires training and great tactile ability.
- **Thermoforming.** Thermoforming uses a mold to form maps made of heat-softened polyvinyl chloride (PVC) sheets. This technique allows to represent different heights in the map, but it is costly, as there is a need for a mold for each map, and vacuum presses are also expensive machines.

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Figure 2.4: Examples of paper-based maps made using different techniques: **microcapsule paper** *(on the left)* and **thermoforming** *(on the right)*

2.5.2 Computer-based maps

- **Augmented paper-based tactile map.** The interactivity of paper-based maps can be enhanced by underlying the map with touchable pad (e.g., tablet), which provide auditory cues. Such maps benefit from increased information density, but their size is limited by the size of the touch-sensitive display.

- **Virtual tactile maps.** Virtual tactile maps allow the user to explore broader areas, as the size of the paper does not limit the space. They are represented as a virtual space in a computer created using information from GIS. As input/output devices are employed, e.g., joysticks, or a Phantom haptic device [63]. Such devices are used to acquire tactile information, but there is usually auditory output: sonification and audio labels.

- **Braille tactile maps.** Braille tactile maps [85], [86] is a completely automatic system for the visually impaired. Map elements are represented as raised pins. This approach offers similar interaction to augmented paper-based tactile maps, and profits from the automatic generation of haptic symbols – exploration area is no longer limited to the size of the display.

2.6 Interactive 3D model of building

This thesis implements interactive haptic plans as one of the parts of the interactive 3D model of building proposed by Macík et al. [44]. The model is intended to be used by visually impaired. According to the utility model [44], it has following properties:

- The model shows the exterior of the building as well as the interior; that is, the whole building can be explored both from inside and outside.
- Each floor in the building is represented by a drawer that can be opened and examined.
- There are also haptic symbols/lines that represent rooms or routes for exploration of the building.
- The model is placed on a desk with height adjustable to the user's preferences.
- Auditory instructions could be employed.
- The model presents elements of the interior and their relations to enhance the orientation.
- The model allows the user to learn routes to important places, e.g., canteen, common room.
- For implementation should be used 3D print on acrylic glass.

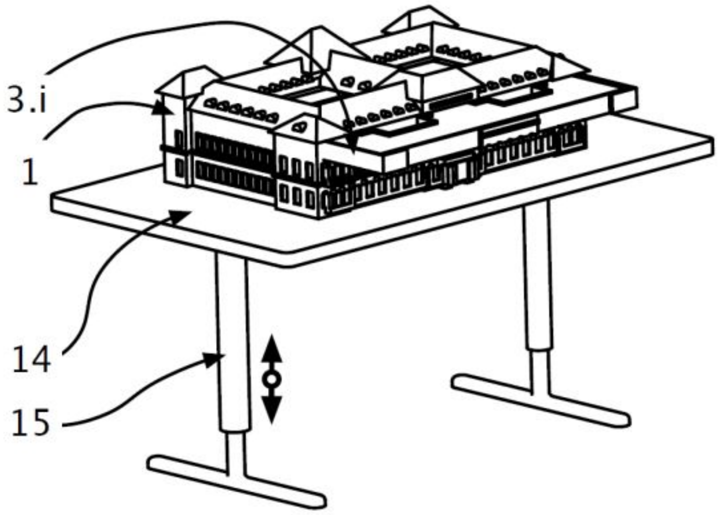

Figure 2.5: Overview of the appearance of the interactive 3D model, from [44]. The aim of this thesis is to design and implement interactive plans/maps that will be located inside each drawer (3i in the Figure).

2.7 Requirements

The requirements for the interactive tactile plans are derived from extensive study of our target user group, and also by the utility model of the interactive 3D model of the building, see Section 2.6 above.

Functional requirements are:

- **R1: Exploration of individual floors within a building.** Adaptation to a new environment is a long, and complicated process for VIOAs. Due to various limitations by the health conditions of individuals, direct exploration of the situation is not efficient without extensive help of another well-oriented in the environment. Furthermore, it does not prevent the user from creating an incorrect mental model of the environment. We will implement the device as a set of interactive tactile maps of floors to allow VIOAs to create the correct mental model of the environment.
- **R2: Exploration of elements of the interior and their relations to enhance the orientation.**

  Have knowledge and overview of landmarks are crucial for both orientation and navigation. Our map should provide a sufficient level of detail of elements present in the interior in a way accessible to our target user group – VIOAs.

- **R3: Support for route-learning.**

  Knowing routes in advance is crucial for VIPs as it helps them to maintain orientation on the route, and it prevents them from getting lost. For VIOAs, developing an overview of routes may motivate them to explore the environment on their own, and increase their independence. The device should allow the users to examine particular routes, and support them to learn such routes.

- **R4: Customization of the UI to the needs of individual users.**

  Our target audience is very diverse in conditions for receiving and processing stimuli from the environment. The customization of the UI is necessary to ensure that the interactive plans will be usable for the majority of the representatives of our target user group.

Non-functional requirements are:

- **R5: Safety.**

  Using the plans should not be dangerous for the user, e.g., it should not contain sharp edges.

- **R6: Hygiene.**

  The plans should be cleanable. VIPs have lower self-control over the purity of their hands, and the device may get dirty quickly.

- **R7: Endurance**

  The plans should be resistant to clumsy use; i.e., it should not contain easily damageable parts.

- **R8: Usability**

  The UI should meet the needs, limitations, and requirements of visually impaired older adults.

2.8 Conclusion

We studied our target audience, and we present the needs, requirement and limitations of visually impaired older adults. We also analyzed tools used for enhancing orientation of visually impaired. Then we focused specifically on usage of non-visual interaction methods, and approaches to implementation of tactile maps, as they are the most traditional tool for acquiring spatial knowledge with visually impaired. Finally, we describe the prior work of Macík et al. [44] focused on design of interactive 3D model of building. We sum up all stated in definition of functional and non-functional requirements for our design.

Chapter 3
Design

In this chapter, we present the design of the interactive tactile maps of interior for the 3D model. In following sections, we define our target users using personas (3.1), then we describe the UI formally using scenarios (3.2.1), and use-cases (3.2.2). Finally, we present the initial designs of individual elements in the map in (3.3.1, and two generations of prototypes: the low-fidelity prototype (3.3.2) and the high-fidelity prototype (3.3.3).

3.1 Personas

To identify more with our target user group, we sum up the insights listed in the Section 2.1, our previous research activities with the clients of Home Palata (semi-structured interviews conducted in subject Psychology in HCI and semi-structured interviews for [41], [43]), and we present two personas – Marie (see Appendix A) and Petr (see Appendix B).

Both personas are positive, and they are clients of Home Palata. The severity of their visual impairments varies:

- **Marie** still uses remaining sight in the majority of her everyday activities, and she would be classified as category four according to the classification of visual impairments of WHO [49].

- **Petr** has only remaining light-perception, and he belongs to category five by WHO [49] – he's being adapted to explore the environment mainly by taction.

We suppose that those two approaches to receiving and processing inputs from the environment will be the most common for our target group. The strategies for exploration used by both Marie and Petr may differ substantially, and we may need to employ different interaction methods to satisfy their needs.

3.2 Formal description of the user interface

In this section, we describe the functions of the user interface formally using scenarios and use-cases.

3.2.1 Scenarios

We describe the expected usage of the interactive tactile plan using scenarios. The participants in the scenarios are our personas Marie and Petr, who are further described in Appendix A and Appendix B.

S1: Adaptation to user's needs
It was a rainy day, and Marie did not have any program for the day, so she decided to explore details of the Palata Building. She went to Entertainment Room, where the interactive 3D model of Palata is located. As she sat down on the chair by the model, the model recognized Marie and modified its setting according to her preferences. It called her by the name and repeated initial instructions. Marie was happy that the device knows her and it is prepared just for her, and she started to explore the environment using the model.

S2: Introduction to the map for a new user
Petr has never used a tactile map before, but he is opened to new technologies, and he wondered how do his surroundings are like – since he is blind, he is never sure about the real appearance of the environment. One day, he decided to explore the new interactive model of Palata. The nurse guided him to the Entertainment Room, and she set on the intro mode of the model. The model explained its purpose to Petr and showed him the elements which are present in the interactive maps. Petr got to know the symbols used for rooms, stairs and the hallway, and he explored the map freely for a while. He liked its interactivity, so he decided to come the next day too to learn a route to Great Culture Room.

S3: Learning locations of the most important places for one's everyday activities
For Petr, there are a few places in his surroundings that are the most important for him: a daily room, staff room, and the nearest elevator. However, he feels safe only when he goes to the daily room. He heard from his friend Alena that the interactive 3D model allows learning traces to important places in one's surroundings. So, one day, he asked the nurse to accompany him to the Entertainment Room to try this program. Then, Petr sat down by the model and the nurse launched the program. The model firstly welcomed Petr and let him select a place he wants to go from his room. He decided to learn a route to the Great Culture Room. Then the model navigated him to his room on the map. Petr followed the route on the map, and he tried to memorize the turns he has to take, the distances and numbers of the doors. He visited

the model the day after too, and he did the same again. Petr was already confident when using the map, and he did not even need the plan to show him the route, because he already remembers it. The next week, he went to the Great Culture Room with the nurse again, but this time he guided her. He made a few mistakes, but the nurse helped him. Finally, he went to the Great Culture Room on his own, and he was delighted he did it.

S4: Introduction to the environment for new clients
Marie is still quite new to Palata, and the environment there seems like a maze for her. For this reason, a nurse took her to the daily room to explore the interactive 3D model of Palata. Marie sat down by the model, and the nurse showed her important places like the entrance, the Great Culture Room, Cafeteria and her room using the model. Marie gained an overview of the building, and she also tried haptic exploration for the first time.

S5: Free exploration of the environment
Due to problems with her leg, Marie can walk only short distances during a day. It prevents her from an exploration of other floors of Palata because she got tired after a while. However, Marie is curious by nature, and she likes to explore: she asked the nurse to accompany her to the Entertainment Room to examine the interactive 3D model. She chose the drawer with the second floor because there lives Marie's friend Jana who Marie meet in the choir. Marie studied the map of the floor freely - she found the location of Jana's room, and other places as well.

3.2.2 Use-cases

We present use-cases that correspond with the scenarios listed above in Subsection 3.2.1. We denote the complete interactive 3D model of the building as System, a representative of our target user group as User, and a member of staff of specialized housing as Nurse.

UC1: Adaptation to User's needs.
Corresponding scenarios: S1-5.

- **Precondition:** The device is plugged into the power supply, and Nurse set the device on.
- **Flow:**
  1. System recognized User.
  2. System adjusted its behavior to pre-defined User's settings: adjusted the volume, type of instructions, height of the desk.
- **Post-conditions:** User starts exploring the model with settings adjusted according to his/her preferences.

UC2: Introduction into the map symbols.
Corresponding scenario: S2.

- **Precondition:** UC1
- **Flow:**
  1. Nurse set on the introductory program for new clients of the Palata.
  2. System presents the representation of the hallway in the map and asks User to explore it by touch.
  3. User explores the hallway.
  4. System detects the touch of User in the area of the hallway and assures User that he/she is going well.
  5. System asks User to press the first button he/she finds.
  6. User presses a button. If it is a button denoting a room, the system plays its audio-label and then explains used representation of the room in the map. Then, System asks the user to press another button similar to this.
  7. User presses a button.
  8. System assures User that he/she is going well.
  9. System asks User to find and press the symbol of stairs. The system also describes its appearance in the map.
  10. User presses the stairs.
  11. System congratulates User and ends the introduction into the map symbols.
- Alternate flow:
  - 3a, 6a, 7a, 10a: When there is no response from User, System repeats the instructions.
  - 6b, 7b: When User presses stairs, the system plays label for stairs and then explains its appearance in the model.
  - 10b: When User presses a room button, a label for the button is played, and then the difference between the room button and stairs is explained.
- **Post-conditions:** User understands the symbols used in the map.

UC3: Free exploration of the map
Corresponding scenario: S5, S4.

- **Precondition:** UC1
- **Flow:**
  1. User sits down by the model and opens a drawer.
  2. System activates a map in the opened drawer.
  3. When User pushes a button, the label for the button is played by the speakers.

UC3: Free exploration of the map using headphones
Corresponding scenarios: S5.

- **Precondition:** UC1, the nurse or the user plugs the headphones into the device
- **Flow:**
  1. User sits down by the model and opens a drawer.
  2. System activates a map in the opened drawer.
  3. When User pushes a button, the label for the button is played to the headphones.

UC4: Room-to-room route-guidance
Corresponding scenario: S3.

- **Precondition:** UC1, the nurse sets on the route-guidance mode, defines a start and target destination for guidance: corresponding parts of hallway are touch-sensitive. Nurse also places on the map tactile symbols denoting start and end of the route.
- **Flow:**
  1. System welcomes User and plays instructions for route-guidance mode.
  2. User finds start tactile symbol for the navigation and follows the instructions.
  3. User finds the doors of the room and using his/her finger, and he/she explores the hallway behind the doors.
  4. System detects User's touch and plays a sound that indicates progress on the route.
  5. User continues to explore the hallway in a random direction.

6. Depending on User's direction in the map, System provides User with audio feedback.
7. When User reaches the final part of the hallway, the system plays success sound and describes the location of the doors of the target room.
8. User finds the target room and pushes its interactive symbol.
9. System plays an audio label of the target room and congratulates User. Then, System encourages the user to go through the route again.

3.3 Prototypes

We followed the UCD methodology: firstly, we used rapid prototyping to select the elementary symbols, and then we implemented our designs into two generations of prototypes.

3.3.1 Initial design

Aiming to represent the indoor space in a way that will be intelligible to our target user group, we decided to create a tangible, interactive tactile map of the space, that will allow the user to explore the environment in advance, and provide them with a better understanding of the space in broader relations.

The very first design phase was focused on the design of mapping of the elements of the interior and choice level of detail presented in the map. Unfortunately, no global standard would define an eligible mapping of the interior environments into tactile plans, and there is also a lack of literature focused on O&M aids suitable for visually impaired, who are older than 60 years. Also, we considered different approaches to the interaction offered by the model.

Tactile design

The second mostly used modality with visually impaired people is the sense of touch. As the majority of our target users deal with the impairment from the older age, we had to resolve several challenges: tactile thresholds for detection of touch and vibrations are increased, and overall tactile acuity decreases [81]. Furthermore, according to [38], due to worsening tactile acuity, late-blind people are at risk they will never learn Braille fluently. Traditionally used approaches to the design (e.g., a legend in Braille) and techniques (thermoforming, microcapsule paper) of maps for visually impaired could not be applied.

We decided to design tactile symbols as representations of the following elements of an interior environment:

- hallways,
- rooms,
- doors,
- stairs.

We consider this set to be fundamental for a map of a single floor. However, in future work, design of between-floors element such as elevators should follow. For each element listed above, we designed a set of tactile symbols and printed it on a 3D printer, as 3D print is a technique that allows us fast and inexpensive production of 3D prototypes. We experimented with heights and widths of lines, textures, and shapes. Quality of the symbols was evaluated by a visually impaired expert user Lukáš Treml. In the paragraphs below, his insights are emphasized in italics.

- **Definition of the area of the hallway and the living quarters.** It should be effortless for the user to distinguish if he/she is outside or inside a room on the map. Firstly, we designed the room sectors and individual rooms as raised areas above the area of the hallway, see Figure 3.1, a. *This was not suitable, as it was almost impossible to recognize the area of the room by taction – there was not any frame that would indicate where the room starts and ends.*

  We moved to another approach - each room was framed by a raised line, and there was also another raised line which denoted the hallway, see Figure 3.1, b. *Differentiation of the hallway was appreciated, but the texture used on its surface was not pleasant to follow by touch.* In the next design (see Figure 3.2), another problem emerged: *The room line and the hallway line were too close, and it resembled a texture by touch. It was too cluttered.*

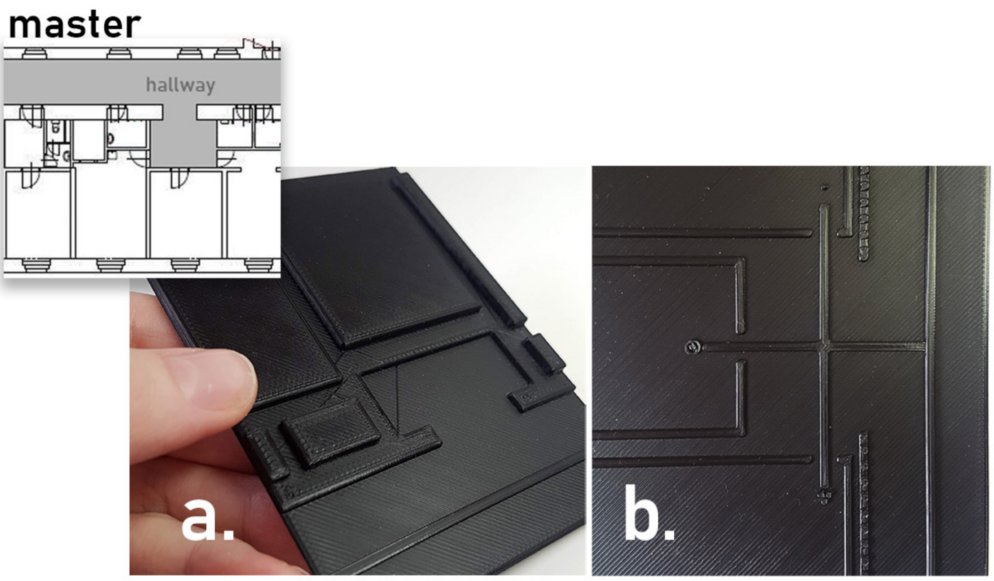

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Figure 3.1: Different approaches to representation of the hallway and the room area

- **Representation of the shape of the hallway.** Having correct knowledge about the shape of the hallway is crucial for both orientation and navigation tasks with the map. In the first design, we represented the hallway as a single raised line (see Figure 3.1). This approach gave a clear overview of the shape, but it also brought a lot of misconceptions. *It was interpreted as a wall, and as it was an artificial construct not present in the real environment, it was tough to understand.* Also, the doors had to be depicted as raised-line branches from the main hallway line. *Visually impaired tend to follow the raised line from one side only: the door branches on the other side of the hallway raised line were impossible to reach, and they remained unnoticeable. We were advised to use two raised lines groove for as the representation of the hallway. It allows the user to distinguish between the sides of the hallway, and it makes it easier to recognize the location of the doors.* This approach was already implemented in our third design (see Figure 3.2), but *the raised line for the hallway was too low.*

- **Doors.** Symbol which represents doors should by noticeable easily and self-explanatory, but it should not be misleading when exploring the shape of the hallway. We tried different approaches: the doors as a change of shape of a raised line, or as a solid object on the raised line. *According to the expert user, the most pleasant and meaningful was the representation by the change in the shape of the raised line of the hallway, but still, it was not noticeable enough.*

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Figure 3.2: Different approaches to representation of doors

- **Stairs.** When designing the tactile symbol for the stairs, we profited from real-life parallel: we created them as a miniature of the real-life object. *This was suitable, and we were advised to map also the stairs that lead down the floor because they are more dangerous than the ones that lead up.*

Tactile-auditory interaction

Due to the mentioned limitations of the sense of touch of older adults, we decided to employ the sense of hearing as another means of interaction with the device. We provide users with audio labels for rooms, and we designed appropriate interactive tactile symbols for this use-case (further referred to as *room buttons*). The *room buttons* should be distinguishable and invoke that they can be pushed. From the initial three designs, see Figure 3.3, we selected the rounded variant, as *it was a compact and a bold shape pleasant for touch. Also, rounded shapes are usually not present in the environment, and they are commonly recognized as classic button shape. The triangular shape invoked an arrow, and three dots were not compact enough.*

The role in the recognizability of the *room button* also plays its position within the room in the map. Firstly, we placed the symbol near the doors to the room. However, *there were too many tactile stimuli in a small area, and it was hard to separate the symbol for doors and the interactive symbol.*

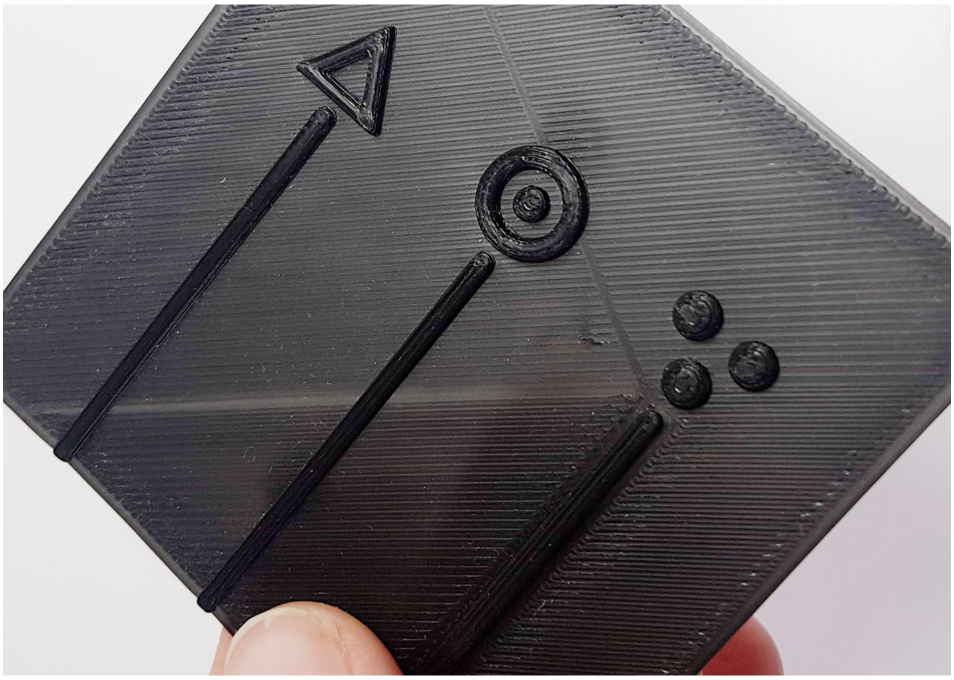

Figure 3.3: Initial designs for interactive tactile szmbols for rooms, *room buttons*.

3.3.2 Low-fidelity prototype

We took the insights gained in the very first design phase and implemented a low-fidelity prototype of the tactile map that employed improved designs of tactile symbols and offered the core interaction. The scope of the prototype was rather small in comparison to the presumed size of the model: its dimensions were 21×23 cm, it showed seven rooms and L-shaped hallway with a niche. Sticking to this ration, the final size of the plan of a floor in Palata would be 76×45 cm.

Tactile design

We redesigned a set of symbols of elements of the interior regarding the feedback from visually impaired expert user Lukáš Treml (see Subsection 3.3.1).

- **Rooms.** The walls between rooms are represented as a raised line (height: 1.2 mm), and each room is also denoted by an interactive *room button* in the middle of its area.
- **Hallway.** The hallway is depicted as a groove of two raised lines. Their height is 1.8 mm.
- **Doors.** Doors are marked in as a gap in a raised line with a low doorstep in the middle (height: 1.0 mm). Location of the doorstep (inside the room or outside the doors) indicates the direction of the door opening.
- **Stairs.** We improved the symbol for stairs – stairs down were added to this symbol, and we employed negative profile of the map to communicate transition between the floors.
- **Toilets.** We experimented with the symbol of toilets, and we designed it as a sphere.

The low-fidelity was implemented in the final platform according to requirements proceeding from the utility model of the 3D model of the building [44]. We employed 3D print on transparent acrylic glass (thickness 2 mm). As there were no references for 3D printing on such a material, we had to develop our method experimentally. As the material for printing, we used PLA (polylactic acid), as it has a high firmness, low elasticity, and it is harmless material. The detailed description of implementation can be found in Section 4.2.

Visual design

As we mentioned in the introduction, the majority of our target user group acquires visual impairment due to age-related disease, and such conditions usually do not lead to total blindness. That is, the visual aspect of the user interface is still important for our target user group. For this reason, we put emphasis on the high-contrast of individual elements, and we coded different items in the prototype by colors, see Figure 3.4.

We also used the parallel with the real life artifact – we depicted a line in the middle of the hallway, which resembles the high-contrast line on the floor in the hallways which is present in Palata, see Figure 2.2.

Interactivity

In the low-fidelity prototype, the only interactive parts of the plan were the room buttons - when the user pushed them, an audio file containing a description of the room, e.g., 'Room number 302' or 'Great Culture Room' was played. We employed method Wizard of Oz to provide the interaction. The sounds were pre-generated using Text-to-speech (TTS) and played using a laptop. The description of the application that simulated interaction can be found in Section 4.2.

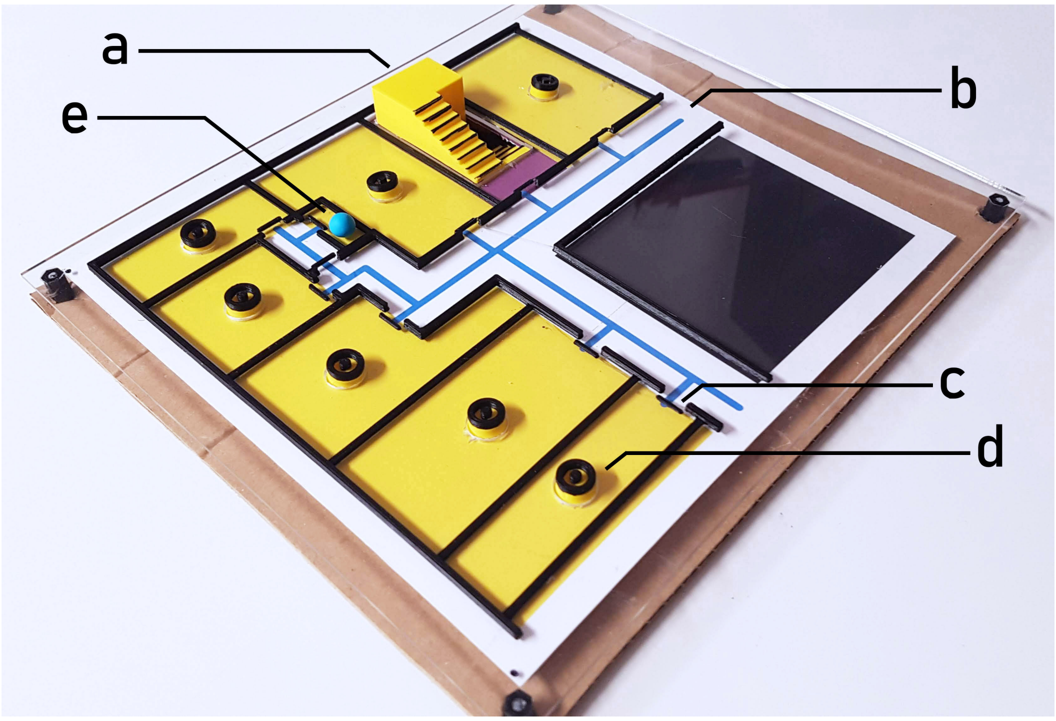

Figure 3.4: The low-fidelity prototype of the map. *a. Stairs, b. Hallway, c. Door, d.* Room button *(when pushed, an audio label was played, e.g., 'Great Culture Room', e. Toilets.*

3.3.3 High-fidelity prototype

In the design of the high-fidelity prototype, we addressed problems found in the evaluation of the previous prototype (see Section 5.1). We increased the height of raised lines that represent hallway to 2.3 mm. We also decreased the size of stairs, made them clickable, and labeled them with audio.

Furthermore, we focused on a solution that would allow the users to use the map for navigational tasks. The results of the evaluation of the low-fidelity prototype confirmed the need for customization when using the map.
The participants of the study (see Section 5.1) were more likely to use the map, if it would allow them to explore the areas and routes that they are interested in the most: their room and its surrounding, and the routes from their room to other places essential for their everyday life (dining room, cafeteria, Great Culture Room). We already tested a navigational task in the study with the low-fidelity prototype, see Section 5.1. There, the user did not receive any support from the map – nor route or start point and endpoint was highlighted. Even for the participants who had the highest visual acuity, this task was time-consuming, because they could not remember the location of the start point and end point for the navigation. We addressed this, and we designed **route-guidance mode** of the map. We list the properties of the *route-guidance mode* below.

Route-guidance mode

Route-guidance mode is a special mode of the map that allows the users to follow a particular room-to-room route in the map. We focused on a non-visual technique for marking a route on the map, as this approach can be likely suitable for all representatives of our target user group. The system uses touch detection to provide audio feedback. We addressed several challenges.

- **Representation of the start point and end point for navigation**

  It was necessary to denote the starting point for navigation so that it could be reached repeatedly without much effort. We designed a tactile symbol (see Figure 3.5, a., Figure 3.7), that can be clipped on the *room button*. It is a green arrow, from the top it resembles a cross. The shape was chosen to be as different from other elements as possible. It forms the highest element on the map, and it should be quickly recognized when exploring by touch. The design was chosen from a set of initial designs, which was, again, evaluated by the visually impaired expert user Lukáš Treml.

- **Representation of the route**

  The fundamental goal is to show the user the turns he/she should take on the route. We divided the hallway virtually into segments, see dashed lines on Figure 3.6. Each segment is a touch-sensitive area located in the middle of the hallway. There is always a segment in front of each room.

Its purpose is to provide the user with the feedback if he/she left the room by the correct door. There are no segments in the middle of the crossing: this should serve as an indicator of a decision point. Then, the route from point A to point B can be perceived as a sequence of subsequent segments.

- **Audio feedback**

  We presumed that using touch detection could be unusual and new for our users. Therefore, we detect touches in the hallways during the *route-guidance mode* only. The user should focus mainly on the shape of the route he/she should take. Thus the provided auditory feedback should serve only as indicator of the correct direction. Providing navigational instructions in natural language is not suitable, as the navigational instructions from the egocentric perspective in the map space may conflict with user's egocentric perspective dependent on his/her position towards the map.

  We indicate progress on the route as a major scale of musical tones: as the user follows the route, each progress towards the goal destination is denoted by a higher tone. When the user takes a wrong turn, another type of sound is played – a subtle warning tone indicates a no-go direction (further in the text denoted as *no-go sound*).

  It was also necessary to give the user feedback when he/she is in the final section of the floor. There, the navigation process is almost over - the final step is to find the correct doors to the target room. We denoted the last touch segment of a route by a special sound followed by information about the location of the doors to the target room. We decided to provide such information in relation to the expected egocentric position of the user in the space – as the instruction will be in natural language, it is most likely that the user will remember its full text, and use it as navigation instruction in the real environment.

  The overview of the auditory cues linked to individual elements of the plan can be found in Table 3.1.

Prototype

We implemented redesigned elements and *route-guidance mode* into another prototype. The prototype represented more complex space than the low-fidelity prototype – it contained 11 rooms, and there were also more decision points for navigation: the hallway had three crossings.

For the implementation of the route-guidance mode, we used Raspberry Pi 3, capacity touch sensor MPR121 and conductive paint to create the segments. Our goal was to make the segments as less noticeable as possible, as they are an only artificial construct that is not present in the environment. *Route-guidance mode* can be turned on or off, and it is off by default. More about the implementation in Section 4.3. The demonstration of the interaction with the prototype can be found here: `http://bit.ly/tactilePlansDemo`.

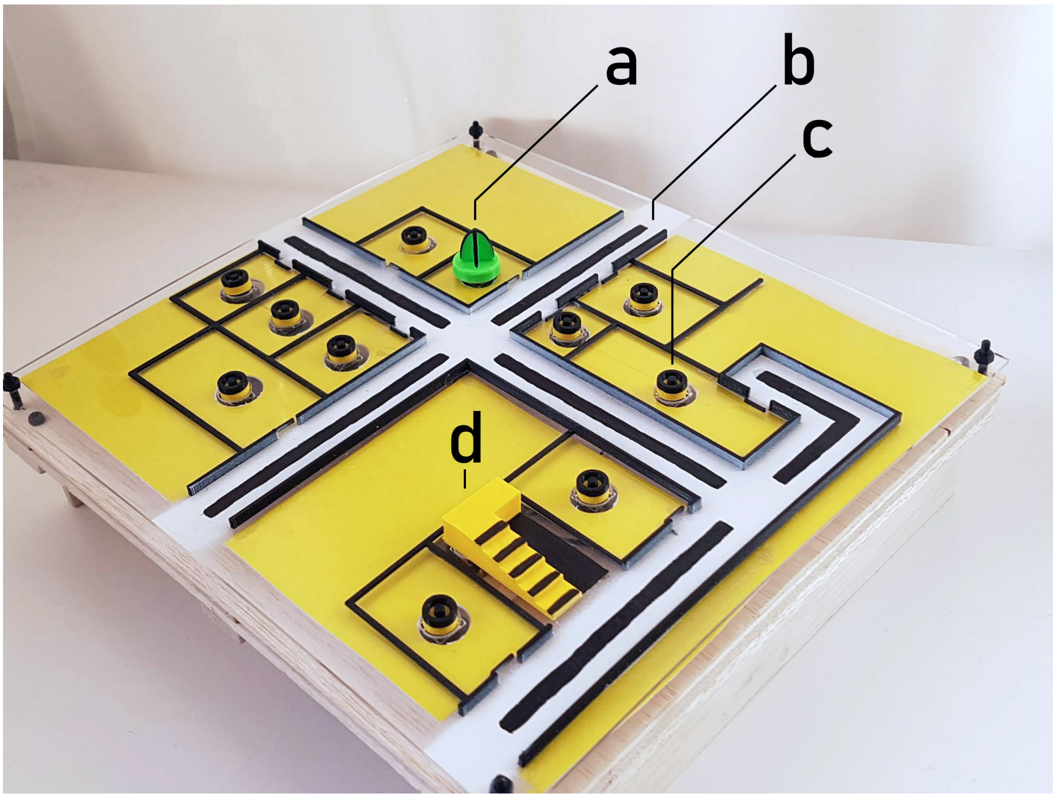

Figure 3.5: High-fidelity prototype. *a. Symbol for the star/end point for navigation, b. Hallway marked by two raised lines and high-contrast, interactive touch segments in the middle of it, c. Symbol for a room (*room button*), d. Stairs.*

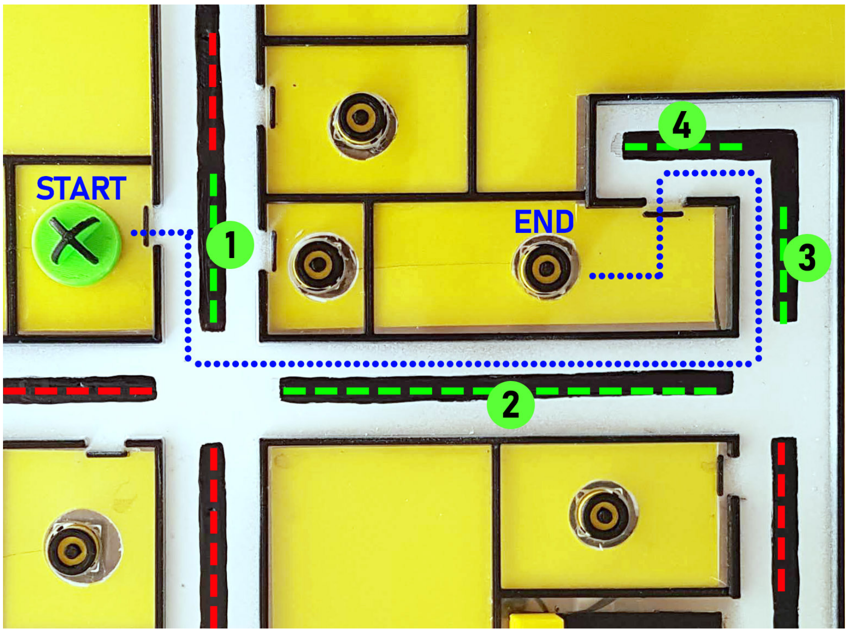

Figure 3.6: Division of the route into touch-sensitive segments. *Blue dotted line* - complete route that the user should follow, *green dashed segments* - segments that belong to the route, on touch they play piano tones; *red dashed lines* – segments off the route, on touch play *no-go sound*.

Figure 3.7: Detail of the tactile symbol which denotes the start point for navigation (the green button in the figure).

Element	**Audio feedback**
Start: *Personal room*	'Room 306, personal room'
Correct segment 1	Piano tone C
Correct segment 2	Piano tone E
Correct segment 3	Piano tone G
Correct segment 4 (final segment)	*success sound* 'You reached the final sector of the hallway. The doors to the cafeteria is located on your left hand.'
Incorrect segment	*no-go sound*

Table 3.1: Overview of auditory cues used during the route-guidance mode. Quotation marks denote sounds generated using TTS.

3.4 Conclusion

In the design, we aimed to comply with requirements specified during the analysis. We focused on the design of an interactive tactile map, that will allow the creation of mental models of the indoor environment for VIOAs. Firstly, we used rapid prototyping to create sets of tactile symbols for representation of the individual elements in the environment, and we selected the symbol for each element based on the evaluation with a visually impaired expert user. Then, two generations of prototypes have been made and evaluated. The low-fidelity employed tactile symbols for the representation of an indoor environment. Its purpose was to examine the usability of the concept for exploration of the space using the tactile map. In the high-fidelity prototype, we focused more on support for navigation tasks. We designed *route-guidance mode* which allows VIOAs to follow a particular route in the map. There, touch-detection and sonification of the progress on the route were employed.

Chapter 4

Implementation

The chapter describes implementation of both low-fidelity (specified in Subsection 3.3.2) and the high-fidelity prototype (specified in Subsection 3.3.3) of the interactive map. Firstly, we present the technologies and methods we used for the implementation in 4.1, and then we present the hardware and software implementation of each prototype individually (low-fidelity prototype in 4.2, high-fidelity prototype in 4.3). Both prototypes were used for formative evaluation of the design of the UI.

4.1 Technologies

In this section, we introduce the methods and technologies used for the implementation of the prototypes of the UI.

4.1.1 Constructive Solid Geometry

Constructive solid geometry (CSG) [14] is a method for representing solids. A CSG solid consists of a set of primitives (e.g., cubes, spheres) connected using Boolean operators (union, intersection, difference). Then, each solid can be represented as a sequence of operations with solids.

CSG is commonly used when modeling 3D objects, and we used this approach for modeling the tactile symbols in the map. For the modeling, we used software Fusion 360 [23], which allows precise definitions of dimensions. The examples of the 3D models can be found in Appendix C.

4.1.2 3D printing

3D printing is a process of making three-dimensional solid objects from a digital file. The most commonly used method of 3D printing is fused filament fabrication (FFF) [22]. It employs additive processes – the object is created by laying down successive layers of material until the object is created. The material used for printing is often called filament, and it is extruded through the preheated nozzle (the default diameter size of the majority of currently used nozzles is 0.4 mm). Variety of materials can be used for printing using this method, and they vary in its properties – see the comparison of properties of individual materials in Figure 4.1.

The common 3D-printing process consists of several steps:

1. **3D modelling.** A 3D-modelling software is used to create a digital 3D representation of a solid object. Then, a file containing a description of the 3D model is exported (e.g., in format STL[1]).

2. **Slicing.** A slicer software (e.g., Ultimaker Cura [74]) is used to convert the exported file into specific instructions for the printer. The slicer divides the object for printing to a stack of flat layers and then describes linear movements for the extruder head of the 3D printer.

3. **Printing.** The file exported from a slicer (e.g., in format gcode) is printed by the 3D printer.

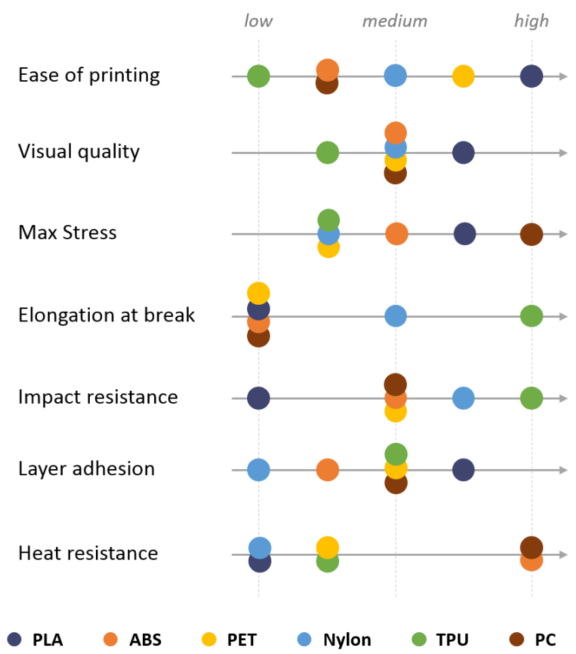

Figure 4.1: Comparision of properties of materials commonly used for FFF 3D printing, from [20]. *PLA* – Polylactic acid, *ABS* - Acrylonitrile Butadiene Styrene, *PET* – Polyethylene terephthalate, *TPU* – Thermoplastic polyurethane, *PC* – Polycarbonate

[1]STL (an abbreviation of "stereolithography") is a file format native to the stereolithography CAD software created by 3D Systems

4.1.3 Raspberry Pi platform

Raspberry Pi [59] is a series of small single-board computers developed by the Raspberry Pi Foundation (United Kingdom). Raspberry Pi computers are widely used thanks to their availability, scalability, and developer-friendliness. Along with a large number of available sensors and extensions compatible with the Raspberry Pi devices, Raspberry Pis are used in a variety of digital maker projects, e.g., smart-home controllers, weather stations, or educational projects. The primary operating system is Raspbian, which is a free operating system based on Debian optimized for the Raspberry Pi hardware.

Raspberry Pi 3 (model B+) is a computer with dimensions 85.6×56.5 mm and built-in Wi-Fi and Bluetooth module. The components used in Raspberry Pi 3 can be seen in Figure 4.2.

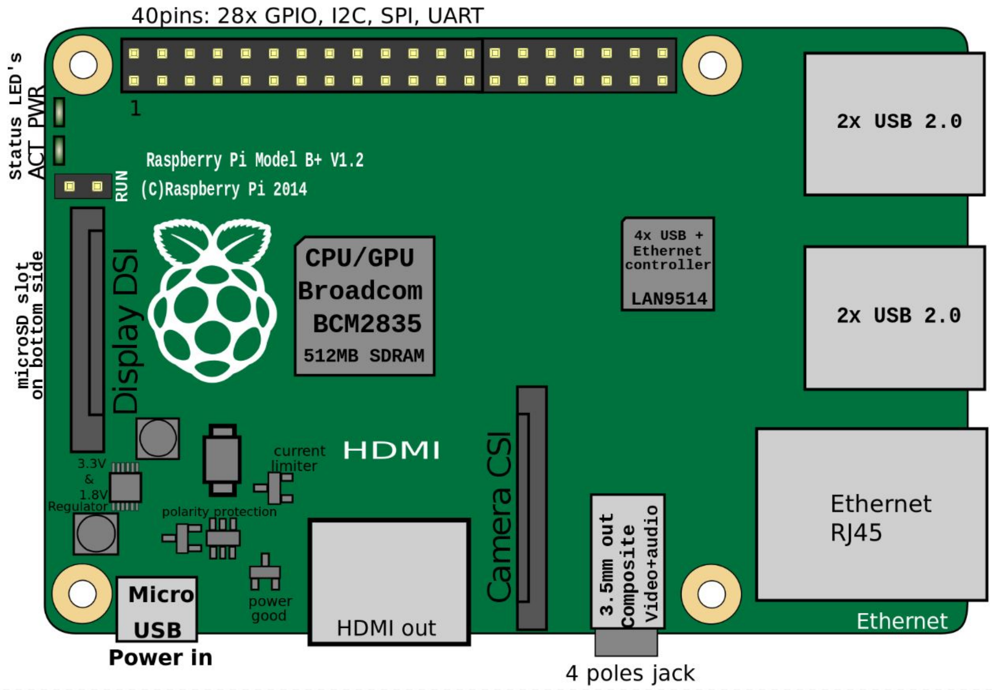

Figure 4.2: Locations of connectors and the main circuits in Raspberry Pi 3, model B+. From [58].

4.1.4 Conductive paint

Bare Conductive's electric paint [7] is a water-based, non-toxic and solvent-free paint that is electrically conductive. It allows for painting any circuits with any kind of brush, same as common water-based paint. It is dry in 15 minutes, and removable with water.

According to [6], the paint has a sheet resistance of approximately 55 ohms/square at 50-micron film thickness. If applied using a brush or screen-printed by hand, the resistance decreases to approximately 32 ohms/square. The resistance of the surface created by the electric paint can be estimated using the equation:

$$Resistance = 19.77(length/width) + 12$$

4.2 Low-fidelity prototype

In this section, we present the methods used for the implementation of the low-fidelity prototype (specified in Subsection 3.3.2). The design of this prototype was focused mainly on the tactile design, visual design, and elementary tactile-auditory interaction.

4.2.1 3D print on acrylic glass

According to the requirements for the interactive 3D model of the building (specified in Section 2.6), the interactive tactile plans should be 3D-printed on acrylic glass. During our research, we did not find any notes on attempts to use acrylic glass as a bed for print. Thus, it was up to us to develop a new method, that would allow it.

We used sheets of transparent acrylic glass (thickness 2.0 mm) placed on the standard bed of Prusa Mk2 i3 [56] 3D printer, and we experimented with settings used for printing.

At first, it was necessary to adjust the z-height used for printing – we used ZOffsetPlugin [89] for Cura [74] to adjust the z-coordinates by 2 mm in the final gcode for printing. Then, we found the best parameters for printing as follows:

- **Filament:** PLA[2]
- **Temperature of the extruder:** 230°C
- **Temperature of the bed:** 90°C
- **Cooling:** disabled for the first layers

Using those parameters ensures proper adhesion of the material on the glass, and the print is durable after it is cooled off, see examples in Figure 4.3.

[2]Polylactic Acid (PLA) is is a vegetable-based plastic material used for 3D printing.

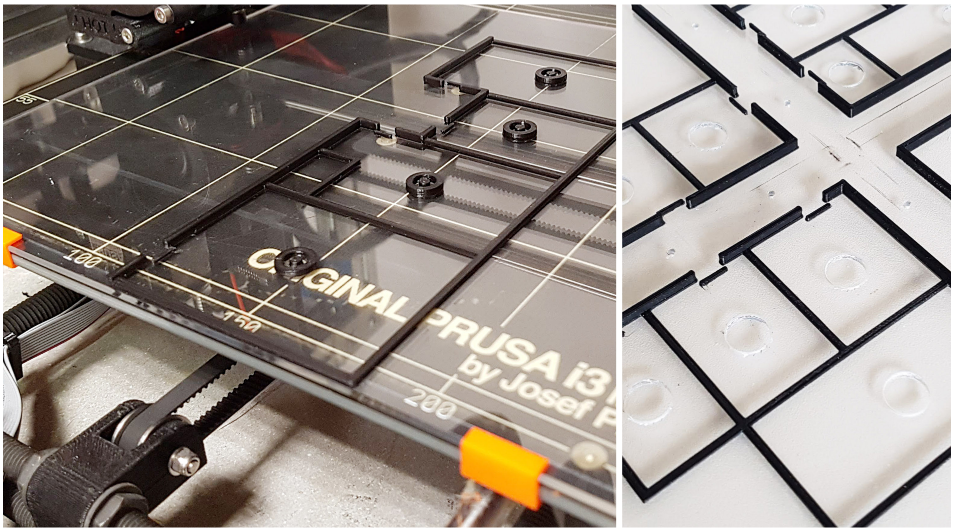

Figure 4.3: Examples of 3D print on acrylic glass.

4.2.2 Application for simulation of interaction

For the simulation of the interaction in the low-fidelity prototype, we implemented an HTML[3] page that allowed playing the audio labels for individual rooms depicted in the prototype (see Figure 4.4). The sounds were generated using Czech TTS[4] provided by Microsoft (voice 'Jakub'), and used in MP3 format[5]. For playing the sounds, we used the `<audio>` markup introduced in HTML5[6].

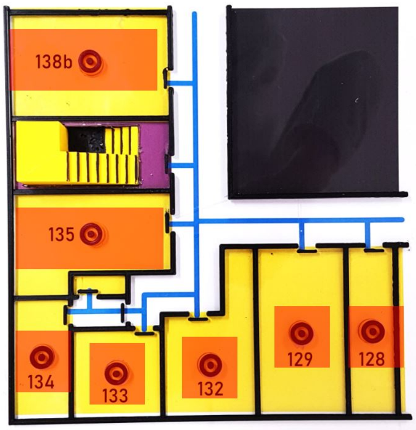

Figure 4.4: UI of the HTML application that simulated interaction of the low-fidelity prototype.

[3] Hypertext Markup Language (HTML) is the standard markup language for creating web pages and web applications

[4] Text-to-speech (TTS) system converts normal language text into speech

[5] MP3 is a loss coding format for digital audio

[6] HTML5 is a standard of HTML introduced in 2014.

4.3 High-fidelity prototype

In the implementation of the high-fidelity prototype (specified in Subsection 3.3.3), we focused on implementation of two modes of the device – *free-exploration mode* and *route-guidance mode*. We implemented our UI as a device, that offers two types of interaction: it provides audio after pressing a button, and when activated the *route-guidance mode*, it provides audio feedback after detecting a touch in a particular area within the hallway.

4.3.1 Hardware

The core of the high-fidelity prototype consists of Raspberry Pi 3, see the wiring visualization in Figure 4.5. For the detection of touch, we used Adafruit 12-Key Capacitive Touch Sensor Breakout MPR121 [4], connected over I2C[7]. The touch-sensitive segments were painted on the surface of the acrylic sheet using *Bare Conductive paint*, and they were connected to the MPR121 through a 1 mm wide hole in the glass filled with a pin, see Figure 4.6. We aimed to make the segments as little noticeable as possible. Finally, the painted touch-segments are fixed with a transparent waterproof lacquer because the conductive paint is normally removable by water. The prototype consists of 12 buttons and 12 active touch-sensitive segments.

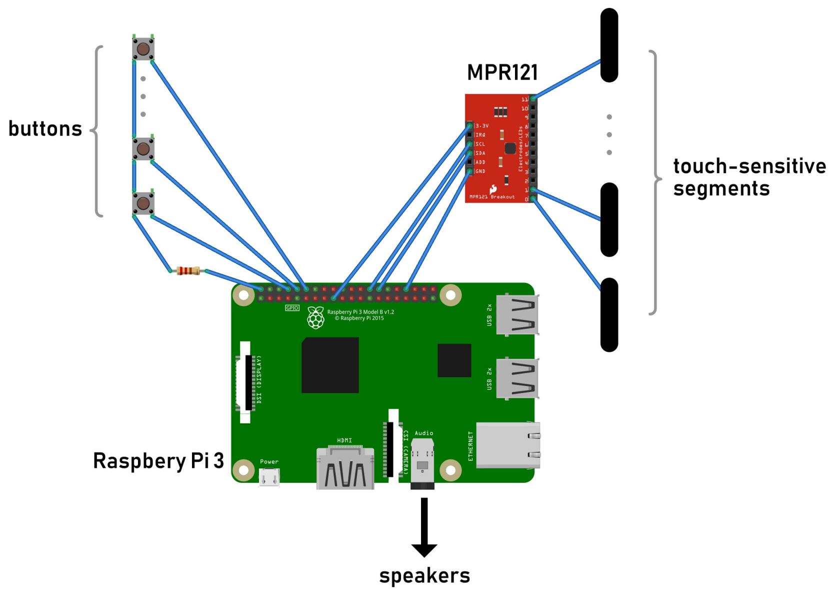

Figure 4.5: Visualization of wiring used in the high-fidelity prototype. Made using Fritzing [21].

[7]Inter-Integrated Circuit (I2C) is synchronous, serial computer bus

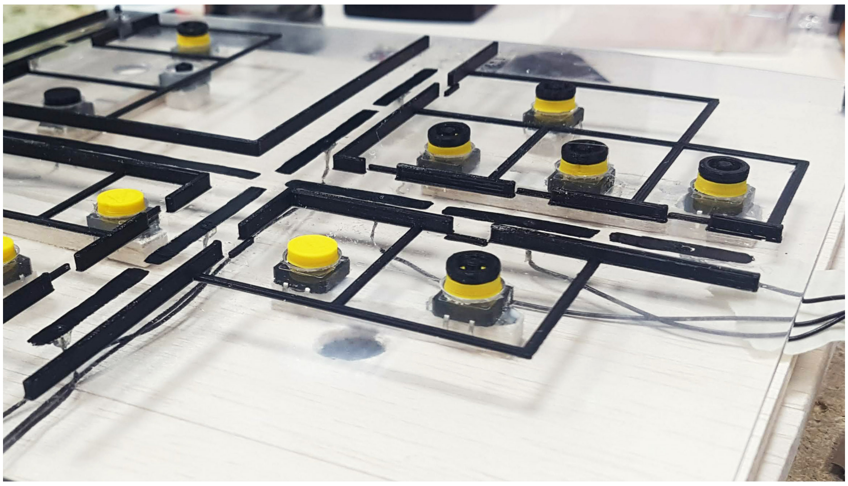

Figure 4.6: Connection of touch-segments.

4.3.2 Software

The interaction of the high-fidelity prototype is simulated using a script written in Python. The script (`tactilePlan.py`) launches automatically at startup of the operating system installed on the Raspberry Pi (Raspbian). In the infinite loop, we check the values set on GPIOs[8], and the values received from the capacitive touch sensor MPR121. For reading the GPIO values, we use package `RPi.GPIO` [61] and the library `Adafruit_MPR121` [5] is employed for reading the data from the capacitive touch sensor MPR121. The library `pygame` [57] is used for playing the audio, as each button and segment has assigned and audio file generated by TTS, or a sound selected downloaded from database of non-licensed sounds.

After startup of the Raspberry Pi, the device is automatically in the free-exploration mode, i.e., the buttons provide audio labels after pressing. Also, the *route-guidance mode* can be activated by long-press of the button with ID 20 (the *room button* next to the stairs). The behavior of the model is illustrated in Figure 4.7. We further describe the implementation of specific interactions.

Push events

Push events appear when a button is pressed (i.e., we read value `GPIO.HIGH` from a particular GPIO input). We apply a rule that ensures that the sound of the button will play only once at a single press. However, the playing sound can be interrupted by pushing another button.

Touch events

When the *route-guidance mode* is activated, we handle touches detected on

[8] General-purpose input/output (GPIO) is an uncommitted digital signal pin on the Raspberry Pi.

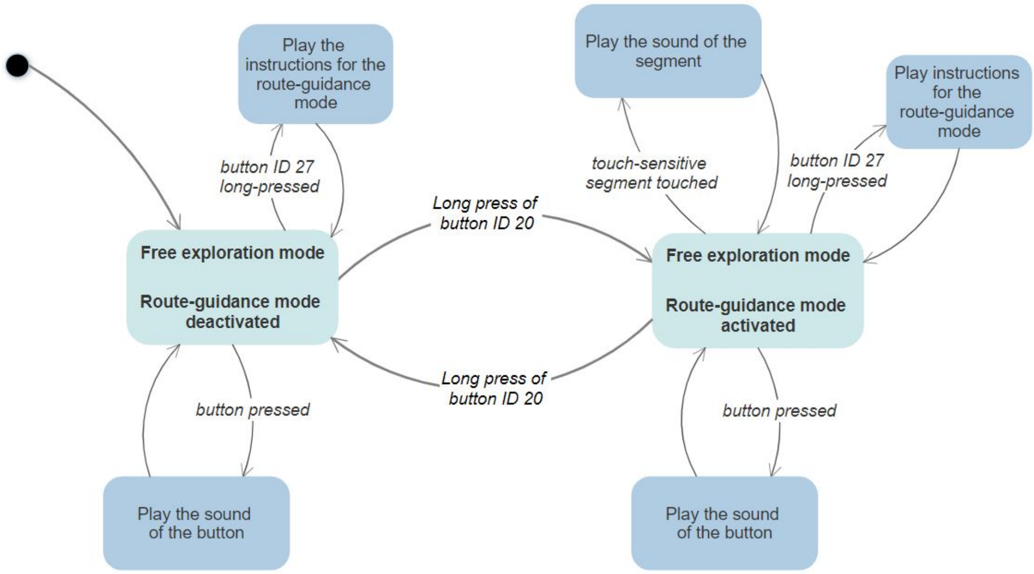

Figure 4.7: Diagram showing the behavior of the high-fidelity prototype.

particular touch-sensitive segments. We tried two different approaches:

- **All touch-sensitive segments active.** In the initial implementation, when the *route-guidance mode* was activated, all the segments shared the same behavior. After the first touch on a segment, there was always one segment that was not active – it was the segment where was registered the last touch, see Figure 4.8.

- **Route as a state machine.** Using the previous approach, there emerged a problem with multi-touch during the usability study (see Section 5.2). As all the segments (besides the one last-touched segment) were active, the resting hand of one of the participant accidentally triggered audio. We tried to eliminate this unwanted behavior by representing the route as a state machine.

  Currently, after activation of the *route-guidance mode*, only the first segment of the route is active. When the first segment is touched, its neighboring segments become active, and vice versa. That is, after the initial touch of the first segment, active segments are only the neighboring segments of the last-touched segment, see overview in Table 4.1. When the button for *Personal room* is touched, the state of the device is reverted to the initial state (state 0 in Table 4.1).

Note that for each segment it was fixed which sound is played after touching it. That is, guidance was provided for only one, pre-defined route showed in Figure 3.6.

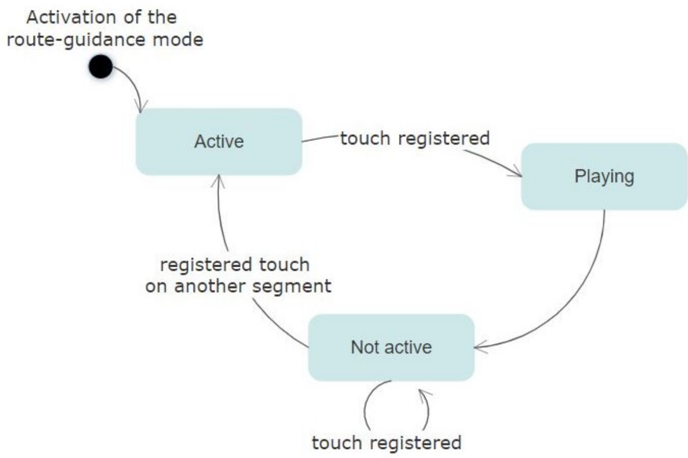

Figure 4.8: States of touch-sensitive segments.

State	ID of last-touched segment	ID(s) of active segments
0	-	7
1	7	6, 0, 4, 10
2	10	7, 0, 4, 9, 8
3	8	10, 9, 11
4	11	8

Table 4.1: Overview of states used for implementation of the *route-guidance* mode.

4.4 Conlusion

We implemented two prototypes of the UI. Both prototypes are in a smaller extent than is the presumed size of the final map. As the purpose of the prototypes was to evaluate our very first designs, the development of prototypes in greater extent may be costly, and the prototypes could be potentially unusable after evaluation of designed interaction.

In the low-fidelity prototype, we developed a new method that allows printing on acrylic glass. Achieving this, we fulfilled the requirement defined in the utility model of the interactive 3D model of the building (see Section 2.6), and we verified that printing on acrylic glass is possible and applicable to practice. We also presented the application that simulated the tactile-auditory interaction of the buttons.

The high-fidelity was implemented as a working, wired device. We aimed to implement designed *route-guidance mode*, which employs detection of touch in the hallways and based on the particular location provides audio feedback. We used Raspberry Pi 3 along with capacitive touch sensor MPR121 and conductive paint. Then, a Python script running on the Raspberry Pi handled playing sounds.

Both prototypes allowed us to examine the usability of designed interaction techniques. We also explored particular approaches to implementation, and used methods can be with improvements also applied for implementation of an advanced prototype of greater scale.

The next prototype of the interactive tactile map should be more robust – we suggest to design a PCB[9] as a support for the hardware implementation. A more sophisticated software solution is also compulsory. User's preferences should be stored, and for the *route-guidance mode* a UI allowing setting a route from point A to point B should be created. Also, we suggest to represent the segments of hallways as a graph and generate the routes with the corresponding assignment of sounds for each segment automatically.

[9]Printed circuit board (PCB) mechanically supports and electrically connects electronic components or electrical components using, e.g., conductive tracks.

Chapter 5
Evaluation

Following the UCD, each of the implemented prototypes was evaluated by the representatives of the target user group. In this chapter, we describe conducted usability studies – the procedures and the results. In Section 5.1 we describe the usability study of the low-fidelity prototype (specified in Subsection 3.3.2). Then, we present two studies focused on the evaluation of the high-fidelity prototype (specified in Subsection 3.3.3): study B1 in 5.2 and B2 in 5.3. The first study was conducted mainly with participants who partially use vision; the latter one was conducted with practically blind participants.

5.1 Study A: Evaluation of the low-fidelity prototype

We evaluated the low-fidelity prototype (see Subsection 3.3.2) in a user study with nine representatives (eight women, average age $= 84.4$, $SD = 6.6$, $MIN = 70$, $MAX = 90$) of our target user group. They were recruited from residential care institution we cooperate with (Home Palata). Severity of visual impairments of the participants ranged from category 3 to 5 of WHO classification [49] ($1 \times cat.3$, $5 \times cat.4$, $3 \times cat.5$), and onset of the impairment varied too ($5\times < 10\ y.$, $2 \times 10 - 25\ y.$, $1\times > 60\ y.$, $1 \times congenitally$).

The main goal was to assess the usability of designed mapping of the interior elements, evaluate the chosen approach to the elementary interaction, and get insights about the strategies that the participants use for exploration of the map depending on the severity and onset of the visual impairment.

5.1.1 Procedure

At first, we asked the participants to explore freely the artifact placed on the table in front of them and guess what it represents. Then, we explained its purpose and asked them to find particular elements:

- the hallway,
- a room,
- a door,
- the stairs,
- the toilets.

After that, we tested if the participants can use the artifact for orientation and navigation tasks. They had to find a particular room (room number 129) and describe the route that leads from this room to stairs. We used method *Wizard of Oz*, and the tactile-auditory interaction with the buttons was mocked utilizing a laptop (see Section 4.2 for details about implementation).

Finally, we asked the participants about their opinions about the UI in the post-test interview.

5.1.2 Results

Strategies that the participants used for exploration varied considerably depending on their visual impairment. Seven participants (*P1-5*, *P7*, *P8*) preferred to explore the map mainly using a sight with sporadic usage of taction. For five of them, the visual aspect of the map was sufficient enough to accomplish the majority of the tasks, and they performed excellently. *P3* and *P4* resisted using taction for exploration, but the visual design only was not sufficient for them. There, the map served as a tool for learning the tactile exploration, but not as a tool for enhancing orientation. *P6* and *P9* explored the map mainly by taction. *P9* also used remaining light-perception to identify elements on the map. She recognized all the features and performed great in the navigational task. On the contrary, for *P6*, the map was too complicated: *'Lines everywhere, I don't understand it'*. She could not distinguish different heights of the lines, and she was not able to recognize the hallway.

The mapping of the elements seemed useful for the majority of the participants, see Table 5.1. The main issue of the mapping was the insufficient representation of the hallway – participants always considered, whether they are on the hallway or not. Another problem was, the users got quickly used to the audio feedback of the room buttons, and they lacked interactivity of other 3D elements in the map, e.g., stairs. Finally, five of the participants did not notice the presence of the room behind the stairs – the stairs were too bold, and they caused occlusion.

The results of the study also indicated the need for improved interactivity. *P1*, *P3*, and *P9* mentioned they would not explore the complete map because it is too complicated for them. They missed highlights of essential places, e.g., their room and the direct surroundings or globally important places, e.g., entrance to the building. Four participants (*P2*, *P3*, *P6*, *P7*) were not able to use the map for navigation, because the map did not offer sufficient feedback – the sequential exploration of room buttons was lengthy, and the participants missed feedback how they should proceed on the hallway. Three participants (*P1*, *P5*, *P6*) mentioned they would appreciate learning a route using the map.

Element	Number of correct answers / Number of trials
Hallway	7 / 9
Rooms	7 / 9
Room buttons	8 / 9
Doors	7 / 9

Table 5.1: Overview of correct mapping for different elements

5.1.3 Summary of found usability issues

We summarize the usability issues of the UI found in the study with their magnitude[1] and possible solution below.

1. **Insufficient representation of the hallway**

   Magnitude: high, occurred to: *P6, P4, P3*, solution: increase the height of raised lines which represent the hallway.

2. **Lack of support for navigation tasks**

   Magnitude: high, occurred to: *P2, P3, P6, P7*, solution: design a new interaction technique, that will allow following a route.

3. **Lack of interactivity of 3D elements in the map**

   Magnitude: moderate, occurred to: *P1, P2, P9, P6*, solution: make the 3D icons clickable.

[1]Low = change of the issue will delight the user, moderate = the issue does not make the UI unusable, but it worsens user's experience, high = the issue makes to a certain extent unusable.

5.2 Study B1: Evaluation of the high-fidelity prototype with users having residual sight

We evaluated the high-fidelity prototype (see Subsection 3.3.3) qualitatively in a user study. We aimed to revisit the usability of the redesigned elements but, the main goal was to evaluate the new *route-guidance mode*, which allows the users following a particular route in the map. We recruited five representatives of our target user group: all women, average age = 86.4 ($SD = 4$, $MIN = 82$, $MAX = 91$). The severity of visual impairments varied as well as the onset of the impairment, see Table 5.2. However, the majority of the participants was still able to use the sight on a significant level (there was only one participant classified with category 6 and none of category 5 according to WHO [49]).

ID	**Age**	**Diagnosis**	**Self-description of visual acuity**	**Onset /Braille**
P1	82	A: Retinal Degeneration	grey stain in the left eye	28 / NO
P2	90	A: Retinal Degeneration, Cataract, Macular Retinopathy	no spatial perception right eye fully blind left eye 30 % of vis. acuity distorted color perception	22 / NO
P3	86	C: Blindness (left eye) A: Myopia	no spatial perception everything is blurry	- / YES
P4	91	C: Myopia A: Retinal Degeneration	sees contours and colors	1 / NO
P5	83	A: Blindness	-	63 / YES

Table 5.2: Demographic information of the participants (C for congenital, A for adventitious)

5.2.1 Procedure

In the pre-test, we collected demographic data and examined skills of the participants related to the exploration of an environment (which modality they prefer to use), and strategies they use for orientation and navigation. Firstly, the experiment proceeded similarly to the previous study – we focused on the recognition of individual elements. After that, we activated the *route-guidance mode*. Firstly, we let the participants listen to the instructions:

*'The map is now in the interactive mode, and the hallways are touch-sensitive. Find your personal room and leave it through the door to the hallway. As long as you hear the major scale of tones *example of tones*, when moving in the*

*hallway, continue. Once you reach the target section of the hallway, the map will tell you so. If you take an incorrect turn, you will hear *no-go sound*'.*

Then, we let them find the route from *Personal room* that was marked by a special tactile symbol in the map to *Cafeteria* using the audio feedback (the route is highlighted in Figure 3.6). Finally, they were asked to remember this route, and tell in detail which turns they should take. Our goal was to examine the ability of the participants to transform the allocentric frame of reference in map mentally to egocentric perspective. Intentionally, we selected the orientation of the map in a way that the turns of the hand on the map were opposite to the turns from an egocentric perspective, see Figure 5.1.

Finally, in the post-test interview, we asked them about their impressions on the device. We examined how pleasant it was to use the tool and enquired about the problems they had when using the device.

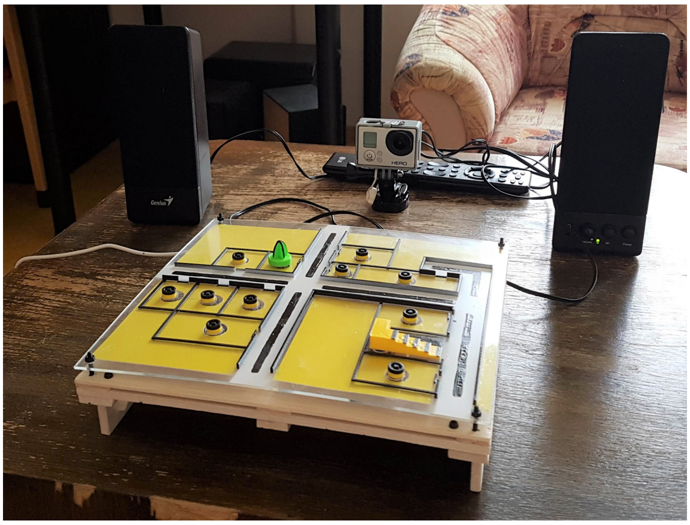

Figure 5.1: Setup of the experiment

5.2.2 Results

Mapping of elements. All the participants were able to discover the shape of the hallway completely without any advice, identified the buttons, and tended to push them. They were also able to distinguish both doors and stairs. Reactions to audio labels were positive. The participants did not have any problem to assign the interactive button to a room, but the area of the room was sometimes misinterpreted – *P4* thought that the whole yellow area is a single room, and *P5* thought there is not depicted the area of the room. The tactile symbol of *Personal room* was recognized by four participants, only *P3* assigned the symbol to be stairs. However, the symbol showed might be too bold – *P5* could not find the doors from a room because the area of the symbol for *personal room* tactfully occluded the door symbol.

Route-guidance mode. The results for *route-guidance mode* were diverse. For three of the participants (*P1, P2, P4*) was the method usable, and they perceived it as it is helping them. They all used also utilized visual design during the process of route-following. On the other hand, for *P3* was the mode unusable. She had moderate problems with orientation in space and time, and the concept was too complex for her. Finally, *P5* employed only taction and audition for exploration of the model. She experienced a problem with multi-touch – her resting hand accidentally triggered sounds, and it made the *route-guidance mode* unusable for her.

The exploration strategies and approaches to *route-guidance mode* were strongly individual. Thus, we describe it individually for each participant.

Participant 1. *P1* recognizes thing on the table mainly by vision, and then she uses taction to assure herself that she recognized the object correctly. When walking around Palata, she watches pictures on the wall (e.g., Masaryk's portrait). When she started to explore the model, she examined it by sight as well as by the touch. She used both hands for the tactile exploration, and she scanned the whole area of the device sequentially. Firstly, she noticed the hallway and followed the shape of the hallway groove by the index finger of her right hand. After instructions, she immediately found her room using the special symbol and pointed at it. *'I don't know if I have to push it'*. She pushed the button for Personal room, and then touched its door gap by her index finger of the right hand. She reached the first segment of the route. Then, she returned to the door to make herself sure she took the right turn. She got to the first crossing, and she was confused that there was no black line on the hallway. *'Can I cross it?'*, she asked. The visual design did not indicate that the parts of the hallway are connected. Then she followed the route step by step, and she did every turn correctly. When *P1* explored the model freely, she enjoyed to push the room buttons sequentially, and she probably remembered the approximate position of the *Cafeteria* on the map. However, there emerged an issue in the final segment of the route. *P1* related the instructions to her current location started to employ her left hand and search in the area of the first segment of the route, and she was confused. *P1* repeated the whole process. The moderator then explained the final instructions, *P1* found the doors, pushed *Personal room button*, and the task was finished.

P1 was able to recall the route without the map, and she made no mistake when explaining the turns. *P1* said she enjoyed the exploration of the device, and she would like to use it more. The most appreciated was the audio feedback: *'It was good, I knew if I was going the right way or not'*.

Participant 2. Similarly to *P1*, *P2* uses mainly vision to recognize objects, but she is skilled in haptic exploration as well. However, in the free exploration time, she did not examine the whole device by touch sequentially – by taction, she studied selected parts only, such as doors and the stairs. While she was listening to the instructions for the route-guidance mode, she showed the route to the *Cafeteria* by pointing. The route she showed was correct, but it was evident she is not sure about it. Similarly to *P1*, previous sequential exploration of the room buttons helped her. However, she followed the given instructions. She found her room, and likewise to *P1*, she asked *'Do I have to push it?'*. Then, using her right index finger, she went through the room by the door, and then followed the route segment by segment, not making a single error. She touched the last three segments of the route again, just for fun. *P2* had no problem to find the target room. She asked *'What if I want to find the stairs?'*, and started the whole process again – she found her room, and she followed the route planned by sight by the index finger on the model. However, this route was not set to be correct by default, and so the error sound was played at the second crossing, where the route to stairs differed from the tested route. She immediately noticed there is something wrong *'Wait, wait..the stairs are there, but it tells me I should not go there'*. This means the error sound is interpreted correctly.

P2 made a mistake in a single turn when explaining the route from the egocentric perspective. In general, she enjoyed using the model, and she was delighted by the sound it does.

Participant 3. *P3* had to learn Braille alphabet for her work, but she did not use it in her life very often. She usually recognizes objects by sight, and she is not used to exploring objects by touch. *P3* have moderate problems with orientation in time and space, and there were noticeable indications of dementia. When she was exploring the model, she used four fingers of her right hand, and she scanned only the right part of it. In the beginning, *P3* did not understand the instructions for the route-guidance mode, and she was confused. It was necessary to navigate her illustratively and break the instructions into steps. Despite the fact she found the symbol for *Personal room* repeatedly and showed all the area of the hallway before, she could not find the symbol now, and she was not able to recognize the hallway correctly. When she touched the first segment on the route, she took the wrong turn, heard the error sound, but ignored it. *'Oh, so not there'*, *P3* said, which indicated that she understands the concept, but still, she proceeded to explore the map in this direction. After that, she did not follow the hallway anymore and noticed a sound only accidentally. The moderator showed her presumed usage of the *route-guidance* mode. From her comments, it was evident she now understands the concept, but she was not able to repeat the procedure because she could not find the starting point again.

We skipped the transformation task because *P3* seemed too confused to continue. In summary, *P3* said she enjoyed the session, but she can not imagine playing with the model by her own: *'Maybe I could use it, but I won't always* *know the right steps. It is very complicated'.*

Participant 4. *P4* uses only sight to recognize objects, and when she travels around Palata, she orientates using the sight only, too. She can describe a route correctly from her room to various places, and despite the fact she needs a walker to support her when walking, she likes to explore new places. When studying the model, she employed sight mainly. Sometimes, she pointed at selected elements using the index finger of her left hand. There, another problem emerged — *P4* has a tremor in her hands. After playing instructions for the route-guidance mode, *P4* found *Personal room*, but she could not find the exit from the room. The moderator showed *P4* the right direction, but she still looked confused. Later found, this was because due to her severe problems with hearing – she did not understand the instructions. The moderator explained how the mode works illustratively. At first, *P4* did not want to try it by her own – she was afraid she would break it. After a little encouragement, she started to explore the route. She pushed the button for *Personal room*, and using the index finger of her left hand, she touched the first segment of the route. Between the first and the second segment of the route, she released the finger from the hallway, but since the second segment, she tried to fix the finger on the surface and did not release it. *P4* successfully reached the target destination, and she was pleased about it. When she was asked to learn the route, she examined it by sight only. However, when she was explaining the turns with the model covered, she virtually showed the way above the model, and on the same scale as was in the model.

P4 made no mistake when recalling the route from the egocentric perspective. In the post-test, *P4* mentioned she liked to explore the space in this way: *'It is a nice toy. I think that it is useful, and I can imagine learning more routes using it, one's got used to it'.*

Participant 5. *P5* is fully blind since her 20's, and she is experienced in tactile exploration – she can read Braille alphabet and tactile graphics. She was new to Palata, she moved there three weeks ago, and she learned only the route from her room to the *Cafeteria*. When she described the route, the level of detail varied greatly from the previous participants – she orientates by the number of the doors, lengths of handrails, by materials. *'It is hard to get used to the new environment and learn at least the essential routes. But still, it is better to learn it than be always waiting for someone to grab you and take you somewhere'.* When she had to explore the model, she used her both hands and mainly her index fingers to study the surface. After she heard the instructions, she found the symbol for *Personal room*. However, she did not know how to continue, because the area of the symbol for *Personal room* caused she was not able to find the door from the room. Another severe issue emerged: *P5* tended to rest her hands on the device, and the resting hand caused accidental touches, which triggered sounds. *P5* was not able to detect their source, and it made the route-guidance mode unusable for her. The moderator showed her intended usage of the technique. *P5* understood the concept, but still, she was not able to perform it by herself, because she could not get rid of accidental touches.

The study could not proceed to route-transformation. However, *P5* liked the device: *'It was nice. It would require more time to learn it...I have never worked such a device, it is entirely new for me. But I would not resist to use it at all'.*

5.2.3 Summary of found usability issues

We summarize the usability issues of the UI found in the study with their magnitude[2] and possible solution below.

1. **Route-guidance mode: Multi-touch issue caused by a hand resting on the device**

   Magnitude: high, occurred to: *P5*, solution: during the *route-guidance* mode, all the segments were touch-sensitive all the time. We will make touch-sensitive only the adjacent segments of the previously touched segment, starting from the first segment of the route.

2. **Improper visual design of hallways**

   Magnitude: moderate, occurred to: *P1*, solution: do not discontinue the black line denoting hallways at the crossings.

3. **Insufficient representation of the area of a room**

   Magnitude: moderate, occurred to: *P4, P5*, solution: decrease the height of raised lines which divide rooms.

4. **Tactful occlusion by the *Personal room button***

   Magnitude: moderate, occurred to: *P5*, solution: decrease the diameter of the *Personal room* on the bottom.

5. **Noninteractive-looking symbol for *Personal room***

   Magnitude: low, occurred to: *P1, P2*, solution: modification of the shape of the top area of the symbol.

[2] Low = change of the issue will delight the user, moderate = the issue does not make the UI unusable, but it worsens user's experience, high = the issue makes to a certain extent unusable.

5.3 Study B2: Evaluation of the high-fidelity prototype with blind users

The exploration strategies may vary substantially depending on the visual acuity of the user. As the majority (4 of 5) participants of our previous study used remaining sight for the exploration of the model, we decided to evaluate our concept with users that are not able to use sight and rely almost fully on tactile and auditory inputs.

We recruited five participants (P6 – P10, 3 men, average age=77, SD=14.9, MIN=52, MAX=89) classified with category 5 and 6 of WHO classification [49], see Table 5.3. All the participants were recruited from Home Palata.

For this study, we slightly enhanced the route-learning mode to eliminate the problem with accidental touches found in the previous study (the modification is specified in Subsection 4.3).

ID /Gender	Age	Diagnosis	Self-description of visual acuity	Onset /Braille
P6 / M	52	A: Diabetic Retinopathy	totally blind	30 / NO
P7 / M	87	A: Accident	totally blind	80 / YES
P8 / F	82	C: eye-disease	LE: blind RE: light perception	60 / YES
P9 / M	75	A: Injury, Diabetes	light perception	7 / NO
P10 / F	89	C: Injury	totally blind	9 / NO

Table 5.3: Demographic information of the participants (C for congenital, A for adventitious, RE for right eye, LE for left eye)

5.3.1 Method

The study followed the same procedure as the previous study, see 5.2.1.

5.3.2 Results

Firstly, we list the results for individual elements present in the map; then we describe the results of *route-guidance mode* individually for each participant.

Mapping of elements

- **Hallway.** The representation of the hallway seemed to be suitable, as all the participants were able to follow its shape. On the other hand, *P7 and P10* were not able to recognize it on their own, and *P10* lacked interactivity of this part of the map: *'Does it has a button I could push?'*.

- **Rooms.** The *room buttons* performed very well – all the participants recognized them, they tended to push them, and they appreciated the audio feedback. On the other hand, representation of the area of the room needs to be improved: three participants (*P7, P9, P10*) were not able to recognize the raised lines which frame rooms.

- **Doors.** Modifications of the symbol of for the doors should be considered as well: the door gaps were mistaken for corners (*P8, P10*), and the raised line in the door gap was unrecognizable for two of the participants (*P7, P8*).

- **Stairs.** The symbol for stairs was recognized by all the participants, but its interpretation varied: *P9* immediately matched the symbol with the real-life object and wondered if there are only so few stairs. *P10*, on the other hand, perceived the symbol as a single step and did not understand the *'serrated part'*.

- **Personal room symbol.** The symbol for *Personal room* was used exactly as it was designed: all the participants got quickly used to its shape, and they were able to find it quickly on the map. Even though there occurred issue with accidental 'bumping' into the symbol for four of the participants (*P6, P7, P9, P10)*, none of them perceived it as a problem, and they appreciated the current design. *P5* stated: *'The symbol My room is good, I don't have to try all the buttons, I know it is specific and easy to find'*. It is important to mention that the 'bumping' issue happened to the participants during the free exploration phase, and in this phase, this symbol should not be clipped on the original *room button*, so this was probably a drawback of the setup of the study.

Route-guidance mode

Again, we verified that the concept of *route-guidance mode* is applicable, as it helped four of five participants (*P6, P7, P9, P10*) to perform a navigation task with the map and create a mental model of the environment. On the other hand, we revealed new issues of the design. For *P8*, the auditory cues provided during the guidance process were confusing. However, the most severe issue is a problem with multi-touch caused by exploration by multiple fingers of the same hand at once. In the paragraphs below, we present the results for each participant individually.

Participant 6. *P6* has an excellent orientation sense, and he is willing to explore new places. He has diabetes, which affects his tactual acuity negatively. When he studied the device, he used actively his right hand, mainly the index and the middle finger, while his left hand was resting on the device.

Immediately after *P6* heard the instructions, he found *Personal room* by its symbol, but it took a while until he discovered its doors. On the first crossing, he took a correct turn, the tone played, but he mistook this sound to indicate the wrong turn. The moderator assured him that piano tone is a positive sign. Since this moment, he followed the route correctly, and he found the doors to the *Cafeteria* and pressed correct *room button*. When he was asked to remember the route, he went through the route in the opposite direction and followed the sound indicators again. Sometimes, exploration by multiple fingers caused problems - it triggered sounds of neighboring touch segments at once. On the other hand, the resting hand on the device was not any longer an issue.

He described the route verbally correctly without any difficulties. Furthermore, he used natural landmarks for description, e.g., *'I'll get to the corner'*.

In the post-test, he stated that he enjoyed using the device, and he liked the idea. *P6* criticized playing multiple sounds at once cause by exploration by two fingers: *'Something played for three times, this could be better'*.

Participant 7. *P7* is blind since his childhood. He knows Braille, and he is quite skilled in tactile exploration. However, he thinks his tactile skills are worse now: *'I used to read Braille, now I cannot distinguish it'*. He can describe known routes around Palata in terms of distances and turns, but as he stated, he definitely would not go somewhere alone based on a description of a route: *'I'm always guided by my wife, she has remaining sight. It's maybe a mistake, though, I should practice orientation more. I'm quite afraid to go somewhere alone now'*.

For exploration, *P7* used both hands simultaneously (mainly the index and middle fingers). However, when *P7* had to follow the route, he used only his right hand (the index, the middle, and the ring finger). After he heard the instructions, he found *Personal room* and its doors. Then, he explored the hallway groove and proceeded in directions based on the provided audio feedback correctly. During the guidance process, he asked *'What is the symbol of the Cafeteria?'*. He was not sure how he would recognize that he is in the target destination. Nevertheless, when he heard the success sound played after he touched the last segment, this uncertainty vanished. He successfully found the doors to *Cafeteria*, and pressed its room button. Finally, he repeated the whole process two times.

P7 described the route without the map correctly. He very enjoyed using the device: *'Well it would not be bad to have such a thing on the room. One would explore it, the map...check the routes and then go somewhere'*.

Similarly to *P6*, *P7* experienced problems caused by exploration by multiple fingers at once during the route-guidance process, and he mentioned this problem in the post-test: *'There were redundant sounds I think. There could be sound on the decision points only, not only on the whole route. Only tell which direction is the next'*. In general, *P6* liked the idea: *'It's handy, a helpful aid'*.

Participant 8. *P8* likes to explore, and she does not mind exploring new places on her own. She is moderately skilled in tactile exploration – she can read Braille, but she had not used it actively for years. She uses only her right hand for exploration (the thumb and the index finger).

At first, *P8* did not hear out the instructions because she started to complete the task while listening to them. Finding *Personal room* and its doors were not a problem for her. Then, she did not know how to proceed, so the moderator played the instructions again and asked her to listen to the whole text, and complete the task after that. *P8* followed the instructions – she got to the hallway and then reached the first crossing, but there the problems started. She took the correct turn there, but thought the opposite: *'Oh, something played, I'm wrong here'*. The moderator explained that the piano tone means the turn was correct. Nevertheless, she was confused. She tried all the *'no-go'* directions on the first crossing, heard corresponding sounds, but she seemed like she does not know their meaning. The moderator asked her about what she hears: *'It's like e-e, like it is not right'*. Then, the moderator played the piano sound and asked her about her thoughts again: *'This means I'm on the wrong way'*. It was evident that she has a problem to distinguish different types of sounds. The moderator explained the purpose of individual kinds of sounds again, including a demonstration of the sound.

P8 started to explore the way again. She left the room and then took a wrong turn. However, she proceeded in this direction, and finally, she went to the door in section opposite to My room and got stuck in the area of rooms. Finally, she found the hallway again – the second segment of the route. The piano played, and she continued in this direction, but suddenly, she turned back and took the wrong turn on the crossing again. The *'no-go'* sound played, but she proceeded. It was evident she now distinguish between 'correct' and *'no-go'* sounds, but she did not understand that there cannot be a correct sound after *'no-go'* sound. Finally, she touched the second segment by chance, and she proceeded correctly into the third segment. Unfortunately, as she sticks to the raised line and did not explore the hallway groove in the middle of it, she missed the touch area of the third symbol. She passed through the *Cafeteria* door by coincidence: *'I'm in a room, but what now?'*. She got back to the hallway and finally touched the last segment. When she repeated the whole process, she repeatedly went through wrong doors opposite to the *Personal room's* doors – she confused doors with a hallway corner. *P8* got lost and could not recover. She was asked to start again, but she was not able to complete the task on her own. The moderator completed the route with her. In the final segment, she found the doors without a problem, but she missed the button of the *Cafeteria*. In the next try, she was able to go through all the route on her own.

When *P8* was asked to describe the route, she used vague formulations, e.g., *'I will get out somehow'*. Later on, she reported that she was so focused on the sounds and their meaning, that she could not concentrate on the route itself. The moderator turned off the route learning mode. Surprisingly, it helped - *P3* went through the all route without any problem, and she was able to describe the route correctly then.

P8 mentioned in the post-test that she enjoyed the session, but the device seemed to be too complicated for her: *'It was fun. But I would need more time to get familiar with the sounds. I was so focused on the sound that plays, I could not focus on anything else'*.

Participant 9. *P9* does not leave his room on his own in Palata, he is usually accompanied by the nurse. However, he can recall the distances and the turns they do on the most common routes. He reports that he perceives much better now than he used to: *'I so much better in exploration by touch. A few years ago, I would not feel anything, but now I use touch in so many activities'*. *P9* explored the model using both hands simultaneously, but during the route-exploration, *P9* used mainly his index finger of the right hand. However, his middle finger caused accidental touches sometimes. He got to the crossing, and when he heard *'no-go'* sound, he correctly stopped to continue exploration in this direction. He could not find the correct path, and he started again. *P4* relied strongly on what he discovered before, and less on what he perceives at the moment. Similarly to *P6, P8*, in the hallway groove, *P9* followed one of its raised lines by a narrow margin, and he sometimes missed the touch-sensitive area. In the final segment, he did not understand correctly the instruction about the location of the doors *'By my left hand...so I have to go back'* – he interpreted the direction relatively to his current location, not to his position in the map. Many times, *P9* missed the line that delimits individual rooms. *P9* understood the technique, he was able to follow the whole route to *Cafeteria* and back, and he described the route without the map correctly. *P9* was happy about the session, and he liked using the map: *'It's crucial to identify individual elements, like the doors, the hallway. I think I'm already better now'*.

Participant 10. *P5* went through a tough situation in her life: after retirement, she lost her sight day-to-day. She reported that the beginnings were very hard, mainly the process of familiarization with the environment of Palata: *'I would not bother anyone with everyday tasks. In my room, I can do almost everything on my own. However, I'm afraid outside. There is only darkness everywhere, and I feel like I miss stability. Everywhere I go, I'm accompanied by my roommate or the nurse'*. *P10* still learns to explore objects by touch: *'I can recognize blouses by their buttons'*. She cannot read Braille: *'I didn't even think of learning it, I would be too hard'*. Her spatial-orientation skills are good; she recalls known routes using distances and landmarks well. However, she lacks the overall picture of Palata's environment completely.

P10 explored the device using both hands simultaneously. During the exploration of the route, she used mainly her index and middle fingers, and she alternated hands. When she heard *'no-go'* sound, she did not proceed in this direction. However, it seemed hard for her to estimate other directions which can be explored. Problems were also caused by using multiple fingers at once – it triggered multiple sounds at once. After a while, she got used to the meaning of the sounds and explored the whole route from *Personal room* to *Cafeteria* without any advice - she even found the correct doors at the first try. She was also able to repeat the process: *'I quite enjoy it'*, she stated. Two times, she could not find the first crossing – she slipped to the opposite room, and she was confused.

When she was asked to recall the route, she was not able to describe the directions verbally, but she painted the correct shape on the table behind her – mental rotations were very difficult for her. *P10* was delighted by the device: *'I think it is usable. Even in the darkness, I live in now. I would take some time, but I like it'*.

5.3.3 Summary of found usability issues

The results of the study B2 revealed usability issues related to insufficient or tactile design or improper interaction design used with the device. We list the issues with their magnitude[3] and possible solution below.

Probably the most severe issue is the problem with exploration by multiple fingers at once. Problem with multi-touch emerged already in Study B1 (Section 5.2). Its cause was different (resting hand on the device was touching the segments located relatively far to the segments touched by the actively-exploring hand), and we managed to eliminate this issue. Unfortunately, the chosen solution did not address the new issue.

1. **Route-guidance mode: Multi-touch issue caused by exploration by multiple fingers at once**

   Magnitude: high, occurred to: *P6, P7, P8, P9, P10*, solution: set a time interval for each touch segment, in which the segment won't be allowed to trigger audio even if it was touched.

2. **Route-guidance: similarity of provided sounds**

   Magnitude: high, occurred to: *P8*, solution: customize the provided sounds for needs of individuals, e.g., the sound for the wrong direction can be replaced by simple natural language instruction *'Wrong direction'*.

3. **Route-guidance: description of the location of doors in the final segment of the route**

[3] low = change of the issue will delight the user, moderate = the issue does not make the UI unusable, but it worsens user's experience, high = the issue makes to a certain extent unusable

Magnitude: high, occurred to: *P9*, solution: describe the location about the position relatively to user's hand, e.g., *'Move your finger right and there you will find the entrance to the room'.*

4. **Route-guidance: too narrow touch-sensitive areas**

   Magnitude: high, occurred to: *P6, P8, P9*, solution: increase the width of the touch sensitive area of segments to the full width of the hallway groove.

5. **Insufficient representation of the room area**

   Magnitude: moderate, occurred to: *P7, P9, P10*, solution: increase the height of the raised lines which frame rooms.

6. **Tactful occlusion by the *Personal room button***

   Magnitude: moderate, occurred to: *P7, P9, P10*, solution: decrease the diameter of the *Personal room* on the bottom.

7. **Non-interactive hallway in the free exploration mode.**

   Magnitude: moderate, occurred to: *P10*, solution: the hallway should provide an audio feedback when exploring its shape.

8. **Unnoticeable doorstep of the door tactile symbol**

   Magnitude: moderate, occurred to: *P7, P8, P10*, solution: increase the height of the doorstep raised line.

5.4 Conclusion

We employed formative evaluation, and we evaluated both low-fidelity and high-fidelity prototype in a usability study with representatives of our target audience – VIOAs. We examined the usability of designed mapping of elements. The results show that employing 3D symbols is a promising direction with VIOAs, and the tactile symbols that we created are usable. We also studied the usability of designed *route-guidance mode*. The method was suitable only for the majority (seven of ten) of the participants, but the mode seems not to be usable with users with moderate/severe symptoms of dementia, and we also revealed issues that must be improved in the future.

Chapter 6

Discussion

Following the UCD methodology and regarding the principles of ability-based design, we designed interactive tactile maps of interior environment tailored for visually impaired older adults. Our designs were implemented into two generations of prototypes. We employed formative evaluation during the process of development – both prototypes were evaluated with representatives of our target audience (4 men, 15 women, average age=83, SD=9.3). The severity of visual impairments of the participants ranged from category 3 to 6 of WHO classification [49] ($1 \times cat.3$, $9 \times cat.4$, $5 \times cat.5$, $4 \times cat.6$).

The analysis of topics related to needs and requirements of visually impaired older adults along with the study of topics related to the acquisition of spatial knowledge indicated that employing interactive tactile map may be a promising approach, as tactile maps proved to be an efficient tool for acquiring spatial knowledge with visually impaired.

In the design, we regarded limitations linked to aging, mainly lowered sensory responses. We designed a tactile representation of an indoor environment, and employed 3D iconic symbols, as the study of Holloway [29] indicated maps with 3D symbols have better performance when compared to classical tactile maps. The representatives of our target group are typically not experienced in tactile exploration, and older age makes more challenging to learn new concepts. Thus, we avoided introducing unnecessary abstract tactile symbols, and instead of labels in Braille, we added audio labels and corresponding interactive tactile symbols.

At first, the tactile symbols representing elements of the interior and the elementary interaction were implemented to the low-fidelity prototype. The results of the evaluation of this prototype indicated that the concept of the map is usable for our target audience. However, requests for improvements also emerged: the tactile representation of the hallway was insufficient, and the participants lacked interactivity of some tactile symbols. We also indicated a need for improved interactivity, as the participants reported that they would appreciate the support for following routes, that are important for their everyday life, within the map.

We addressed the need for improved interactivity, and we designed a new interaction technique, *route-guidance mode* of the map. The mode uses touch detection to provide the user with audio feedback about progress on a particular route. We implemented the *route-guidance mode* along with improved mapping of the elements to the high-fidelity prototype.

The high-fidelity prototype was tested with ten representatives of our target user group. Again, the study confirmed that the map enables the creation of mental models of an environment. However, the results also revealed insights for further improvements to the design. The visual design along with interactivity in the map is usable for the users with remaining sight (classified with category 3 and four by WHO classification [49]). On the other hand, the results for users relying on tactile design (classified with category five and six by WHO classification [49]) showed the need for improvements of individual tactile symbols.

Also, the feedback on the *route-guidance mode* was diverse. The majority (7 of 10) of participants were pleased and perceived it as it is helping them build a cognitive map. However, others either did not understand the concept (1 of 10) or had difficulties to interact with the map in this mode (2 of 10).

The exploration techniques of the participants varied substantially. We agree with Witntjes [82] – three methods of tactile exploration appeared: exploration by one hand, by one hand with the second resting on the device, and exploration using both hands simultaneously. It is crucial to provide users with interaction methods that are not in conflict with any of the techniques. When we asked the participants to explore the device using taction, every strategy was used multiple times. An interesting fact is, during the *route-guidance mode*, none of the participants explored the route using both hands simultaneously, even the users who employed both hands for free exploration of the artifact before.

The design of the touch interaction with the device was quite complicated. We had to define rules when a particular touch-sensitive segment is active and triggers audio. Still, there was an issue of triggering the audio feedback multiple times at once caused by accidental touches of neighboring fingers. We will focus on suitable settings of the touch interaction in the future. Another issue of the *route-guidance mode* was that for one of the participants, the audio feedback was not suitable, as it overloaded her cognitive capacity and prevented her from following the route itself. This issue may be eliminated by a different selection of sounds for the audio feedback or employing tactile feedback by vibrations instead. Finally, our current design does not seem applicable to users with moderate or severe symptoms of dementia, and we consider further simplifications of the interface for such users.

Ruggerio in [62] presents studies indicating that the visually impaired rely mainly on their egocentric frames of reference when exploring space. As our map shows the space from the allocentric point of reference, we examined if it will allow the users to use the information presented there from the egocentric frame of reference, too. The users who were able to follow a route in the map using the *route-guidance mode* were also capable of recalling the route without the map and describing it in terms of distances and turns they should travel. That is, they were able to translate the space presented in the plan from allocentric perspective to instructions from the egocentric perspective. It indicates that *route-guidance* may help the users to perform navigational tasks in the real environment.

The implemented concept was tested only qualitatively. In the next phases, we plan to evaluate the idea in greater extent on a long-term basis through a diary study. A comparative study with a tactile map of different design is also applicable as a method of quantitative evaluation. For purposes of further evaluation, we must create more complex and robust prototypes.

Chapter 7

Conclusion

The thesis aimed to design interactive tactile plans of the indoor environment for visually impaired older adults. The process of development of the plans comprised of several steps, while each of the steps corresponds to a goal defined in Section 1.2.2. We describe the realization of our goals below.

- G1: **Analyze characteristics of visually impaired older adults.** The analysis of our target audience is found in Section 2.1. In Subsection 2.1.2, we discuss the problems related to vision loss and other conditions associated with aging. Then, in Subsection 2.1.3, we describe Home Palata – a residential care facility for VIOAs with which we cooperate. The clients of Home Palata represent our target user group. Therefore we studied their needs extensively in the past. We summarize our up-to-now results of studies related to orientation and navigation of the clients in Subsection 2.1.4.

- G2: **Analyze terms related to spatial cognition and discuss spatial cognition abilities of visually impaired.** We studied the topics related to processing and acquiring spatial knowledge, we defined fundamental terms, and we also analyzed spatial cognition of visually impaired in Section 2.2.

- G3: **Study the tools and techniques used for acquiring spatial cognition without vision.** The analysis of the tools used for the acquisition of spatial knowledge with visually impaired is described in Section 2.3. We also provide analysis of non-visual interaction methods used in such devices in Section 2.4, and in Section 2.5 we study methods used for the implementation of maps for visually impaired.

- G4: **Analyze the requirements for the 3D model of the building related to the creation of interactive tactile plans, and define requirements for the interactive tactile plans.** Our work follows prior work of Macík et al. In [44], they proposed an interactive 3D model of building for enhancing the spatial knowledge of visually impaired.

Our design should comply with the cited utility model of the device. We describe these requirements in Section 2.6, and we define the the functional and non-functional requirements for the tactile plans in Section 2.7.

- G5: **According to UCD methodology, create prototypes of the UI.** The design process is covered in Chapter 3. Firstly, we present the functions offered by the interactive tactile maps using scenarios, and use-cases. Then, we created two prototypes: the low-fidelity prototype (specified in Subsection 3.3.2) and the high-fidelity prototype (specified in Subsection 3.3.3), and we propose two levels of interaction with the map (core tactile-auditory exploration and the *route-guidance mode*).

- G6: **Describe the implementation of the prototypes.** The implementation of the prototypes is described in Chapter 4. Both prototypes were implemented in the final platform defined by the utility model of the 3D model of building in [44]. The application for simulation of the interaction of the low-fidelity prototype was realized as an HTML web page. The core of the high-fidelity prototype runs on Raspberry Pi, and the software implementation employs Python.

- G7: **Evaluate the prototypes with the target user group.** The formative evaluation of prototypes is described in Chapter 5. We conducted three usability studies with visually impaired older adults. The participants were recruited from Home Palata, and the severity of visual impairments varied. We realized a user study with the low-fidelity prototype (N=9), and the high-fidelity prototype was evaluated in two studies (N=5 and N=5).

We successfully designed interaction techniques that allow visually impaired older adults to explore an indoor environment using an interactive tactile map. Our design was created based on the analysis of the target user audience, and we also studied the work related to existing tools used to enhance orientation of visually impaired. The design was implemented into two generations of prototypes and evaluated the prototypes with the target audience. The results show that our orientation aid allows the creation of a mental model of an indoor environment, but we also found issues of the design that should be improved in the next prototype of the UI.

7.1 Future work

For future development, we suggest implementing a more complex and robust prototype of the interactive map. The elimination of the issues found in the evaluation of the high-fidelity prototype should be verified in a user study. Then, quantitative evaluation should follow, as our up-to-now assessments were only qualitative. We recommend a diary-study on a long-term basis, or a comparative study of our concept and another commonly used design of the interactive tactile map.

Furthermore, an interaction technique that would allow the transition between individual floors within the 3D model of the building should be designed, and we evaluated. There, haptic animation could be employed.

Appendix A
Persona: Marie

Figure A.1: Marie. Picture from [54]

- **Gender / age:** Female / 82
- **Category of visual impairment by WHO [49]:** 4
- **Audition:** she has slight hearing loss (20 - 40 dB)
- **Other problems:** mobility issues - she walks with a stick

Marie was born in Mladá Boleslav. She spent most of her life here, as she worked there as an accountant in a factory. She raised two children, both girls. Soon after her retirement, she started to have problems with her sight. She wore glasses to correct her impairment: *'I wore glasses, they were simply part of me. Sometimes, I forgot where I left them, but this was still fine.'* However, in 2016, she was diagnosed with glaucoma, and year after with macular degeneration. Her sight worsens rapidly since then. *'It was quite quick. It took two years, and suddenly, I was not able to read anymore, even with a magnifying glass. It was not happy years. My husband died, I was alone, and everyday activities were more and more difficult. This is why I moved to*

Palata a month ago'. For Marie, moving into a new environment is difficult: *'Everything is new. Palata seems like a maze for me, still. I already know my room a bit, but I'm afraid to leave it on my own. It's a pity because I need to move, it's good for my health.'*. Currently, Marie leaves her room only with her roommate, or with a nurse. But still, the independence plays a crucial role for Marie. *'I don't want to rely on someone all the time, always wait for someone.'*

She misses reading, so she joined a choir in Palata: *'I sing in a choir here, we're called Sluníčka. I used to read books a lot. This is at least a little substitute for it because I can't read anything. I see only contours and colors, magnifying glass won't help me. And I can't read Braille, and I've never even thought of learning it. I'm too old for it.'* Marie worries about her future with the impairment: *'It will be worse, I know it. The doctor told me I would never be fully blind, and I'm so glad about it. But I'm afraid.'*.

Marie is not very used to modern technologies: *"I have a mobile phone, but I do not dial. Nurses dial for me, I don't need it."*

Appendix B

Persona: Petr

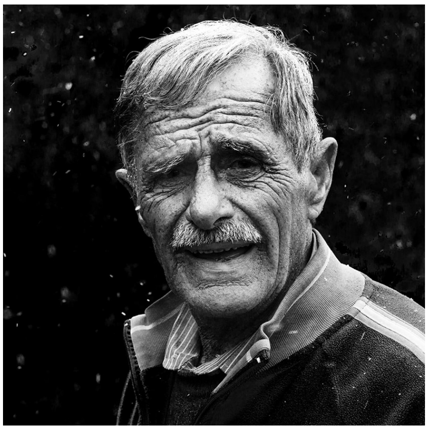

Figure B.1: Petr. Picture from [54]

- **Gender / age:** Male / 75
- **Category of visual impairment by WHO [49]:** 5
- **Audition:** normal
- **Other problems:** diabetes

Petr was born in Prague, and he lived in Žižkov all his life. He was trained to be an electrician, and he also got maturity at a technical school. He worked as an electrical fitter: *'Work with high voltage, that requires certitude. One must be able to make quick decisions.'*. He has a son, but he does not see him very often: *'My son works abroad, in Leipzig. He's a doctor, I'm very proud of him.'*.

Problems with a vision came early after Petr's 51st birthday: *'I have scars on my eyes caused by my profession. They started to cause me problems soon after my 50's, but I was still able to do my job. Everything got much worse* *after 1999, I got diagnosed with diabetes.'*. Petr had diabetes for a long time, but he did not know about his illness, and therefore, he did not take medicine for many years. *'It was quick. Three years, and I was blind. When there is a window somewhere, I see it - I can perceive light on the right eye, but that's all. It was difficult, but I'm a fighter. One deal with the conditions he has.'*

Petr started to employ more his hands and taction to explore the world around him: *'Diabetes is a bastard. It worsens the sensitivity of my fingers...but still, I'm so much better in exploring things using my hands that I used to be when I had sight. I was even willing to learn Braille, but it was too hard.'*.

Petr moved to Palata ten years ago, and he explored its environment a lot: *'I always love sport, I did windsurfing, volleyball. Here in Palata, I exercise regularly, and I do a little walk on my floor. Learning the environment here was hard, but I'm quite confident here now. I'm a Boy Scout, I have good orientation skills. Three doors, turn left, turn right, and I'm in the cafeteria.'*. He's also skilled in using modern technologies, he uses a smartphone: *'I received a smartphone from my son, and I'm using it, it is not so hard.'*

Appendix C

3D models of the prototypes

For creation of the models, software Autodesk Fusion 360 [23] was employed.

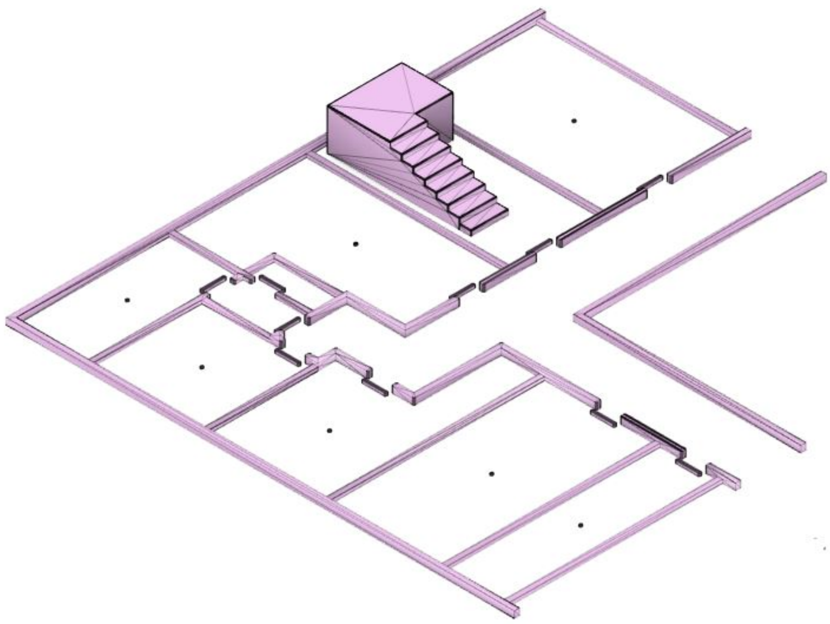

Figure C.1: The 3D model used for printing the low-fidelity prototype.

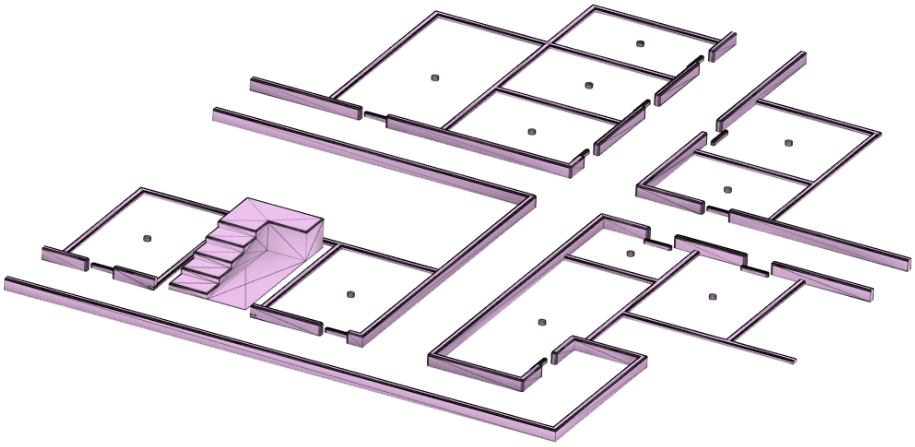

Figure C.2: The 3D model used for printing the high-fidelity prototype.

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Figure C.3: The 3D model of the interactive buttons (*room buttons*)

Appendix D
Acronyms

AMD Age-related macular degeneration. 1, 10

HCI Human-Computer Interaction. 13, 29

O&M Orientation and mobility. 20

TTS Text-to-speech. viii, 40, 44

UCD User-Centered Design. 4–6, 9, 35, 57, 73, 78

UI User Interface. viii, 5, 11, 27, 29, 47, 51, 52, 55, 56, 58, 59, 65, 78

VIOAs Visually impaired older adults. 4, 14, 21, 26, 27, 45, 72, 77

VIPs Visually impaired people. 2, 4, 27

WHO World Health Organization. 9, 13, 29, 57, 60, 66, 73, 74, 81, 83

Appendix E

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