Cognitive Maps Acquisition by Those with Vision Impairments in Virtual Reality

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Abstract

Individuals with vision impairments (VI) require specific methods to acquire spatial knowledge of the environment they need to orientate themselves. Such knowledge is called a cognitive map 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. Our research focuses on the employment of Virtual Reality adapted for VI as a novel method for acquiring cognitive maps. We leverage a combination of interaction modalities (vibrations, haptic feedback through a modified white cane, and in the future even spatial audio) to provide spatial knowledge of indoor environments.

Keywords: Virtual Reality, Haptics, Tactile, Spatial orientation, Visually impaired.

1 Introduction

Visually impaired (VI) individuals deal with more difficulties when exploring a new environment than users without visual impairment. Depending on the environment, it may take them more time and effort to orientate themselves, or in some cases, it may even be dangerous. The creation of even basic cognitive maps (CMs) beforehand may lead to a significant improvement during their first real experience with said environment.

We reflect this issue in our research question, which for this work is: If we implement a simple haptic feedback source via a white cane, is it enough information for a VI individual to create at least a rough CM in a safe and controlled environment?

To provide VI individuals with the option above, we have created virtual environments – scenes made in the Unity game development engine with the inclusion of Virtual Reality (VR) libraries needed. We have created so far two environments that, in one case, represent a singular room with basic boundaries and an obstacle, as can be seen in Figure 1. The other scene (shown in Figure 2) represents a more complex scene based on a real environment. It comprises a study room and a section of an adjacent corridor. There are more obstacles than in the basic scene. It contains both hallways, doors, and furniture and is accessible to us on demand. Modeling part of a real environment will allow for more complex evaluation based on the test procedures where it is involved.

These environments are then projected into a VR head-

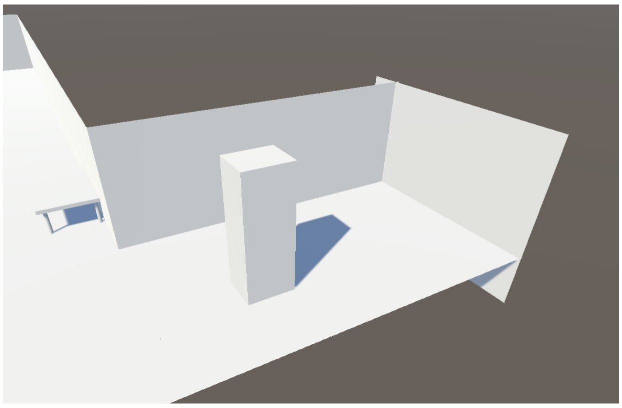

Figure 1: The virtual preliminary testing area - due to real space limitations, the participant was exploring only this part of the room

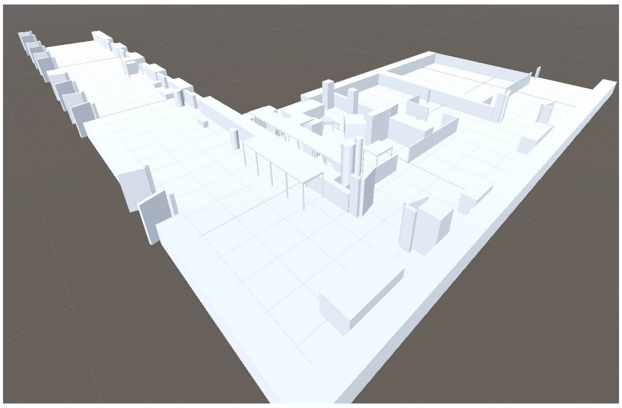

Figure 2: A screenshot of the Unity scene with the study room and halls

set, which the VI participant is wearing. The participant is also provided with a modified white cane, with which they can then explore the created environment.

The paper is structured as follows. In Section 2, we summarize the related work, including examples of methods that utilize VR for purposes of creation of CMs by VI individuals. In Section 3, we discuss the details of two developed prototypes that implement the aforementioned scenes. Section 4 presents only preliminary evaluation that, however, provides strong indications that even simple interaction methods can be utilized for the creation of a CM for VI participants in VR conditions. We describe the testing process for the preliminary evaluation as well as for the more advanced tests we have planned for the near future. Finally, in Section 5, we focus on the results of this work and evaluate the preliminary results.

2 Related work

This section focuses on the cognitive maps and means for their acquisition as an important contributing factor for efficient spatial orientation of VI individuals. Later, we list examples of methods that leverage VR for the VI.

Cognitive map refers to the internally represented model of a spatial environment [9], which contains knowledge of landmarks, route connections, distance and direction relations, and non-spatial attributes. *Cognitive maps* comprise more types of spatial knowledge: locations, layout, routes, distance, and directions between locations [7]. Two basic frames of reference related to spatial knowledge exist – allocentric (object-to-object) and egocentric (subject-to-object) [2]. Well-developed cognitive maps contribute to good spatial orientation and efficient navigation through both indoor and outdoor environments [3].

Interaction methods that employ different sensory modalities can contribute to the acquisition of cognitive maps. For sighted individuals, the natural method is a direct experience in the visited environment, but in many cases, different kinds of topographical maps are used (classical, digital, 2D, 3D) [4]. In some cases, Virtual Reality and Augmented Reality are useful to increase efficiency safety (training of movement in dangerous areas) or provide specific information that would be less accessible using other methods (i.e., the spatial position of electrical wires or plumbing) [5]. In the case of VI individuals, the situation is similar; however, they (VI individuals) have specific needs, abilities, and preferences. For them, it is more complicated to get information in the allocentric frame of reference. For this purpose, (interactive) tactile maps are usually employed [1].

The formation of *cognitive maps* is a challenging process for VI individuals as it requires substituting vision with other sensory modalities or their combination. Ottink et al. [7] provide a literature overview of methods for cognitive map acquisition based on non-visual modalities, with a particular focus on the auditory, haptic, and multimodal approach for the VI. The authors conclude that VI individuals can form *cognitive maps* using more sensory modalities or their combination. However, some modalities are better suited for building different types of spatial knowledge in *cognitive maps*. Navigational strategies that affect the formation of *cognitive maps* are the route and survey strategies. Survey strategies require map-like (allocentric) representations of the spatial environment in a *cognitive map* and are usually connected with a better orientation performance.

Kunz et al. [6] and Siu et al. [8] provide examples of approaches that utilize walkable VR for purposes of creation of *cognitive maps* for the VI.

Kunz et al. [6] focus on implementing and testing a purely auditory method for the navigation and orientation of non-VI blindfolded users, who then navigated a virtual maze based on the audio feedback that has been supplied to them via headphones. The main source of feedback — audio — is spatial, so the participant can change his movement according to where the obstacle is detected. From the results of this study, it is apparent that audio feedback by itself, while definitely providing enough information about the environment to improve the participant's awareness of their surroundings, is not enough to sufficiently improve the participant's orientation capabilities for it to be the only source of information about the environment. This is an important takeaway for our work, as while not being completely sufficient, the auditory feedback nevertheless improved the creation process of CMs.

The work of Siu et al. [8], however, is 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 served mainly as an inspiration as to what the end goal of the work may be while focusing on a more straightforward and less complex solution in terms of the hardware (HW) used.

The aforementioned approaches are focused on a similar goal as this work, albeit they utilize slightly different means of implementation than what is done in this preliminary work or planned for future work (Section6). We utilize these works as points of reference, sources, and inspirations during the design and implementation of our work, and they also help us to orientate ourselves more in the area of interest and understand the issues that may arise during our own development.

3 Prototypes

As mentioned in Section 1, the whole setup for our work consists of a single Virtual Reality headset (Oculus Quest 2), one prototype white cane consisting of a VR controller coupled with an actual white cane, and two virtual environments, which can be switched to at will through the Unity editor on a computer connected to the headset.

The real-world prototype white cane is coupled with the controller via a 3D-printed holder, as shown in Figure 3, which affixes the controller near the handle of the white cane so as not to overly affect the balance, which would impact the overall handling. This placement with a direct fixation on the cane serves to transmit the controller vibrations directly into the cane, from where the participant can comfortably feel them. Also, the holder can be rotated to customize the placement of the controller according to the participant's preference.

Figure 3: Implementation of the real world cane with a controller coupled via a 3D-printed holder, mounted right at the end of the cane next to the handle

The participant wears the Virtual Reality headset, and even though the visual information it provides is redundant, it is necessary for the tracking of the participant's body and head in the virtual environment. This procedure is similar to the approach used in articles by Kunz et al. [6] or Siu et al. [8] – both of which served as the initial inspiration for this approach.

Where our approach differs is the implementation of the way we provide feedback to the participant about his surroundings. The aforementioned articles either had a custom-built harness with a white cane or only audio feedback. The virtual cane used in this preliminary state is still only an actual adjustable white cane coupled with a Virtual Reality controller, and the haptic feedback is provided via the vibrations of the controller and its intensity. This is, at the current state, a limited fidelity haptic feedback that can be provided by the available hardware. It is important for this and the following works so that we can determine if even this is enough for the creation of cognitive maps and then follow up on it by adding more and better feedback to the participant.

The vibrations themselves are set up so they trigger during the contact of the virtual white cane with any obstacle - be it a wall or a piece of furniture - excluding the floor. The floor is excluded, as the cane is supposed to be in contact with it during the whole test. Therefore, it would provide no additional information during these tests. The interaction method also leverages a variable intensity of the vibrations. The vibrations are set up in a way that they get more intense and faster as the participant pushes the cane deeper into objects. This is supposed to provide the participant with stronger feedback in case they miss the initial vibrations or get so far into an object that they are unsure which way to go into open space.

The last part of the physical setup, the computer, is optional since the virtual environments may be compiled and entirely run inside the specific headset we are using - that being Oculus Quest 2, as mentioned above. For our preliminary test, however, it is still necessary to fine-tune and calibrate the virtual cane and the position of the participant in the virtual environment, so at this stage, we can not omit a computer as a part of the setup.

The virtual part of our setup includes the two virtual environments running in the Unity game development engine and its associated editor. The first scene, as seen in Figure 1, serves mostly as a proof of concept with the main purpose being to check the validity of our methods and whether they are at all suitable for the most basic of obstacles, such as walls and bigger obstacles with uncomplicated bounding boxes.

The second environment, as seen in Figure 2, is a virtualization of a real-world study room (as shown in Figure 4 and Figure 5) and 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, again desks and chairs along with some other obstacles as well (fire extinguishers etc.). This is a more intermediate environment, containing many obstacles, and should be a little harder to navigate. And since it is a virtual copy of a real-world environment, the participant who will test this room has the option of exploring the real-world counterpart as well, so we could evaluate whether the cognitive map he or she has created during the virtual exploration has helped in any way.

4 Evaluation

This section focuses on experiments to evaluate the utility and usability of our method. The primary aim is to answer our research question, whether or not our current implementation of haptic feedback is enough for a VI participant to create at least a rough CM in a safe and controlled environment.

4.1 Preliminary Test

The implemented prototype used for the preliminary evaluation does not employ multi-modal interaction. It uses only haptic feedback and is focused primarily on an egocentric orientation in a virtual environment.

4.1.1 Procedure

The testing that has been done so far has a clearly defined procedure that will be adhered to during the testing if pos-

Figure 4: A comparison of the real and virtualized study room

Figure 5: A comparison of the real hallway and the virtualized version of the view from approximately the same spot

sible. The procedure is as follows:

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

Calibration: The participant 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 participant 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.

Test walk-trough: This phase is self-explanatory. The participant 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.

Feedback gathering: This will be the last phase, during which the participant will describe his experience with the application and provide feedback.

4.1.2 Measures:

During the experiment, we focused on subjective qualitative feedback (obstacle and boundary detection, the usability of the interaction method) and the ability of the participant to describe the explored virtual environment.

4.1.3 Participants

One participant with vision impairment was involved in the experiment. He has no previous experience with workable Virtual Reality based on wearable devices. He is male, has been late blind for more than 20 years, and is 40–50 years old.

4.1.4 Test setup and execution

For the preliminary evaluation, we used a simple virtual environment – a room with a nook as depicted in Figure 1. The experiment was conducted in a room with an available empty space 2.5×2.5 meters. The participant used a prototype white cane with the attached controller, as depicted in Figure 3. Two members of the project team were present to ensure the participant's safety (avoid possible collisions with objects in the real environment).

The preliminary testing followed the procedure described above, with the repetition of the test walk-through.

One instance has adhered strictly to the description above, so the participant explored the virtual environment without additional interference from the supervisor's side using the cane. The second instance of the testing was done on demand by the participant, as he wanted to explore the environment more. He has now included a discussion with the supervisors about the mechanics and features of the prototype. We will discuss the mentioned feedback along with our observations in Section 5.

4.1.5 Results

After we received the participant's feedback, the main takeaway points were these:

- The main goal – orientation in a room is possible, as even in the current prototype, implementing only vibrations of various intensities, the participant was able to use them to quickly and efficiently find his bearing. He was able to find walls and navigate along them without much of a problem, even finding obstacles. The participant, however, perceived different dimensions of the obstacles he found, so much so that he determined a narrow space between the pillar seen in Figure 1 to be too narrow to move through. This may be a result of inaccuracies in calibration, but for future work, it may need to be accounted for.
- The lack of feedback for the participant being in an object or obstacle sometimes caused problems, as the participant's virtual body has no collision detection in place, and the participant can step outside of the current boundaries, which then severely complicates navigation and will end up needing intervention from a supervisor.
- What seemed to be a problem, in general, was the perception of the vibrations caused by the room having a carpet. Even this very slight roughness of the ground sometimes caused the participant not to be able to feel the vibrations, and after a while, he resorted to using the cane raised slightly in the air to counteract this.
- An unexpected discovery was the fact that the participants can and will use audio queues in the real world to center themselves in the virtual environment, as static audio sources can be used as an anchor of sorts.

4.2 Evaluation of complex environment

In this section, we describe the planned evaluation of the prototype that will comprise the complex environment as depicted in Figure 6.

4.2.1 Procedure

The test procedure regarding the VR setup will be similar to the preliminary evaluation with further differences. However, the advanced prototype, as described in this section, resembles a real environment (as depicted in Figure 6) and allows for the creation of a simple 3D printed tactile map as depicted in Figure 7. This evaluation will be done mainly to explore the boundaries of how far we can go with just basic haptic feedback in a more complicated and cluttered virtual environment. Furthermore, during this testing, the users will have a clear goal – that is to navigate into the study room, with a start in the hallways outside of it. Once in the room, they should explore it and be able to describe the layout of the room at least approximately – they will probably not be able to differentiate between objects themselves, but what is the main goal is to be able to determine obstacles in general and their rough placements. During the feedback-gathering phases of this evaluation, the users will have either the tactile map (Figure 7) or the real-world environment at their disposal – we plan to utilize both.

Figure 6: A photo of the real world environment around the study room area

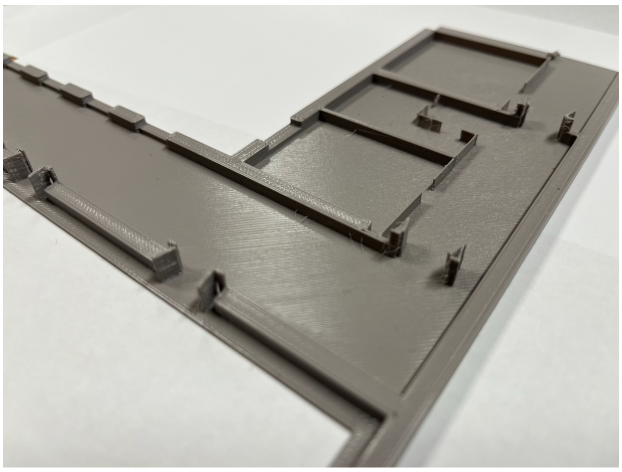

Figure 7: A photo of a tactile map printed according to the virtual environment seen in Figure 2

The preparation and calibration phases will be similar to the preliminary evaluation.

Test walk-trough: As mentioned at the beginning of this subsection, the procedure during this evaluation will differ both in the environment the users will be exploring and the goal. The users will begin in the empty hallways connected to the study room, with the goal of navigating to it. For this purpose, they will be given a rough verbal description of where the room is supposed to be (e.g., at the end of this hallway, there is a door, on the left side, go through it and a few meters after the door on your left, you should expect the entry to the room). After they have successfully navigated to the study room, they will now begin the free exploration of the room with the goal of remembering the layout and creating a CM of it and preferably of the environment around it.

Feedback gathering: This will be the last phase, during which the participant will both describe his experience with the application and provide feedback verbally, but also will be asked to describe or show the landmarks, obstacles, and objects encountered during their exploration, along with the path they took.

4.2.2 Measures

As in the preliminary evaluation, we will focus on subjective qualitative feedback. Moreover, we will evaluate the quality of the acquired cognitive maps by requesting the participants to:

- Show/describe the position of objects and landmarks encountered in the VR using the tactile map.
- Show/describe the position of objects and landmarks encountered in the VR using the real environment.

4.2.3 Participants

We plan to recruit six participants with vision impairment. The inclusion criterion is that they are capable of independent orientation in simple indoor environments other than their own flat (i.e. workplace, nearby convenience store, etc.). We plan to sample the audience by selecting at least two congenitally blind and two late blind participants.

5 Discussion

The preliminary evaluation indicates that even a simple interaction method based on tactile feedback provided by vibrations allows for the creation of CMs. This is alongside the results of Kunz et al. [6] a somewhat expected, but nonetheless significant result, as it proves that even basic tactile feedback is enough of a foundation that can be built upon with further enhancements with auditory feedback and further refining of tactile feedback.

However, there were also drawbacks discovered that were not observed by Kunz et al. [6] or Siu et al. [8] as they were exclusive to our testing environment and implementation. There were difficulties with calibration, where a white cane – if set up in such a way that its length does not correspond to the height of the VR participant perfectly, will go through the floor. Therefore, it will interact with obstacle hitboxes/boundary boxes under the floor if they are present or will not collide with the tip of the white cane but with its body. This causes slight but perceivable changes in obstacle placement and, therefore, provides spatial information different from what the virtual environment depicts.

Another problem was, as mentioned in the previous Section 4, the floor surface of the real-world testing environment. In our case, it was covered by a carpet, which caused vibrations in the white cane, interfering with the tactile feedback from the vibrations of the controller. This is of great importance for future testing, as flooring with as smooth a surface as possible will be needed. But once again, the participant was able to explore the environment even with this disadvantage, which only further confirms our conclusions on the viability of this feedback method.

The last takeaway for discussion is actually not much of a problem and has been mentioned by Siu et al. [8] as well. This takeaway is the mechanic of an auditory *anchor* of sorts. Siu et al. [8] utilize virtual audio sources as checkpoints through which the users travel and which help them to put their surroundings into perspective and center themselves around them and in relation to them. We unintentionally provided the participant with a real-world auditory anchor in the form of the computer, through which the virtual environment was running, which had noisy ventilators and, as such, provided the participant with a point of reference he then automatically used for orientation. This is a feature that we plan on using in the future, most probably in the form of a virtual auditory source along with headphones for the participant so as to filter out outside influences.

6 Conclusions and Future work

In this paper, we described the results of a project that aims to employ VR for the purpose of the creation of CMs. These CM are used for the improvement of the spatial orientation of those with visual impairments in indoor settings. Our preliminary results show that VR is a promising method to achieve this goal.

It is the subject of future work to evaluate the advanced prototype as described in Section 4.2. Along with this, we will construct more complicated virtual environments that will incorporate different goals and exploration methods. We also plan on enhancing our current form of haptic feedback by itself with proprietary hardware and further white cane prototypes, along with adding auditory feedback in a few different forms (auditory *anchor* and also obstacle or collision detection). This will also warrant further evaluation in relation to our results gathered so far. In the end, we will further explore how to combine different methods for the acquisition of CM to achieve optimal results for specific environments and individuals with specific needs, abilities, and preferences.

Acknowledgments

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References

[1] Anke M Brock, Philippe Truillet, Bernard Oriola, Delphine Picard, and Christophe Jouffrais. Interactivity improves usability of geographic maps for visually impaired people. *Human–Computer Interaction*, 30(2):156–194, 2015.

[2] Neil Burgess. Spatial cognition and the brain. *Annals of the New York Academy of Sciences*, 1124(1):77–97, 2008.

[3] Reginald G Golledge, R Daniel Jacobson, Robert Kitchin, and Mark Blades. Cognitive maps, spatial abilities, and human wayfinding. *Geographical Review of Japan, Series B.*, 73(2):93–104, 2000.

[4] Hongyun Guo, Nai Yang, Zhong Wang, and Hao Fang. Effects of spatial reference frames, map dimensionality, and navigation modes on spatial orientation efficiency. *ISPRS International Journal of Geo-Information*, 12(12):476, 2023.

[5] Lasse H Hansen, Philipp Fleck, Marco Stranner, Dieter Schmalstieg, and Clemens Arth. Augmented reality for subsurface utility engineering, revisited. *IEEE Transactions on Visualization and Computer Graphics*, 27(11):4119–4128, 2021.

[6] Andreas Kunz, 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*, pages 114–122. Springer, 2018.

[7] Loes Ottink, Hendrik Buimer, Bram van Raalte, Christian F Doeller, Thea M van der Geest, and Richard JA van Wezel. Cognitive map formation supported by auditory, haptic, and multimodal information in persons with blindness. *Neuroscience & Biobehavioral Reviews*, 140(104797), 2022.

[8] Alexa F Siu, Mike Sinclair, Robert Kovacs, Eyal Ofek, Christian Holz, and Edward Cutrell. Virtual reality without vision: A haptic and auditory white cane to navigate complex virtual worlds. In *Proceedings of the 2020 CHI conference on human factors in computing systems*, pages 1–13, 2020.

[9] Edward C Tolman. Cognitive maps in rats and men. *Psychological review*, 55(4):189, 1948.