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Self-Overlapping Maze and Map Design for Asymmetric Collaboration in Room-Scale Virtual Reality for Public Spaces

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Abstract:

This thesis addresses two problems of public virtual reality (VR) setups found in cultural places such as museums and libraries. These are the lack of walkable space due to the restricted room-scale tracking area, and the head-mounted-display (HMD) technology providing a single-user experience.

We propose and demonstrate a design for constructing a naturally walkable self-overlapping maze and a map of the maze to facilitate asymmetric collaboration between the user wearing an HMD and the non-HMD participants close to the setup.

Three experiments are conducted, where the first two evaluate usability of the design. The last experiment compares collaboration and engagement of the HMD and non-HMD participants, as well as spectators, in three conditions: a mirrored HMD view, the map, and a combination of the two. Results from our findings can be used when designing self-overlapping architectures for limited physical spaces and when facilitating engaging asymmetric experiences for public VR setups.

Preface

This thesis is submitted by Denisa Skantarova, Sule Serubugo and Nicolaj Evers, as a Master thesis for the 10th semester project for Medialogy with specialization in Computer Graphics at Aalborg University. The work submitted was done in the spring semester of 2017 by the authors, under the supervision of Martin Kraus. It has always been fascinating to create experiences that bring social engagement for people. With the introduction of room-scale virtual reality, we saw a gap that it does lack the social aspect when set up in public. Through previous experience of working for museums and conversation with the supervisor, it became apparent that it would be interesting to create a public social experience in virtual reality. The experience would allow people to freely walk in a virtual environment but also motivate the friends standing by to join the experience, instead of just watching. This has been the drive of this thesis.

The authors wish to thank supervisor Martin Kraus for his guidance and supervision. We would also like to thank Aalborg Hovedbibliotek for their assistance with providing a space for the field experiments, and the participants that attended the experiments. Their assistance has helped push forward the efforts depicted in this thesis.

In addition to this thesis, the hand-in includes an audio-visual production demonstrating our work.

Denisa Skantarova, Sule Serubugo and Nicolaj Evers
Aalborg University, May 22, 2017

Contents

Abstract

This thesis addresses two problems of public virtual reality (VR) setups found in cultural places such as museums and libraries. These are the lack of walkable space due to the restricted room-scale tracking area, and the head-mounted-display (HMD) technology providing a single-user experience. We propose and demonstrate a design for constructing a naturally walkable self-overlapping maze and a map of the maze to facilitate asymmetric collaboration between the user wearing an HMD and the non-HMD participants close to the setup. Three experiments are conducted, where the first two evaluate the design based on the criteria that the expansive self-overlapping maze has to be walkable in a $2.5\,\mathrm{m} \times 2.5\,\mathrm{m}$ physical space without people noticing changes to the environment. We evaluate the features added to the map so that it correctly represents the self-overlapping maze, and a system for discouraging people from trespassing through virtual walls. In the last experiment, three conditions are compared: a mirrored HMD view, the map, and a combination of the two, to evaluate which facilitates more collaboration and is more engaging for the non-HMD participants and spectators, as well as the HMD participants. Results from our findings can be used when designing self-overlapping architectures for limited physical spaces and when facilitating engaging asymmetric experiences for public VR setups.

Keywords: Self-overlapping maze, Virtual reality, Asymmetric collaboration, Room-scale virtual reality, Impossible spaces, Visualization, Public spaces, Computer graphics

1 | Introduction

Virtual reality has proven to be a rapidly developing technology with a myriad of useful applications. Many public cultural centers such as libraries and museums have a growing interest in this technology to further entertain and immerse their visitors in cultural and informative experiences as a supplement to conveying information through traditional media such as books or film (Massis, 2015; Carrozzino & Bergamasco, 2010). Recent advances in the state-of-the-art virtual reality (VR) head-mounted displays (HMDs) have developed to allow for natural interaction as well as locomotion in the virtual environments. HMDs such as the HTC Vive have introduced innovative solutions such as the so-called room-scale VR technology, which makes it easier to accurately track users' motions within physical room-sized areas. This allows users to naturally navigate through walking, and use motion tracked handheld controllers to manipulate objects in the virtual worlds.

Room-scale VR has introduced a stronger match between human body proprioceptive information and the sensory feedback supplied by computer generated virtual objects, thus increasing immersion. However for a public setup, it has two main limitations: limited physical space and providing only a single-person experience. Several VR applications demand that the user has to move through extensive virtual environments, the size of which is much larger than that of tracked physical space (Suma, Lipps, Finkelstein, Krum, & Bolas, 2012). This physical space requirement makes it difficult to design large virtual areas that can be walkable as the user cannot move beyond the boundaries of the tracking setup. To overcome the space requirement, some developers have used self-overlapping architecture for instance in the game Unseen Diplomacy (Triangular Pixels, 2016). Others (Hodgson, Bachmann, & Waller, 2008) have used redirection techniques, also as an attempt to diverge the user from their perceived physical movement while following a path in the virtual environment.

Besides the limited size of the tracked physical space, the HMD technology can only be worn by one user at a time, making it a single-person experience. This is another limitation specifically for public cultural centers that are devoted to a large group of people (Carrozzino & Bergamasco, 2010). There have been attempts made to bring a social experience into VR, such as using multiple HMDs to bring several users into the same virtual environment, however this is currently a costly setup for the public centers who have to manage large groups of visitors. In commercial products, there has also emerged a different approach that allows an asymmetric collaboration between one HMD participant and the non-HMD participants. Examples include games such as VR

The Diner Duo (Whirlybird Games, 2016), The Playroom VR (SIE Japan Studio, 2016), and Keep Talking and Nobody Explodes (Steel Crate Games, 2015). In these examples, one person wears an HMD and the other people use a different medium such as a computer, book, smartphone, or controllers, to enable them to collaborate or compete with the HMD participant in the same virtual environment. However, there is a lack of research that explores this asymmetric phenomenon for the public setting.

To address this problem, we investigate asymmetric collaboration between the HMD participant in room-scale VR and the non-HMD participants in the scenario of a public cultural center. Our research utilizes the advantage of room scale VR tracking, thus the ability to navigate by natural locomotion in a virtual environment, but also addresses the HMD limitation of a single-person experience. We explore this problem using a VR maze as it represents a simple navigation-based task that can allow the HMD user to naturally navigate in the maze, and asymmetrically involve the non-HMD participants into the VR experience by giving them a view of the whole maze on a map to collaborate on finding their way through.

A typical room-scale VR setup could have one HMD, trackers to monitor user's movement, and a side display placed close by, showing the virtual environment. In this setup, we promote an asymmetric collaboration where the non-HMD participants read from a map of the VR maze on the side display to assist the HMD user who has to navigate and find the way around the VR maze. In order to construct an expansive VR maze that can be walkable in a physical room-scale area, we investigate how such a virtual environment can be compressed into a smaller physical space, a phenomenon Suma et al. (2012) termed impossible spaces. This can be achieved using several techniques such as making a self-overlapping architecture, where multiple rooms of a maze can be layered to fit into a restricted physical area. Furthermore, we investigate how this self-overlapping VR maze can be effectively visualized on the side display with a map that shows the whole maze at once for the non-HMD participants to assist the HMD participant navigate. Lastly, since walking in such a VR maze is merely walking in an empty physical space, the HMD participant can ignore all instructions and just walk through objects and virtual walls, breaking the experience. Therefore, we investigate solutions for how to design for when the participant trespasses through walls.

A design for constructing the self-overlapping maze and visualizing the map is proposed and tested through a usability experiment to find out whether HMD users can walk in the expansive maze without interruptions. Furthermore, it investigates whether the design of the map can be understood and used by the non-HMD participants. We also test whether the proposed system can facilitate asymmetric collaboration and compare three views on the side display – a mirrored HMD view, a map, and a combination with both views. The comparison investigates their influence on collaboration and engagement of the participants and spectators in the public setting. In summary this thesis makes the following novelties and contributions:

- A formal design and demonstration of how a self-overlapping maze-like architecture can be constructed for the public setting

- Demonstration of how to visualize self-overlapping architectures on a map
- Demonstration of a wall non-trespassing system
- Evaluation of the system with the self-overlapping architecture on a large audience in a public cultural center
- A comparison of different views on the side display in order to facilitate asymmetric collaboration between the HMD and non-HMD participants

Findings from our research can among others be used when supporting asymmetric collaboration for VR setups in public cultural centers, and as inspiration when designing walkable compressed VR architectures in limited physical areas.

A literature review of related work and methods for construction of the walkable maze with asymmetric collaboration is presented in Chapter 2. Chapter 3 discusses the design of the system followed by its implementation in Chapter 4. The design is evaluated in two usability experiments in Chapter 5. The side display visualizations are compared in the public setting in Chapter 6, where the asymmetric collaboration and engagement are observed and evaluated. Lastly, conclusions are drawn from the experiments and future work is suggested in Chapter 7.

2 Related Work

This chapter contains related studies about facilitating natural locomotion and work that can be used as inspiration when constructing and visualizing the walkable maze and the map. Furthermore, studies that investigate which components are necessary to facilitate asymmetric collaboration are presented.

2.1 Navigation in Room-Scale Virtual Reality

Navigation in the real world is a universal and intuitive task that is usually performed without conscious effort. This navigation is based on sensory information from several cognitive processes such as vision, proprioception, and vestibular information (Ruddle & Lessels, 2009). However, navigation in an immersive virtual world can often be challenging as traditional navigation tools (controllers, keyboard, mouse, etc.) usually only facilitate the visual information. These tools also have a tendency to induce motion sickness and do not provide sufficient sensory feedback compromising the sense of presence (Ruddle & Lessels, 2009; Usoh et al., 1999; Suma et al., 2012).

These challenges can be overcome with real walking explored by Ruddle and Lessels (2009), who presented several advantages to walking over the traditional VR navigation methods. They compared three different forms of navigation: a desktop display using mouse and keyboard, an HMD for rotation with a button for translation, and an HMD facilitating physical walking for rotations and translation. They had the participants explore the virtual environment by opening boxes until they found all eight targets. In their research, they found that the walking group performed significantly better at recollecting the targets without searching the boxes multiple times, traveled along the shortest path, and was better at avoiding obstacles.

While walking provides some advantages over the traditional tools, it also introduces some limitations. For example, free movement in large virtual environments without the user walking into a wall requires a large physical space. There is also a need for a tracking setup to facilitate the user's movement in VR. Several researchers (Razzaque, Kohn, & Whitton, 2001; Suma et al., 2012) have attempted to overcome these limitations through two methods – manipulating the user's motion or manipulating the environment while still providing full natural locomotion.

2.1.1 Manipulating the User's Motion

Manipulating the user's perceived motion can be achieved by slowly amplifying or diminishing a component of the user's motion in the virtual environment. Motion can generally be manipulated based on three categories of techniques: translation gains, rotation gains, and curvature gains (Suma et al., 2012). The translation gain techniques modify the translation component, which scales the motion to move the user a greater or smaller distance in the virtual world compared to their actual locomotion. Rotation gain techniques measure the difference in head orientation and scale the virtual rotation to direct the user towards a desired path. Lastly, the curvature gain techniques add an offset to the real world movement that the user unconsciously compensates for by walking along an arc (Interrante, Ries, & Anderson, 2007; Engel, Curio, Tcheang, Mohler, & Bülthoff, 2008). These techniques work because vision tends to dominate over vestibular and proprioceptive information when they conflict as long as the conflict is within bearable limits (Berthoz, 2000).

A combination of these gains has been applied in a locomotion technique known as redirected walking, which allows users to explore large virtual worlds by rotating the world around them. It enables the users to feel like they are moving forward in the virtual environment while actually moving around in circles. By maintaining consistency in the virtual environment between visual, aural, and vestibular cues as the user's viewpoint is rotated, the technique exploits the limitations of human perception for sensing position, orientation, and movement. This is similar to how people will accidentally move in circles while blindfolded. Redirected walking was developed and explored by Razzaque et al. (2001) through having users walk in zigzag patterns in a virtual environment larger than the $4m \times 10m$ testing space, and rotating the world when the users stood still, walked, and reoriented themselves. They found that redirected walking had potential, but required a large tracking space or way-points for the user to circle the real space fully. This makes it problematic for room-scale VR setups in public spaces, where the spatial limitation is already a limiting factor.

2.1.2 Manipulating the Virtual Environment

A somewhat newer approach is manipulating the virtual environment instead of the user. An example of this is use of the perceptual phenomenon "change blindness", which occurs as people fail to notice differences when provided with a change in visual stimulus. This allows for instantaneous architectural shifts in the virtual environment without the user noticing, thus reorienting the user in the physical space.

Change blindness has been examined in VR by Suma et al. (2011), who conducted two different experiments. The first experiment had two between-subjects conditions: one with a distraction, where the participant was given a memorization task related to the virtual environment, and one without. They found that the participants did not notice a change in the virtual environment, but felt like they were walking in circles. In the second experiment, they attempted to break the technique by comparing low and high field of view, and including a pointing task, where participants were required to point towards their virtual starting point when the environment was changed. Similarly to the first experiment, they found that the participants did not notice a change in the virtual environment. However, while useful, this technique requires a very specific scenario, where the user has to be guided to turn away before changing the virtual environment.

A different, practical way of leveraging spatial manipulation is the use of "impossible spaces". This technique compresses a larger virtual environment into a smaller physical area by dynamically changing the environment as the user navigates it. This ensures that only one room is visible at the time. As such it creates environments that are not possible in Euclidean space (two rooms cannot exist in the same space). This technique was examined by Suma et al. (2012), who conducted two experiments to evaluate navigation in VR. In the first experiment, the participants navigated a series of virtual buildings. Some of these buildings were possible in the real world while others were designed as impossible spaces. The participants then had to evaluate the possibility of the space and perform a distance estimation task. They found that a space could overlap up to 56% before the participants noticed. In their second experiment, they combined impossible spaces with redirected walking for a usability study. They found that only two out of 14 participants noticed the impossible spaces. A commercial example of this technique has been implemented in the VR game Unseen Diplomacy (Triangular Pixels, 2016), where it is utilized to construct maze-like virtual environments for the players to navigate using a $4\,\text{m} \times 3\,\text{m}$ tracking area. However, navigating the environments is in this example trivial as the layout only supports a single path. Of all the techniques, impossible spaces seems to be the most appropriate for constructing the VR maze as it is less affected by the spatial requirement and does not require a directed experience like change blindness.

2.2 Construction of the Virtual Reality Maze

This section discusses related work for how an impossible VR maze can be constructed through use of self-overlapping architecture and visualized on the side display for the non-HMD participants to accurately assist the HMD participant.

2.2.1 Self-Overlapping Architectures

A self-overlapping maze can be constructed out of two subtypes of virtual environments, informational such as rooms, which can contain content and features, and transitional such as corridors, which can link the rooms (Vasylevska, Kaufmann, Bolas, & Suma, 2013). Rooms can be rearranged to overlap spatially, allowing for large architectures to be compressed in smaller physical areas. By switching different segments of the environment based on location and the direction the user is moving in, it is possible to have only one visible room at a time despite the spatial overlap (Suma et al., 2012). The transitional corridors are necessary to ensure that the rooms are switched out without being visible in the user's field of view. Switching out the informational rooms can be done for instance when the user gets to the middle of a transitional corridor (Suma et al., 2012). The transitional corridors can be made to vary based on the positions of the rooms. Furthermore, positions of the doors that give access to the rooms can be varied in all directions in order to break the pattern (Vasylevska et al., 2013). This allows the virtual maze to be rendered for natural navigation, although its size is larger than the room-scale tracking area. Splitting the environment into the subtypes can be used as inspiration when designing a self-overlapping VR maze that obeys the lack of physical space in the public setting.

2.2.2 Visualization of Self-Overlapping Architectures on a Map

To the best of our knowledge, there have not been studies on visualizing self-overlapping architectures on a map. In his book Video Game Spaces, Nitsche (2008) discusses visualization of impossible spaces in video games during the 2D era. The tunnel in Pac-man, where the right side of the screen is connected to the left side, is one example of how a three-dimensional wrapped cylindrical playground was used to make the player reappear on the right side immediately after exiting through the left tunnel. This wraparound effect can also be seen in Asteroids that used a torus to make an asteroid reappear from the opposite side of the screen once it leaves one side (Nitsche, 2008).

Pac-man and Asteroids are both games that are visualized in a single segment of the environment. However, another visualization approach discussed by Nitsche (2008) is to divide a map into smaller segments. Here the segments hidden from the camera can be switched in as the character walks from one location to another. This is the case in the 2D maze game Adventure for the game console Atari 2600. The game includes impossible interconnections and jumps between the different maze segments, where the movement from one segment to another is camouflaged through a camera cut. Players and spectators do not experience the world as separate units, but perceive it as a continuous world. Visualization in Adventure shows how a basic camera cut to view the character in a new segment can be used to hide spatial distortion and simulate consistent movement in the virtual world (Nitsche, 2008). Although this can be an effective way of showing a map of the VR maze to the non-HMD participants, showing only segments of the VR maze would limit the information available for guidance. The non-HMD participants would not know what to expect from the other segments. A more informative way would be to find a solution of how these impossible interconnections and jumps can be visualized on a single map of the whole maze. This is explored further in the construction process of the self-overlapping VR maze.

2.3 Asymmetric Collaboration in Virtual Reality

Besides locomotion challenges, another fundamental problem with VR in public spaces is that HMD technology can only be worn by one person limiting the experience to a single user (Carrozzino & Bergamasco, 2010; Liszio & Masuch, 2016). This challenge can be addressed by creating asymmetric collaboration, which is a rarely considered for public VR setups. Most related work done in this direction (Liszio & Masuch, 2016; Sajjadi, Cebolledo Gutierrez, Trullemans, & De Troyer, 2014) is linked to VR gaming, where various ways of how to design experiences for multiple users are discussed. According to Azadegan and Harteveld (2014), most collaborations can be grouped into three categories: supportive, where participants get to plan strategies and make decisions at a conscious cognitive level before the experience; instructional, where the experience is based on participants' instincts; and integrative collaboration, where participants get to make decisions while the experience is running. Our work with asymmetric collaboration can be characterized as a combination of instructional and integrative collaboration because the non-HMD participants can both plan and discuss with the HMD participants, and direct them based on the map.

Letting participants in the physical space interact with the HMD participant expands the experience to happen in both the physical and virtual world. Thus the experience can be expanded beyond the mere virtual world. This creates an experience similar to that in pervasive or mixed reality games, where the expansion can be made either socially, temporary, or spatially, combining the virtual elements with the involvement from the physical world (Liszio & Masuch, 2016). When designing experiences that support collaboration between the participants experiencing the same virtual environment through asymmetric media, there is a common trend to use specific components as the building blocks. These are found in different literature (Liszio & Masuch, 2016; Sajjadi et al., 2014; Wendel, Gutjahr, Gobel, & Steinmetz, 2012) discussing support for collaboration and multiplayer. Some of the common components include unification of participants' experiences through story and theme, use of multiple media, assigning different roles, and emphasizing communication. These are discussed in the following sections.

2.3.1 Unification of Asymmetric Experiences

Several studies (Liszio & Masuch, 2016; Sajjadi et al., 2014) agree that one of the fundamental elements for facilitating collaboration is that the game or experience must be designed in a way that both participants are presented with a common story, theme, and goal. Elements of the interface, its graphics, and sounds should relate to this theme and story. Unification of both theme and story brings meaning to the actions done by the participants and the events they experience in the virtual world (Liszio & Masuch, 2016). In their work, Liszio and Masuch (2016) make a case study for a VR game, where they design a collaborative game called Lunar Escape with a futuristic theme, where the story is about repairing a spaceship in order to escape from a foreign planet. Sajjadi et al. (2014) develop a game with a maze-theme to support collaborative play, where the players have a common goal to escape from a maze filled with explosives and monsters.

Having a unified experience as shown in these studies can be helpful in our work to inform both participants about what is happening in each other's world while bridging the two worlds under one uniform theme.

2.3.2 Use of Multiple Media

Besides having a unified theme and story, collaborative digital interfaces tend to present the experience across different media. This is specifically important for VR setups, where it is currently rare to find more than one HMD for a group of people. Therefore, VR experiences that include more than one participant are desirable (Liszio & Masuch, 2016). In several related studies, this is achieved by making setups that make use of a combination of multiple devices, such as controllers, displays, or tablets. Having the possibility to use several devices allows information to be distributed asymmetrically, where each participant has their own abilities, and an individual perspective on the virtual environment (Liszio & Masuch, 2016), which opens up for new ways when designing experiences (Schmitz, Akbal, & Zehle, 2015; Sra et al., 2016). In Liszio and Masuch's (2016) game Lunar Escape, participants use an Oculus Rift DK2 and two tablet PCs to fulfil a collaborative task. Similarly in Keep Talking and Nobody Explodes (Steel Crate Games, 2015), one participant wears an HMD to interact with the virtual world while the other uses a paper manual for how to defuse a virtual bomb.

2.3.3 Different Roles and Communication

Communication and assigning participants different roles are also two fundamental building blocks of collaborative experience. Different roles enforce an asymmetric distribution of information and abilities that make the participants collaborate or compete for an objective. This adds more dynamics and enhances participants' involvement in the experience (Liszio & Masuch, 2016). Lunar Escape contains three roles, a mech operator, a copilot, and a scout. Schmitz et al. (2015) also explore role-based asymmetric collaboration using a media combination of Oculus Rift and CAVE, where participants were given a collaborative task to maneuver a ship around a sea, which was split into two roles - the captain and the crew. As shown in these studies, roles mean that participants have to depend on each other's abilities and communicate in order to accomplish the objectives.

For room-scale VR, an example of role-based VR interaction is in the local multiplayer game VR The Diner Duo (Whirlybird Games, 2016), where two participants are assigned roles of a cook and a waiter that have to collaborate to serve the guests. However, the game makes little use of natural navigation in the room. In our study, we want to extend this, getting inspired from literature on impossible spaces to allow natural navigation and also support asymmetric collaboration via a side display in a public VR setup.

3 | Design

In this chapter, a design is proposed for how to create a walkable self-overlapping VR maze and visualize it on a map to encourage asymmetric collaboration with non-HMD participants for a public VR setup.

Knowledge of how room-scale VR works is necessary to set up the right design. Room-scale VR is a design paradigm that uses 360° tracking equipment to monitor the user's physical movement in all directions inside a tracked play area. There are essentially two high-end room-scale solutions – the HTC Vive with its Lighthouse tracking system and Oculus Rift with its three-sensor experimental setup. Oculus Rift supports room-scale VR with three sensors that can track a maximum recommended play area of 2.5 m × 2.5 m. On the other hand, the HTC Vive uses two bases to track a maximum recommended play area of approximately 3.5 m × 3.5 m. Our design and the experiments conducted use the HTC Vive setup to create a system that considers the limited area in the public space. However, the system could also be used for an Oculus Rift setup. Based on the equipment and related work discussed, the design aims to fulfil the following criteria in order to create a walkable VR maze that can be used in a public space.

- The maze has to be walkable in VR in a limited physical space that is approximately 2.5 m × 2.5 m
- Following Suma et al.'s (2012) impossible space technique, changes for updating the maze should not be noticeable to the HMD participant
- The overall area of the walkable maze should be perceived larger than the actual physical space
- To support asymmetric collaboration, the maze should be visualized on a map allowing non-HMD participants to engage in the experience
- The maze should discourage participants from trespassing through walls to avoid breaking the experience

3.1 Constructing a Self-Overlapping VR Maze

To design a self-overlapping maze, initial inspiration was taken from Suma et al.'s (2012) and Vasylevska et al.'s (2013) work described in Chapter 2. As in their studies, the VR maze would consist of two basic building blocks, informational rooms and transitional corridors that have to be updated without the user noticing. To make the maze non-trivial, so that the participants feel challenged towards the goal, corridors could also be split into branching paths in the maze. Our design considers architectures where it is not necessary to use doors as is the case for Unseen Diplomacy (Triangular Pixels, 2016) or Vasylevska et al.'s (2013) study. Although this would be a good way of hiding the updates to the environment, we propose a novel approach for designing walkable seamless virtual environments.

3.1.1 Physical Space Constraints

Before creating the self-overlapping maze, it is important to first consider constraints of the physical environment, and understand the minimum size of a corridor needed to walk through the maze. Based on the HTC Vive tracking area of approximately 3.5 m × 3.5 m and in order to maximize the limited opportunity of space in public cultural places, three sizes were considered, 3 m × 3 m, 2.5 m × 2.5 m, and 2 m × 2 m area. We initially constrained the physical space to 2.5 m × 2.5 m since the 3 m × 3 m area seemed to be a too large physical space to request for public spaces and the 2 m × 2 m area on the other hand seems too small for walking in when it is split into corridors and rooms. This constraint was later evaluated in a usability test based on the participants' feedback as discussed in Chapter 5. The 2.5 m × 2.5 m constraint can however be adjusted to fit larger or smaller physical spaces when available in a specific public place.

We define one part of the virtual environment that fills the 2.5 m × 2.5 m physical space as a "cell". A cell can be split into a grid layout to define the placement of corridors and rooms in the virtual environment. Using the grid layout helps to define the appropriate corridor width needed to walk through, and allows for a clearer structure when planning a path through the maze. It is also used when unfolding the self-overlapping maze and mapping it to a side display. With the average width of a person being approximately 0.456 m (First In Architecture, n.d.), different grid layouts were considered as shown in Figure 3.1. Without the use of doors, the smallest grid that would allow for having corridors split in branching paths in the maze, is a 3×3 grid. This grid would consist of nine tiles, each with a size of 0.75 m × 0.75 m. On the other hand, taking into account the minimum corridor, which the users would need to walk in, the largest grid is a 5×5 grid. It would consist of 25 tiles, each with a size of 0.5 m × 0.5 m. Choosing the right grid layout would be based on the size of the physical tracking area and the amount of variation needed for a single cell, while still considering the minimum width for a person.

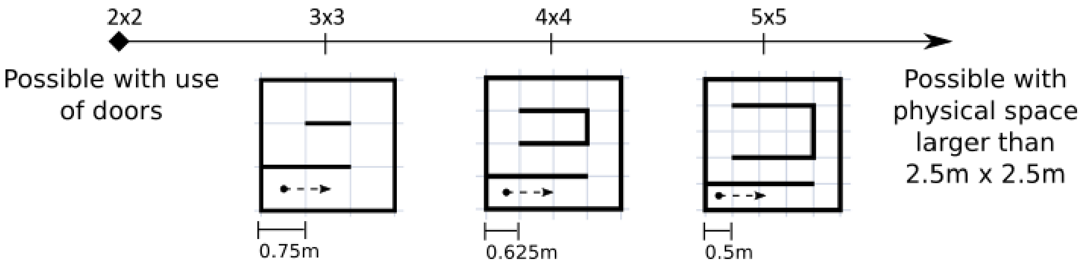

Figure 3.1: Possible grid layouts for the 2.5 m × 2.5 m self-overlapping maze

For this study with a 2.5 m × 2.5 m tracking space, a 4 × 4 grid layout is used, which consists of 16 tiles, each with a size of 0.625 m × 0.625 m. Findings from our design can however also be applied for the other grid layouts. Grid layouts can also be combined to add variation to the experience of walking in VR, thus variating the width of corridors the person walks through.

3.1.2 Interior of the Maze

The interior of each cell of the self-overlapping maze can consist of informational rooms and transitional corridors. Informational rooms provide space to include content such as landmarks, and allow for more walkable space adding variation in the maze. In a 4 × 4 grid layout, rooms can have a maximum size of 3 × 4 tiles in order to leave space for the transitional corridors. Other possible sizes are 2 × 2, 3 × 2, 3 × 3, and 4 × 2. It is possible to fit rooms of various sizes together as demonstrated in Figure 3.2 while leaving space for transitional corridors. Rooms give natural open area for placing objects without bumping into them, which is more constrained in corridors. In the open areas, decorative and thematic content can be added that can be game related such as treasure, traps, puzzles, or culture related such as art galleries, architecture and historical structures like cathedral interiors. This content can also serve as landmarks to create a sense of location when navigating through the maze.

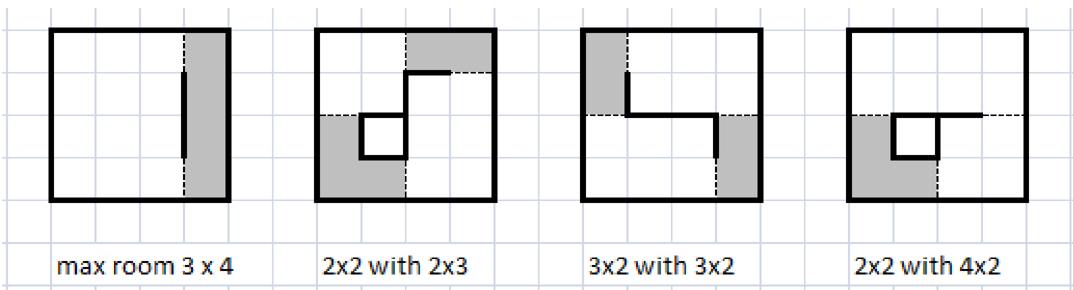

Figure 3.2: Rooms (white) of different sizes together in one cell connected by corridors (gray). The entrance/exit points of the rooms are marked by dotted lines.

Transitional corridors are passageways whose primary purpose is to connect different rooms together. They have a width of one tile and can take up the remaining tiles not filled by rooms. When positioned right, corridors can help change the direction the user is walking in, thus breaking the pattern of for instance walking in a circle. They can have a form of straight hallways or bent hallways, which can further be combined to create more complex transitions such as U-shapes. Furthermore as can be seen in Figure 3.3, corridors can also have a shape of cross-intersections or T-intersections to allow for branching to different paths in the virtual environment. Despite being transitional, they can also include game or cultural information such as images, themes, or scenery that can be seen through windows.

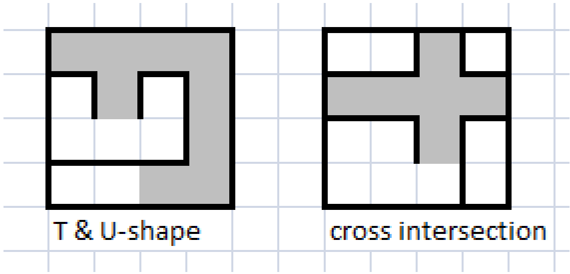

Figure 3.3: Corridors (gray) of different shapes and branching

3.1.3 Self-Overlap of the Maze

In order to create a self-overlapping maze, several cells are made and placed on top of each other. These are then swapped one after the other, allowing the user to move forward. The result is an architecture whose perceived area is larger than the physical space of 2.5 m × 2.5 m. When swapping one cell out with another, the tile where the user is positioned and the content seen on its neighbouring tiles have to be maintained until they are out of the user's field of view. As can be seen in Figure 3.4, the process of constructing cells for a self-overlapping maze can be broken up into two steps. Initially the maze is built starting with key cells (marked with K) showing the paths in the maze. Afterwards, in-between cells (marked with I-B) are added between the key cells in order to be able to swap cells without it being noticed both when the user is moving forward in the maze or going back to the previous cells. In the in-between cells, parts visible in the user's field of view from the previous cell are duplicated, while the remaining part that is occluded from the user's sight is updated, resulting in a gradual transitioning where cells are swapped unnoticeably. The transitional tiles, where one cell is swapped for the other, are marked by numbers.

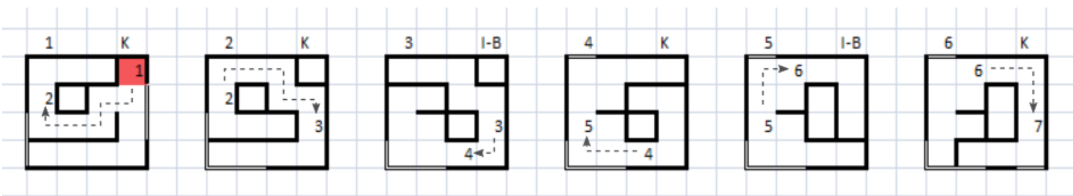

Figure 3.4: Key cells (K) and in-between cells (I-B) for unnoticeable updates

A typical maze will have a number of decision points with various passages to choose from, which often makes it more interesting and challenging to complete. In order to add more complexity to the maze, some cells are made to branch out to different parts, challenging the user to choose which way to walk. Non-trivial branching can be included in such a way that some branching paths continue across multiple cells, creating more complex ways that can lead to dead ends and new rooms.

3.1.4 Enlarging the Space

To create a feeling of navigating in a larger space, additional environment sceneries can be added outside or inside of the maze. Scenery can be seen through windows or rooms can be expanded, where the walkable parts would still be of the size of a cell, but the displayed virtual environment would be seen larger. This would be similar to when a person stands on a staircase, balcony, or in front of a barrier rope. The result is a non-walkable space that has a more natural form than just having walls. These spaces can be used to present thematic or cultural information through use of 360° images of nature or outdoor and indoor architectural spaces. Besides providing contextual information, some views can also allow users to see previous and unreached parts of the environment that they can navigate towards, thus creating a sense of progression in a larger environment.

Using the design principles presented in this section, Figure 3.5 demonstrates a walkable VR maze designed with 26 cells. The maze includes cells that branch out to different parts or lead to dead ends. To enlarge the space, windows have been added at places marked by double lines.

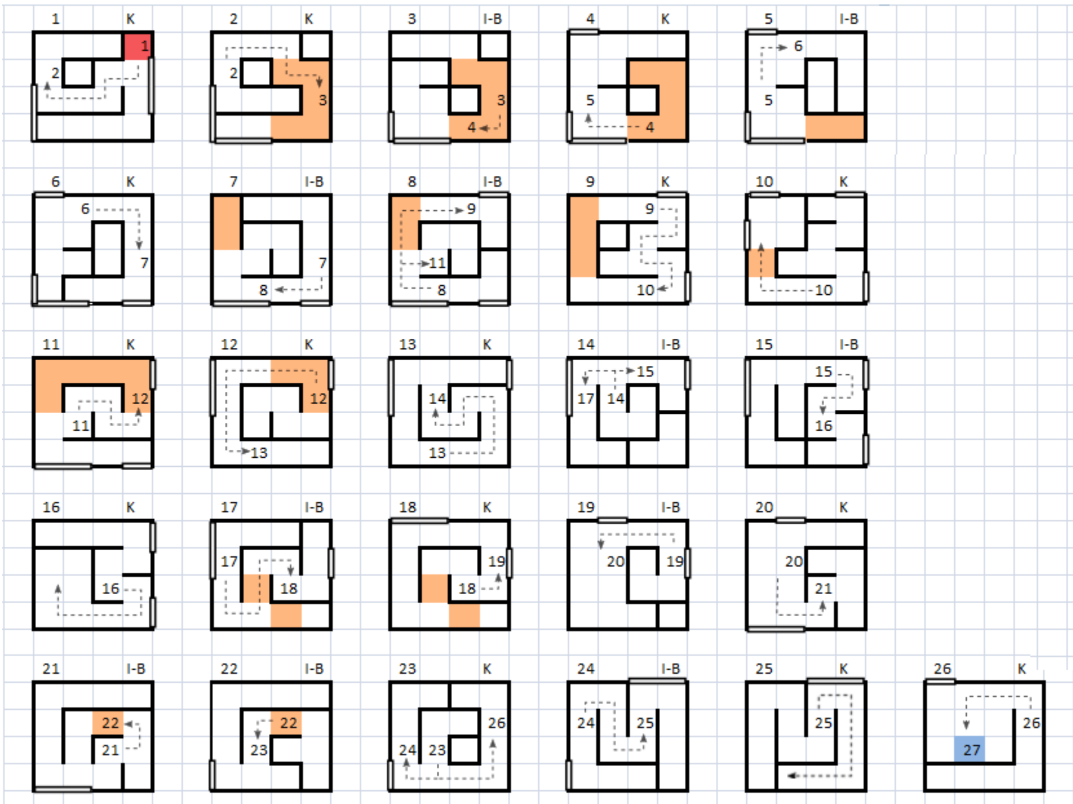

Figure 3.5: A self-overlapping maze with 26 cells. Double lines mark the windows and orange tiles mark the tunnels corresponding to the map (see Section 3.2).

3.1.5 Discouraging Trespassing through Walls

The use of natural locomotion in VR provides a set of challenges with regards to collisions with virtual obstacles. With traditional controllers, it is possible to limit the movement of the virtual camera, so that users do not walk through walls. However with motion tracking, the movement of the virtual camera corresponds to the movement of the user, who cannot be restricted by virtual collisions. This results in the often undesired feature that the user can pass through virtual walls. This feature could in combination with back-face culling (where back faces of objects are not rendered) allow them to see through geometry, breaking the experience. By design, it is not possible to prevent the users from moving through a wall as that would require either moving the wall together with the rest of the cell outside of the available physical area or stopping the movement of the virtual camera before passing through the wall. However, the cell cannot be moved out of the physical tracking space and stopping the movement of virtual camera would introduce an undesirable mismatch between users' movement in physical and virtual environment (Lindeman, 1999; Akiduki et al., 2003).

Instead of preventing, discouraging trespassing can be designed with the idea that once users pass through a wall, what they see on the other side would not reveal the undiscovered parts of the maze. Through manipulation of the content displayed behind the wall, users walking in the VR maze can be prevented from cheating, but also from breaking the system of swapping the cells. In order to discourage users from trespassing, the content displayed on the other side should be information of what just happened and how to return back to the experience. Based on this argument, our system displays only the wall that the user walked through and a single floor tile that the user was standing on before trespassing through the wall, and hides the rest of the cell. While in this mode, the surroundings are presented as a dark space with a bright colored barricade tape notifying the user to return back to their previous location on the displayed tile.

3.2 Visualizing a Self-Overlapping Maze on a Map

In order to encourage asymmetric collaboration with the non-HMD participants and engage them in the experience of the HMD participant, a map is designed to represent the self-overlapping VR maze in a top-down orthographic view. From this view, the whole maze can be presented to the non-HMD participants at once, allowing them to lead the way through the maze. To maintain an accurate representation when making the map, cells from the self-overlapping VR maze are reused. All key cells are laid out next to each other in a grid in such a way that they do not overlap. This is achieved by laying each key cell next to its previous key cell in the x or z direction following the direction the user would be heading to when swapping to the new key cell. When the key cells are unfolded and placed next to each other, there are gaps formed between the transitional tiles (marked by numbers in Figure 3.6) that have to be connected. This is achieved by adding tiles in the gaps to prolong some of the corridors so that they connect with the following key cells, as is demonstrated in Figure 3.6 for the first three key cells.

In some cases, it is not possible to place the connected cells right next to each other, and therefore in order to continue in the unfolding, the next cell is placed further away, resulting in some prolongations crossing over each other. These crossings form prolonged bridges and tunnels, which is also demonstrated in Figure 3.6 in the orange transition going from the second key cell to the third key cell between transitional tiles 3 and 4.

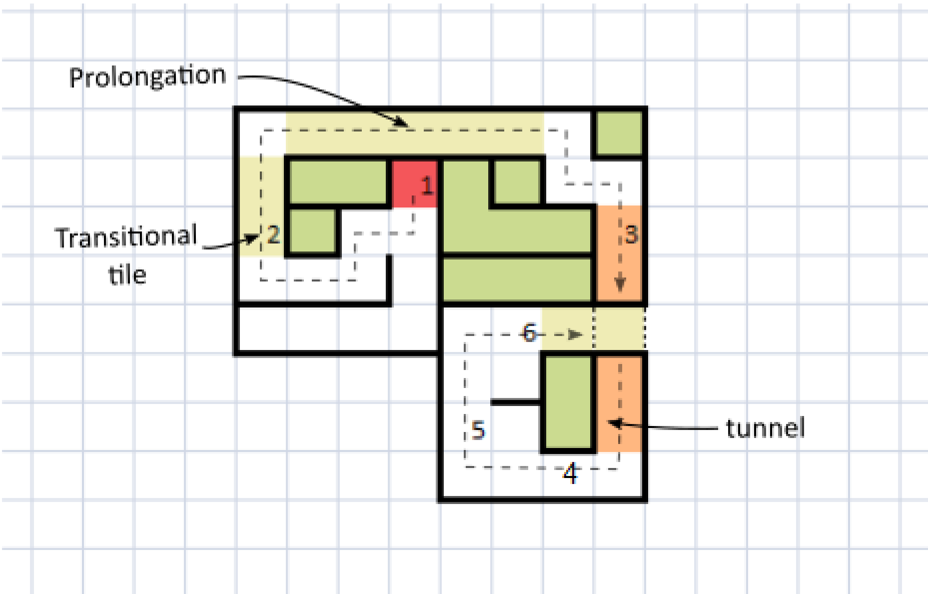

Figure 3.6: Unfolding the maze by placing the key cells next to each other

Figure 3.7 demonstrates a fully unfolded map representation of the self-overlapping maze from Figure 3.5. In order to keep the map understandable, the case where one prolongation becomes both a bridge and a tunnel, whereby creating multiple height levels, should be avoided. Having for example one tunnel crossing under two bridges is more clear than having a tunnel that knits under a bridge and afterwards over a different tunnel, thus being both a bridge and a tunnel.

In order to make the bridges and tunnels a unified part of the whole design in line with the VR maze, they have to also be replicated in the self-overlapping architecture. In this case they can be represented in form of small tunnels - areas with lower ceiling in the maze (marked as orange tiles in Figure 3.5). The prolongations also leave empty spaces in the map as can also be seen marked by green in Figure 3.7. These spaces can be filled with sceneries used to enlarge the space in the self-overlapping architecture such as nature or panoramic views out through windows.

Besides the self-overlapping architecture, the map has to also represent the movement of the HMD-users and the direction they are facing for the non-HMD participants to be able to guide them. This can be achieved using a mimicking object, an avatar, with clear indication of the front side, such as a circle with a pointy edge. This avatar can mimic the HMD-user's movement, and when it reaches the prolonged areas, the movements can be made faster in order to cover the prolonged distance in the map.

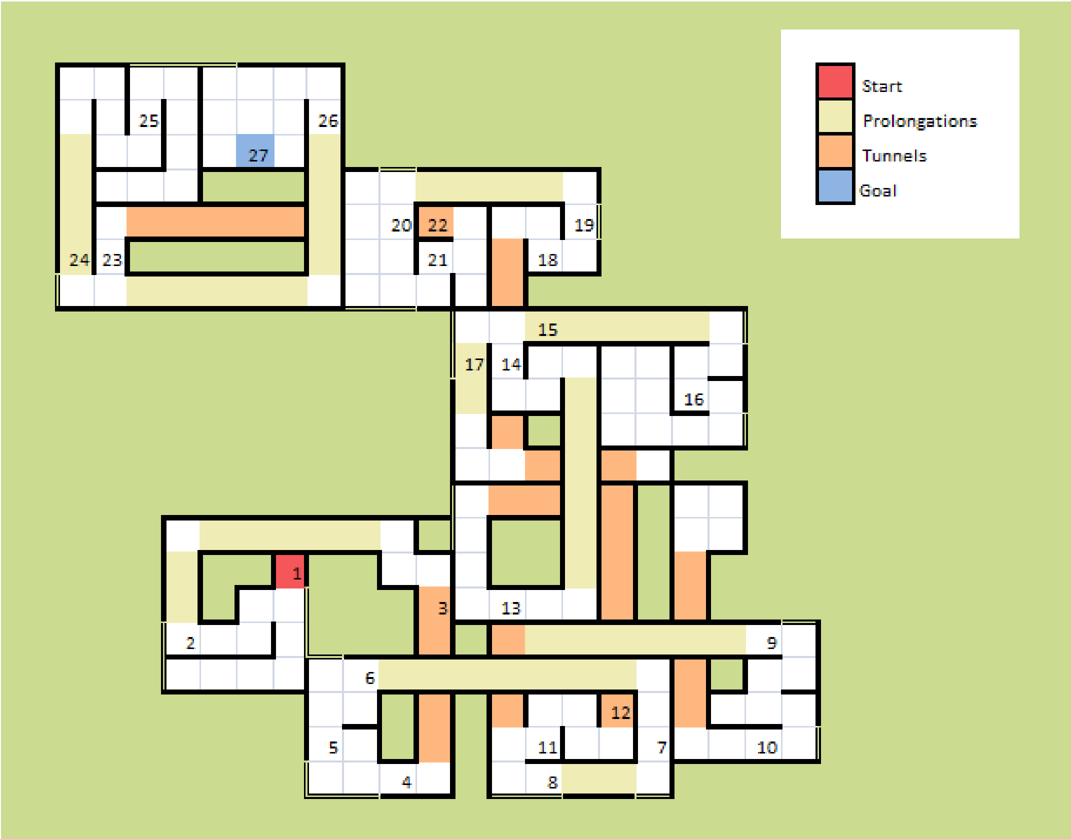

Figure 3.7: A map visualization with an unfolded version of the self-overlapping maze from Figure 3.5

3.3 Asymmetric Collaboration in the VR Maze

For the purpose of the study, content is added to the VR maze following the building blocks of asymmetric collaboration discussed in the related work. Due to our design using multiple media – the HMD to display the self-overlapping maze and the side display to present the map, different roles naturally emerge. These roles can be combined with a theme since the design is flexible and new thematic content can easily be added. We set the theme of exploration in a castle, where two roles are assigned – the navigator for the non-HMD participants and the follower for the HMD participant. For the exploration, the participants are given a common task of collaborating to find a diamond in the maze. Based on the design, the different roles have different abilities and information. The navigator has an overview over the whole maze and the information of where the diamond is in the maze, while the follower has the ability to move in the maze and get to the diamond. This setup demands that the two roles have to collaborate and by so doing, they can get engaged in the experience.

The next chapter further discusses how this design and the experience can be implemented, so that the HMD user can walk through the VR maze while collaborating with the non-HMD participants.

4 Implementation

The proposed design was implemented for the room-scale setup of the HTC Vive headset. The VR maze experience was implemented in the Unity 3D game engine and 3D models were made in a 3D computer graphics software Blender. This chapter continues with the presentation of the HTC Vive setup, and the implementation of the self-overlapping maze and its map visualization.

4.1 HTC Vive and SteamVR Setup

The HTC Vive room-scale VR setup tracks an area of $2.5\,\mathrm{m} \times 2.5\,\mathrm{m}$ using two base stations that rapidly sweep the room with infra-red lasers horizontally and vertically. These lasers are tracked by small sensors on the HTC Vive HMD and controllers with high accuracy and low latency, giving a tracked setup that can be naturally walkable. For implementing the walkable VR maze, our system used the SteamVR Unity plugin published by Valve. This plugin has toolsets such as a camera rig, access to the tracked controllers, and chaperon grid, which allows for an easier way of getting started with VR development.

SteamVR comes with a CameraRig prefab that follows the movement and renders the visuals in the HMD. Since our system aims to facilitate collaboration on a side display, it is important to have a new camera in the scene besides the Steam VR CameraRig that can render the map. However if not set up right, the two cameras would conflict. Therefore, in order to have the new camera set correctly in Unity, it must target "Display 1" just like the HMD camera, and have a different depth than the HMD camera. It also has to be set to target "Nothing", unlike the HMD camera which targets "Both eyes". The self-overlapping maze and the map are also separated by placing the map on a separate "Map" render layer that is only rendered by this new camera.

4.2 Implementing a Self-Overlapping Maze

The self-overlapping maze in the Unity scene is composed of cells, which are represented as empty game objects centered in the world. Each cell is filled with meshes and content of the virtual environment per one tracking area, which are arranged in the 4x4 grid layout as shown in Figure 4.1.

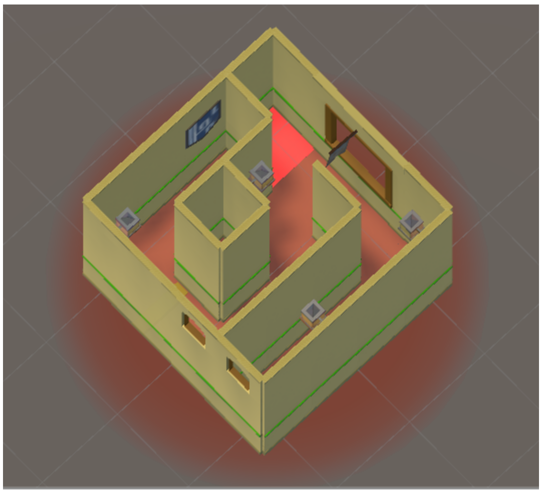

Figure 4.1: Cell 1 with its contents in the 4x4 grid layout

Each tile in the grid consists primarily of a floor and a number of surrounding walls. In addition, other objects are added on the tiles, representing the theme of a castle in this case, such as lamps, pictures, and flags. The models used are modelled in Blender, which included a floor tile and three kinds of walls – one with a small window, one with a double window and one without windows. The roof is set at the height of 2.6 m and the lower ceiling in the tunnels at the height of 1.5 m.

4.2.1 HMD Camera Colliders

The interaction in the self-overlapping maze is designed around the HMD camera because it represents the HMD user. It triggers updates of cells and detects collisions with walls. In order to detect collisions, colliders are added to the SteamVR's CameraRig as can be seen in Figure 4.2.

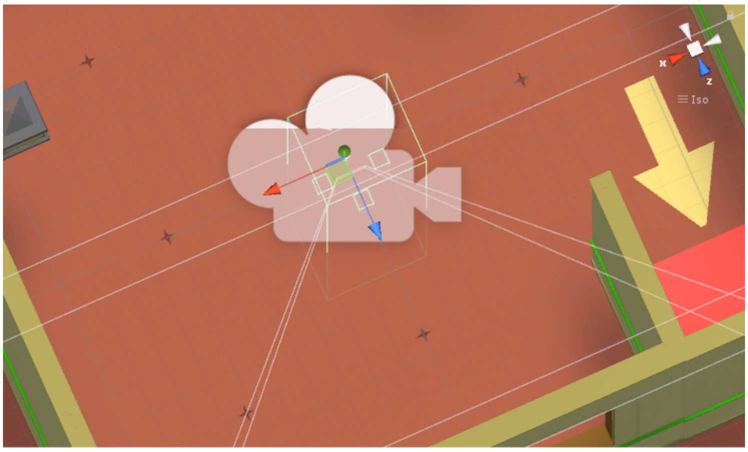

Figure 4.2: Colliders added to the CameraRig containing front, left, and right triggers and an overlap collider.

The colliders are three triggers placed on the front, left, and right side of the HMD camera with the primary purpose to detect events when they collide with objects in the

Unity scene. Instead of being centered on the camera's pivot, they are placed around the HMD user's view, where the collisions with objects like walls are visually perceived. The front trigger is the main collider used when swapping between cells while the side triggers are there to help decide whether the HMD user has walked through a wall. In addition, a new box collider is added to the HMD camera to serve as an overlap collider that checks which walls and floors are around the user when trespassing through a wall. Further description of how these colliders on the HMD camera help the user to interact in the virtual environment is detailed in the following sections.

4.2.2 Updating Cells

One of the key features of our designed system that allows users to walk in the virtual environment, is the idea of unnoticeably updating cells. As mentioned in Chapter 3, this is achieved by duplicating parts from the current cell visible to the user before updating into the next cell. Furthermore, all other objects placed in the cell such as lamps are also duplicated if they could be visible to the user. When updating the virtual environment, cells are swapped based on "swap triggers", which are box colliders placed on transitional tiles. When the HMD user enters a swap trigger, the following cell is enabled and the current cell is disabled, thus opening a new area for the user to continue walking in. In order to allow the user to return to the previous cell, the newly enabled cell also contains a swap trigger, which when entered, enables the previous cell. For swapping between two cells, the two swap triggers are spaced out on the transitional tile, so that the user cannot be in both at once. This also means that the layout of the cells for the self-overlapping architecture has to be planned carefully to account for the swapping. A demonstration of how swap triggers are set up in Cell 14 and Cell 17 is shown in Figure 4.3.

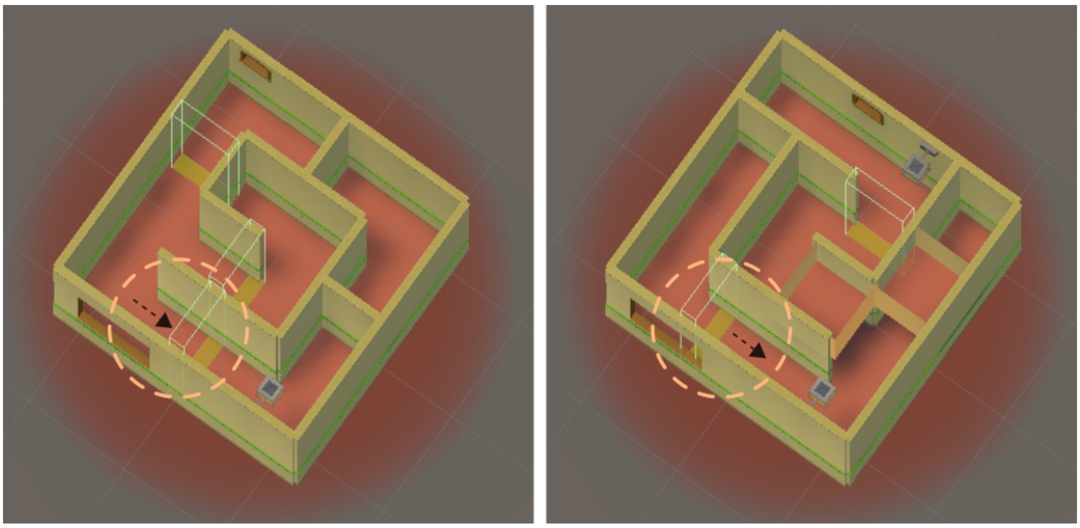

Figure 4.3: Swap triggers in Cell 14 (left) and Cell 17 (right). The transitional tile between the two cells is marked by a circle.

Each swap trigger has a Swap script, which when attached will have two fields in Unity's inspector, where the cells to be shown and hidden can be assigned. When the front trigger attached to the CameraRig enters the swap trigger, the Swap script uses Unity's OnTriggerEnter() function and SetActive() function to swap the cells as shown in the following pseudocode.

OnTriggerEnter
if HMD user entered the swap trigger
enable the next cell
disable the current cell

4.2.3 Calibration

In order to start the self-overlapping maze correctly as well as have it in sync with the map, it is important to have the HMD users' starting position on the red floor tile of Cell 1 in Figure 4.1. To set this position correctly, a calibration room (Cell 0) is added before Cell 1, thus when HMD users put on the HMD, they find themselves in a 4x4 room as shown in Figure 4.4. While the HMD users are in this calibration room, an arrow on the ground directs them where to go. When they have entered a box trigger added to the starting red tile, the system waits for approximately five seconds and afterwards fades to black using SteamVR_Fade() function. Afterwards, the calibration cell is made inactive and Cell 1 of the maze is activated.

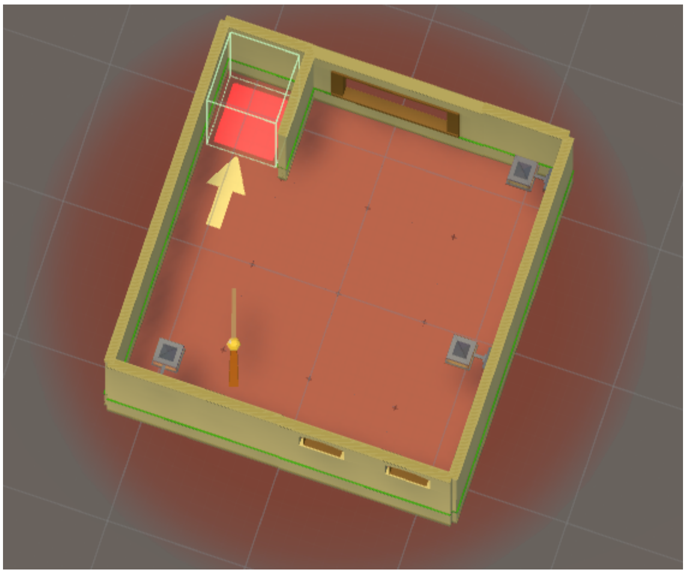

Figure 4.4: A 4x4 room of the calibration cell with a starting box trigger on the red tile

4.2.4 Enlarging the Space with 360° Images

After setting up the cells such that it is possible to transition from one to the other, the next step is to add thematic content to some of the cells in order to provide meaning, a sense of location and an illusion of a larger virtual environment. This is achieved by adding 360° images outside of the windows to show that the architecture is surrounded by for example gardens and vegetation. 360° images are made by placing equirectangular images on a sphere that was created and UV unwrapped through a spherical projection in Blender. The UV unwrap of the sphere, placed on top of an equirectangular image, can be seen in Figure 4.5. This sphere was then imported to the Unity scene and aligned with cells so that the 360° images could be seen out of the windows.

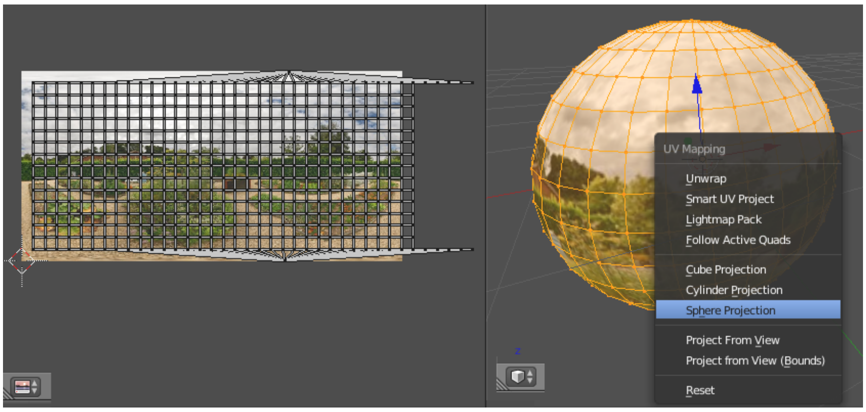

Figure 4.5: UV unwrapping a sphere through spherical projection for 360° images

4.2.5 Discouraging Trespassing

Since HMD users are naturally walking in the maze, one problem as mentioned in Chapter 3 is that people can easily trespass through virtual walls, which could break the system and the designed experience. Therefore, a system had to be implemented to handle these situations.

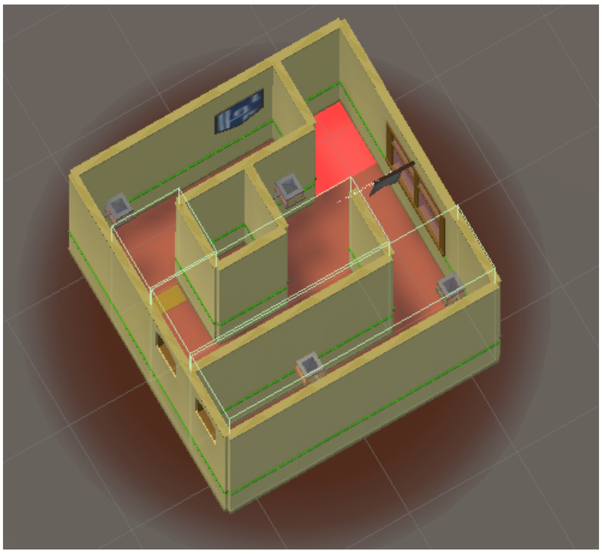

Figure 4.6: Corridor boxes representing rooms and corridors in the cell

As can be seen in Figure 4.6, the trespassing system is first set up by adding a number of "corridor boxes" to each cell defined by the placement of the walls, where one corridor box could represent for instance one room or one corridor. Each corridor box is then implemented as a trigger attached to an empty game object and tagged "CorridorBox". In addition, all walls are given a box collider and are tagged "Wall".

When walking in the maze, HMD users can walk from one corridor box to another without entering walls. However, when they enter a wall and cross from one corridor box to another, it is recognized as trespassing, and progression in the maze is stopped by changing the world to the trespassing mode as shown in Figure 4.7. In this mode, a different skybox material is displayed, a warning sign is shown around the user, and most of the cell is disabled leaving only the part the user should return back to. When detecting which part of the cell should remain rendered, the overlap collider attached to the CameraRig is used along with Unity's Physics.OverlapBox() function. All colliders intersecting with the overlap collider are saved in an array. Afterwards, all objects in the cell are disabled and only the objects with the colliders saved in the array are enabled again. Since the overlap collider's width and depth correspond to approximately half of the tile size, the result is that only one or two tiles where the trespassing happened are visible. Besides the walls and floors, the overlap collider also intersects with the corridor box that the user has just left. This corridor box is also kept enabled to allow the user to return back to the maze when they enter through it again.

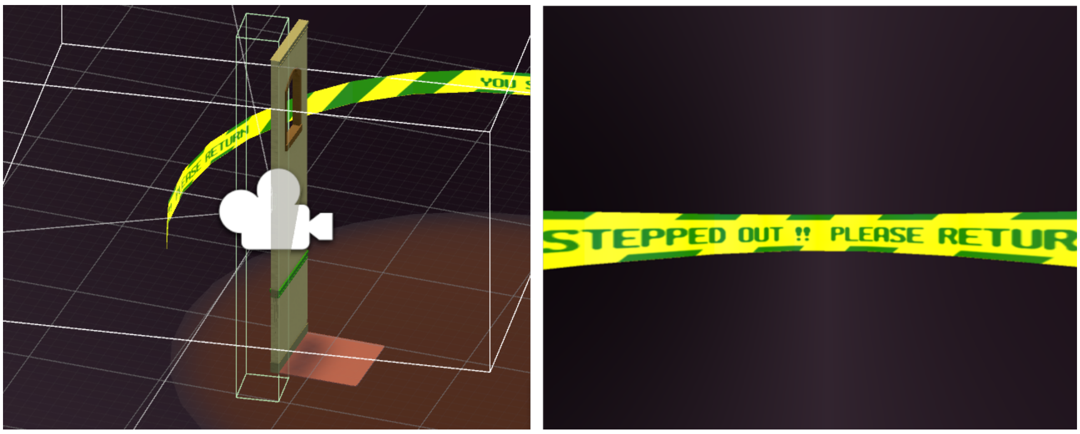

Figure 4.7: The virtual world in the trespassing mode and the corresponding HMD view

The three triggers attached to the CameraRig are used to detect when the user has crossed through a wall. The front trigger takes care of the front direction. However, it is unable to detect accurately when the user moves sideways through a wall. Therefore, two more triggers are needed on the left and right side to cover for this situation. By pushing the three triggers further in front slightly offset from the camera center, it is possible to make the change from the maze world to the trespassing mode happen more accurately at the point when the user's view clips through the wall. The flowchart in Figure 4.8 demonstrates the algorithm in the script used for trespassing walls. This algorithm is used by all three triggers.

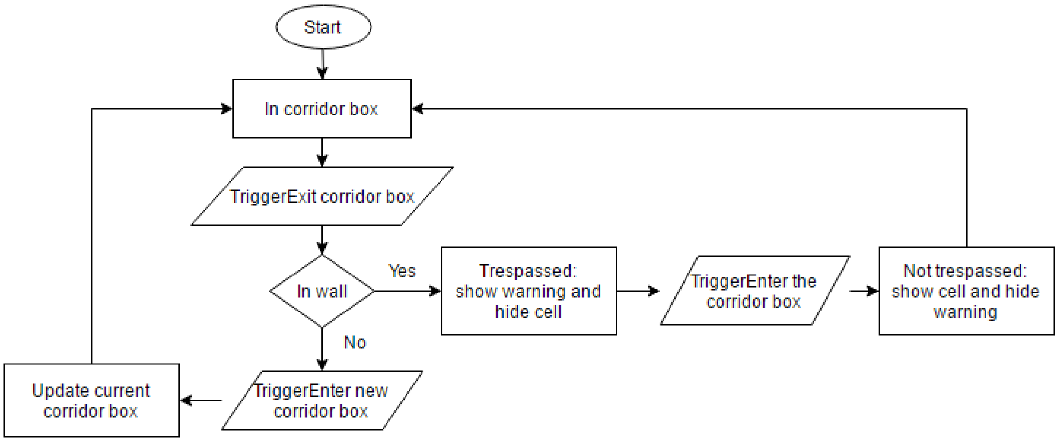

Figure 4.8: Flowchart of detecting trespassing and changing the virtual world

All three triggers can at the same time be detecting a different state from each other, for example trespassing, returning to the maze, or continuing to the next corridor box. Therefore, the decisions they make about whether to for example show the trespassing mode have to be synchronized. In the code, the functions for changing the environment and variables for checking whether the user has left the corridor box or entered a wall are defined in a SolidWalls class. This class is extended by two scripts called SolidWallsFront, attached to the front trigger, and SolidWallsSide, attached to the left and right triggers. Both scripts use Unity's OnTriggerEnter() and OnTriggerExit() functions and are able to detect when the HMD users have entered from one corridor box to the next, or whether they have exited a corridor box through a wall. The front trigger is considered the main trigger on the CameraRig, therefore it defines whether the user has correctly exited one corridor box and entered the next one. At this point, if none of the side triggers is in the trespassing mode, the SolidWallsFront script updates the current corridor box for all triggers.

4.3 Implementing a Map

Implementation of map followed a similar process as described in the design. In the Unity scene, an empty game object called “MonitorMap” is created and placed away from the cells of the self-overlapping maze on the x-axis, so that it is not covered by the cells. Key cells from the maze setup are duplicated and added to the MonitorMap game object following the layout of the unfolded map design from Figure 3.7. Afterwards, prolongations connecting the cells are filled in, resulting in a non-overlapping version of the self-overlapping maze, which can be seen in Figure 4.9.

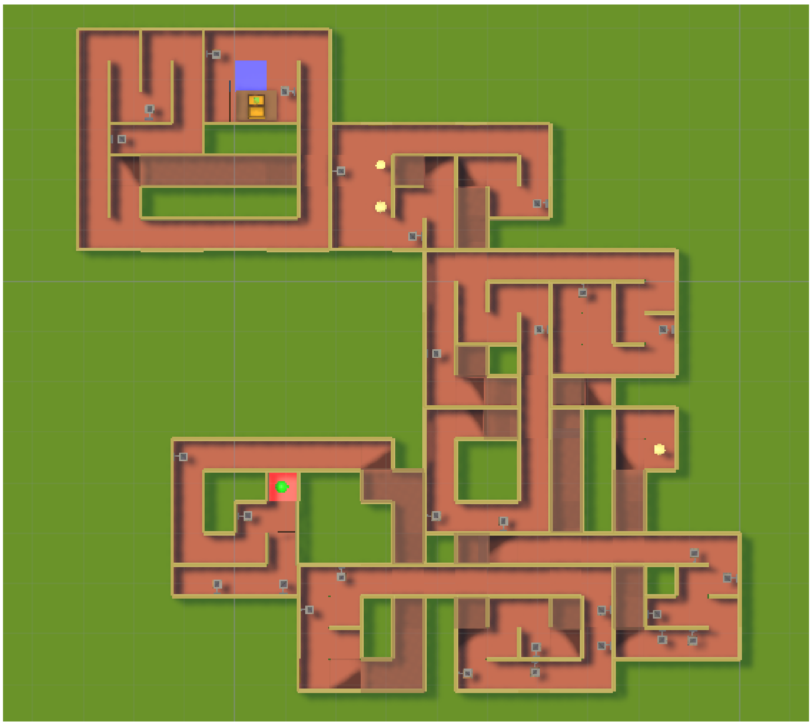

Figure 4.9: The map in the scene based on the layout in Figure 3.7

In the map, the HMD user is represented by an avatar in form of a sphere with an arrow pointing in the same direction as the HMD camera. To accurately represent the HMD user's movement, the avatar is assigned a MimicFollower script that copies the CameraRig's position and rotation in the maze onto the avatar game object. When copying the position, it is important to account for the placement of the MonitorMap in the scene (refPoint) and also the offset that comes as a result of all the prolongations added between the cells on the map (prolongOffset) that the avatar has gone through to reach that position on the map. Based on this information, the avatar's position (pos) can be calculated as follows.

$$pos = HMD\ pos + refPoint + prolongOffset$$

4.3.1 Avatar Movement in a Prolongation

Despite the offsets added, the mapping between the HMD camera's movement and the avatar's movement in this case is 1:1 for areas that are not prolonged. However, when the avatar gets in a prolongation, it has to speed up to cover the prolonged distance in the map, thus changing the mapping. Since the prolongations are tile based, it is possible to use piecewise linear interpolation to calculate the avatar's position. This is done by linearly interpolating the position of the avatar on the map based on the HMD camera's position in a cell as shown in Figure 4.10.

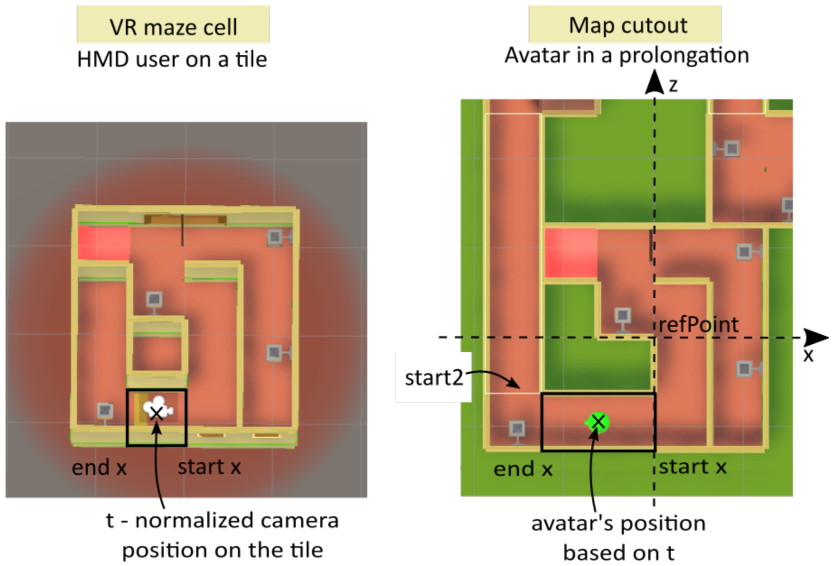

Figure 4.10: Linear interpolation to calculate the avatar's position on the map while in a prolongation

Each prolongation on the map is designed to correspond to one tile in the self-overlapping maze. Thus, there is always only one tile in the self-overlapping maze being prolonged by multiple tiles on the map. A prolongation is done either in x or z direction. Each prolongable tile in the self-overlapping maze has a start and an end coordinate along the prolongation axis. These coordinates are linked to the start and end coordinate of the tile's corresponding prolongation in the map with the reference point (refPoint) as origin. For instance in Figure 4.10, the first prolongation in the map has its start coordinate at x=0 tiles in the map grid, while the start coordinate of the second prolongation that starts at the "start 2" position is at z=-1 tile away from the reference point. Given this information, it is possible to find the normalized HMD camera's position (t) on the tile. This can be used as an interpolation factor to interpolate between the start and end coordinate of the prolongation (P) to calculate the position of the avatar (pos) along the prolongation axis as shown in the following pseudocode for the x axis.

t = (HMD pos x - tile start x) / (tile end x - tile start x)
interpolated pos x = P start x + t · (P end x - P start x)
pos x = refPoint x + interpolated pos x + prolongOffset x

While in the prolongation, the avatar's position along the prolongation direction is computed with respect to the HMD camera's position (HMD pos). As the avatar exits the prolongation and continues on the map, the length of tiles along the direction that the prolongation added to the original one tile in the self-overlapping maze is added to the prolongOffset for that direction, so the avatar can proceed with the right position. However, if the avatar goes back through the prolongation towards the start, the length of tiles added by this prolongation has to be subtracted from the prolongOffset for that direction. This way, the prolongOffset keeps updating every time the avatar exits a prolongation.

The avatar has a collider attached to it, and as it goes through the map, it is detected by "prolongation triggers". These are empty game objects with a box collider added to detect the avatar entering and exiting the prolongation. A Prolongation script is attached to each prolongation trigger in Unity's inspector, where it is possible to define the number of extra tiles that the prolongation has on x or z axis. The start and end coordinates of the prolongation both in the self-overlapping maze (tile) and in the map (P) are also defined here to be used when calculating avatar's position.

4.3.2 Error Between Avatar's Collider and Prolongation Start

One problem with using triggers is that often events are not registered fully precisely when the avatar is on the bounds of a prolongation due to the size of the avatar's collider. This affects the calculation of the interpolation factor t in the pseudocode above, where it goes out of its bounds between 0 and 1 and becomes greater or smaller depending on where the center of the avatar is with respect to the prolongation trigger as shown in Figure 4.11.

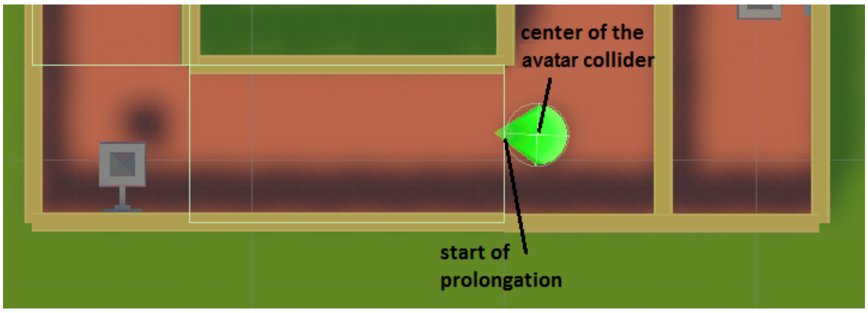

Figure 4.11: The error between the center of avatar's collider and the start of the prolongation trigger

When t is out of bounds, the avatar's movement should not be sped up. However, the prolongOffset has to be set correctly. We compensate for this "error" by applying a 1:1 mapping on the difference from the center of the avatar (the calculated t) to the start of the prolongation ($t = 0$) or to the end of the prolongation ($t = 1$). The prolongation between $t = 0$ and $t = 1$ remains sped up until the avatar's collider exits the prolongation trigger. Here the prolongOffset is updated by either adding or subtracting the length of the exited prolongation.

4.3.3 Bridges and Tunnels

The map has junctions where multiple prolongations cross over each other as shown in Figure 4.12. This means that the prolongation triggers in these junctions also have to cross each other, which causes confusion for which direction the avatar should take. To account for this, once the avatar has entered a prolongation trigger, it cannot enter a different prolongation trigger until it has exited the current one. Furthermore, a new variable is added to the Prolongation script, so that prolongations can be defined either as bridges or tunnels in the inspector. Since tunnels can go under places that are not prolonged, when crossing over a tunnel in such places, the avatar would enter the tunnel prolongation trigger and wrongly change direction. To prevent the avatar from entering the tunnels while in such places, the tunnels are made so that they can only be entered through their two entrances marked by colliders with a tag “TunnelEntrance”, and not from the side. Therefore, before entering a tunnel prolongation trigger, the MimicFollower script checks whether the avatar has entered the tunnel entrance.

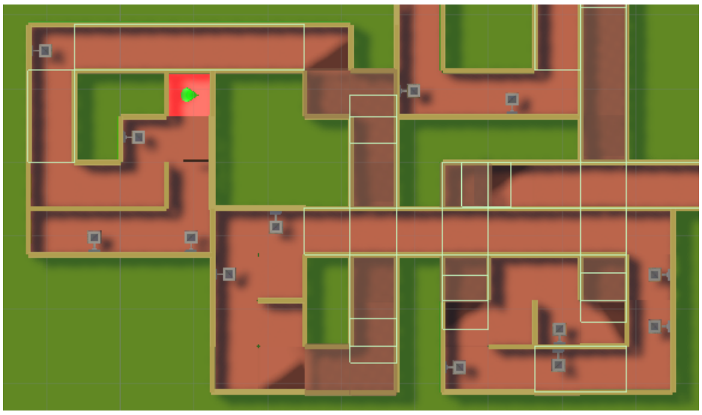

Figure 4.12: Tunnels and bridges crossing over each other. The tunnels have a TunnelEntrance collider added on each end.

When all parameters are set right, the result is a map with an avatar that follows the HMD user with a 1:1 mapping in non-prolonged areas, speeds up while in prolonged areas, and is capable of moving through tunnels on its way to the final goal of the maze. This setup of the self-overlapping maze and the map is further tested on users and evaluated as described in the following chapter.

5 | Test of the Design

This chapter discusses two experiments used to refine the design and evaluate its specific features. It contains relevant information regarding the experiment setups, questionnaires and results, which are described in depth in their respective sections.

5.1 Experiment 1: Testing the Design in a Lab

To evaluate the experience and usability of the proposed design, a usability test was conducted. This test consisted of three parts: first an examination of the size of the corridors, second an investigation of the asymmetric experience between the non-HMD participant and the HMD participant, the self-overlapping maze, and the map, and third an examination of the system for discouraging trespassing. The tested system included and examined the features designed in Chapter 3 and implemented in Chapter 4. This first experiment was conducted in a university setting, where questionnaires were used to get feedback on the system.

5.1.1 Experiment Design

The experiment was set up in a lab with the HTC Vive's tracking system. In total, 18 participants between the age of 20 - 34 were tested in pairs and the design was evaluated using four distinct questionnaires. The participant pairs started by taking turns trying the different corridor sizes in VR to complete a simple navigation task and answering questionnaires. They received an identical questionnaire after each corridor variation to evaluate how comfortable they felt in each of the tracking sizes: $2\,m \times 2\,m$, $2.5\,m \times 2.5\,m$ and $3\,m \times 3\,m$. The corridor sizes were ranked using a five-point Likert scale ranking from "Very Uncomfortable" to "Very Comfortable". These three variations were given in a counterbalanced randomized order to account for carryover effects.

After the pair had tried and evaluated each corridor variation, they continued to the second part of the experiment. In this, one participant was equipped with an HMD and acted as a follower, while the other with the role of the navigator was instructed to guide the HMD participant through the maze. While in the calibration room, the HMD participant was asked to estimate its size in meters. Afterwards, the non-HMD participant used a regular monitor displaying the map visualization to guide the HMD participant from the starting red square to the blue square positioned at the end of the maze. After completing the maze, each participant was given a separate questionnaire based on their role, which can be seen in Table 5.1 and Table 5.2. As such each role was evaluated on nine participants. Two out of the nine HMD participants had previous experience with VR. The questionnaires also asked them to explain their ratings, and in addition, the HMD participants were asked whether they noticed any changes in the maze, or thought about walking through walls, and to estimate the size of the overall maze in meters. In the third and final part, all participants were asked to put on the HMD and walk through a virtual wall twice in order to examine and evaluate the trespassing system using a questionnaire seen in Table 5.3. Lastly, a short semi-structured interview was conducted to get more insight into their experience.

Table 5.1: A table containing the Likert items for the HMD participant

HMD items	
Maze	**HQ1:** To what extent did the maze allow you to freely walk in the VR environment? **HQ2:** To what extent did you have a sense of where you came from in the environment? **HQ3:** I got motion sick during the experience
Collaboration	**HQ4:**To what extent did the help from the person without the head-mounted-display help you progress in the maze? **HQ5:**To what extent did you use the guidance of the other participant without the HMD?

Table 5.2: A table containing the Likert items for the non-HMD participant

Non-HMD items	
Map	**NQ1:** How representative was the movement of the HMD participant on the map? **NQ2:** To what extent did you understand the map representation of the virtual world? **NQ3:** How challenging was it to find the path from start to finish? **NQ4:** How challenging was it to guide the other participant? **NQ5:** To what degree did the sudden speeding up of the HMD participant's movements on the map affect your guidance and communication?
Collaboration	**NQ6:** To what extent did the map involve you in the VR experience? **NQ7:** To what extent did the map facilitate collaboration between you and the HMD participant?

Table 5.3: A table containing the Likert items for the trespassing system

Trespassing items
TQ1: To what extent were you aware of that you had walked through a wall?
TQ2: To what extent did you know how to return back after you had walked through a wall?

5.1.2 Results

Responses on Corridor Sizes

The data derived from the corridor questionnaires can be seen in Figure 5.1. With a median of 2, the 2 m×2 m tracking space with a corridor size of 50 cm was rated as uncomfortable (M = 2.78). The 2.5 m×2.5 m was somewhat comfortable with a median of 3.5, (M = 3.39), while the 3 m×3 m was comfortable with a similar median of 4, (M = 3.78). In the design, the initial constraint was a 2.5 m×2.5 m tracking space taking into account the limited space in public places and the tracking equipment. Therefore, this tracking area was tested against the two other areas in a two-tailed Wilcoxon Signed-rank test with an alpha value of 0.05. When compared to the 2 m×2 m tracking space, the 2.5 m×2.5 m area was significantly more comfortable, $W = 8$, $p = 0.005$. However, no significant difference was found when the 2.5 m×2.5 m area was compared to the 3 m×3 m tracking area, $W = 42.5$, $p = 0.32$.

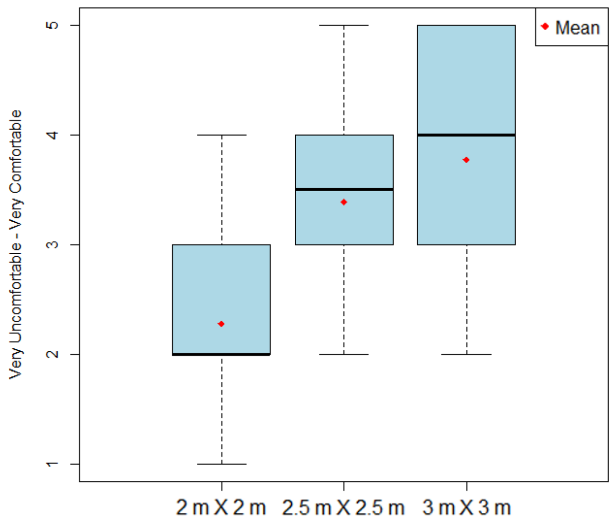

Figure 5.1: Box plots of ratings on “How comfortable was the size of corridors?”

HMD Role Responses

Results from the second part of the experiment that investigated the asymmetric experience between the non-HMD participant and the HMD participant, the self-overlapping maze, and the map, can be seen in Figure 5.2. Generally, the HMD participants' responses were fairly spread out, the majority with a variance above 1. When evaluating the self-overlapping maze, a median of 4 in HQ1 (M = 3.44) shows that participants felt that the maze allowed them to freely walk in the virtual environment. In HQ2 (M = 3.11) that evaluated the participants' overview in the maze, a median of 3 shows that participants were undecided if they had a sense of where they came from. Furthermore, responses from HQ3 (M = 1.89) with median of 1 and one outlier show that physically walking around in the maze did not cause motion sickness. When asked whether they had noticed any changes in the maze, the question was misunderstood. Participants' responses provided different feedback that was related to "lower ceiling" or "pillars", and nothing related to the updates of the maze. Only one participant might have noticed with the comment "after I made a turn round the corner", but it did not specify whether it was an update or the contents of the maze.

For the collaboration, ratings in HQ4 (M = 3.67) with a median of 3 show the directions the HMD participant obtained from the non-HMD participants were only somewhat helpful in solving the maze, as all responses to this question have ratings between 3 and 5. Even though the directions were not always helpful in solving the maze, responses in HQ5 (M = 3.89) show that most HMD participants still followed the guidance based on a median of 4.

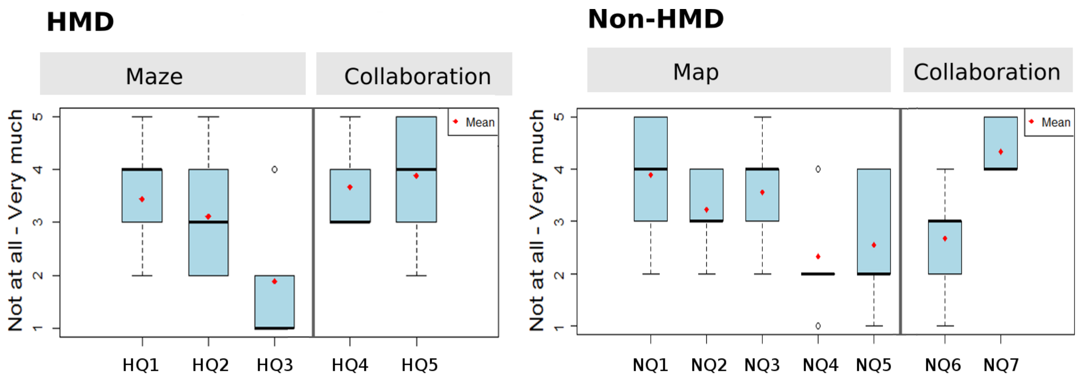

Figure 5.2: Box plots of ratings on HMD and non-HMD experience based on Table 5.1 and Table 5.2

Non-HMD Role Responses

When evaluating the map, responses in the non-HMD questionnaire for NQ1 (M = 3.89) with a median of 4 and NQ5 (M = 2.56) with a median of 2 show that non-HMD participants felt the movement of the HMD-participant on the map was consistent with their actual movement (Q1). Furthermore, the speeding-up on the map did not affect their ability to guide and communicate with the HMD participant (NQ5). Responses in NQ2 (M = 3.22) with a median of 3 show that the map was somewhat clear. Seven participants noted in comment to this question that they struggled with finding the exit point of a tunnel. When evaluating the non-triviality of the maze, in NQ3 (M = 3.56) with a median of 4, the non-HMD participant found the maze adequate in difficulty as it was neither too difficult nor too easy. They also found guiding not very challenging as can be seen in NQ4 (M = 2.33) with a median of 2.

Feedback on collaboration from the non-HMD participants showed that they did not feel the map sufficiently involved them in the VR experience as can be seen in NQ6 (M = 2.67) with a median of 3. However, they felt that the map facilitated their collaboration with the HMD participant as shown by the responses in NQ7 (M = 4.33) with a median of 4.

Responses for the Trespassing System

In terms of trespassing walls, only 3 out of the 9 HMD participants had thought about walking through the virtual walls while they walked through the self-overlapping maze in the second part of the experiment. In the third part of the experiment, all participants were asked to walk through a virtual wall and give feedback on the design of the trespassing system. As seen in Figure 5.3, responses for both TQ1 (M = 4.5) and TQ2 (M = 4.72) with a median of 5 show that all participant felt that they were aware when they walked through the wall (TQ1), and knew how to return back afterwards (TQ2).

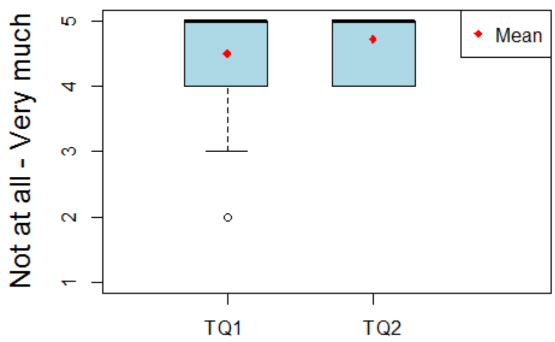

Figure 5.3: Box plots of ratings on the trespassing system based on Table 5.3

5.1.3 Discussion

The purpose of this test was to evaluate the design and whether it fulfills the criteria set for the self-overlapping maze and the corresponding map, so that they can be used in a public space. During the discussion of the design, one of the key questions was to understand the minimum spatial requirements for the tracking area that can be walkable. Three constraints were defined with the tracking areas of measurements of $2\,m \times 2\,m$, $2.5\,m \times 2.5\,m$ and lastly $3\,m \times 3\,m$. After the testing, results show that $2\,m \times 2\,m$ was the least comfortable. There was no significant difference between $2.5\,m \times 2.5\,m$ and $3\,m \times 3\,m$. This implies that the minimum tracking area to utilize should remain a $2.5\,m \times 2.5\,m$ with the corridor width of approximately 0.625 m as was also initially set up in the design.

Results in the second part of the experiment show that the self-overlapping maze was fully walkable, even though it was challenging to create an overview of how participants progressed. It could also be argued that because only one of the nine HMD participants commented on an undesired change in the maze, people generally did not notice the updates in the maze. With regards to whether the virtual environment felt larger, the HMD participants did not give accurate measurements, but most of them gave it a larger measurement than the actual physical size of $2.5\,\text{m} \times 2.5\,\text{m}$ and their estimates for the calibration room. Based on these results, it can be stated that the designed self-overlapping maze allowed people to walk in a larger virtual environment in a limited physical area. Responses from the experiment also show that natural walking in the room-scale VR setup does not elicit motion sickness.

For the map, most responses show that the non-HMD participants felt that the avatar's movement on the map corresponded well with that of the HMD participant. The prolongations and the speeding up of the avatar did not affect the guidance and were taken as an integrated part of the map. Although the map received positive feedback, there is need for some improvements. The HMD participants rated the guidance from the non-HMD participants as not always helpful (HQ4), which could be attributed to a poor understanding of the tunnels from the non-HMD participants. This meant that they would often misdirect the HMD participants down a wrong tunnel leading to a dead end in places where the tunnels were crossing under multiple bridges. The understanding of the tunnels could be improved by for example increasing the length of certain prolongations to avoid having multiple tunnels placed close together giving the impression that they connect. In the interview, one non-HMD participant also suggested to color-code the entrances and exits of tunnels. Besides the tunnels, two participants mentioned that they found it "hard to see which way the HMD participant was facing". This could be solved by making a more clearer identification of the avatar's front. Overall, it was observed that the map was challenging to understand at first, but made more sense as the HMD-participant moved through the maze.

In terms of asymmetric collaboration, observations show that participants used their roles as designed. This can also be seen in the questionnaires, where the HMD participants said that they used the guidance. In the interviews, two HMD participants mentioned they "couldn't have continued without help from the non-HMD participant", and one also said that "being two made it more fun and interesting". Non-HMD participants also stated that the map facilitated their collaboration with the HMD participants. A few participants mentioned in the interview that the fact that the HMD participants followed the directions made them more part of the experience. Two said: "I felt part of the experience because she was reacting to what I was saying, we worked on it connected" and "she kept asking, I felt like I contributed", but also "I felt like a person on the other end of the phone call".

Although this was the case for some, responses from the questionnaire show that the map facilitated only average involvement of the non-HMD participants in the VR experience. Therefore, further improvements are needed, which could be done through giving the non-HMD participants more tasks for their role, or presenting them more information and a view similar to that of the HMD participant. One non-HMD participant for example mentioned that "it would maybe help if I could also see what she [the HMD participant] was seeing". He suggested to use both map and the mirrored HMD view on the side display. The HMD participant in pair with him agreed that this would also be "helpful to understand what is left and right for me". Another non-HMD participant also mentioned that he wants to "be able to see what he [the HMD participant] sees" and that he feels that "that would be more engaging maybe". Therefore, one solution could be providing them additional information such as allowing the non-HMD participants to see the HMD participant's view on the side display. However, this might decrease the amount of necessary collaboration, as the HMD participants might no longer have a reason to communicate what they are seeing with the non-HMD participants. Therefore, it is further investigated in Experiment 3 how providing this additional information on the side display would influence involvement, engagement and collaboration for both roles.

Lastly, the experiment also evaluated the trespassing system. Observations show that participants were not inclined to walk through walls, which could be because they had not tried VR beforehand. Responses from the questionnaire show that once they were asked to go through the walls, they were aware that they had trespassed, and understood how to return back to the maze.

Overall, the self-overlapping maze and the map fulfilled the design criteria based on feedback from the lab experiment. In the next section, the design is further tested in a field study to observe how people use it in a public setting.

5.2 Experiment 2: Testing the Design in a Public Library

After testing in the lab, a second experiment was planned as an observational study to evaluate the proposed design in Aalborg Hovedbibliotek. Similar to the first experiment, the primary aim of Experiment 2 was to investigate whether users in the public understand the design, find it intuitive, and whether the self-overlapping maze and map facilitate collaboration. Before testing, the system was improved to include the spacing around tunnels, since as discussed in Experiment 1, some participants found it challenging seeing where the tunnels lead. Furthermore, the forward direction of the avatar was made clearer and text instructions were added both in the self-overlapping maze and on the side display to instruct the participants about the goal of the maze as shown in Figure 5.4.

Figure 5.4: Improvements added before Experiment 2: instructions (top), clearer front of the avatar and spaces around tunnels in the map (bottom)

5.2.1 Experiment Design

The proposed system was set up for the observational study in the library, where it was tried by a total of 20 participants, of which two were female and 18 male. The participants' age group was observed to be between 9 and 40 years. Figure 5.5 shows pictures taken of the setup of the experiment and a pair of participants interacting with the self-overlapping maze and the map.

Figure 5.5: The setup of the experiment and participants interacting with the system

On arrival, participants were instructed to collaborate and find a diamond in the maze. Afterwards, an instructor helped them put on the HMD. The experiment setup also included two observers nearby that noted down how people behaved while they were using the system. Number of participants and playthroughs was counted, where one playthrough was considered the whole session where participants maintained their roles. Besides this, the observations focused on intuitiveness & usability of the system, collaboration & communication, and engagement. Observations were made based on a set of criteria that were related to the design of the self-overlapping maze and the map. To evaluate intuitiveness & usability, we observed how far participants progressed without giving up, for collaboration, we observed whether participants fulfilled their roles and were communicating. Lastly, engagement was observed on whether they completed the maze, whether the experience was engaging enough to try it again and catch the interest of spectators. The observations in Table 5.4 were noted for evaluation.

Table 5.4: Observations for Experiment 2

Topic	Observations
Intuitiveness & usability	How often and where do they feel stuck and are unable to progress How many reach Cell 13, thus understand the tunnels How many reach Cell 3, thus understand the prolongation, and cell swaps in the maze do not interrupt
Collaboration & communication	How they communicate Do they collaborate, use their roles How many non-HMD participants help navigate the maze How many passive spectators are standing by and watching
Engagement	How many pairs complete the maze (success rate) How many try their role more than once How many times do they retry the system

5.2.2 Results

During the experiment, the system was played through 21 times. Results from the observation can be seen in Table 5.5. In terms of the intuitiveness & usability, all playthroughs reached Cell 3, thus all participants understood the prolongations, and the cell swaps in the self-overlapping maze did not interrupt the experience. 17 (81 %) playthroughs reached Cell 13, and thus understood the more complex tunnel junctions. For the remaining 4 playthroughs, 2 struggled to understand the tunnels, got stuck and never progressed past the junction in Cell 13. The other 2 did not reach that far due to technical failure when the HMD wire tangled and was disconnected from power, or when they trespassed through the wall and could not return to the maze. In some cases this was caused by the non-HMD participant grabbing the HMD participant and physically dragging them in, what they perceived to be, the correct direction. 16 (78 %) playthroughs completed the maze and found the diamond. In addition, it was observed that at least five participants needed guidance to realize the goal of the maze as the blue square in the final room on the map was not a clear indication of the diamond's location.

Table 5.5: The observations taken during the test

Observation	Count
Number of participants	20
Number of playthroughs	21
How many pass Cell 3 - understand the prolongations and cell swaps	21
How many pass Cell 13 - understand the tunnels	17
Do they collaborate	21
Does the HMD participant follow the directions	20
How many completed the maze	16
How many participants tried both roles	17
How many participants tried their role more than once	4

In all playthroughs, participants actively tried to collaborate and fulfill their roles. There were always one to three non-HMD participants directing during a playthrough, which gives total of 32 directing participants for all playthroughs. 13 (62%) of 21 playthroughs were observed by a total of 30 spectators standing by.

All participants were observed to be engaged in the experience. 17 (81%) out of the 20 participants tried both the HMD and non-HMD role. Four participants tried their roles again, where three retried the non-HMD role three times and the HMD role once. The other fourth participant retried the HMD role three times.

5.2.3 Discussion

This experiment investigated the usability of the designed self-overlapping maze and map in a public space and highlighted some improvements that could provide a better and more intuitive experience for the participants. Based on the observations made on the intuitiveness and usability, results from the field study confirm the results from Experiment 1. They show that having prolongations on the map does not negatively affect the user's experience, and the swapping of cells in the self-overlapping maze does not interrupt the experience. The tunnels are also clear for the majority of participants both on the map and in the self-overlapping maze. This was also observed when the HMD participants responded correctly by bending down when they came across a lower ceiling in the maze. Observations from some playthroughs show that there is still confusion about the tunnel leading to Cell 13 on the map. More spacing out of the connected tunnels in this area is needed to make it clearer. In addition, since the goal on the map did not always seem clear, the blue square marking the finish should be replaced with a clear icon representing the goal described in the instructions, in this case a diamond icon.

Observations in the library show that the system is capable of promoting collaboration between the roles. In several cases non-HMD participants were observed helping each other to find the path through the maze. All HMD participants respected the collaboration from the non-HMD participants and awaited their guidance. It was observed that talking was not the only communication channel between the two roles. In 8 playthroughs, the non-HMD participants started physically dragging the HMD participants in their desired direction. This was helpful, but sometimes it also made the HMD participants trespass through walls as the non-HMD participants did not see where they were dragging them. It might have been caused by the non-HMD participants not being able to recognize which way the avatar was facing. These non-HMD participants often used directions related to the map perspective like "up" and "down" or "left" and "right", which did not correspond with the HMD participant's perspective. The trespassing often broke the system, showing that the trespassing system should be made more robust. Furthermore, as discussed in Experiment 1, providing different views to the non-HMD participant could help them understand the HMD participants' world better.

Observing communication was challenging because nine of the participants communicated in a different language than Danish or English when collaborating in the maze. Nonetheless, observing the participants' body language and gestures while talking helped understand the context of the communication. Their communication can be said to have mainly consisted of directions from the non-HMD participants and the discussion about how to continue at the junctions.

There were only four participants observed to have retried their roles. The low retry number could be attributed to the fact that there only was one maze for them to solve, therefore there was little reason to replay it, as it had already been solved. A solution to this would be to make more mazes that are picked randomly per playthrough. Lastly, it was observed that the participants in the public area were very active, which resulted in the HMD participants often tripping over the HMD wire and some non-HMD participants walking in the tracking area. The wire remains a key problem with the hardware. One solution would be to make a self-overlapping maze that can change the users' walking direction so the wire remains untangled throughout the experience.

6 Asymmetric Collaboration Experiment

Results from the previous experiments suggested that for some non-HMD participants seeing what the HMD user is seeing could make them more involved in the experience than just having a map. This is explored further in this experiment which compares how the views presented on the side display influence engagement and collaboration around the VR system. Before conducting the experiment, improvements were made based on discussions from Experiment 1 and 2, as can be seen in Figure 6.1.

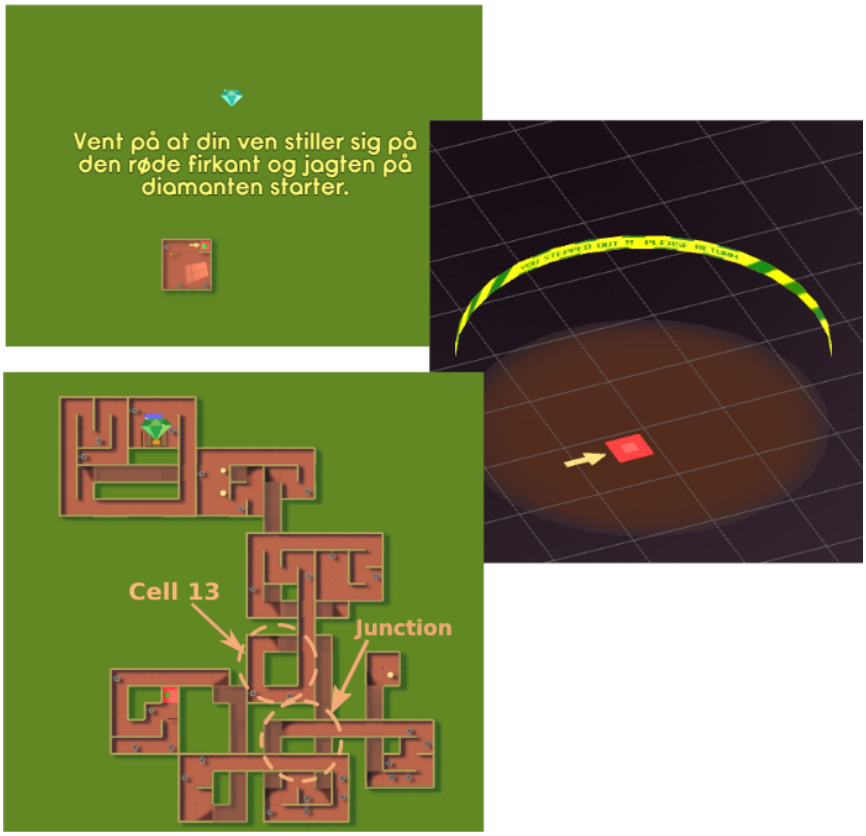

Figure 6.1: Improvements before the experiment: calibration room added for the side display (top left), spaced out junction to Cell 13 and diamond icon (bottom left), and a red square with an arrow in the trespassing mode (right)

On the map, the junction to Cell 13 was spaced out to allow clearer understanding. Also to make the goal on the map more visible to the non-HMD participants, it was marked with a diamond icon, and the calibration cell was also added on the side display, so the non-HMD participants knew the location of HMD user's avatar before the start of the VR maze. Lastly, since it was observed in Experiment 2 that HMD participants could not find their way back to the maze after trespassing, the wall and floor rendered in the trespassing mode were substituted by a red square and an arrow similar to that in the calibration room.

6.1 Experiment 3: Asymmetric Collaboration in a Public Library

For exploring how the view presented on the side display influences the experience, three conditions are tested with different views for the non-HMD participants: the mirror display condition (MIR), where the HMD user's view is mirrored on the side display, the map condition (MAP), where the map is shown on the side display, and a third combination condition (COMB), where the side display is split to show both the mirror display and the map. The side display for the different conditions can be seen in Figure 6.2.

Figure 6.2: The side display in MIR (top left), MAP (top right), and COMB (bottom) conditions

To compare the three conditions, hypotheses are made to find out which of the conditions facilitates more collaboration and engagement for participants and spectators in a public setup. Since, as discussed in related work, roles are an important element of facilitating asymmetric collaboration, one hypothesis is that conditions with the map would bring more collaboration because participants have different roles with different information and abilities. This would not be the case in the MIR condition because the non-HMD participant does not have unique abilities and information compared to the HMD role. To determine how participants collaborate, observations are made for how much they communicate and whether they use their roles. Furthermore when the two map conditions are compared, we hypothesize that the collaboration in the COMB condition would be more effective than in the MAP because in the COMB condition, the virtual world is more unified for both participants. It would therefore be easier for the non-HMD participants to give understandable directions to the HMD participant because of the mirror display added to the map. Based on these assumptions, the following two hypotheses are formulated about collaboration.

H1: The map in conditions MAP and COMB facilitates more collaboration than only the mirror display in condition MIR.

H2: The combination of the map and mirror display in the COMB condition facilitates a more effective collaboration than only the map in MAP condition.

Besides collaboration, observations were also made for participant engagement in the three conditions. Due to the fact that roles brought about by the map conditions allow both participants to contribute towards a common goal, one hypothesis is that the MAP and COMB conditions would be more engaging than the MIR condition. Furthermore, due to the addition of the mirror display in the COMB condition, this would be more engaging than the MAP condition. The COMB condition might help improve the case observed in Experiment 1, where some non-HMD participants commented that they would be more engaged if they saw the HMD participant's world. To determine engagement, observations are made for how many times people try the system, how many try both roles, and their facial expressions – smiles and frowns. Since the system is set up in a public area, the experiment also observes the engagement of spectators in the experience. The following two hypotheses are formulated for engagement of both participants and spectators.

H3: The map in MAP and COMB conditions facilitates more engagement than only the mirror display in MIR.

H4: The combination of the map and the mirror display in COMB facilitates more engagement than only the map in MAP condition.

6.1.1 Experiment Design

Similar to the field study in Experiment 2, the self-overlapping maze and the map were again set up for an observational study in the library Aalborg Hovedbibliotek. Beforehand, a short pilot test on eight participants was made in the public space of the canteen at the university to evaluate the experiment design. At the library, the experiment was run over three days with the conditions MIR, MAP, and COMB assigned for each day in the respective order. 20 participants tried the MIR condition, where one was female and 19 were male. The estimated age in this condition was from 10 to 28 years (M = 16.35, SD = 4.6). The MAP condition was tried by 23 participants, three female and 20 male, whose estimated age was from 4 to 40 years (M = 16.09, SD = 11.07). Lastly, 28 participants tried the COMB condition, of which 13 were female and 15 male, and their estimated age ranged from 7 to 34 years (M = 15.07, SD = 7.44). Images of participants interacting with the VR setup can be seen in Figure 6.3.

Figure 6.3: Setup for Experiment 3

Participants were instructed at the start that their task is to collaborate to find a diamond in the maze, and the HMD participant was helped to put on the HMD. Their playthrough was observed by two observers nearby. One playthrough was considered to be the period from when participants started to move in the maze after the calibration room until they either found the diamond or stopped the experience due to giving up, changing roles, or the system breaking. As is summarized in Table 6.1, for each playthrough, the observers noted which roles participants had and how they used them, communication, engagement, spectators, and participants' comments. Communication was counted as utterances for the HMD and non-HMD participants, where one utterance was considered as a piece of speech when a person starts talking until holding a clear pause or until another person starts talking. Two-way communication was also observed, where each utterance of the HMD participant that is replied to by the non-HMD participants or vice versa was counted as one instance. The content of the communication and the directions that non-HMD participants used were also noted down together with non-verbal forms of communication used, e.g. the physical dragging of HMD participants to direct them as observed in Experiment 2.

Table 6.1: Observations noted in Experiment 3

Topic	Observations
Collaboration	How they use their roles
	Content of communication
	Amount of communication: HMD and non-HMD utterances, two-way communication
	Communication of directions: from the map perspective (e.g. up, down) or from the point of view the HMD user is facing
	Non-verbal communication, e.g. physical dragging
Engagement	Playthroughs per participant
	How many try both roles
	How many try one role more than once
	Number of non-HMD participants per playthrough
	Facial expressions for non-HMD participants: smiles, frowns
	Self-reported evaluation of experience: Likert scale for HMD and non-HMD participants
	Number and involvement of spectators: passive, moderate, and active
Other	Do they complete the maze
	Time duration of playthrough

Observations for engagement included how many times participants try the HMD and non-HMD role, the number of non-HMD participants for a playthrough, and the non-HMD participants' facial expressions – smiles and frowns were also counted. After each playthrough, both the HMD and the non-HMD participants had to evaluate their experience on a five-point Likert scale. The Likert scale was presented in form of smiley faces, implemented for the side display. In case more non-HMD participants were present in the playthrough, they were left to agree on the rating either through a discussion or by leaving it for the primary non-HMD participant if there was one. Besides observing participants' engagement, spectators were also counted based on their involvement in the experience as passive, moderate, or active. Passive spectators would be considered as people standing nearby and watching, while moderate were people who approached to watch the side display. Lastly, the active spectators would be the ones who approached the side display and helped to guide the HMD participant at some point during the playthrough. Additionally, the time duration of the playthrough was also noted because during the pilot test, it was observed that the durations varied and could be useful in the analysis of the conditions.

6.1.2 Results

The observations from the experiment were analyzed using statistical tests with a significance value of $alpha = 0.05$. During the experiment, participants in the MIR condition made a total of 18 playthroughs, in the MAP condition 29 playthroughs, and in the COMB 40 playthroughs were made. The average completion time for the MIR condition was 3.86 minutes, for the MAP condition it took 2.88 minutes and for the COMB condition 3.11 minutes. When these times were compared in the analysis of variance (ANOVA), results showed that the time it took to finish the experience, either through finishing the maze or giving up, was not significantly different across the three conditions, $F(2,84) = 2.21$, $p = 0.12$. This was also the case when accounting only for the completed playthroughs across the conditions, $F(2,62) = 0.73$, $p = 0.49$.

Results for observation on the rate of how many times participants completed or did not complete their playthroughs can be seen in Table 6.2. Here, "Completed" denotes completed playthroughs where the HMD participant reached the end of the maze. "Not Completed" denotes playthroughs where either the HMD participant or the non-HMD participant gave up either due to frustration or their inability to complete the maze. "System Broke" denotes times when the system had to be rebooted as it ceased to function as expected or the HMD participant accidentally pulled out the wire to the HTC Vive. As seen in the table, the system in MIR condition never broke, but in more than half of the playthroughs, participants gave up on completing the maze. For the MAP condition the system broke four times and nobody gave up. Similarly for the COMB condition the system broke eight times and no one gave up on completing the maze. Statistical analysis with Pearson's chi-squared test and Post-hoc pair-wise comparison test showed that the completion rate was significantly higher in the MAP, $p = 0.01$, and COMB, $p = 0.02$, conditions than in the MIR condition.

Table 6.2: The completion rate of the maze

	Completed	Not Completed	System Broke
MIR	8 (44%)	10	0
MAP	25 (86%)	0	4
COMB	32 (80%)	0	8

Collaboration

Observations on communication between the three conditions for the total amount of participants' utterances were compared using Kruskal-Wallis test, which showed no significant difference between the conditions, $H(2) = 0.39$, $p = 0.82$. The amount of total utterances per minute was also not significantly different when compared across conditions using ANOVA, $F(2,84) = 2.69$, $p = 0.07$. However, when utterances from only the HMD participants were compared, a significant difference was found. Dunn's multiple comparison test with Holm-Bonferroni correction showed that there were significantly more HMD participant utterances in both MIR ($M = 15.33$), $p = 0.0001$, and COMB

(M= 11.70), p = 0.001, than in the MAP (M = 6.93). Similarly as seen in the left part of Figure 6.4 showing HMD participant utterances per minute, Tukey HSD test showed that the MIR (M = 4.04), p = 0.049, and COMB (M = 3.84), p: 0.03, conditions had significantly more HMD participant utterances per minute compared to the MAP condition (M = 2.50). There was no significant difference, $H(2)$ = 3.04, p: 0.22, found for non-HMD participant utterances across conditions. However as seen in the right part of Figure 6.4, when compared per minute, the non-HMD participants had significantly more utterances in the MAP (M = 11.69), p = 0.0003, and COMB (M = 10.28), p = 0.01, conditions than in the MIR condition (M = 6.64).

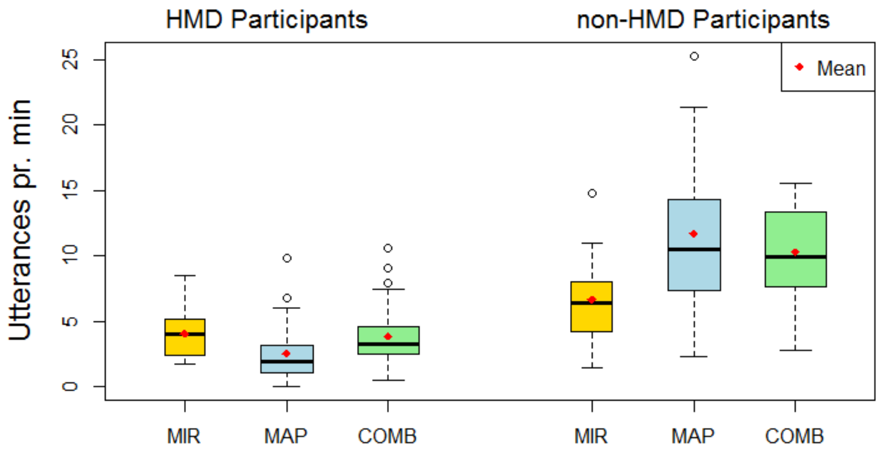

Figure 6.4: HMD and non-HMD participant utterances per minute

Observations seen in Figure 6.5 from the two-way communication between participants show that there was a significant difference between conditions. The MIR (M = 13.50) condition had significantly more two-way communication than the MAP (M = 6.48), p = 0.0002, and COMB (M = 9.48), p = 0.046. Further, the COMB condition showed to encourage significantly more two-way communication, p: 0.006 than the MAP condition. Two-way communication per minute was not significantly different across conditions, $F(2,84)$ = 2.58, p = 0.08.

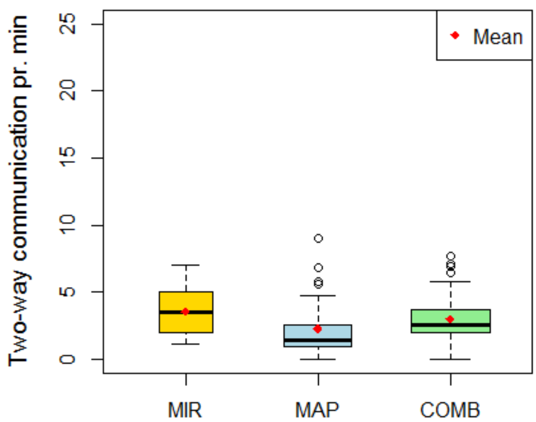

Figure 6.5: Two-way communication per minute

Besides communication, collaboration was also analyzed by looking at whether participants used their roles. Results from the observation are shown in Table 6.3, where Pearson's chi-squared test shows that there was a significant difference. However, although the Post-hoc pair-wise comparison test showed a significant difference between the MIR and COMB conditions with a raw p-value p = 0.026, the adjusted p-value p = 0.079 did not show a significant difference between the MIR and COMB condition. Furthermore, it was observed whether the non-HMD participants gave directions based on the point of view the HMD participant was facing or based on the map perspective. Fisher's exact test, $p = 0.46$, did not show that significantly more non-HMD participants used directions based on the HMD participant's facing in COMB (60%) than in the MAP (50%). However, there was significantly less physical dragging of HMD participants in the COMB (5%) than in the MAP condition (24%), $p = 0.03$.

Table 6.3: Number of playthroughs where participants used and did not use their roles

	Used roles	Did not use roles
MIR	15 (83%)	3
MAP	28 (97%)	1
COMB	40 (100%)	0

Engagement

As seen in Figure 6.6, the logged Likert scales evaluating both the HMD participant's and non-HMD participants' experience had a median of 5 across all three conditions with the exception of MIR condition where the non-HMD had a median of 4.5. Kruskal Wallis test showed that the experience across conditions was not significantly different for the HMD participants, $H(2) = 5.47$, $p = 0.06$, and neither for the non-HMD participants, $H(2) = 3.39$, $p = 0.18$.

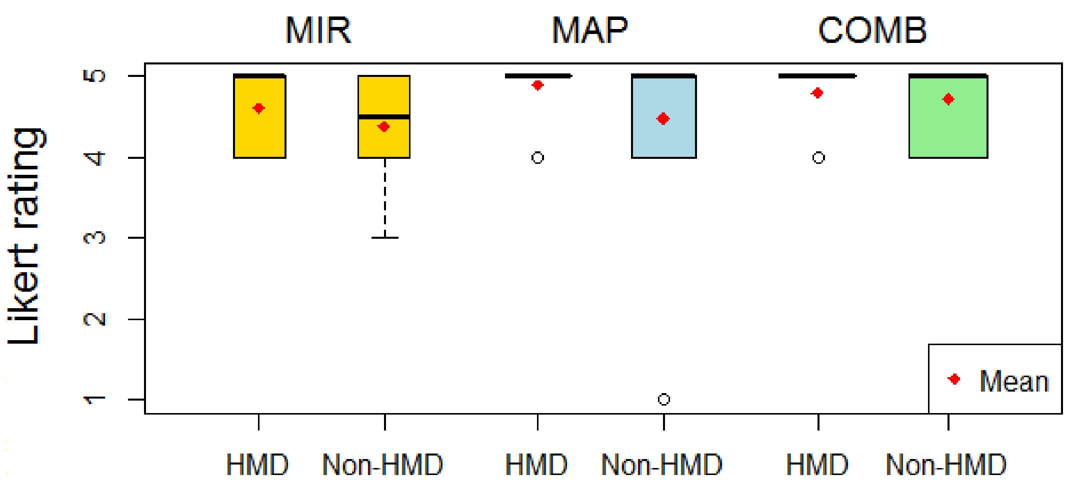

Figure 6.6: HMD and non-HMD participants' ratings on the experience

The HMD and non-HMD participants' experience ratings obtained from the Likert scales were also compared using Mann-Whitney U test within each condition. In the MIR condition, ratings from the HMD participants (M = 4.61) were not significantly different to those from the non-HMD participants (M = 4.39), W = 187, p = 0.38. This was neither the case in the MAP condition between the HMD (M = 4.89) and non-HMD (M = 4.48), W = 418.5, p = 0.17. This condition had an outlier of one non-HMD participant, who did not understand the tunnels on the map and thus rated her experience as 1. Since this experiment was not focused on usability but on the engagement in the different conditions, her responses were removed as outlier. For the COMB condition, no significant difference was found, W = 860, p = 0.44), between the HMD (M = 4.80) and the non-HMD participants (M = 4.73).

When the number of playthroughs seen in Figure 6.7 was compared, Dunn's multiple comparison test showed that the COMB (M = 3.11) condition had significantly more playthroughs per participant than the MIR (M = 1.90), p = 0.02, and MAP (M = 2.78), p = 0.03, conditions. The COMB (M = 1.89) condition also had significantly more tries of the non-HMD role per participant than the MIR (M = 1), p = 0.008. However, there was no significant difference when the COMB condition was compared to the MAP condition (M = 1.74), p = 0.08. For the number of tries of the HMD role per participant, there was no significant difference between conditions, $H(2)$ = 3.12, p = 0.21. There was significantly more non-HMD participants per playthrough in MAP (M = 1.76), p = 0.001, and COMB (M = 1.53), p = 0.007, conditions than in MIR (M = 1.11). No significant correlations were found between playthroughs and age or playthroughs and gender using Kendall rank correlation.

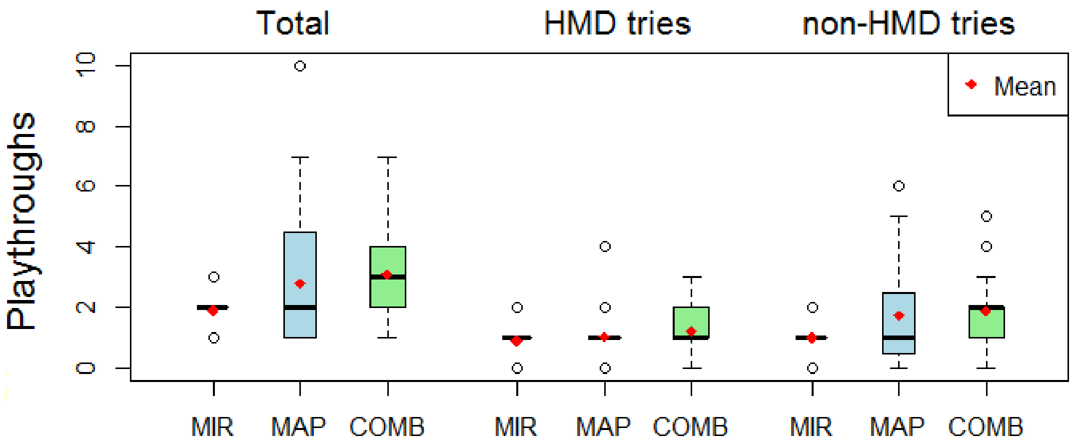

Figure 6.7: Number of playthroughs, and tries of the HMD and non-HMD role per participant

Pearson's chi-squared test and Post-hoc pair-wise comparison test showed that in the COMB condition (86%), significantly more participants tried both roles than in the MAP condition (52%), p = 0.04, while no significant difference was found between the COMB and MIR (72%), p = 0.28, and between the MAP and the MIR, p = 0.28. Significantly more participants tried one role more than once in the MAP (52%), p = 0.03, and COMB (89%), $p < 0.0001$, conditions than in the MIR (17%), and in the COMB than in the MAP condition, p = 0.007.

Facial expressions observed show a significantly different number of smiles from the non-HMD participants in the three conditions. Based on the Dunn's multiple comparison test, the MIR (M = 3.78) condition and the COMB (M = 2.33) had significantly more smiles per non-HMD participant than the MAP(M = 1.10), p = 0.006, p = 0.0002, respectively. No frowns were observed during any of the conditions.

The observed amount of spectators for each condition can be seen in Figure 6.8. The MAP (M = 6.31) had a significantly higher number of spectators per playthrough than the MIR (M = 2.17), p = 0), and COMB (M = 2.88), p = 0). Based on the Pearson's chi-squared test and Post-hoc pair-wise comparison test, out of all spectators, the percentage of those classified as "active" was significantly higher in the MAP (21%), p = 0.007, and in COMB (26%), p = 0.003, than in the MIR (3%) (see Table 6.4 and the right part of Figure 6.8).

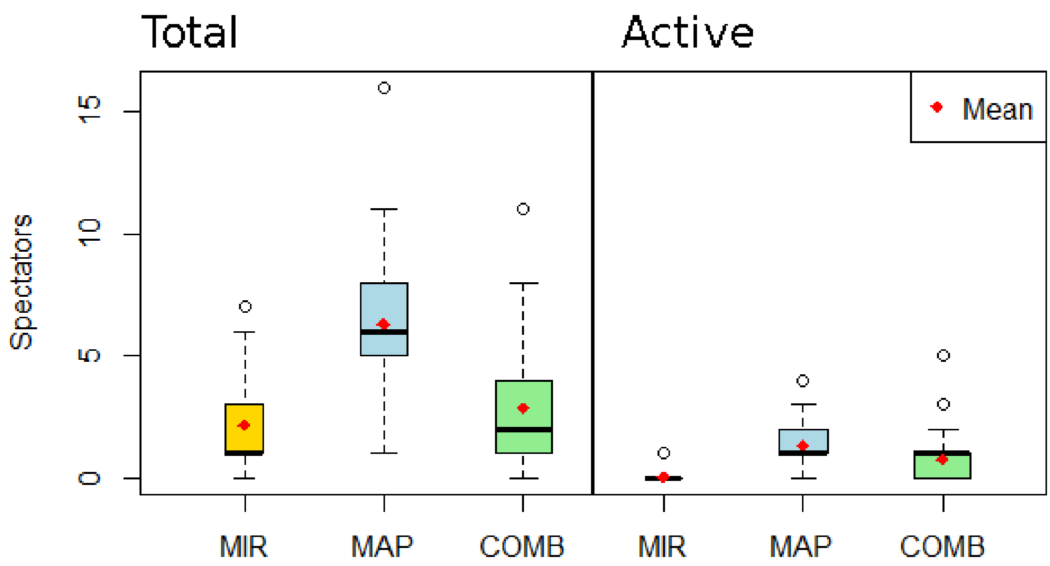

Figure 6.8: Number of all spectators (left) and active spectators (right)

Table 6.4: Percentage of active spectators

	Active	Passive or moderate
MIR	1 (3%)	38
MAP	39 (21%)	144
COMB	30 (26%)	85

6.1.3 Discussion

This experiment investigated three conditions of different views on the side display, MIR, MAP, and COMB, to find out their influence on asymmetric collaboration and engagement for HMD and non-HMD participants in a public library.

The system's ability to facilitate collaboration in the different conditions was evaluated by observing whether the participants used their roles, thus contributed to the goal, how much they communicated, and what directions they used. Statistical tests did not show a significant difference for use of roles in the conditions. Results on communication in the three conditions show that HMD participants made the most amount of utterances in the MIR condition compared to the other conditions, which also meant that there was more two-way communication for this condition than in the two map conditions. Observations indicate that most communication in the MIR condition consisted of participants discussing at junctions about where to go next and whether they have been at the same place before: "don't go back here, I think it's a dead end" or "wasn't that the way you came from?". In contrast to the HMD participant making more utterances in the MIR condition, statistical analysis showed that non-HMD participants had significantly more utterances in the conditions with the map than without. From the observation, this difference in non-HMD utterances was because in the map conditions, the non-HMD participants were giving directions, guiding the HMD participants towards the goal. The MAP condition though facilitated less HMD utterances and two-way communication than the MIR. The communication in the COMB condition was similar to the MIR condition with regards to HMD utterances and two-way communication, but with much more non-HMD utterances. This could be explained through observation that the mirror display provided additional topics for conversation such as the view out of the windows, paintings or other objects in the environment that the HMD and non-HMD participants could discuss.

With the use of roles not having significant differences, the data from communication alone has not shown enough evidence for accepting the hypothesis *H1* that the map conditions MAP and COMB would facilitate more collaboration than the MIR condition. It could therefore be reasoned that merely observing utterances might not be sufficient for accurately evaluating collaboration. Also the fact that the participants in all conditions were instructed to collaborate on completing the goal may have made them feel as if they were required to talk. On the other hand, the communication results showed that the two map conditions include the non-HMD participants more into the collaboration than the MIR condition.

The hypothesis *H2* that compares the MAP and COMB conditions can be accepted as the COMB condition facilitated more effective collaboration than the MAP condition. That the COMB condition performs better than the MAP could be attributed to the additional topics for conversation. Although not significant, observation shows that there were more non-HMD participants giving directions based on the point of view the HMD participant was facing rather than the map perspective in the COMB than in the MAP. This made the following of non-HMD directions more understandable, which was further shown with significantly less physical dragging when directing the HMD participant in the COMB condition.

Statistical analysis also looked at the three conditions' ability to facilitate engagement in the participants. This was measured through a Likert scale, smiles, number of playthroughs, spectators and completion rate to evaluate hypotheses *H3* and *H4*. The Likert scale provided nearly identical high ratings across all conditions and roles. This shows that participants had an engaging experience with both roles in all conditions and nine people said that it was "cool", one said that "it was not bad to walk around" and that he "never tried to control virtual reality before - it was fun". Although, the MIR condition provided the most smiles, the non-HMD participants in five out of the 18 playthroughs were observed disengaged and were for instance checking messages on the phone. Results from the total playthroughs per person show that there was significantly more playthroughs in the COMB than in the MAP and MIR conditions. A participant would try the non-HMD role significantly more times in COMB than MIR, but trying the HMD role was not significantly different across conditions. Analysis also shows that significantly more participants retried their role several times in the map conditions compared to the MIR condition and in the COMB condition compared to the MAP condition.

The MAP condition had the most amount of total spectators and spectators who actively directed the HMD participant, suggesting that the MAP provided the most engaging viewing experience. The fact that in more than half of the MIR playthroughs, participants stopped playing due to frustration, while nobody did in both the MAP and COMB conditions also suggests that the MIR condition was overall less engaging. Six non-HMD participants in the MIR condition were observed saying that "I think we are stuck", "we have been all the ways" and one saying "I'd like a minimap", which shows that participants were frustrated without having the map.

Overall, the statement in hypothesis *H3* that the map in conditions MAP and COMB facilitates more engagement than the MIR for participants and spectators, can be accepted due to the low completion rate of the MIR condition, the number of retries of one role in the two map conditions, and the high spectator engagement of the MAP condition. For hypothesis *H4*, the experiment also shows evidence that the COMB condition facilitates more engagement than the MAP condition for the participants. However for the spectators, it is still unclear which of the conditions MAP or COMB is more engaging.

During the experiment, several other useful comments were noted and behaviors were observed. The adjustments made on the system based on feedback from Experiments 1 and 2 generally improved the experience. Some people were still initially confused by the tunnels, however the majority figured them out as they played. The system broke less than in Experiment 2, as adding the red square similar to that in the calibration cell to the trespassing system made it easier for the participants to realize how to get back after trespassing through a wall. Including the new icon for the diamond also made the goal clearer, as fewer participants required directions from the instructor. The quality of the experience was equal across the observed ages and genders and all measured ages and genders were equally able to complete the maze since no correlation was found with respect to age and gender. That the MIR condition was the most challenging of all conditions to complete shows that the maze is not trivial and requires assistance from non-HMD participants with additional information. Finally, none of the participants got motion sickness during the test as there was no visual-vestibular conflict induced by walking.

7 | Conclusion

Setting up a room-scale VR system in a public place and in general has two fundamental limitations – the lack of large physical space to allow for natural navigation, and the HMD providing only a single-person experience. To address these two limitations, this project has investigated how to facilitate asymmetric collaboration in public cultural spaces for both the HMD user in VR and non-HMD participants following the experience on a side display near the VR setup, while still accounting for the lack of physical space. We have proposed a self-overlapping maze that the HMD participant can naturally walk through and a corresponding unfolded map that brings roles to the VR experience in order to asymmetrically involve the non-HMD participants on the side display into the virtual world. We demonstrate a design for how to construct such a self-overlapping maze by creating cells that overlap to fit in a limited public physical space of $2.5\,\text{m} \times 2.5\,\text{m}$. The design further demonstrates how to create a map that can show the whole maze at once where prolongations, tunnels, and bridges are added to create transitions from one cell to the next. We report how to implement the design in Unity 3D game engine for the HTC Vive room-scale VR setup, and how to develop a map with an avatar that mimics the HMD users' movement so the non-HMD participants can keep track of where they are and can guide them towards the goal in the maze.

Three experiments were carried out to test the VR system. The first experiment evaluated the proposed design in a lab setting to get formal usability feedback. This experiment tested whether participants could freely walk in the self-overlapping maze without noticing that the virtual world is changing, and whether the prolongations, tunnels, and bridges added to the map are understandable and do not affect the experience of guiding the HMD participant. It also evaluated the trespassing system, so that participants are discouraged from walking through virtual walls. The second experiment also evaluated the design but was carried out as a field study in a public library that observed participants' behaviors around the system and whether they understood the self-overlapping maze and the map. Results from these two experiments showed that the self-overlapping maze was fully walkable, although it was challenging for HMD participants to get an overview of where they came from in the maze. Participants did not give an accurate measurement for how large the virtual environment felt, but most responses gave larger measurement than the actual physical size of $2.5\,\text{m} \times 2.5\,\text{m}$. For the map, most responses show that the non-HMD participants felt that the avatar movement on the map corresponded well with that of the HMD participant. The prolongations and the speeding up of the avatar did not affect the guidance and were taken as an integrated part of the map. The experiments showed that there was need for spacing out the tunnels in the map, so people could see where they lead to, and clearly integrating information about the collaborative goal of the VR experience to the system, so people would know what to do.

The third experiment investigated asymmetric collaboration based on different views displayed on the side display for the non-HMD participants. Here, three conditions, the mirror display, the map, and the combination of the mirror display and the map, were compared, in order to find out which condition facilitates more collaboration and engagement for both participants as well as spectators. Based on the statistical analysis of communication between participants, it was not possible to conclude that the two conditions with the map facilitate significantly more collaboration than the mirror display condition. This is because the HMD participants made significantly more utterances in both the mirror display and the combination conditions than in the map condition. On the other hand, there were significantly more non-HMD participant utterances in the map and combination conditions than in the mirror display condition, which showed that the two conditions with the map involved non-HMD participants in the collaboration more than the mirror display only condition. Observations on engagement however show that there were significantly more retries and successful completions of the maze in the two conditions with the map than in the mirror display condition. There was also a significantly higher number of spectators in the map conditions than in the mirror display condition. From this a conclusion can be drawn that the proposed design and the VR system are capable of engaging the non-HMD participants in the VR experience, but also involve the spectators following along in the public setting.

Work from this study can be generalized and applied in other areas working with VR setups that can be walkable in small physical spaces or include non-HMD participants. Such areas could include architectural installations, where the designed buildings could be experienced through natural walking, public installations in libraries, museums and schools that could implement new themes and exhibitions that are engaging both for the HMD and non-HMD users. The content in such themes and exhibitions can be made entertaining or educational for their attendees while still using our proposed design of self-overlapping architectures and the unfolded map visualization.

7.1 Future Work

Although it is possible to generalize the design, the system could be improved in many areas in future studies. Future work should investigate how to improve the visualization of the tunnels and bridges on the map, so that the non-HMD participants can clearly see where the tunnels start and where they lead. Furthermore, future work should investigate methods for how to manipulate the HMD participants' movement so they can feel like they are walking up or down in tunnels and bridges on a slope. More work should be made also on finding new techniques for facilitating asymmetric collaboration. Inspiration could be drawn from games and interaction theories to create content that can engage the non-HMD viewers even more. Other media such as smartphones that are typically used by people in public places could also be explored in further studies for how they can be used as controllers, thus giving the non-HMD role new abilities. In this project, a self-overlapping maze was made with walls that can hide the updates of cells, however future studies should investigate new ways of creating walkable architectures without need for walls to hide the updates. These studies could also investigate the effect of seeing the cell updates, and whether it is possible to create a system where noticing updates is not a problem. One update that could be made to the maze is the possibility of creating the cells procedurally. This would add more variability to the maze, so that every time people try it, there would be a new path to go, which could motivate them to try it even more times. Lastly, sound was not included in our design, however future work should investigate how to introduce it, and what effect it has on users' experience when the system is set up in the public setting.

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