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Master's Thesis

Acquisition of cognitive maps by individuals with vision impairments using virtual reality

Master's Thesis

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Master's thesis title in English:

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Tvorba kognitivních map pro zrakově postižené pomocí virtuální reality

Guidelines:

Individuals with vision impairments (VI) need specific tools to acquire spatial knowledge of the environment they need to orientate themselves, such as building floors. Such knowledge is called a cognitive map (CM) of the spatial environment and has multiple components (landmarks, distances, directions, routes, etc.).

The performance of interaction methods varies in the acquisition of different components of spatial knowledge. Virtual reality (VR) adapted for VI is a promising method for acquiring CM and practicing movement in a new environment while preserving safety. Methods that improve the feeling of being in the virtual environment (presence) exist. However, there is room for improvement in the case of VI.

Analyze the current state of the art in the acquisition of CM by VI and VR for VI [1-4]. Analyze the target user audience of VI and focus on their needs, preferences, and requirements related to spatial mental modeling, haptic interaction, and sensory substitution. Specify functional and non-functional requirements for a VR solution to acquire CM tailored for VI. The system should enable integration with actuators that allow multimodal representation of spatial knowledge. Create a testable prototype of the system. Evaluate the final prototype with representatives of the target audience, focus on its usability (usability test) and utility (employ methods for externalization of cognitive maps), and involve at least four representatives of the target user audience.

Bibliography / sources:

[1] Ottink, L., Buimer, H., van Raalte, B., Doeller, C. F., van der Geest, T. M., & van Wezel, R. J. (2022). Cognitive map formation supported by auditory, haptic, and multimodal information in persons with blindness. *Neuroscience & Biobehavioral Reviews*, 104797.

[2] Kreimeier, J., & Götzelmann, T. (2020). Two decades of touchable and walkable virtual reality for blind and visually impaired people: A high-level taxonomy. *Multimodal Technologies and Interaction*, 4(4), 79.

[3] Lahav, Orly. "Virtual Reality Systems as an Orientation Aid for People Who Are Blind to Acquire New Spatial Information." *Sensors* 22, no. 4 (2022): 1307.

[4] Kunz, Andreas, Klaus Miesenberger, Limin Zeng, and Gerhard Weber. "Virtual navigation environment for blind and low vision people." In *International Conference on Computers Helping People with Special Needs*, pp. 114-122. Cham: Springer International Publishing, 2018.

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III. Assignment receipt

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

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Acknowledgement / Declaration

I would like to thank the supervisor of this thesis, Ing. Miroslav Macík, Ph.D. for all the consultations, leadership, patience and advice he has provided me with throughout the course of this work, furthermore I would like to thank my family, friends, and my partner, without whose support, I would not have been able to create this thesis at all.

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I hereby declare that I have prepared the submitted thesis independently and that I have listed all the literature and sources used, in accordance with the Guideline for adhering to ethical principles in the preparation of university final theses.

In Prague, 24.05.2024

.....

Abstrakt / Abstract

Jedinci se zrakovým postižením potřebují specifické nástroje k získávání prostorových informací o prostředí, ve kterém se potřebují zorientovat, jako jsou například jednotlivá podlaží domů. Tento typ znalostí se kolektivně nazývá kognitivní mapa prostředí a skládá se z několika komponent (orientační body, vzdálenosti, směry, cesty atp.). Různé interakční metody jsou různě vhodné pro získávání různých komponent prostorové orientace. Virtuální realita upravená pro zrakově postižené je slibnou metodou pro tvorbu kognitivních map a procvičení pohybu v novém prostředí při zachování maximálního bezpečí. Existují metody, které pomáhají ke zlepšení pocitu, že se uživatel skutečně nachází ve virtuálním prostředí (prezence), nicméně tyto metody nebyly ještě plně ověřeny s uživateli se zrakovým postižením.

Obsahem této práce je průzkum a analýza současných dostupných řešení a technologií. Na základě tohoto průzkumu následovalo prototypování virtuálně realitního řešení, které pomůže uživatelům s tvorbou kognitivních map co nejjednodušším a nejbezpečnějším způsobem v kontrolovaném prostředí. Výslednou kognitivní mapu uživatelé budou moci dále využít k orientaci v reálném prostředí.

Klíčová slova: Virtuální Realita, Unity 3D, Interakce Člověka s Počítačem, Kognitivní mapy, Zrakové postižení, Orientace

Individuals with vision impairments need specific tools to acquire spatial knowledge of the environment they need to orientate themselves, such as building floors. Such knowledge is called a cognitive map of the spatial environment and has multiple components (landmarks, distances, directions, and routes). Different interaction methods have various performances in the acquisition of different components of spatial knowledge. Virtual Reality adapted for visually impaired individuals is a promising method for the acquisition of cognitive maps and practicing movement in a new environment while preserving safety. Methods that improve the feeling of being in the virtual environment (presence) exist. However, there is room for improvement in the case of visually impaired users.

Thus the scope of this work is focused on the research, analysis, and prototyping of a virtual reality solution, that assists and provides an easy and safe way for visually impaired individuals to create a cognitive map in a controlled environment, which could then be used to navigate a real environment.

Keywords: Virtual Reality, Unity 3D, Human Computer Interaction, Cognitive maps, Visual impairment, Orientation

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Chapter 1

Introduction

Individuals with vision impairments (VI) deal with more difficulties when exploring a new environment than the general population. Depending on the environment, it may require more time and effort to orientate themselves, or in some cases, it may even be dangerous. Therefore the creation of even basic cognitive maps (CMs - referring to a mental image of the spatial structure of the environment and spatial relationships with objects in the environment - citation from [3]) beforehand may lead to a significant improvement during their first real experience with said environment.

This is the main idea and motivation behind this work. The goal in general is to try and find the most appropriate combinations of methods including VR for different groups of individuals with VI to try and provide them with the option to explore a potential real environment before in a virtual environment beforehand and thus make it easier and more importantly less stressful.

Thus the main goals of this work are focused on the following:

1. **Research and analysis** of the current state of the art in the field of VR for VI
2. **A prototype** of a VR solution, that would assist and provide an easy and safe way for VI users to create a CM in a controlled environment, which could then be used to navigate a real environment.
3. **Evaluate** how the users interact with the implemented methods.
4. **Improve** upon the implemented prototype as much as possible, according to feedback gathered throughout the testing.
5. **Ability to generate** a virtual reality environment from a pre-implemented model

The prototype should be usable for individuals with VI, therefore it has to mirror interaction methods, they are used in real life, while providing them with the information about a chosen real-world environment.

Chapter 2

Analysis

A significant part of this work lies in the analysis of already existing solutions and works, that may have the same or similar goal to this work and the state of the art (SOA) for this problem. Therefore an analysis of these relevant sources has been done, so as not to repeat already existing projects, but to build upon them and try to innovate to some degree. The contents of this part include the analysis mentioned above, along with separate sub-parts dedicated to the hardware (HW) and software (SW) chosen to be utilized during this work. ¹

2.1 User group analysis

The user group for this work has already been mentioned several times – individuals with VI.

Visual impairment is widely considered to be a broad term describing a loss in visual function, which can have many aspects. From the ability to focus, lower fields of vision, visual acuity, and more [5].

There are unified methods available for measuring the severity of the visual impairment, such as the Snellen chart (depicted in Figure 2.1) for the measurement of the potential optical correction and a further severity table as can be seen in Figure 2.2.

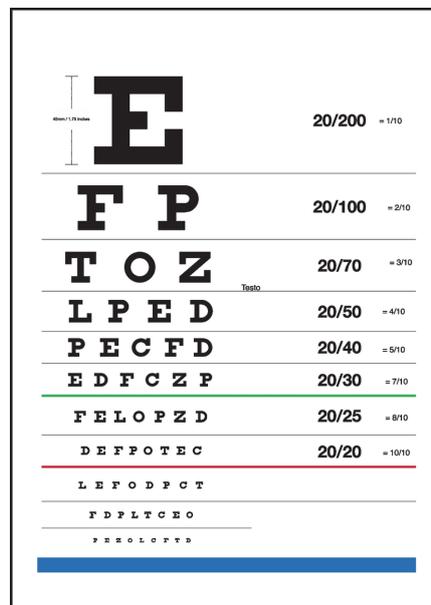


Figure 2.1. A Snellen chart used for the measurement of needed optical correction, Source [6]

¹ Various parts of this text have been spellchecked an AI model which also in part served for consultation on the specific text formulations [4]

Acuity measurement scales		Vision categories (using best achievable acuity with both eyes open)		
LogMAR (linear scale)	Snellen (geometric scale)	WHO definition of visual impairment	UK criteria for visual impairment certification	
			Full field of vision	Very reduced field of vision
-0.1	6/4.8	No sight impairment	No sight impairment*	No sight impairment
0.0	6/6			
0.1	6/7.5			
0.2	6/9			
0.3	6/12			
0.4	6/15	Moderate visual impairment	Sight impairment	Sight impairment (previously termed partially sighted)
0.5	6/18			
0.6	6/24	Severe visual impairment	Severe sight impairment	Severe sight impairment
0.7	6/30			
0.8	6/36			
0.9	6/48	Blindness	Severe sight impairment	Severe sight impairment
1.0	6/60			
1.1	5/60			
1.2	4/60	Blindness	Severe sight impairment	Severe sight impairment
1.3	3/60			
1.4	2/60			

Figure 2.2. A vision impairment scale, source [7]. The geometric scale shows the distance from which you can read letters of a certain size. Being able to only read 60mm (or bigger) letters from 2 meters are considered to be blind by this scale.

In the context of these evaluations, our user group falls into the categories of either blindness or severe visual impairments.

There are further important distinctions of the individuals in this user group. That being the onset of their VI. This can divide the group further into congenitally blind (since birth or developed due to mainly hereditary causes before 16 years of age) or late-onset blindness, which in this work we consider both of these parts of the user group.

2.2 Analysis of the state of the art

For this analysis, the materials used were sourced via online digital archives, such as Google Scholar. This part is divided into the four sub-parts. Each one concerning one of the articles served as a basis for our works. Keywords that were looked for in the research were virtual reality, cognitive maps, orientation, visually impaired, late-onset blindness, severity scale, congenital and blind.

■ 2.2.1 Taxonomy of walkable virtual reality for individuals with VI

In full „ Two decades of touchable and walkable virtual reality for blind and visually impaired people: A high-level taxonomy“ by Kreimeier and Götzelmann. As the name of the article [8] itself suggests, this work is mainly a taxonomy of all the previous documented works concerning VI people utilizing VR for the creation of CMs.

This work put into perspective, that the way this project aims to utilize VR has not been especially common in the two decades before the creation of this article (the year 2020). VR is not only limited to the use of virtual-reality headsets and controllers, which is how we interpret it in the context of this project, but can also be any method, that virtualizes the real environment and replaces it with a proxy, be it a haptic map, an acoustic proxy, or a virtual environment, that the VI explores using a controller.

Using the definitions of this work, our project aims to be medium-scale, utilizing a wearable/holdable controller with audio-haptic feedback. According to the taxonomy works with the same scale and approach to this only consist of about a tenth (5 articles/works) of the analyzed volume of works.

■ 2.2.2 Cognitive map formation

The main source for this part of our research was an article by Ottink et al. [9] which explored for this work an important problem, that individuals with VI, especially those who were not born as one but have become one during their life recently (late-onset VI), may have a similar predisposition to creating CM and orientation in the environment as individuals without VI (blindfolded). In the context of orientation, this means, they may tend to create their cognitive maps allocentrically - meaning that they often create the cognitive map and place objects in it in relation to other objects and landmarks, not just in relation to themselves.

Individuals whose VI are congenital (with VI since birth) on the other hand tend to have more of an egocentric approach, which results in difficulties when measuring distances and putting objects into perspective in relation to each other, but it is in general not an obstacle, as this can be learned with practice.

This, combined with the work of Majerova [10] who describes the change between a regular four-stage formation of cognitive maps, consisting of:

- Obtaining information through the senses.
- Selection and conscious processing.
- Storage in the form of spatial representation.
- Decision-making, movement, and orientation based on the stored representation.

Into a four-stage process of CM acquisition by individuals with VI:

- Obtaining information through lower compensatory functions, or remaining vision.
- Use of higher compensatory functions in data selection and information processing.
- Storage of spatial representation with respect to differences in obtaining and processing information.
- Spatial orientation and mobility in an individual using spatial mental mapping.

Served as our theoretical basis for approaching the problem of CM creation for our user group.

■ 2.2.3 Haptic and auditory white cane

The full name of the most prominent article in this part is „ Virtual Reality without vision: A haptic and auditory white cane to navigate complex virtual worlds“ by Siu

et al. Out of all the other works researched, this one [1] was closest in both its aim and realization to this work. The authors developed and created a wearable harness connected with pulleys and motors to a physical white cane, which was then controlled accordingly by collisions with VR objects by the pulleys. This system is depicted in Figure 2.3. This resulted in the simulation of a certain VR environment into a real environment, the user could explore and accomplish goals, such as finding specific objects, highlighted by audio feedback.

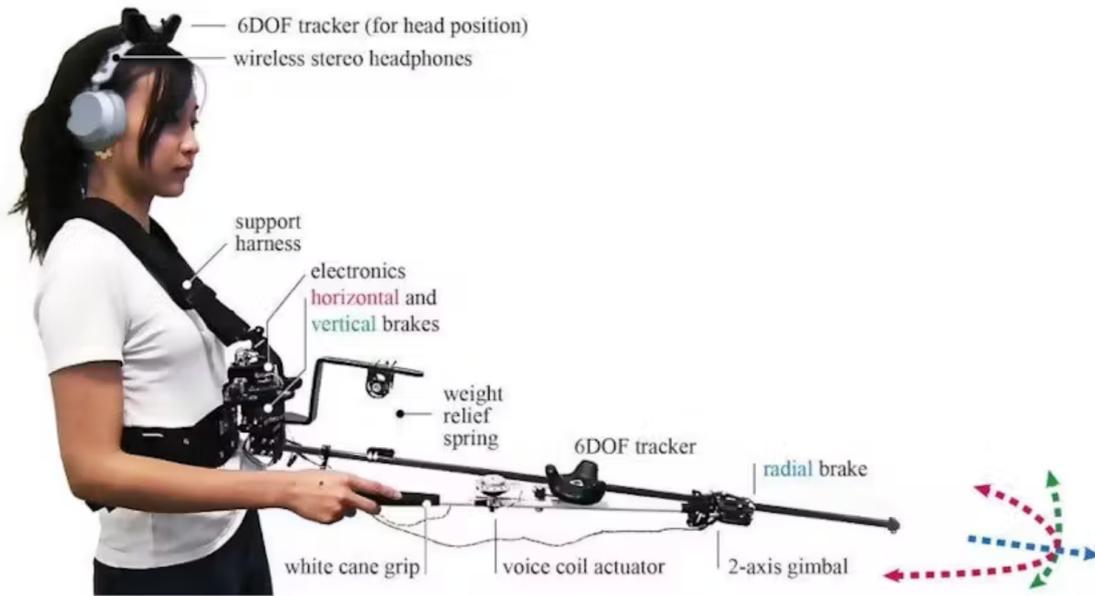


Figure 2.3. Picture of the white cane setup taken from the work of Siu et al.[1]

The main takeaway observations from this work are that the user's cane must be modifiable in its length, as this is one of the key attributes for the ease of use of the cane. It is also a good idea to combine haptic feedback with audio, as the sound of the cane dragging over objects or hitting them can give a surprising amount of relevant feedback to the individual with VI. Similarly to this, objects, that should draw the user's attention or the user should navigate towards, can benefit greatly from emitting sound clues. The areas, that could be improved upon include the sounds, as the more variability there is, the closer it could match the sounds a real environment would make when interacted with. Also, it should be noted, that users do not have to only utilise the tip of the cane for navigation, but most of the length of it, so it has to be taken into account as well in terms of feedback. The last takeaway from this work is also the fact, that users have a variety of different grip techniques they can use, and having a set harness limits their options significantly.

A similar approach in terms of HW was also already employed by Zhao et al. [2] in their **Canetroller** (pictured in Figure 2.4) - which by their description is "A haptic cane controller that simulates white cane interactions, enabling people with visual impairments to navigate a virtual environment by transferring their cane skills into the virtual world".

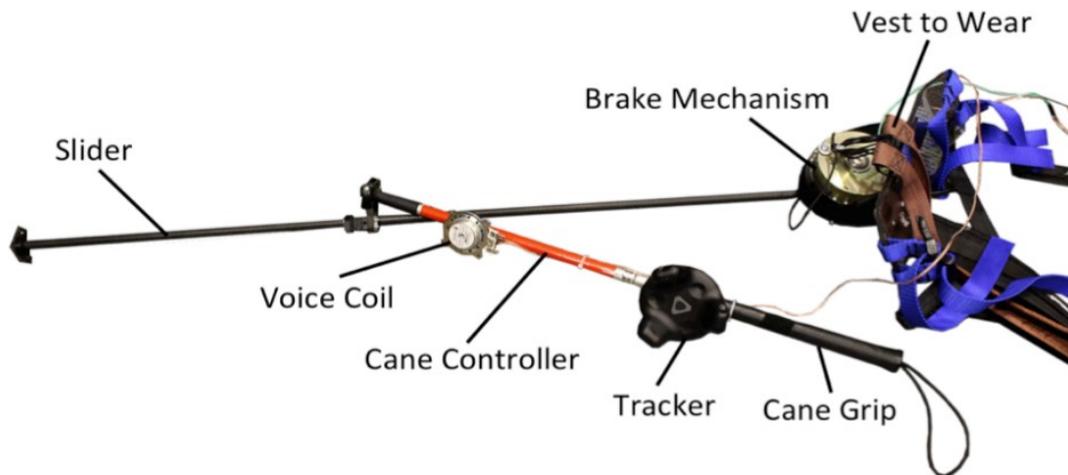


Figure 2.4. Picture of the Canetroller taken from the work of Zhao et al.[2]

Similarly, Kim's work [11] explores the use of a white cane modified for virtual reality and enhanced via artificial intelligence, initially designed to recognize virtual braille blocks, this approach has potential applications in the real world as well. While this method is highly specialized and not directly applicable to the broader scope of this work, it offers valuable insights and could inform future developments and refinements in this area.

2.2.4 Virtual navigation using auditory feedback

„ Virtual navigation environment for blind and low vision people “ by Kunz et al. This work [12] has in short tested a purely audio method for the navigation and orientation of non-VI blindfolded users, who then navigated a virtual maze, based on the audio feedback, that had been supplied to them via headphones. The feedback is spatial, so the user can change his movement according to where the obstacle is detected. The distance of the user to the obstacles was always computed from the closest point on the object to the user. The audio feedback was split into three phases. The first phase is silence - the user is sufficiently away from any obstacles (walls of the maze in this case) and can move in any direction he desires. The second phase is beeping at an increasing rate, according to the distance from the obstacle. The third phase is a continuous beep, after crossing a threshold distance to the obstacle, or when the continuation of movement at the current speed for a certain time would result in a collision.

From this study, it is apparent, that audio feedback by itself, while providing enough information about the environment to improve the user's CM, may not be sufficient by itself, or at least may be hard to interpret, as according to the results of the study, the participants spent up to 47% of the time in the maze stationary, trying to interpret the feedback to continue. Also, this method may not be ideal for more complicated objects, such as signs, lamps, tight corridors, or similar. This work also only utilizes an egocentric approach, where the user is supplied information about himself therefore a more allocentric information about the area as a whole may be difficult to create in this way.

This is consistent with the results of Picinali et al. [13], who explored the options of assisting blind individuals with the learning process of indoor environments through 3D audio recording and simulation techniques.

Their results show, that high interactivity in the learning process leads to an improvement in the resulting cognitive map and in turn, when the interactivity is not present during the learning process, the quality of the resulting spatial information suffers as well.

Another important work in this area was the work of Lahav and Mioduser [14] who developed a multisensory virtual environment to support blind individuals in acquiring spatial cognitive mapping, orientation, and mobility skills. By utilizing compensatory sensory channels such as haptics and audio feedback, the virtual environment provided spatial information that visually impaired users could use to build cognitive maps. Their study demonstrated that users could effectively navigate both virtual and real spaces after training in the virtual environment. This is in accord with the findings of the previous works as well. This approach also highlights the potential of VR technology, combined with tactile and auditory inputs, to enhance spatial awareness and mobility skills for the visually impaired, aligning well with the objectives of using a modified white cane for cognitive mapping in VR settings.

Overall the analyzed studies show that auditory feedback is a promising avenue of approach as a secondary feedback source, as it enhances the CM but may need additional approaches to interaction with the environment to create a more general idea about the surroundings.

2.3 Analysis of the Suitable Development Engines

In the initial phases of this project, a pivotal decision had to be made – the selection of a development engine that would significantly shape the trajectory of the entire implementation process. There were a few primary criteria for this choice. Mainly the ease of use of the engine and associated libraries for VR integration, previous experience with the engine, aiming to minimize the need for additional time investments in acquainting with a new tool and the approach to running the resulting prototype in development mode from the engine as in the beginning phases, there will be a definite need to adjust the prototype during testing.

The two contenders for the development engine were the widely acclaimed Unity and Unreal Engine, both renowned and used in the industry for their capabilities in crafting immersive virtual experiences.

■ 2.3.1 Unity:

The SteamVR library (a library providing ready-to-use tools and scripts for VR development), is integrated seamlessly into Unity and simplifies complex aspects of VR development, such as controller management and headset tracking.

The author has had previous experience with Unity, mainly consisting of development of computer and virtual reality games and experiences, which is a significant benefit, in favour of this engine overall.

The Unity Engine provides the option of running the developed application without the need to build it directly in the editor. This functionality is supported even with VR headsets and therefore makes it suitable for prototyping.

■ 2.3.2 Unreal Engine:

It has to be noted first, that the author has quite a bit less experience working with the Unreal Engine platform, therefore all the information presented has been researched as a part of the preliminary preparation of this work.

Research revealed that Unreal Engine supported various VR development libraries for the most common VR headsets available, however, they were predominantly designed for Unreal Engine 4 at the original time of research.

Unreal Engine as well as Unity features a preview mode available straight from the editor itself, which includes support for VR development.

■ 2.3.3 Engine choice summary

The research shows, that the two engines are both quite capable in being used for the development of VR applications, and both fit the required parameters.

The research also shows that Unity is generally praised for its accessibility and widespread adoption, particularly in indie and smaller development teams, since it has a robust community, ensuring that developers have access to a wealth of knowledge, tutorials, and support forums, which can be invaluable when navigating the intricacies of VR development.

Unreal Engine on the other hand is utilized especially for projects where cutting-edge graphics and visual fidelity are paramount, of which neither are particularly important in the scope of this work. This along with the discrepancy in previous experience in using the two engines meant that the choice was made to utilize Unity.

■ 2.4 Analysis of the available VR headsets

This part is dedicated to the explanation of the selection process of a suitable VR headset for this work. The selection was limited both by the availability of the headsets to the author and their viability, as for body/user tracking in a controlled, room-sized environment, not every headset is suitable, especially wired ones. This left us either with a choice of a wireless headset or a headset using the lighthouse principle or a similar tracking base station.

The wired and wireless principles are self-explanatory. A wired headset needs to be connected to the computer via a cable, whereas a wireless headset does not have this limitation and is connected via other means, for example by connecting to the same Internet network. A lighthouse system is distinct from these two, as it is a "technology (SteamVR Tracking), used in the HTC VIVE, which uses patterned infrared light projected from the base stations onto tracked objects embedded with photo diodes along with precision timer circuitry to estimate the positions of the trackers. Each photo diode on the tracked object generates a digital signal when infrared light is detected, enabling the object to reconstruct its global spatial position and orientation, or pose, with prior knowledge of the photo-diode spatial configuration in the object's local reference frame" (citation from [15])

From the readily available VR headsets, the main standouts were the Oculus Quest 2 (displayed in Figure 2.5) and HTC Vive series VR head-mounted displays - Oculus being a wireless headset able to connect to a computer via the WiFi and HTC Vive being wireless, but requiring a lighthouse station. According to the research and articles concerning these two headsets [16] and [17], it was determined, that both in terms of precision, availability, and cost, the Oculus Quest 2 is a preferred choice for this work.



Figure 2.5. Picture of the whole Oculus Quest 2 setup¹

2.5 Analysis research summary

The user for our work group consists of individuals with VI, categorized by the severity and onset of their impairment. Key distinctions include congenital blindness and late-onset blindness, each with unique needs and challenges in cognitive mapping and orientation.

Kreimeier and Götzelmann's work [8] highlights the rare use of VR for CM in VI users, particularly at medium scales involving wearable controllers with audio-haptic feedback.

Studies by Ottink et al. [9] and Majerova [10] reveal different CM approaches between congenital and late-onset VI individuals, emphasizing the need for both egocentric and allocentric mapping techniques.

¹ Image source: <https://www.xiaomimarket.cz/oculus-quest-2-256gb-bryle-pro-virtualni-realitu/>

Works by Siu et al. [1], Zhao et al. [2], and Kim [11] demonstrate the effectiveness of modified white canes in VR, stressing the importance of combining haptic and auditory feedback.

Research by Kunz et al. [12], Picinali et al. [13], and Lahav and Mioduser [14] shows the potential and limitations of using auditory feedback alone and in combination with other sensory inputs for spatial awareness.

The work in terms of implementation will take the form of a single Unity project, containing multiple scenes with different rooms/environments for the user to explore and both get familiar with the system and test its purpose and performance. The scripts needed for the work will be written in C# and again a part of the project. Necessary props and models will be either obtained from open-source repositories or made personally in Blender - a free open-source 3D modeling software (among other things).

Chapter 3

Requirements

In this chapter, general requirements were transformed into formal functional and non-functional requirements, using the knowledge summarized in the previous chapter.

The requirements for the project are therefore set as follows:

3.1 Functional requirements

■ **FR1 Moving the virtual white cane**

The user will be able to move the virtual white cane by moving the real virtual-reality controller. This will affect both the position on the XYZ axis and the rotation of the cane in the 3D virtual environment.

■ **FR2 The user's movement will be tracked**

The user's movement in the real world will be reflected in the virtual reality environment as well.

■ **FR3 Audio-haptic feedback for collisions with VR objects**

The user will receive appropriate audio-haptic feedback upon causing a collision of the virtual white cane with any relevant objects in the VR environment.

■ **FR4 The length of the virtual cane will be adjustable**

One of the key customizable parameters of each individual's white cane is its length which has to correspond to the user's height and grip technique, therefore it is necessary to be able to adjust this as a part of the setup.

■ **FR5 The information about collisions will be exportable**

Since the main goal of this project consists among others in tracking the user and a white cane in a VR environment, it is necessary, to be able to export this information, to other devices in real-time or as close to real-time as possible.

3.2 Non-functional requirements

■ **NFR1 The whole virtual environment will be implemented in Unity game development engine**

This requirement has been set by the author himself, the choice of this particular engine is explained in 2.3. Included in this is the fact, that the logic and scripts included in the work will be written in C#.

■ **NFR2 The VR environment should be as optimized as possible**

For the VR environment to be as precise as possible, and therefore provide as close of a virtual model, it needs to be optimized, so the performance does not affect the realization of the purpose of this environment.

■ **NFR3 The process of interaction should be as close to reality as possible**

We want to eliminate any or most of the need to teach the VI user new approaches or methods and instead build upon the methods of orientation he/she has already learned in his life.

■ **NFR4 Several testing and preparation scenarios/environments**

The user should have the option to familiarize himself with the functionality of the project in a short training scenarios/session shortly before the actual testing.

■ **NFR5 User Centered Design** The prototyping and implementation will follow the User Centered Design (UCD) pattern, which focuses mainly on relatively quick iterations of the prototype, which is then tested by the users from the defined user group and improved based on their feedback.

These are the functional and non-functional requirements set for this work. Their successful implementation should cover the technical needs of this work, while the user feedback that will be gathered as a part of the user testing should provide us with a result of how well the goal mentioned as a part of the introduction in Chapter 1 was achieved.

Chapter 4

Design

The design process followed the user-centered approach, therefore new ideas and improvements kept either being suggested via user feedback or considered based on the author's observations throughout the work. In general, the design phase could be divided into three parts, the first being the initial design, the second the design changes made according to the testing of the first design and finally a third iteration of the design, which will not be covered in this chapter, but in chapter 8.

At the end, a short description of the design evolution during the scope of the work is provided as well.

4.1 First design iteration

The first iteration of the design focused on designing the basic functionalities of the prototype, only using basic haptic feedback, and creating a suitable virtual environment, where the prototype could be tested.

The main design goal was to test, whether the above-mentioned interaction method would suffice for the basic approach to navigation for individuals with VI – walking along guiding lines.

4.1.1 Basic principle

As mentioned in the requirements (chapter 3) the white cane used for the testing and through which the user will feel the haptic feedback, will implement a real adjustable telescopic white cane combined with a VR controller (as illustrated by Figure 4.1).



Figure 4.1. The implementation of the real world cane with a controller

The users may need to adjust the size of real-world white cane according to their needs and to resemble their real-world white cane as closely as possible. This in turn requires our project to be able to reflect the size change and either adapt or be able to change the size of the virtual white cane as well.

This interaction logic implementation should ensure, that upon entering into a collision with a different object, the VR controller will start to vibrate. If the cane stays in collision with an object, then the vibrations get stronger, which indicates to the user, that the cane is stuck in an object.

Another important part is the graduation of the vibration strength as the cane gets closer to the object itself at the point of the collision. This should be used as an indication for the user, that to exit the collision, he should move the cane in a direction, where vibrations get weaker.

These functionalities together achieve both FR1 and FR3 (see section 3.1).

FR4 should be implemented intrinsically, by the option to adjust the length of the actual model object in the scene from the Unity editor environment. As mentioned above.

4.1.2 First environment design

The scenes of the Unity project, or in game development terms, `levels` are in our case each a separate environment designed to determine how well the user can create a cognitive map of the environment, sometimes using places or features, that may be harder for them to navigate in a real environment.

The whole process made sure not to overdo the difficulty of the environments, and not utilize unreasonable obstacles, and especially avoid putting the user in uncomfortable scenarios.

The design of the first room was mainly recommended by the supervisor of the work itself, with the room only containing straight walls, sharp corners, some elementary obstacles, and a nook, where the user would start (the rough sketch of the room included in Figure 4.2). The simplicity of the first environment should serve to test the main mechanics of individuals with VI approach to orientation, that being movement along guiding lines.

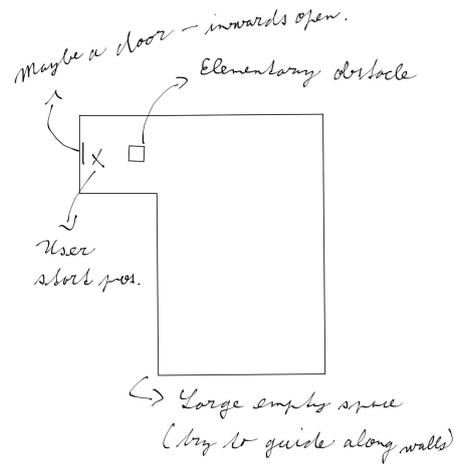


Figure 4.2. A preliminary sketch of the first implemented test room

The first environment combined with the basic interaction logic described above would form the rough outline of the project, and therefore served as the first low-fidelity prototype.

4.2 Second design iteration

After the first round of testing (chapter 6), we took the results of the test as a proof of concept of our work and started improving the prototype and utilizing the feedback gathered from it.

4.2.1 Basic principle

Further development in the basic principle of interaction was aimed at implementing a real-world physical brake into the cane, which would actually stop the motion of the real-world cane, giving substantial feedback to the user.

As mentioned in the requirement FR5 (in section 3.1) and as apparent from the need for a real-world physical brake, the project requires the ability to communicate with an external HW device (the physical brake). The way of communication was chosen to be using a User Datagram Protocol (UDP) protocol connection.

UDP is a communication protocol widely used, especially for time-sensitive transmissions such as video playback or DNS lookups. It speeds up communications by not formally establishing a connection before data is transferred. This allows data to be transferred very quickly, but it can also cause packets to become lost in transit ¹

This protocol should be suitable for our purposes, as it may be volatile in terms of data lost in transmission, but is fast, which will ensure minimal latency.

The device the project will communicate with will be an ESP32 microcontroller chip, which among other features has an integrated Wi-Fi module, which allows for the connection via the UDP protocol. It can also operate using an

¹ Source: <https://www.cloudflare.com/learning/ddos/glossary/user-datagram-protocol-udp/>

external energy source such as a battery, which makes it suitable for being a standalone device in the tip of the cane without any other connecting cables necessary.

Along with the tactile feedback, the user will receive audio feedback via headphones, or another isolated audio source, for when the cane collides with virtual objects, they will receive feedback, that will allow the user to differentiate between objects (e.g. a wall has a different impact sound than a chair).

4.2.2 Second environment design

The design of the second room was aimed at virtualizing a real-world environment (as can be seen in Figure 4.3), and for this purpose, we chose the E-318c study room at the E building of the CTU university campus at Charles Square. The design of this room has not been altered by the author, and the main blueprint for it has been the fire evacuation plan of the floor for the surrounding halls and room layouts, with real world photos of the environments used for reference.

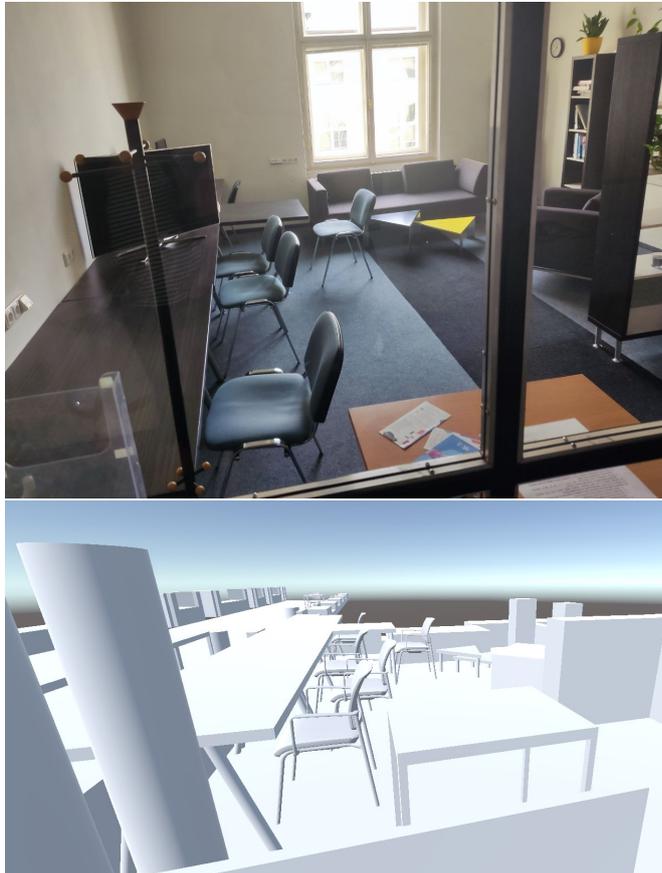


Figure 4.3. A comparison of the photo of the room layout used for reference with the Unity scene result¹

¹ The scene contains one model, I am not author of – the chair. The chair is a royalty-free model available at <https://www.cgtrader.com/free-3d-models/furniture/chair/gaya-ergonomic-upholstered-chair-with-armrests>

4.3 The evolution

During this project, the design requirements evolved along with it, as described above. First, the design idea was simple - implement a prototype application, that would utilize a VR environment, which would initially only via haptic feedback provide the user with the necessary information, to create a cognitive map.

After the analysis, this idea mostly did not change. There were minor adjustments that were being considered, such as including also audio feedback, but mostly the analysis served as a specification of the requirements and served as a rough indication as to how they could be implemented.

Following the analysis a low-fidelity (Lo-Fi) prototype was designed along with options to adjust the white cane tracking in the application - a calibration of sorts.

Afterward, small adjustments needed to be made to the logic of the prototype, as it became clear that the analysis did not cover all the aspects of the implementation and floors, for example, are not suitable to have collisions, since the real-world floor would suffice by itself.

This was the part, where the first testing of the prototype occurred.

When the first round of testing was finished, the low-fidelity prototype had to be adjusted, and new requirements and design choices had to be made, for example this is the part where a new requirement from section 3.1) concerning the option of utilizing UDP was made and designed (4.2.2).

Along with the design of the actual application, the design of proprietary HW (hardware) was done in parallel by the supervisor.

During the design process, we started with the idea of a white cane, that could stop and release itself using electromagnets (which would provide better haptic feedback, than vibrations). However, this would require a real-world testing environment to have ferromagnetic flooring.

This idea evolved and we have eventually settled on the approach of having a protruding rubber tip, which would mechanically stop the movement of the cane, via friction. This rubber tip would be controlled via a servomotor, connected to the logic of the system via a UDP protocol, and this whole upgrade was encased in a 3D printed case. This case connected to the tip of the cane the same way as a regular one would (pictured in Figure 5.2).

The last design obstacle currently standing is the import of data for the environment from an outside source, so the environments could be generated somewhat dynamically according to the needs of the user and the room/floor/building data they have available to them.

Chapter 5

Implementation

The implementation itself consists of a single Unity project, which contains a level (or a scene to be more precise in Unity terminology) for every test environment, along with the scripts, implementing the logic of the project located in the main repository of the project. A more detailed description of how the work is structured can be found in the attached Appendix D with a detailed description how to set up the implementation being provided by a user manual in Appendix C

5.1 Interaction logic

The interaction logic for the white cane is so far implemented in the script called `white_cane` and it is a script, that is attached to the virtual object of the white cane.

A part of this script is also the keeping of transformations and rotations of the white cane object, if it was left as it were, it would be affected physically by the collisions which would result in the cane moving and rotating by itself.

Implemented in this script is also the connection logic to the ESP32 microcontroller chip, which at the start of a collision with either a wall or an obstacle protrudes the rubber tip in the front of the white cane, causing friction. The tip stays protruded for 0.3 seconds, after which it retracts back into a position, where it does not cause friction. This time for which the tip stays protruded has been selected via empirical testing.

Another interaction method implemented is the tracking of the head of the user and collision detection of the head. The user may physically step into an obstacle while keeping the white cane outstretched and in free space, which would normally not cause any feedback for the user. Therefore audio feedback, informing the user, that they are inside of an object or a wall was implemented.

5.2 UDP protocol

The protocol itself was implemented as a separate script, called `UDPSocket`, serving as a socket for establishing communication with the ESP32 chip.

This socket is created as a part of the `white_cane` script. This is due to the logic for triggering the communication being present in there as well, and to make the code as straightforward as possible, where most of the interaction logic is covered in one place.

An overview of the reactionary working principle is shown in the diagram depicted in Figure 5.1.

When a virtual object comes into a collision with the white cane (or vice versa), it triggers multiple feedback methods, mainly the VR controller gets a signal to start vibrating and the ESP32 chip receives a data packet via the UDP to push out the servo motor.

Then the white cane goes into a waiting state, where after 0.3 seconds, it sends another data packet to the ESP32 chip, signaling the servomotors to pull themselves back into the tip, therefore releasing the friction-based physical break.

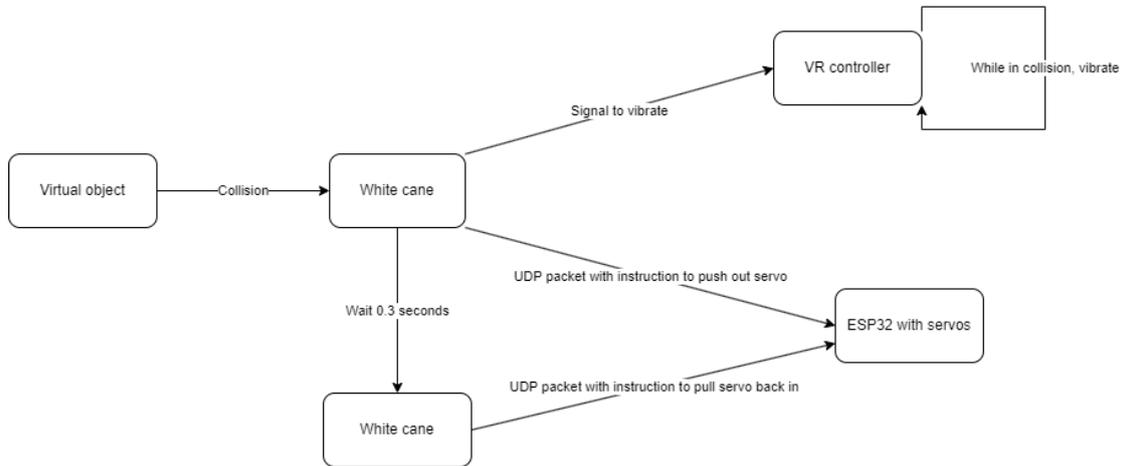


Figure 5.1. A diagram showing the working principle of the interactions

5.3 White cane

At first (Chapter 6), the white cane only consisted of the cane itself and a VR controller, as pictured in Figure 4.1. However for more tangible haptic feedback, as mentioned in the design process in Chapter 4.3, we have deemed it necessary to include a physical brake onto the cane, which ended up modifying the cane into the state pictured in Figure 5.2.



Figure 5.2. A photo of the white cane including the physical brake

5.4 Environments

The final aim of the project is to be able to import Open Street Maps data for indoor environments and then recreate them in VR for the user to walk through them, but for the proof of concept and initial testing along with prototyping, this feature is not yet available and therefore it was needed to manually create testing environments for the users to utilize. These environments are described in detail in the following subsections.

5.4.1 SampleScene

At first, there was a single environment implemented called Sample Scene (pictured in Figure 5.3), which contains a single room with a nook, which is walled, has a floor, and a singular cube (pillar) as an obstacle. All of these mentioned objects, apart from the floor have a collider and are therefore obstacles, as far as the cane is concerned.

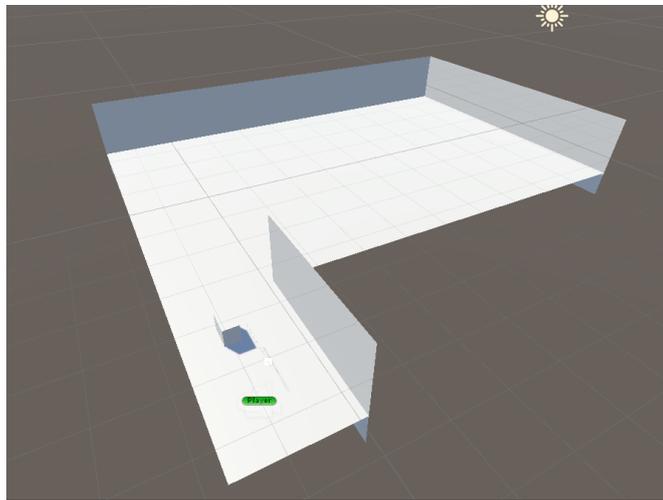


Figure 5.3. Screenshot of the room with a nook, implemented in Unity

5.4.2 Triangle room

The second implemented environment was a study room at the E building of the CTU University campus at Charles Square. The specific room in question is E-318c, also called **Triangle** – this room and the hallways connected to it were chosen by the supervisor as the next testing environment.

In short, it is a square room containing multiple obstacles such as chairs, tables, counters and shelves, with the associated hallways being obstructed by plants, slight nooks in walls, desks, and chairs along with some other obstacles as well (fire extinguishers etc.).

This is a more intermediate environment, containing many obstacles, and is expected to be harder to navigate. Since it is a virtual copy of a real-world environment, the user who will test this room has the option of exploring the real-world counterpart as well, so we could evaluate whether the cognitive map they have created during the virtual exploration has helped in any way.

The main blueprint for the creation of the Unity scene for this environment, were the fire evacuation plans of the floor as pictured in Figure 5.4



Figure 5.4. A photo of the fire evacuation plan for the whole third floor

This fire plan served only as a basis for the empty rooms and hallways, with the contents of the rooms and hallways being modeled and placed according to real world photos taken of these environments by the author in February 2024 (example pictured in Figures 5.5 and 5.6).

The result of this virtualization can be seen in Figure 5.5, along with a real-world photo taken approximately from the same spot for reference.

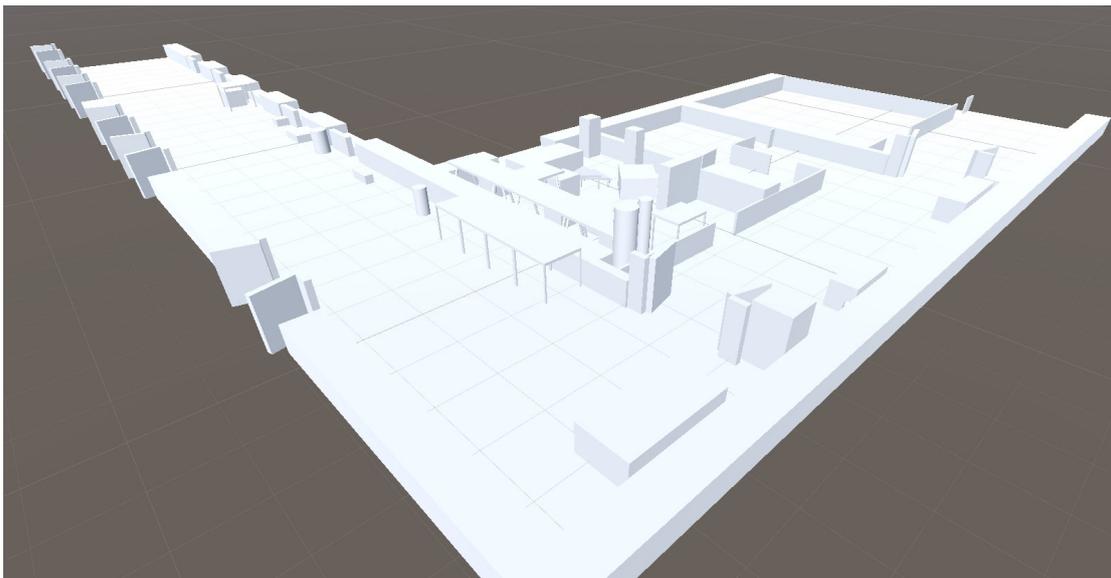


Figure 5.5. A screenshot of the Unity scene with the Triangle study room and halls



Figure 5.6. A photo of the real world Triangle study room and halls

Chapter 6

Evaluation

This chapter is focused on describing the evaluation process of this work, which consisted primarily of user testing, followed by the evaluation of the tests and further design and suggestions for modifications or improvements.

6.1 First round of testing

The first round of testing was done early in the project, to serve as a proof of concept and a test of the basic forms of navigation along straight lines. As this was also quite early in the development of the project, this testing only included haptic feedback.

6.1.1 Procedure

The procedure employed during the testing was unified and divided into four main parts:

1. Preparation

The user will be familiarized with how the VR setup works, how will he use it, and what he should expect going into the testing. This will prepare the user for the actual testing phase and should limit any unnecessary confusion, that may arise from the possible inexperience with VR.

2. Calibration

The user will stand in one place, will put on the VR headset, and will be handed the real-world white cane with an attached VR controller. The user will then point the cane straight down and touch the floor with the tip of it. Then the supervisor of the test will adjust the size and orientation of the cane in the VR application, so it corresponds with the real-world placement.

3. Test walkthrough

This phase is self-explanatory. The user will have the option to explore the VR environment using the provided HW. In the beginning phases, this will be without specific goals to check the whole proof of concept. In later stages, this will include objectives, such as finding specific objects or navigating to a specific place.

The participant's walkthroughs will be recorded mainly for later examination, however due to the agreement of not publishing these recordings later, they will not be a part of the virtual attachments of this work.

4. Feedback gathering

This will be the last phase, during which the user will describe his experience with the application and provide feedback.

Participant feedback will be anonymized, therefore only stand-in designations such as P1-P4 will be used.

6.1.2 Testing

Following are the specifications of the test itself, verbal description of the process employed (further building upon the procedure described in the section above), feedback, and outtakes.

- Testing level: Room with a nook (as seen in Figure 5.3)
- Real-world environment: A 2x2 meters big, empty space in a room
- Number of users: 1
- Used PC: Legion 5 Pro 16ACH6H
- Used cane: Prototype white cane with an attached controller (shown in Figure 4.1) without headphones

Test description: The user went through the standard Preparation and Calibration phase as described in chapter 6, the only difference being that the Test walkthrough has been done twice. The real room, that has been utilized was not sufficiently large to explore the whole virtual room, there was enough space to explore the nook with the pillar in it. Due to technical difficulties, the headset had to be connected to the main PC used for the execution of the VR prototype via cable.

User feedback:

- The user was surprised at different types of vibrations for seemingly the same objects - this seemed to confuse him somewhat as he expected the type of vibration to be associated with the surface of the object.
- The user complained about the real room floor - a carpet, saying that even though the carpet causes minimal vibrations, it is interrupting and overshadowing the vibrations of the white cane.
- He also praised the presence of the computer with which the VR environment was simulated, as the whirring of the fans gave him an audio anchor to which he could relate and with which he could orientate himself.
- The user also suggested that the thin walls could be used as a guiding line for a specific route.

Observer feedback:

- The user was able to find the main walls quite quickly, and was able to orientate himself around corners, but had difficulty with measuring the gaps between the pillar and the walls, feeling that they were too narrow.
- The limited real space available for testing affected the ability to explore the environment fully.
- The user was able to push the tip of the virtual white cane through the floor, which caused him to receive imprecise audio feedback.

Main Outtakes:

- The vibration variations/strengths may be confusing and require further attention and were not really helpful to the participant
- Calibration may require a refactor
- The main goal – orientation in a room seems to be possible, even in the current prototype the user was able to find his bearing

- The usage of vibrations as guiding lines may require a different approach for example the computation of directional vectors vs. a wall
- Audio queues may be utilized to control the user's perception of the environment, maybe even with the potential to approximate redirected walking when leading a user along a curved line and moving an audio source appropriately
- The real ground has to be as smooth as possible

6.2 Improvements

Based on the gathered and observed data, we have improved upon the first prototype in two ways, corresponding to our two ways of providing feedback to the user. The auditory and haptic feedback both were developed further.

6.2.1 Haptic Feedback improvement

As mentioned in Chapter 4.3, the white cane evolved during the project. It was at this point, where we have implemented the physical brake into the physical white cane, to provide the user with presumably better and more tangible haptic feedback when providing information about collisions with virtual objects.

Another improvement was disabling the variable intensity of vibrations, as it only confused the participants and provided no additional benefit to the prototype as a whole.

6.2.2 Audio feedback

After the first round of testing, it became apparent that to be able to receive relevant feedback, we would have to isolate the participant from the outside disturbances, that could unintentionally affect the exploration process. This included giving the participant headphones, so no audio sources would interrupt the user.

6.2.3 Cane caused feedback

Headphones also served as the source for our auditory feedback, which we were now able to provide to the user. New logic was implemented, that now provides feedback as described in 4.1.1. The user would receive an audio queue describing the object when colliding with it. In the case of walls, it was the simple sound of an impact on the wall, however for more intermediate objects such as chairs or tables, for each kind of an object an audio clue in the Czech language saying what type of an object it was, was recorded.

The objects in the scene were afterward sorted into different layers (one layer for each type of object), and the audio feedback logic determined which sound to play depending on the layer in which the object was. The source of the audio always moved to play the description of the object or the impact sound from the point where the impact happened.

6.2.4 User-caused feedback

Another form of audio feedback implemented differed in the fact that the source of the audio was not a collision of the white cane with a virtual object, but the users themselves colliding with virtual objects.

This feedback was mainly implemented to stop the users from moving into virtual obstacles with their body, which until now was being tracked via the VR headset, but the information was not being used in any way. Therefore we implemented a collider for the head of the user and recorded an audio tracking explaining to the user in the Czech language, that they have stepped inside of an obstacle.

6.3 Second round of testing

The second round of testing was done a month before the submission of this work and was aimed primarily at the testing of the implemented features based on user feedback from the previous testing, while also giving the users a harder environment to navigate and more difficult and specific tasks to complete. The participants signed a consent form that is included in Appendix A.

6.3.1 Testing

Following are the specifications of the test itself, description of the process employed, feedback, and take-away information.

- Testing level: Triangle room (shown in Figure 5.5)
- Real-world environment: PE hall (17x5 meters)
- Number of users: 4
- Used PC: Legion 5 Pro 16ACH6H
- Used cane: Prototype white cane with an attached controller and a physical brake (as depicted in Figure 5.2)

Test description:

This testing has been done in combination with another project concerning the generation and creation of tactile maps (environmental maps, that are supposed to be read via touching them, serving primarily VI users, pictured in Figure 6.1), therefore the testing group was split into halves.



Figure 6.1. A tactile map created from the .fbx model of the Unity scene, enhanced by orientation symbols

One half began their testing with the interaction with tactile maps while the other started by exploring our virtual environment. After they have finished exploring the project they started with, they have moved on to the other one.

This was mainly done to test the combination of two approaches to the creation of tactile maps, as the ultimate scope of this and other works is to find the best combination of approaches to the problem of the CM creation. This may appear at the first glance to invalidate the results of this testing in the scope of only this work, but ultimately, haptic or tactile feedback is a part of the feedback we can provide to the participants and a tactile map, while a distinctly separate method fits this purpose as well.

As mentioned in the chapter concerning virtual environments, the environment used for this round of testing was modeled after a real-world environment, meaning that we could and also did use the real-world Triangle room for the final evaluation, whether the users have created at least a rough cognitive map of the environment they were supposed to explore.

During the VR testing, they were tasked with finding their way into the main Triangle room, while the participants started in the halls outside of it. They were given verbal descriptions of the route they had to take and after that, it was up to them to navigate to the target room.

After they got in there, they were tasked with exploring the room and memorizing the layout of it, so they could give a verbal description. Apart from this, the users were also presented with a final questionnaire (Appendix B) so we could also gather some quantitative (although subjective) results. During the whole testing process of both the virtual environment and tactile maps, the participants were recorded for future analysis of their experience.

6.3.2 Qualitative User Feedback

After the test, we gathered the participant's feedback and made some observations from the point of view of the supervisors of the tests as well. This section lists the most prominent feedback from each of the participants as well as the general supervisor feedback.

User feedback P1:

- The participant felt that they were not fully in control of the orientation. When successfully navigating through doors, they felt it was random
- Walking backward when running into an obstacle was unintuitive
- The physical brake was not tangible enough
- The participant expressed the feelings, that the weight of the tip of the cane affected their performance
- The angle of the tip colliding with the floor affected, whether the physical brake had any effect at all
- The auditory feedback while helpful in determining the obstacle did not help in differentiating between different objects of the same kind.

User feedback P2:

- The participant had trouble perceiving physical brake feedback, until they started to hold the white cane steadily at the same angle at all times
- The participant felt isolated from the outside world, maybe even lost. They were used to perceiving the world around them and headphones combined with the VR headset negated this completely.
- The participant praised being able to use walls as guiding lines and walk alongside them.

User feedback P3:

- The participant didn't perceive the physical brakes feedback at all
- The participant felt unsure of where they were during most of the testing

User feedback P4:

- The participant felt that the virtual environment was a lot smaller than the real-world counterpart.
- The participant felt that the testing would benefit from an environment, which had more free space.
- The participant was unsure of how many doors they went through, as their uniqueness was hard to determine.
- The participant mainly relied on the auditory feedback coupled with the vibrations from the controller, not the physical brake.
- The participant discovered, that the feedback was tied to the position of the cane, not his body, therefore he knew whether the cane was in a collision, but not if his body or head were inside of an object.
- The participant felt that it may be beneficial to include an auditory anchor for both a stable point for orientation and the goal of the navigation, maybe even with sound pitch changing according to whether he was facing the destination goal or not.
- The participant expressed, that they would prefer to utilize the vibrations as a means of a guiding line, that they would walk on, not alongside.

Observer feedback:

- We have received mixed user feedback, as every participant who tested the project had a slightly different approach to their usual orientation, which affected the overall performance during testing.
- The difficulties with receiving physical brake feedback mainly arose from inconsistent angles of the tip of the cane - some participants were used to utilizing fast movements, which tilted the cane (as can be seen in Figure 6.2), therefore they did not receive the haptic feedback.



Figure 6.2. The cane tip can be quite easily tilted when in fast motion and even the slightest angling of the tip can lead to the haptic feedback not being perceivable.

- It was sometimes necessary to manually adjust the participant's position, as while they were supposed to have enough real-world room, due to inconsistencies in their orientation on startup, it resulted in them having less space than intended.
- The participants had no way of returning to a place they were familiar with unless they asked for help from the supervisor
- The angles and turns the participants were doing were not perceivable to them - they were not sure if they just crossed a corner or adjusted slightly.
- There will be a need to overhaul the body collision detection, as at this point, the user may have the cane outstretched in a free space, their head may be tilted in a free space as well, but their body may be in a collision with an obstacle.
- The auditory feedback while useful had inconsistent lengths and sometimes started with milliseconds of delay which with fast cane movements was enough not to play it (or play only the silent part of the feedback).
- It would be best to disable the interruption of auditory feedback whenever one was already being played - again with rapid white cane movements, the different audio tracks describing the obstacle interrupted one another.
- While the prototype is still in the testing phase, and therefore requires supervisor interaction, at this point, the user might not even be self-reliant, as the system could be improved, so as not to require more supervisor interaction, than necessary.

6.3.3 Quantitative Feedback

The participants were presented with a questionnaire consisting of 10 statements related to their experience during the testing of the system, where for each question they could grade how strongly they agreed or disagreed with the current statement, on a scale of 1-5. The form of the questionnaire was inspired by the SUS usability questionnaire, however, it did not adhere to the precise formulation of SUS questions. Therefore we can have a 1-5 grade for each of the statements, which depending on the formulation of the statement itself can either be a good result or an indication of an area we should focus on in future development. A sample questionnaire is included as a part of the attachments (as a part of the session guide in Appendix B).

However, if we were to calculate a SUS score, the mean is 55.63 which would translate into an OK result, right in the middle of the learnability scale.

The questionnaire was presented in written form, therefore for the VI participants, it was read out loud and their responses were written down by the supervisor.

This section serves for the evaluation and visualization of gathered answers.

6.3.4 Quantitative Feedback Results

In this section we list all the different responses we have received anonymized and transformed into a bar chart and a final table with the results and explanation of the meaning of the result.

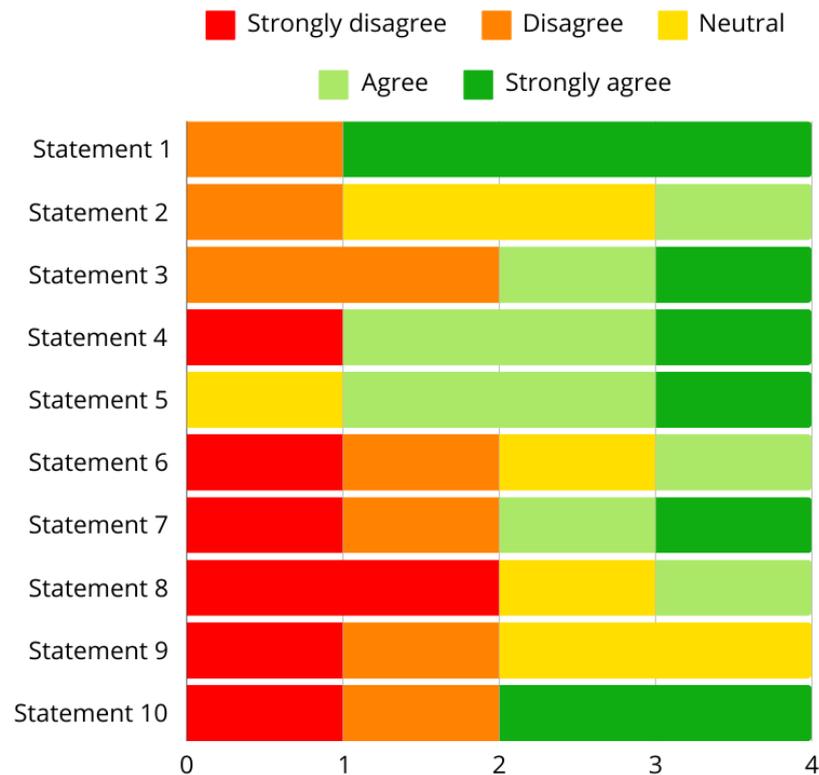


Figure 6.3. A bar chart displaying the responses of the participants to the statements of the questionnaire

Statement	Score	Goal
1	4,25	5
2	3	1
3	3.25	5
4	3.5	1
5	4	5
6	2.5	1
7	3	5
8	2.25	1
9	2.25	5
10	3.25	1

Table 6.1. The resulting scores for the questionnaire statements.

6.3.5 Areas to focus on in the future

These are the areas, that received either a score under 2.5 when the goal was to reach a 5 or above 3.5 when the goal was to get closest to 1 (that is including the border values).

The statements that fit this criterion are statements 4 and 9.

Statement 4 covered the feeling of the user of needing help with the system at the beginning. The score here is completely understandable, as even the prototype featured help from the supervisors at the beginning in the form of giving the users instructions, telling them what they should expect, etc. However, this is a valid area to improve upon, whenever the prototype should start to be considered a stand-alone application, that would need no outside interference at all.

The results of statement 9 show us, that the participants were uncertain when using the system. Especially, as can be seen in the bar chart shown in Figure 6.3, none of the users agreed to feeling certain, they were either neutral on the system or disagreed. This is a very important feedback note for us, as the user's certainty affects their trust in the system and their comfort when using it.

6.3.6 Areas with middling results

These are the areas with scores between 2.5 and 3.5 (including the border values and excluding the already covered ones), independent of what the goal was. These areas show possible means of improvement, as the reception of the current implementation may have been mixed and not neutral- which according to the graphs is the case in many of our results.

This may be caused by the variations in the participant's expertise, predispositions or differences in their approaches to orientation in their daily lives.

Statements fitting this criterion are statements 2, 3, 6, 7 and 10.

In statement 2, we can see, that the participants were unsure, whether the system helped them create an idea about a real-world environment - this question was unfortunately asked before they had a chance to compare with a real environment, however the main feedback from the users provided us with information that while they remembered what they could expect in terms of obstacle types and where approximately, they could expect them for example in a room, they could not create a CM of the whole layout, as the angles, turns and lack of orientational information left them confused in the virtual environment.

Statement 3 shows, that participants had trouble using the system. From the supervisor's observations as well as the participant's feedback, this score may very well be the result of the physical brake not providing sufficient feedback when angled, the added weight on the cane, and the unintuitive approach to exploring their surroundings, with missing physical obstacles.

The results of statement 6 are quite mixed, as the replies are each unique. This signifies that while for some users we may have found an approach that was natural for them and they found it consistent, others would disagree. The causes may be multiple, mainly again the physical limitations of the current brake system and the audio track interruption/delay at times, which could be in these circumstances perceived as random by the participants, thus the inconsistency.

Statement 7 is a further generalization of the statement 4. It mainly serves as a way for the participant to express, if they think they had issues, that would be unique to them and therefore a wider sample of participants may not encounter them. However, mixed results in responses to this statement show, that at best, the current implementation is not very self-explanatory and may require a tutorial or an intro session, for the average user to start using it, at least according to our current participants.

Finally, statement 10 is all about the load of information, the users had to process and start paying attention to when using the system. As apparent from the participants feedback as well as this result, the users while finding the interaction methods similar to their everyday approach, felt that they had to learn to use them slightly differently.

6.3.7 Well-received components of the system

This part is dedicated to the rest of the system components, that were, at least according to the mean of the feedback score, well received by the participants. However, this in no way means that the areas can not be improved upon.

Such areas are covered by statements 1, 5, and 8.

The first statement is a clear indication, that while the system may be rough around the edges at this moment, most of our participants would not mind using it repeatedly and maybe even master the current implementation until they would be comfortable using it. This, while not providing much information for future improvements shows an optimistic outlook on the willingness of the users of the system to continue using it.

Results of statement 5 show, that the participants were able to differentiate between individual aspects of the system and most agreed, that by themselves the aspects seemed to be well implemented, at least from their perspective. This shows that an issue with the functionalities of the system as a whole may in part also arise from the combination of the different aspects.

The last statement to review the results of is the statement 8. This one is focused on the accuracy of the system. The results show that the users feel the system is accurate enough for half of them to completely disagree with an opposite statement and it shows that the interactions, while inconsistent are accurate in the information they convey to the user, when they convey it successfully.

Chapter 7

Conclusions

This Chapter contains a summary, of how we have approached the goals of this work declared in Chapter 1 and whether they have been completed and to what degree.

1. *Research and analysis of the current state of the art in the field of VR for VI*

The analysis has been done mostly in Chapter 2, where we have looked for works with the most similar approach to ours. We have found quite a few already existing works, that while similar to our intent approached it differently from either a technical or a hardware standpoint and that we drew upon during this work.

2. *A prototype of a VR solution, that would assist and provide an easy and safe way for VI users to create a CM in a controlled environment, which could then be used to navigate a real environment.*

This goal can not be precisely pinpointed to one part of the thesis, as the implementation, design, testing, and further improvements are described throughout the whole thesis, where relevant. However, this goal has been completed successfully, with the result being attached in the form of the prototype files.

3. *Evaluate how the users interact with the implemented methods.*

This goal was completed in Chapter 6, where we have taken the prototype and tested it with participants from our user group, made evaluations based on these tests and either implemented new improvements or suggested them for future work as in Chapter 8.

4. *Improve upon the implemented prototype as much as possible, according to feedback gathered throughout the testing.*

Again, this goal can be mainly traced to the chapter 6, which covered both the testing, evaluation, and improvement process. The prototype went through two testing phases, with one improvement implementation phase between them and with improvements based on the last testing phase being suggested, as mentioned in the goal above.

5. *Ability to generate a virtual reality environment from a pre-implemented model*

This part of the work has not been completed, as it was left out during the creation of functional requirements and has been considered mostly as an option for development with surplus time, as this feature depends heavily on other projects running in parallel, which implement the export and creation of the pre-implemented models. However, at this moment, this feature has been left fully for future development.

In summary, during this project, we analyzed available sources and state-of-the-art articles for the problem of the creation of CM by individuals with VI. We have created an early prototype to test our approach to this problem, tested it with a participant from our user group, made further developments according to the user feedback and UCD pattern and then made further tests.

In terms of functional and non-functional requirements, all of the functional requirements described in the section 3.1 have been fulfilled.

Similarly with two exceptions, non-functional requirements described in the section 3.2 have been fulfilled as well.

One exception was **NFR4**, which has not been implemented fully, as the users had only one optional testing environment, however, familiarization with the system could and was done in the same scene as testing.

The other exception was **NFR3**. While we have modeled the interaction methods with the goal to be as realistic and similar to real-world interaction methods in mind, this can not be classified as fully successfully implemented as complications listed during the testing show, that user preference in the available interaction methods varies greatly and can not be declared as fully satisfactory for all of them.

Chapter 8

Future work

As the scope of this work was focused mainly on prototyping and evaluation of the project, it will be necessary to improve upon this work if it is to serve as a foundation for further research into this problem. As is apparent from Chapter 6, there are many ways in which this work can be improved upon, and while there may not be enough resources and time available to implement further improvements as a part of this work, we can at least suggest and think up solutions that may help further connected projects. This is the main purpose of this chapter.

8.1 Directional orientation

As apparent from the participant feedback in Chapter 6, the participants commonly felt unsure about the turns they made, the angles at which they were walking and in general how much they have been turning around. This trend was especially apparent in congenitally blind participants, for whom angles, may have held no actual meaning at all, since their allocentric perception of environments may have been quite different from what a non-congenitally blind user may experience.

This left them confused and sometimes unable to process how far have they gone and in which direction.

8.1.1 Solution via clearer instructions

While this may be solved by the emphasis on the user to only navigate along walls, stop at crucial points and mainly explore their surrounding stationary before moving further, this may not be a good approach as the participants are used to navigation during movement (this was observed during the testing) and stopping and especially retracing their steps comes unnaturally to them.

One issue that is inherent to our approach that can not be fixed at this moment is the interaction with the physical break of the cane during movement. Since the break is friction based, if it protrudes during forward movement where the user is swiping the cane at the same time (a situation where the user is walking alongside a wall and hits the wall with the cane from a side), then the cane stops all movement since friction can not limit only one axis of movement, therefore it stops the users movement, affecting his sense of presence in the environment. This issue may only be fixed by exploring an entirely different approach to implementing the physical break.

8.1.2 Systematical solution

A systematical solution to this problem may require the implementation of further new features. A solution for this problem may be an on-demand auditory anchor - an audio source that will be set in the same place at all times in the virtual environment and which will provide the user with auditory feedback, the user may use to figure out how much has he turned around.

The feedback could either play a single sound after pushing a button on the virtual reality controller attached to the white cane, or could be toggled on and off and play a constant non-intrusive noise that the user could use at all times or be on by default and instead disabled on-demand.

It will need to be tested which approach would be best suited for the average user, but a recommended approach based on the observations would be to have the auditory anchor active by default with the option of on-demand deactivation, as this provides the unfamiliar user with a constant feedback source with which they can orientate themselves and once they feel comfortable with their bearings, they can disable it at will.

8.2 Environmental orientation

As already mentioned in the previous section 8.1, the participants sometimes felt unsure in which part of the environment they were at the moment. The transitions through doors were unclear as well, as there was no feedback for going through the door, except for the user finding a door and then having to figure out that there may be an open space next to it, that they could walk through.

A solution for this could be to split the environments into sections representing different rooms or transitions between areas, which would have a description / name that the user would be given via audio feedback whenever they would change the area they were in (an example split of rooms can be seen in Figure 8.1). This information may also be handy to be able to be played on-demand, as this would allow the user to not stress about remembering where they were at the moment.

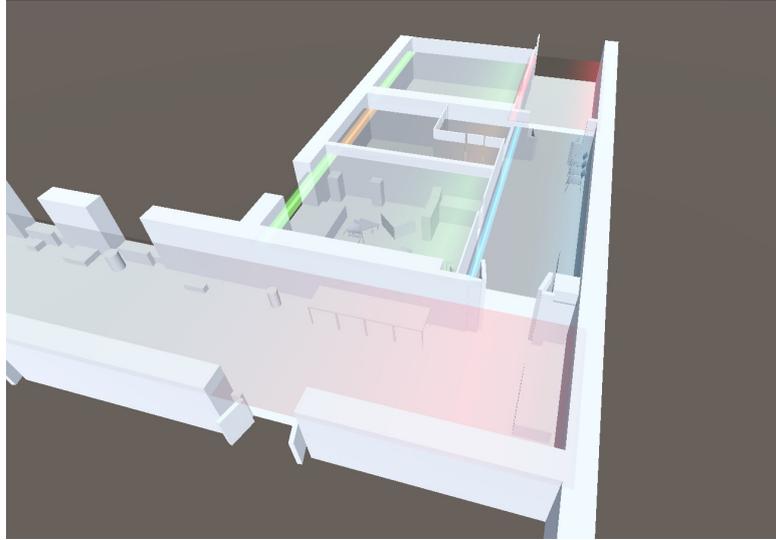


Figure 8.1. A screenshot showing an example of a divided environment into separate rooms, colour coded for better visualization.

Another improvement, that could be made is to label different parts of a virtual obstacle separately – for example, divide a two-winged door into a left and a right door wing, with each of them having a unique audio queue. This may help the user with finding an empty space in between unique objects, instead of guessing, since until now, the objects were unrecognizable from each other. This may also be applied to objects of the same type next to each other.

Another approach all together could be inspired by the work of Han et al. [18], where their work included among others a virtual guide dog, which served as a guide to the nearest points of interest, just as a real-world one would. An approach like this would both improve the user's orientation capabilities, by leading them to important parts of the environment and build upon the experience they may already have with utilizing real-world guide dogs.

8.3 User collision with obstacles

Another issue found during testing was the fact that the only tracked objects were the white cane and the participant's heads, however, when using the white cane, the feedback of the cane was self-explanatory and it can always be maneuvered outside of objects. However, if the user collides with an obstacle with their head, they only received feedback that a collision was happening, however the participants got confused as to where they should walk to not be in collision (this may also be caused by the previously discussed issue in section (8.1) of imperceptible angles and rotations the participant has undertaken). Also, the fact that their body did not have any collision meant that they could be standing inside shorter objects, such as chairs and tables, where the head collider was well above the obstacle.

The solution here may require multiple interconnected improvements.

The first would be implementing a collider logic for the user's body as well, however, it should be noted that this collider should follow the same logic as the already existing collider, so it should not react to the floor of the environments and the white cane (we do not want to trigger haptic feedback, when the virtual user's body collides with the handle of the white cane).

Then there may be two approaches for solving the issues with navigating into an open space.

One would be implementing a system, that would be able to find the closest empty (meaning with enough space for the user's body head and preferably at least most of the length of the white cane) and valid space, that the user would then be guided to via audio feedback telling them where to go. This however would need to be heavily tested, as there may be invalid empty spaces, that would only confuse the user, such as outside spaces or empty spaces completely surrounded by obstacles (think a circle of tables, where the user would get navigated inside).

Another approach may be, to implement the previously suggested features and see whether they are not sufficient enough by themselves. A stable auditory anchor paired with the auditory descriptions of sensible sub-parts of the virtual environments could prove to be enough for the user to be able to navigate outside of collisions with obstacles as they would now have both directional and spatial information about their location and their location relative to a stable point.

This issue may also be translated into the real world, as in the current prototype, the user is limited by the real space they have to explore the virtual one. However, when they start to run out of space and for example may encounter a wall, they again rely on the white cane, or the supervisor to adjust their movement and inform them about obstacles. This could however be automated, for example, using the Meta Quest point cloud object detection.

8.4 White cane improvement

As pictured in Figure 5.2, the tip of the white cane includes a casing with flat underside, where the physical rubber break is located. However, the tangibility of this feedback heavily depends on the angle of the whole casing. Even a slight deviation causes the feedback to become intangible, which especially for users, who are used to a more rapid exploration with their white canes causes issues when perceiving it.

One solution would be to change the shape of the rubber tip and the amount it protrudes outwards, if possible. Further protrusion will counteract slight angling of the underside of the casings and for example, a semi-sphere may be better, as again it would not require the casing to be flush with the flooring and instead may work even when tilted.

8.5 An improvement for participants with leftover vision

A part of our participant group was not fully blind, as they had leftover vision and were quite used to utilizing it in well-lit and contrasting environments. While the main user group we focus on are users with no vision whatsoever, participants with leftover vision are still a part of the whole visually impaired user group. As such, there would be no reason not to try to improve the informational capabilities of the system towards these users as well.

A significant improvement for these users may be utilizing the headset and instead of showing the virtual environment with all objects having no texture, it may be viable to preprocess the scene and either apply visually contrasting materials (for example, blue flooring, white walls and red obstacles or similar, as pictured in Figure 8.2) or eventually going as far as implementing a separate shader that could draw thick outlines on all objects in the scene, which could help users with leftover vision to benefit from it even in this system.

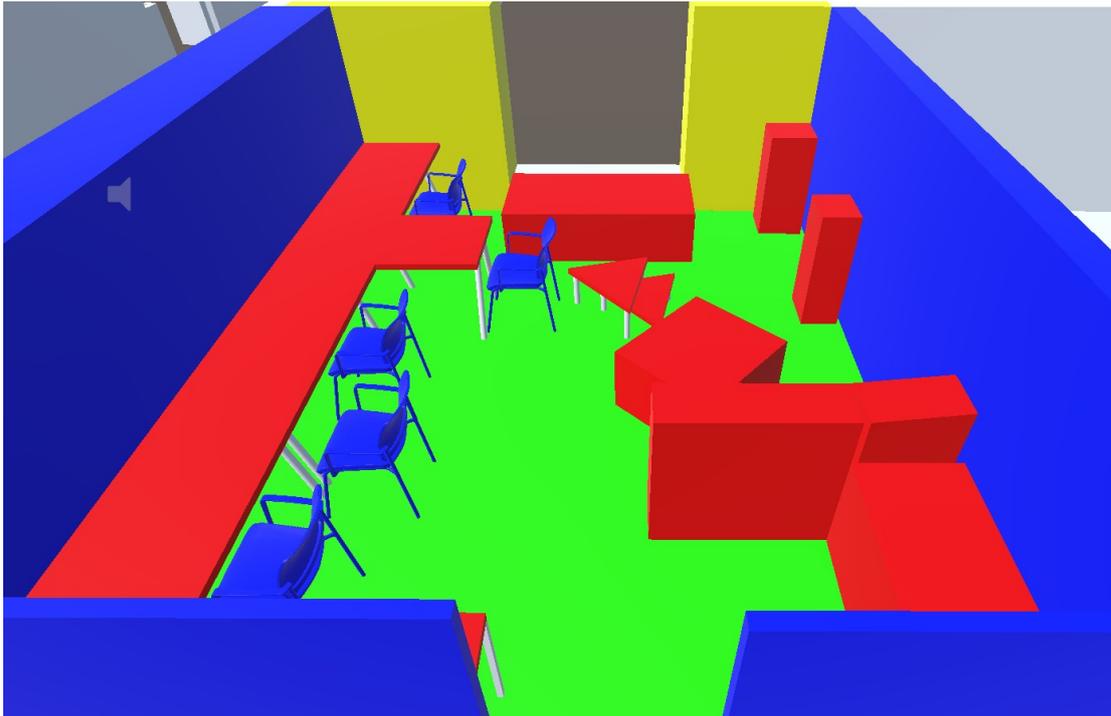


Figure 8.2. A screenshot showing an example of obstacles coloured contrasting colours.

8.6 Audio feedback overhaul

The audio feedback logic at this point consisted of playing prerecorded audio tracks for the user when a collision between a white cane and a virtual object happens or when the participant's head collided with an object.

The rudimentary logic implemented for this caused the participants a few issues when registering the audio feedback, as the audio tracks could be interrupted and played from the start again without finishing, for example when the user quickly collided with multiple objects in a short time. The fact that the audio tracks were only prerecorded also limits the usability for future virtual environments as all new types of objects may need to have a new separate recording made.

While this approach may be suitable for manually created environments and prototypes testing the functionality, a standalone system that would dynamically create virtual environments would need a more flexible approach. One option for this would be implementing or utilizing an already existing text-to-speech solution (possibly even utilizing artificial intelligence), that could read out loud the names of the objects the user is colliding with, and in the case of future implementations, even announce the change of the environment section the user is currently in, as described in this section 8.2.

After implementing any number of these suggestions, I believe that the prototype would be ready for further testing, so that we could keep following the UCD pattern and further improve this prototype until the requirements are met without exception and the users feel comfortable and safe using this system to create CMs of before unexplored indoor environments.

Chapter 9

Glossary

- CM ■ cognitive map
- HW ■ hardware
- SW ■ software
- UCD ■ User Centered Design
- UDP ■ User Datagram Protocol
- VI ■ vision impairments

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Appendix A

Consent form given to participants

INFORMOVANÝ SOUHLAS S ÚČASTÍ VE VÝZKUMU

Název studie: **Ověření nových metod pro podporu tvorby kognitivní mapy prostředí**
Vedoucí výzkumník: **Ing. Miroslav Macík, Ph.D.**
Instituce: **ČVUT v Praze**

Jméno účastníka:

1. ÚČEL STUDIE

Cílem projektu *Cog Map* je výzkum podpory získávání kognitivní (mentální) mapy prostředí - interiérů budov pomocí hmatových map a speciálních metod pro virtuální realitu pro osoby se zrakovým postižením.

Žádáme Vás tímto, abyste se dobrovolně zapojil(a) do výzkumné studie. Tento formulář obsahuje informace o této studii. Rádi bychom se ujistili, že jste obeznámen(a) s účelem této studie a s tím, co pro Vás účast v této studii bude znamenat. Prosíme, nepodepisujte tento formulář, pokud nerozumíte některé části tohoto textu. V takovém případě se nás neváhejte na cokoli zeptat.

Díky Vám a Vaším názorům budeme schopni upravit produkt tak, aby jeho použití bylo efektivní a snadné.

2. ÚČAST VE STUDII

Očekáváme, že se této studii zúčastní 4 až 6 osob. Kritériem pro výběr účastníků je přítomnost zrakového postižení.

Vaše účast v této studii je dobrovolná. Očekáváme, že se zúčastníte jednoho sezení, které se bude skládat z krátkého rozhovoru zaměřeného na prostorovou orientaci. Následovat bude samotný uživatelský test prozkoumávání prostoru pomocí virtuální reality a interakci pomocí hmatových map. Tento test nevyžaduje jakoukoli přípravu ze strany uživatele. Celková doba sezení bude přibližně 80 minut.

3. ÚHRADA NÁKLADŮ

Veškeré výdaje spojené s Vaší účastí ve studii budou hrazeny z prostředků ČVUT. Odměnu od nás, jako výraz našich díků za Váš čas, dostanete i v případě, že se rozhodnete předčasně ukončit vaši účast ve studii.

4. UTAJENÍ ZÍSKANÝCH INFORMACÍ

Vaše odpovědi zaznamenáme do našich poznámek, které budou vedeny anonymně, a nijak z nich nebude možné zpětně identifikovat Vaši osobu. Informace budou zpracovány během analýzy získaných dat a objeví se ve výsledcích projektu, ale opět jen tak, že nebude možné dohledat, od koho jsme je získali.

V průběhu experimentu můžeme dělat zvukový nebo obrazový záznam pro potřeby pozdějšího vyhodnocení. Takto získaná data nebudou přímo publikována, ale poslouží jen pro potřeby členů výzkumného týmu související s tímto experimentem.

5. NÁHRADA MOŽNÝCH ŠKOD

Podpisem tohoto dokumentu se nezříkáte svých zákonných práv žádat odškodnění v případě úrazu, který byste utrpěl(a) v přímé souvislosti s touto studií.

6. DOBROVOLNÁ ÚČAST A AUTORIZACE

Vaše rozhodnutí zúčastnit se této studie je zcela dobrovolné.

7. Odstoupení od studie či stažení autorizace

Budete-li si to kdykoliv přát, můžete odstoupit od této studie bez jakýchkoliv negativních důsledků. Pokud se rozhodnete od studie odstoupit později (tj. nebudete chtít, abychom s Vašimi údaji dále pracovali), kontaktujte prosím písemně vedoucího výzkumníka:

Ing. Miroslav Macík, Ph.D.
Katedra počítačové grafiky a interakce, ČVUT FEL
Karlovo náměstí 13, 121 35 Praha 2
Tel.: +420-22435-7678

Od okamžiku Vašeho odstoupení nebudou již Vaše data nově zpracovávána v žádných dalších fázích výzkumného projektu. Nebude však možné měnit již existující publikované dokumenty či hotové a odevzdané výstupy z projektu.

8. KONTAKTNÍ OSOBY

Pro další informace o Vašich právech coby účastníka experimentu, či pokud nebudete spokojen(a) se způsobem, jak je tato studie provozována, můžete kontaktovat výzkumníka odpovídajícího za testování uživatelských rozhraní. Pokud máte libovolnou otázku či pokud utrpíte jakoukoliv újmu během studie, prosím kontaktujte vedoucího projektu:

Ing. Miroslav Macík, Ph.D.
Katedra počítačové grafiky a interakce, ČVUT FEL
Karlovo náměstí 13, 121 35 Praha 2
Tel.: +420-22435-7678

9. POTVRZENÍ

Zaškrtněte jednu z těchto variant	
<input type="checkbox"/> Přečetl(a) jsem si informace v tomto formuláři.	
<input type="checkbox"/> Informace v tomto formuláři mi přečetl:	
Na veškeré otázky, které jsem měl, mi odpověděl:	
Dobrovolně souhlasím s účastí na tomto výzkumu provedeném pracovníky ČVUT FEL. Obdržím podepsanou kopii tohoto formuláře.	
Jméno a příjmení účastníka:	
Datum:	
Podpis účastníka:	

Jméno a příjmení osoby přebírající tento souhlas:	
Datum:	
Podpis této osoby:	

Appendix B

Session guide with a questionnaire

Studie použitelnosti virtuální reality pro tvorbu kognitivních map

Participant

Děkujeme Vám, že se zúčastníte studie o vhodnosti využití virtuální reality pro tvorbu kognitivních map.

Součástí experimentu, je několik úkolů. Prosíme Vás, abyste se je pokusil/a provádět sama. Snažíme se navodit situaci, která bude co nejbližší běžnému samostatnému používání. Veškeré problémy, na které narazíme, jsou potenciální nedokonalosti návrhu uživatelského rozhraní testovaného systému. Přesně tato místa je pro nás velice cenné identifikovat. Pokuste se také prosím o "přemýšlení nahlas", může nám to pomoci identifikovat potenciálně problematická místa, či nám na první pohled skryté problémy.

- Věk, pohlaví, vzdělání, zkušenost s virtuální realitou
- Zrakové postižení (vhodný sampling)
 - Úplně nevidomí
 - Onset (congenitally vs. early, late).

Virtuální prostředí funguje následovně. Na hlavě budete mít virtuálně-realistní headset a v ruce nastavitelnou bílou hůl, u jejíhož držadla je připevněný virtuálně-realistní kontroler. S ani jednou z těchto věcí není třeba z vaší strany interagovat, jsou pouze součástí nutných součástí které k testu potřebujeme.

Dále budete mít na hlavě sluchátka. Za pomoci bílé hole budete prozkoumávat prostředí, ve kterém se nacházíte - v reálném prostředí zde nejsou žádné překážky, pouze prázdná tělocvična - není tedy čeho se bát. Pokud holí narazíte na virtuální překážku, do sluchátek se vám ozve specifický zvuk, pokud se jedná o stěnu a jiný zvuk, pokud jde o nábytek či dveře.

Hůl při kontaktu s překážkou zavibruje a zadrhne na místě, kde překážka začíná a po krátké chvíli opět povolí, abyste mohli pokračovat ve zkoumání prostředí.

=== Úkol 1 ===

Zkuste se dle verbálního popisu cesty dostat do místnosti Triangl

=== Úkol 2 ===

Verbálně popište na kolik překážek jste po cestě narazil/a a kde.

=== Úkol 3 ===

Popište na kolik překážek a kde jste po cestě narazili na taktilní mapě.

=== Úkol 4 ===

Popište prostředí místnosti Triangl

=== Úkol 5 ===

Dle verbálního popisu se přesuňte k záchodům

Post test

Prosíme Vás o vyplnění následujícího dotazníku. Jednotlivé body ve vztahují k Vaší celkové zkušenosti s testovaným systémem.

1. Rád bych systém používal opakovaně

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Rozhodně nesouhlasím Rozhodně souhlasím

2. Systém mi pomohl udělat si obrázek o skutečném prostředí

--	--	--	--	--

Rozhodně nesouhlasím Rozhodně souhlasím

3. Systém se snadno používá

--	--	--	--	--

Rozhodně nesouhlasím Rozhodně souhlasím

4. Potřeboval bych nejdříve asistenci s naučením

--	--	--	--	--

Rozhodně nesouhlasím Rozhodně souhlasím

5. Různé funkce systému jsou do něj dobře začleněny

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Rozhodně nesouhlasím Rozhodně souhlasím

6. Systém je příliš nekonzistentní

--	--	--	--	--

Rozhodně nesouhlasím Rozhodně souhlasím

7. Řekl bych, že většina lidí se se systémem naučí pracovat rychle

--	--	--	--	--

Rozhodně nesouhlasím Rozhodně souhlasím

8. Systém je příliš nepřesný

--	--	--	--	--

Rozhodně nesouhlasím Rozhodně souhlasím

9. Při práci se systémem se cítím jistě

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Rozhodně nesouhlasím Rozhodně souhlasím

10. Musel jsem se hodně naučit, než jsem se systémem dokázal pracovat

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Rozhodně nesouhlasím Rozhodně souhlasím

Appendix C

User manual

A user manual for the „Acquisition of cognitive maps by individuals with vision impairments using virtual reality“ prototype

Requirements:

Oculus Quest 2 virtual reality headset with controllers

Wi-Fi 6 network

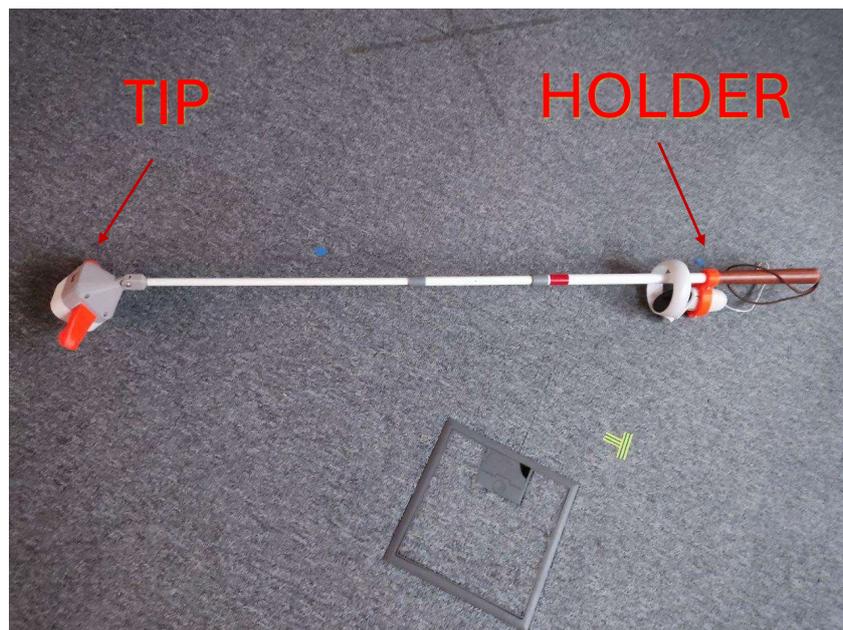
A computer with installed [SteamVR](#), [Unity Hub](#) with Unity 2022.3.13f1 version, [Arduino IDE](#) and finally [Meta Quest Link](#) application.

Project Cogmap extracted from the .zip file from [GitHub](#).

Setup:

First prepare the necessary hardware. If necessary, the prototype can be used without the modified white cane and just with a VR controller. Be advised, that you need to have an the headset connected to a Wi-Fi network.

If you however want to utilize the white cane, it is necessary to first slot the right virtual reality controller into the holder dedicated to this purpose and tighten it using an Allen key. For this, you will need to remove the tip of the cane first, as without this step, the controller will not fit over it.



When using the white cane, if you want to utilize the physical break as well, you will need to make sure to set up the physical break accordingly, as the chip has to have information about the Wi-Fi connection to function properly.

This has to be done by opening Arduino IDE, downloading the ESP32 library (guide [here](#)), connecting the chip via and USB-C cable to the computer, and then uploading to it the modified version of the following code:

```
#include <ESP32Servo.h>
#include <ESP32PWM.h>

#include <WiFi.h>
#include <WiFiUdp.h>

#include "AsyncUDP.h"

// WiFi network name and password:
const char * networkName = ;
const char * networkPswd = ;

//IP address to send UDP data to:
// either use the ip address of the server or
// a network broadcast address
//const char * udpAddress = "192.168.2.113";
const int udpPort = 3333;

//Are we currently connected?
boolean connected = false;

AsyncUDP udp;

//The udp library class
//WiFiUDP udp;

int pos = 0; // variable to store the servo position
Servo myservo; // create servo object to control a servo
int servoPin = 10;

void setup()
{
  Serial.begin(115200);
```

```
Serial.println("test");

ESP32PWM::allocateTimer(0);
ESP32PWM::allocateTimer(1);
ESP32PWM::allocateTimer(2);
ESP32PWM::allocateTimer(3);
myservo.setPeriodHertz(50); // standard 50 hz servo
myservo.attach(servoPin, 800, 4000); // attaches the servo on pin 18 to the
servo object
// using default min/max of 1000us and 2000us
// different servos may require different min/max settings
// for an accurate 0 to 180 sweep

myservo.write(50);

connectToWiFi(networkName, networkPswd);

if (WiFi.waitForConnectResult() != WL_CONNECTED) {
  Serial.println("WiFi Failed");
  while(1) {
    delay(1000);
  }
}

if(udp.listen(3333)) {
  Serial.print("UDP Listening on IP: ");
  Serial.println(WiFi.localIP());
  udp.onPacket([](AsyncUDPPacket packet) {
    Serial.print("UDP Packet Type: ");
    Serial.print(packet.isBroadcast()?"Broadcast":packet.isMulticast()
?"Multicast":"Unicast");
    Serial.print(", From: ");
    Serial.print(packet.remoteIP());
    Serial.print(":");
    Serial.print(packet.remotePort());
    Serial.print(", To: ");
    Serial.print(packet.localIP());
    Serial.print(":");
    Serial.print(packet.localPort());
    Serial.print(", Length: ");
    Serial.print(packet.length());
    Serial.print(", Data: ");
    Serial.write(packet.data(), packet.length());
    Serial.println();

    int servoValue = atoi((char *)packet.data());
```

```
Serial.print(", ServoValue: ");
Serial.print(servoValue);

if (servoValue > 50 && servoValue < 70)
    myservo.write(servoValue);

    packet.printf("Got %u bytes of data", packet.length());
});
}
}

void connectToWiFi(const char * ssid, const char * pwd) {
    Serial.println("Connecting to WiFi network: " + String(ssid));

    // delete old config
    WiFi.disconnect(true);

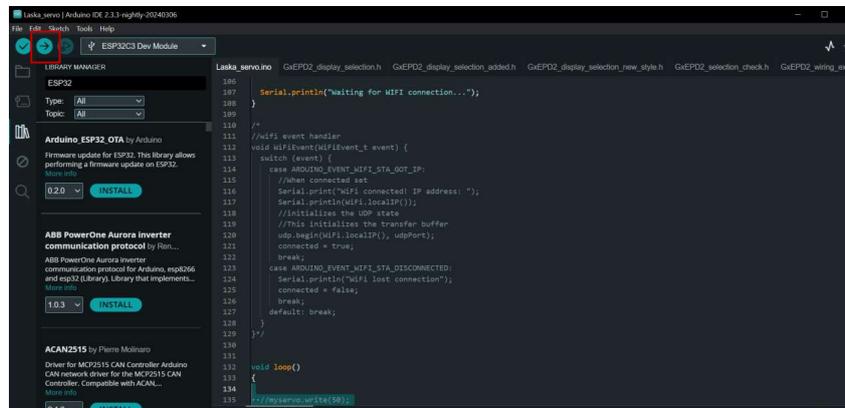
    WiFi.begin(ssid, pwd);

    Serial.println("Waiting for WIFI connection...");
}

void loop()
{
};
```

It is necessary to change the Wi-Fi name and password parameters from the beginning to be for the same Wi-Fi as the headset is connected to.

After this modification, you need to upload this code to the chip connected via the cable.



After the upload is done, the “Serial monitor” interface in Arduino IDE will show you the IP address the chip is connected to. This IP address will have to be written manually into one of the scripts of the prototype in the next steps.

After this, it is necessary to start the Steam VR application, connect the headset to the computer using the Meta Quest Link application (guide available [here](#)) and after that, open the repository with the project using the Unity Hub.

This will open the editor interface of the Unity Development engine.

There it is best to navigate into the „Assets“ folder, where you will see the „Scenes“ folder. This folder contains the levels of the prototype – RoomNook, which was the first developed environment, TriangleTall, which is the second environment developed and Triangle, which was used as a basis for the creation of the tactile maps used in testing.

Furthermore, the “Assets” also contain the “Scripts” folder, which in turn includes the WhiteCane script. If you want to utilize the physical break, you need to open this script, and change the IP address of the client in the “Start” function to correspond to the address the chip is connected to.

After this, you can choose a scene by navigating to the “Scenes” folder and double clicking on a scene. Doing this will load it in the editor. By clicking the arrow symbol in the top part of the editor, you will start the prototype, and if you had done all the previous

preparation steps, it will be transmitted to the headset.



Usage:

After starting the prototype, it is recommended to follow the standard testing procedure described in the main text – therefore start with adjusting the cane length to fit your height, if you are using the white cane, adjust the height of the character player object in Unity to fit as well and change the dimensions of the cane to correspond to the real world counterpart.

After this, you can start exploring the prototype – any and all impacts with the virtual cane with the objects in the prototype should be causing a sound feedback of either an impact sound for a collision with a wall or a verbal description of the object encountered.

Any impact with the virtual obstacles should also trigger the physical break. If this does not happen, please try resetting the break via the pins located at the front of the tip of the cane or checking whether the battery the chip is connected to has ran out.

Appendix D

Attachments

ATTACHMENTS

