Crash! An Evaluation of Collision Prevention Mechanisms in an Immersive Multiplayer Room-scale Virtual Reality Experience

- Master Thesis -

Denisa Formáčková

Aalborg University
Department of Architecture, Design and Media Technology

AALBORG UNIVERSITY
STUDENT REPORT

Department of Architecture, Design and Media Technology
Aalborg University
http://www.aau.dk

Title:
Crash! An Evaluation of Collision Prevention Mechanisms in an Immersive Multiplayer Room-scale Virtual Reality Experience

Theme:
Master Thesis

Project Period:
Spring Semester 2019

Project Group:
mta191045

Participant(s):
Denisa Formáčková

Supervisor(s):
Kasper Rodil

Copies: 1

Page Numbers: 86

Date of Completion:
May 26, 2019

Abstract:

The goal of this project is to investigate collision-prevention methods that can be used in immersive multiplayer room-scale (IMRS) virtual reality experiences. Previous studies did not deal with the cases where players cannot see each other in a virtual environment (VE) as it is in an IMRS arena. This is problematic, because potential crashes can lead to injuries, damaged hardware and break-in-presence. This project therefore tests a number of collision prevention techniques in a simulation of DIVR arena in Hamleys and also on a similar detoured version. Lastly, a new concept called HUB was tested. The results show that there is not a significant difference between the original and the detour arena but both perform safer when the suggested prevention mechanisms are active. HUB performed the best in terms of time efficiency and with zero collisions. Further work on the HUB concept is suggested to counter its downsides.

AALBORG UNIVERSITET
STUDENTERRAPPORT

Institut for Arkitektur og Medieteknologi
Aalborg Universitet
http://www.aau.dk

Titel:
Crash! En Evaluering af Kollisions-Forebyggelsesmetoder i en Immersive Multiplayer Room-scale Virtual Reality-oplevelse

Tema:
Kandidatafhandling

Projektperiode:
Forårssemestret 2019

Projektgruppe:
mta191045

Deltager(e):
Denisa Formáčková

Vejleder(e):
Kasper Rodil

Oplagstal: 1

Sidetal: 86

Afleveringsdato:
26. maj 2019

Abstract:

Målet med dette projekt er at undersøge kollisions-forebyggelsesmetoder, som kan bruges i 'immersive multiplayer room-scale' (IMRS) virtual reality-oplevelser. Tidligere undersøgelser håndterede ikke de tilfælde hvor spillerne ikke kan se hinanden i et virtuelt miljø, som er tilfældet i en IMRS arena. Dette er problematisk da potentielle nedbrud kan føre til skader, beskadiget hardware og break-in-presence. Dette projekt tester derfor en række kollisions-forebyggende teknikker i en simulering af DIVR arena i Hamleys og også en lignende 'detoured' version. Derudover blev et nyt koncept ved navn HUB testet. Resultaterne viser at der ikke er nogen signifikant forskel mellem den oprindelige og den 'detoured' arena, men begge performer sikrere når de foreslåede forebyggelsesmekanismer er aktive. HUB performede bedst med hensyn til effektivitet af tid og med nul kollisioner. Yderligere arbejde af HUB konceptet foreslås for at imødekomme dets ulemper.

Contents

List of Abbreviations

HMD Head-mounted Display

IMRS Immersive Multiplayer Room-scale

LBE Location-based Entertainment

VE Virtual Environment

VR Virtual Reality

Glossary

Immersive Multiplayer Room-scale A form of virtual reality entertainment in which players can free-roam and interact with the virtual world. The physical gaming arena is often built to resemble the virtual world in order to enhance the players' presence.

Location-based Entertainment A sub-field of virtual reality entertainment focusing on out-of-home virtual experiences. By some journalists or experts in the field (but not so in this report!), the terms *Location-based Virtual Reality* and *Immersive Multiplayer Room-Scale Virtual Reality* are considered interchangeable.

Location-based Virtual Reality See Location-based Entertainment

List of Figures

List of Tables

Prologue

As part of my ninth semester at Medialogy, I got to partake in an internship at DIVR Labs, a Czech company creating and providing experiences in immersive multiplayer room-scale (IMRS) virtual reality. As an intern, I got to take on many roles, most notably a game and level designer. The internship was beneficial in terms of social and professional competences, but also academically. I got to try how my academical skills apply in praxis. Furthermore, as the field is very new and therefore fairly unexplored from the academic perspective, I was able to identify a research gap. As the internship was beneficial for both parties, it was decided to continue the collaboration also during my master thesis, this time focusing on a specific problem area related to IMRS virtual reality.

I am very grateful for the opportunity that DIVR gave me and I am happy to inform that DIVR found the delivered report and its enclosed findings relevant to such a degree as to earnestly consider and discuss building a HUB arena and producing future IMRS VR experiences for it.

Introduction

While virtual reality (VR) has been around for decades, location-based VR entertainment emerged only in the recent years. The idea is to combine a social aspect with new high-end VR technology, something that cannot be experienced with an in-home VR setup due to its size and price. In a way, location-based VR can be seen as a product of experience economy, that is, the willingness of consumers to decide what to pay for depending on the quality of the experience in addition to the quality of the product. In other words, the consumers are willing to pay for the experience as is, to try new high-end technology and to socialize with their friends and family. This is why there is a certain analogy between location-based VR and video game arcades or cyber cafes, which popularized video games before consoles or personal computers became affordable for an average household.

Location-based entertainment is a superordinate word for a multitude of VR-related out-of-home entertainments, for example VR motion chairs, high-end VR arcades or immersive multiplayer room-scale (IMRS) VR. In IMRS experiences, groups are allowed to physically touch and interact with a large-scale arena, which is built to reflect the virtual setting. The players are not tethered by a cable, because they carry in-built laptops in backpacks. Usually, there are additional props in the arena, such as 3D printed tools or modified controllers. Many IMRS experiences use Leap Motion technology to substitute controllers with input from hand or finger gestures in real time. People sharing the same group can cooperate and communicate while in the game. However, other groups are invisible to them, therefore having multiple groups in the arena can result in a collision of players. Collisions are problematic for various reasons, most notably the loss of presence, potential damage of hardware and injuries of the players. This project analyses existing solutions and ideas from both the industry field and also from the academic perspective and proposes a multitude of design solutions.

Three different arena floor plans are evaluated: original arena used by DIVR, modified arena which uses the concept of detours and a HUB, an arena which has a shared space at the center and is surrounded by a number of smaller rooms each fitting only one group. The three arenas are tested in a simulated environment and use real data provided by DIVR. The tests in this report use various combinations of collision prevention mechanisms. From the results, it can be seen that a proposed HUB floor plan has the highest efficiency, when it comes to the number of potential collisions, which is zero, and the number of groups the arena can accommodate in relation to time. Even then, it is important to consider the nature of the gameplay and tailor it to the chosen floor plan.

Chapter 1

Background Research

This chapter is split into five subsections. The first subsection describes virtual reality, its history and the emerging subfield of location-based virtual reality. The second subsection looks into other industries where certain analogies can be relevant. The third and fourth subsections are looking into the location-based virtual reality field with the industrial and academic perspectives respectively. Lastly, these three subsections contribute to the final one, in which a research question of this project is formulated.

1.1 Virtual Reality and the Emergence of Location-based Entertainment

There is more than one definition of virtual reality [19, p. 9], but the accepted definition for the purpose of this study is the definition by Jason Jerald, which says that virtual reality (VR) is

> “(...) a computer-generated digital environment that can be experienced and interacted with as if that environment were real.“ [19, p. 9]

In other words, the user of the VR system can enter a computer-generated three-dimensional (3D) environment and often interact with the environment by using special electronic devices. Unlike using a computer, the user is "surrounded" by the environment just as if it was real. This allows the user to experience being at a different location, real or fictional, while actually being at home by their computer. This experience is possible thanks to immersive VR devices, usually consisting of a head-mounted display (HMD) and controllers, but can also be enriched by, for example, supplementary trackers for feet, modified controllers, moving platforms or treadmills [19]. Some of the most known VR systems are Oculus Rift (and a standalone version Oculus Go), Sony PlayStation VR, HTC Vive and Samsung Gear VR.

VR can be used in many industries and areas, most notably the entertainment industry such as video games and immersive film, but it is also successful in other industries such as architecture, visualization, military training, therapy, flight simulation etc. [19, p. 12].

1.1.1 A Brief History of Virtual Reality

There are a few inventions from the 1800s that helped to give birth to VR [19, p. 15-18], such as the stereoscope, a device which enables a stereoscopic vision of a scene by using two separate images, one for each eye, taken at slightly different angles. The two images are viewed together through the stereoscope and create an impression of depth. The technology did not always only focus on the visual presentation of images, as can be seen by looking at Pratt's patent for a head-mounted weapon from 1916 [30]. The helmet is a pointing and firing devices which is operated hands-free, just by blowing into a tube fastened to its side. The virtual reality field was yet taking shape and thus fast forward a few decades to the point when Morton Heilig patents two inventions, the *Stereoscopic-television apparatus for individual use* [13] in 1960 (see Figure 1.1) and the *Sensorama simulator* [12] in 1962 (see Figure 1.2). Especially the stereoscopic-television apparatus bears a striking resemblance to HMDs of today. The Sensorama machine provided a wide field of vision (140 degrees), coloured visuals, stereo sounds, seat tilting, vibrations and even different scents and air temperature produced by in-built nozzles [19, p. 20 - 21]. In 1968, Ivan Sutherland was working on a head-mounted display called the Sword of Damocles [51]. This HMD, which was attached to a contraption hanging from the ceiling, was the first to use head tracking and computer-generated imagery (CGI).

In 1984, Eric Howlett was hired by NASA to create the Virtual Interface Environment Workstation lab. The lab's technology and accompanying funding allowed many VR companies, such as VPL, LEEP System and Fakespace, to thrive [19, 38]. At around the same time, the term *virtual reality* finally started to be used to describe the field, even though the VR technology had been long in the development [18].

VR arcade games made the virtual technology accessible to the public in the early 1990s. These arcades were a simpler version of the ones we know today, as they only included a headpiece through which one could see the graphics [18]. Even though 1990s were full of books, movies (such as The Matrix) and journals about VR, the technology was not developing fast enough to satisfy the consumers and the public *hype* slowly died down [19, 18]. This all changed with the creation of Field of View To Go (FOV2GO), which was presented at a conference in California in 2012 [19]. The device once again gave hope to the VR industry. One

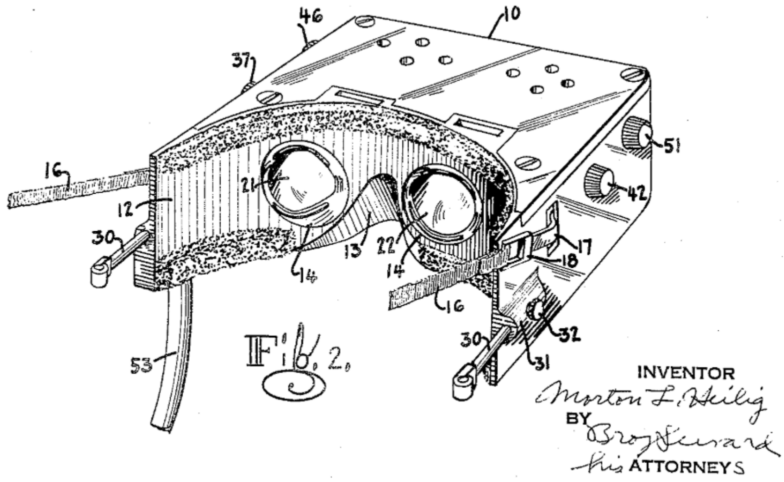

Figure 1.1: Stereoscopic-television apparatus for individual use. Figure from Google Patents [13].

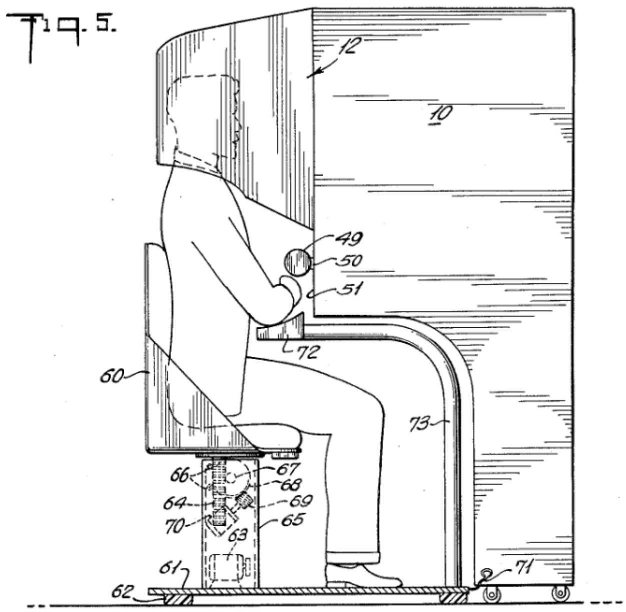

Figure 1.2: Sensorama simulator. Figure from Google Patents [12].

of the men behind the prototype later co-founded Oculus VR, which got acquired by Facebook in 2014. Since 2012, the VR industry has been on the rise again [19, 18].

Nowadays, as the price for these devices is becoming more accessible for customers [19, p. 12], the sales are increasing and are expected to increase even more in 2019 [39, 45, 24]. However, as can be seen from reports from the United States [39] and also claimed by field experts [33], most of the U.S. households might not be able to afford a VR device yet due to the price. Furthermore, some sellers such as Amazon are actually reporting a decline in the sales ranking [10] of four major VR headsets by Sony, Samsung, Facebook, and HTC. Sales ranking refers to how a product is selling compared to other products, for example bundles, games, equipment, in the same category on Amazon. This is why their report has to be taken with a grain of salt as it does **not** reflect the actual sales of the product but merely a comparison. The important information is, however, that they also blame the price and the lack of content for this decline [10]. The price and the lack of content are two of the drives that made rise to a new branch of the VR industry [39]: location-based virtual reality.

1.1.2 Location-based Virtual Reality

Location-based virtual reality, sometimes also referred to as *Location-based entertainment (LBE) VR*, is an emerging part of the VR industry [57, 33]. While VR itself has been around for over 30 years (see Subsection 1.1.1), location-based VR has mostly emerged in the past two years 2017-2018 [57, 5]. LBE VR is a subfield of the virtual reality industry, which focuses on providing digital experiences that cannot be enjoyed at home. A large part of the experience is its social aspect, as the experience is often enjoyed by a group of users. Furthermore, the experience often includes additional senses, apart from visual and auditory, such as somatosensation, a sense of touch, or proprioception, a sense of self-movement. Some experts also believe that this new field is the result of the effort to eliminate the cables tethering the players to the computer and the effort to bring the physical world closer to the virtual one [57]. Anshel Sag, a tech industry analyst focusing on mobility and VR, provides a very accurate definition of LBE VR:

> "LBE VR is essentially a place of business that hosts VR experiences, allowing users to physically interact with the environment in a way they can't in their own home." [33]

He compares LBE VR to cyber cafes of the early days of PC gaming. This analogy, though in relation to arcades and video game consoles, was also mentioned repeated by Ondřej Bach, Co-founder and CPO at DIVR Labs, during the meeting sessions where we discussed LBE industry and its history. Unlike in-home VR setups, the LBE VR are places where the players go to hang out socially and get a dose of new technology, which is unfit for home use due to its size or price. This is why it feels similar to the aforementioned cyber cafes or arcades. Similarly as these two types of entertainment evolved, there is a belief that LBE VR is a vital and natural step in the development of VR and, even more importantly, in making this technology available to an average consumer. This does not necessarily mean that LBE VR is going to end up dying off like the vast majority of cyber cafes. On the contrary, it is predicted that VR arcades and generally LBE VR could generate more than 800 million dollars in revenue by 2022 [32] and the continuous growth of the VR industry as a whole (usage of VR in training, architecture, therapy etc.) certainly supports the prediction [24].

As an interesting side note, there is a term called *experience economy*, which was already defined by Pine and Gilmore in 1998. This economy is described as a new step, in which we moved from commodities (for example coffee beans) to goods (packed coffee), then over to services (brewed coffee) and lastly to experiences (Starbucks) [28]. Naturally, with each step the price increases as well (see Figure 1.3). This can be seen as the willingness of consumers to decide what to pay for depending on the quality of the experience in addition to the quality of the goods or service. It would not be surprising if there were already cases in which consumers make their purchase decisions based on the experience alone and with the quality of the product or service actually being the secondary factor. To relate this back to the topic of VR, LBE VR would not succeed if it was not for this trend. People pay for LBE VR not only because of the technology, afterall they cannot walk away with the equipment or the game, but because they actually go there to *buy* the experience, the memories [5], the atmosphere and also to socialize with their friends or family.

Classification of Location-based Virtual Reality

While there is not a unified or agreed classification of LBE VR, this project is adopting a categorization presented by a company called Jaunt China at the 2018 VR Days conference in Amsterdam, which divides location-based entertainment into two groups:

- Impulse-Driven LBE
- Destination-Driven LBE

As can be deducted by the naming, Impulse-Driven LBE are the attractions in which the main customers are passerby, therefore it fits into high-traffic places such as malls, airports etc. Their motivation to engage in the experience is impulsive and that is also reflected in the low price and short duration of the experience.

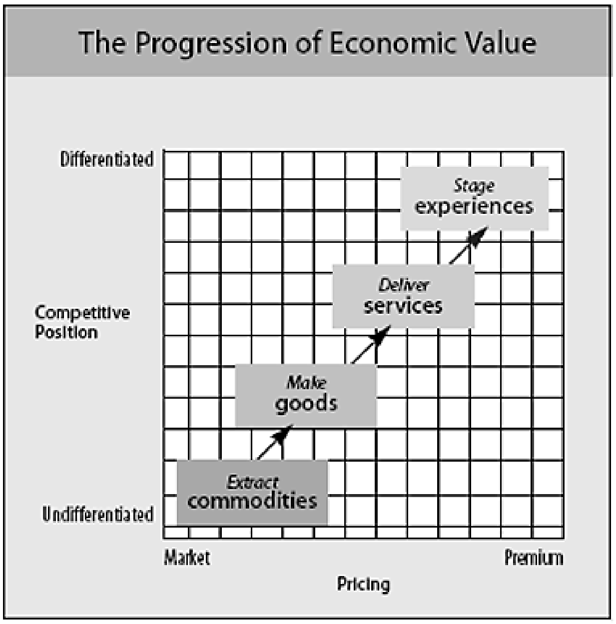

Figure 1.3: The progression of economic value. Figure from Pine II and Gilmore [28].

On the contrary, Destination-Driven LBE finds mainly audience in people who are willing to pay a higher price in exchange for a lengthier and more immersive experience. Often, they would book their experience beforehand. As expected, with low price of Impulse-Driven LBE comes low revenue per customer, however, with low fixed and operating costs, this does not strike as a problem. Destination-driven LBE operates with high costs and has a high initial investment, but the revenue is also higher.

Further classification of these two categories is based on the growing price (first one being the cheapest and the last one being the most expensive), which is also reflected in the average revenue per user:

- Impulse-Driven LBE
  - VR Kiosks
  - VR Motion Chairs
  - VR Arcades
- Destination-Driven LBE
  - High-End VR Cinemas, Arcades
  - Interactive, Multi-Players, Room-Scale (IMRS)
  - Exhibitions, Museums

As can be seen, this classification is very industry-oriented and does not have its counterpart in the academic field. Furthermore, the classification has the disadvantage of relying on the price (or the average revenue per user), which does not scale well on the global market. The price for an experience in a VR kiosk might be more pricey than a high-end exhibition in a different country. Similarly, the motivation of the target audience might not reflect its category, for example, *Golem VR* staff often attracts Hamleys customers on the spot, rendering them as the target group of the *Impulse-Driven LBE*, even though *Golem VR* belongs to the – Interactive Multiplayer Room-Scale (IMRS) category.

Focus on Immersive Multiplayer Room-Scale Virtual Reality

The focus of this project is on the IMRS category. A category, which is often mistakenly named location-based entertainment, as can be seen in some of the referenced articles [57, 33]. However, as shown in the adopted classification, the words are not interchangeable, the term *location-based virtual reality* is superordinate, while *IMRS* is only a branch of Destination-Driven LBE VR.

In the usual IMRS experience, a group of players gets head-mounted displays (HMDs) just like they would at their in-home VR stations. Next, they would usually each get a backpack with a computer inside. This is what eliminates the need for long cables, as the cables only need to reach the backpack and thus allowing the players to roam freely. The last element is the location, in which the players can walk around, interact and get immersed in with the help of various physical props [57, 20, 33]. For example, when players walk around an open fire, they might feel heat from a physical heat lamp. When they look down from a bridge, they might feel actual wind simulated by a fan. Both examples are taken from the DIVR Labs arena located at Hamleys toy shop in Prague, Czech Republic [20] (see arena in Figure 1.4), but can be found in other IMRS companies as well, such as The VOID [55] (see an estimated schema of the arena in Figure 1.5). The size of the location can be varying from around 19 square meters like in VRMaze [53] all the way to 372 square meters such as one of the Zero Latency arenas [23]. As apparent by the name, all IMRS experiences are multiplayer. Some large-scale arenas are not only that but also allow more than one group of players inside the arena. However, this might lead to a problem of players colliding, because some groups might solve puzzles faster or slower than other groups present in the arena. This issue was observed and reported by DIVR employees managing the arena in Hamleys toy store.

Figure 1.4: The schema of the arena. Courtesy of DIVR.

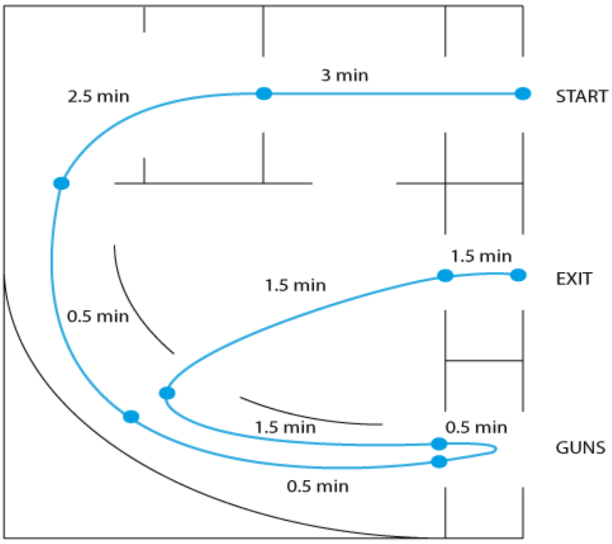

Figure 1.5: An approximation of The VOID arena. Based on personal estimation and a schema from an image published at The Verge [3].

What makes these collisions so problematic? First of all, players might get injured. This is very dangerous in sections where players tend to run or search for things on the floor causing others to trip over. Secondly, all players are wearing very expensive equipment which can get damaged. Lastly, it breaks the presence. Presence is a sense of *being there* in a location that is not necessarily the actual physical location of the player [19, p. 46]. IMRS helps to deepen this feeling of presence by the use of real locomotion and interaction. The use of avatars which copy the actual movements of the players is a very large factor as well [44]. The full definition of presence is written by a collection of scholars from the International Society of Presence Research (ISPR):

> "Presence (a shortened version of the term "telepresence") is a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience. Except in the most extreme cases, the individual can indicate correctly that s/he is using the technology, but at *some level* and to *some degree*, her/his perceptions overlook that knowledge and objects, events, entities, and environments are perceived as if the technology was not involved in the experience..." [31]

Immersion, on the other hand, is provided by the technology [19, p. 45-46]. It is a collection of objective traits and therefore needs the user of the VR system to subjectively experience it. Generally, the greater the immersion, the greater potential for evoking the feeling of presence in the player [19, p. 46]. When players collide inside the arena, the illusion of presence is broken [19, p. 47], because players suddenly realize that they are in the real world. This is known as break-in-presence [41] and should be avoided because it destroys the VR experience [19, p. 47] and revenue.

1.2 Other Industries Dealing with Potential Collisions

Collisions of people or objects is problematic in any context. This is why this subsection looks into similar industries dealing with potential collisions. A certain analogy can be drawn between these examples and IMRS, which also means that the proposed solution at the end of this project might be applicable to other areas of industry as well.

1.2.1 Escape Room Games

Escape rooms or *Escape games* is a similar type of entertainment to IMRS. In these physical games, players are given a time limit for solving puzzles and riddles that are hidden around one or more physical rooms. These games are usually designed for a small team, that is, two to five people, but it can vary. Whenever players are unable to progress with a task or find the answer or solution to a riddle or a puzzle, the game moderator can provide further hints or suggestions to help the players. As the name suggests, the goal of the game is to escape in the given time limit. Unlike virtual games, there is a large amount of upkeep that needs to be done whenever a game is finished. The game moderator has to walk through all the rooms and reset the puzzles, padlocks etc. As can be seen from a booking system of an escape room *The Butcher of Prague* (see Figure 1.6), a new game can be booked every two hours, which means that the game moderator has an hour to reset the game. The game's time limit is usually one hour, but if the players are not able to finish the game in set time, they can go overtime, which leaves less time for the upkeep, but generally responds well with the players, since they are allowed to finish their game. Due to the obligatory upkeep of escape room games, there is no danger of groups colliding into each other, but it also lowers the daily revenue.

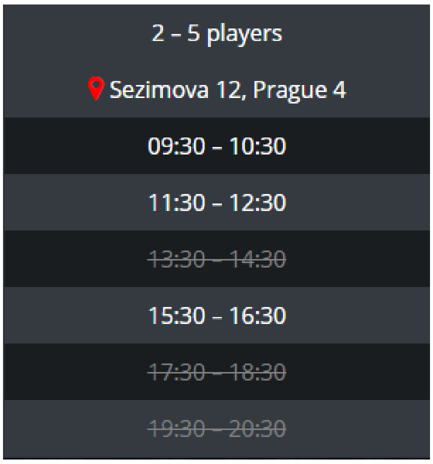

Figure 1.6: An example of escape room scheduling. The game lasts for an hour and there is an extra hour in-between each game, which allows for a reset. Figure from The Butcher of Prague booking system [52].

1.2.2 Analogy between Airport Ground Control and IMRS VR

On the other side of the spectrum, where there is a high risk of collision due to high traffic, a certain analogy can be seen between IMRS VR and ground control at airports. Naturally, when the air traffic increases so does the number of airplanes moving on airport grounds [4], which in turn increases the need for managing such movements thus preventing unnecessary delays of airplanes [47]. In this analogy, the airplanes entering the airport can be seen as the players entering the VR arena. The goal of the airplane is to safely land, park at a designated gate, where the passengers disembark and different passengers board, and lastly navigate the taxiways back onto the runway where the airplane takes off. Similarly, the players of the VR experience don the equipment, walk through the arena, in which they solve puzzles and do various interactions and then leave the VR arena with the help of the staff. The operators at the control tower can then be seen as the staff in the VR arena, as they are the ones handling the flow of airplanes entering and leaving the vicinity of the airport. Even though there is tight scheduling, the ground control is based on first-come first-serve basis. Furthermore, the control tower staff also takes care of *push-back*, the process of moving an aircraft from a terminal to a runway or taxiway. Depending on the size of the airport, there can be multiple runways (see Figure 1.7). There are several projects dealing with the problem of ground control management [47, 4]. The problem of not being able to efficiently traverse the taxiways results in missing assigned slots at the runway, which causes delays, and also wasted fuel caused by additional waiting for other aircrafts to clear [4]. What can be learned from this analogy is that there can be multiple taxiways and even runways on which the aircrafts can move. There is a need for automated taxiing technologies, which in the IMRS VR analogy can mean, that there is a need for automated navigation system in a VR arena. This analogy is revisited again in the design phase of this project (see chapter 2).

While the problem of groups colliding in an IMRS arena is primarily emerging from the field of industry and from personal experiences acquired during my internship, it is just as important to scout the academic landscape for its underpinning concepts and theories. The following two sections are focusing on the industry state-of-the art and the academic underpinning respectively.

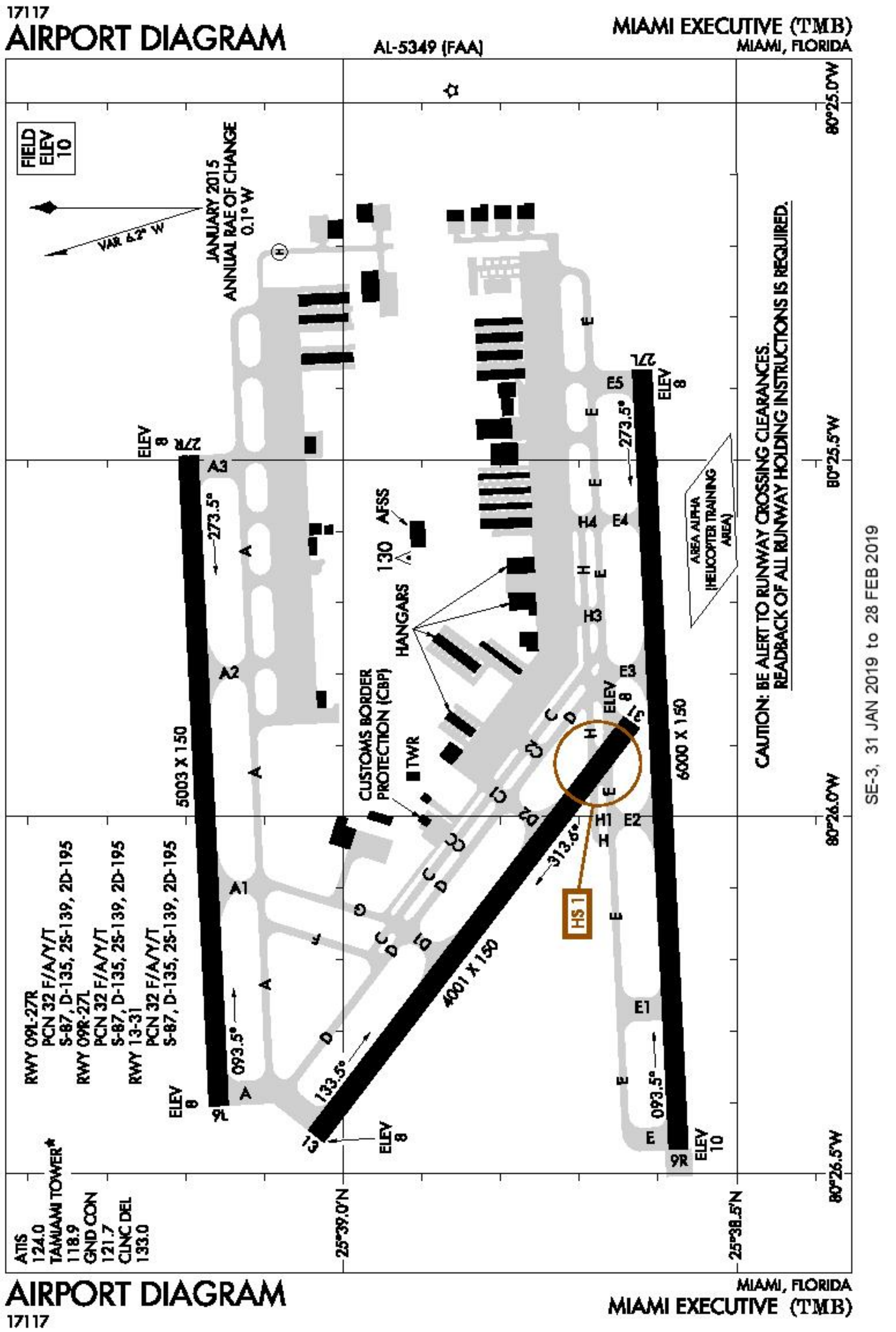

Figure 1.7: An example of an airport diagram. This diagram depicts the layout of runways (depicted as thick black lines) and taxiways (depicted in grey) at Miami Executive airport. Figure from SkyVector Aeronautical Charts [40].

1.3 The Industry of Location-based Virtual Reality

Charlie Fink, an AR/VR consultant, and Kevin Williams, a specialist in amusement and attraction applications and technologies, took on the task of counting all the LBE VR companies and they came up with 42 different establishments [6]. By their own words, the list is incomplete and probably undergone a number of changes since the release date of the article in September 2018. Seeing as not all of the companies of that list are in the free-roam and multiplayer department, they are not mentioned in this section as they are not relevant to the research problem focusing on IMRS VR.

Starting from the very beginning of location-based VR, the idea of free-roaming multiplayer VR experience already emerged in 2012 and resulted in the establishment of Zero Latency company [23]. The world had to wait another year before it finally saw a prototype of such system and, finally, in August 2015 Zero Latency opened its first publicly-available venue [54]. As of today, Zero Latency is still in the lead with impressive 23 venues, located in 13 different countries [23]. The company's main focus is on shooter games in large open arenas from approx. 200 to 400 square meters, which can hold up to eight people at a time. Since the players are allowed to free-roam at any point in the game, only one group is allowed in the arena at a time. Similarly, Nomadic with their *Arizona Sunshine: Contagion Z* game is also located in a warehouse-scale arena with unlimited free-roaming, but the full capacity of the arena is four players [26]. Nomadic only has one released title, the room-scale VR version of a popular zombie shooter game *Arizona Sunshine*, which was originally released for PS4. In the case of additional games that the players could experience, the arena can be reconfigured into smaller spaces with little effort due to its modular nature [32]. This modular approach is very promising as it allows for relatively fast and cheap changes to the environment.

Very prominent is an American establishment called The VOID, which has 11 open locations, out of which most are located in the US and Canada plus one in Dubai [55]. The VOID is known for its cooperation with Disney, which gave birth to IMRS VR experiences such as *Star Wars: Secrets of the Empire* or *Ralph Breaks VR*. Since its establishment in 2016, The VOID has been able to develop its own technology called Rapture system, which features a haptic vest with a built-in, ultralight computer. Additionally, they also have a slightly modified version of the Oculus Rift HMD [11]. The size of the arena is about 80 square meters, with physical walls and props, such as weapons, heaters and fans to add to the haptic feedback and presence. There can be up to four players in a group and the arena can accommodate two to three groups at a time. There are usually two mirrored arenas running at a location during busy days. The experience itself takes about 12 minutes and every 5 minutes a new group is sent inside. Shortly after the company was established, they realized their biggest issue was space, which then led to creation of *the infinite hallway*, which the company owns the Intellectual Property (IP) for (as stated during the Dutch VR DAYS conference in 2015). The idea is based on redirected walking (more about that in chapter 2), which made the perceived size of the arena much larger [11]. However, this concept is not used in their experiences anymore.

Moving away from the larger-scale multiplayer experience, using pods or platforms is also a popular way of building a VR experience. Companies such as Dreamspace, Sandbox VR and Spaces are good examples of such setups. Even though these companies might not be as *room-scale* as the typical examples of IMRS, they still allow for some degree of free-roaming. As a single pod or a platform can only accommodate one group at a time, the problem of groups colliding is non-existent. All three aforementioned companies were established in 2016, but each of them tackles LBE in a different way. The most distinct is Sandbox VR since they use a green-screen covered room as their play area [56]. This allows for mixed reality videos to be generated and provided for interested customers. There can be 2-6 players at a time and they are all suited up in motion-tracked equipment. Sandbox VR operates in six different locations and offers three different experiences, most of which are shooters. Spaces company so far only offers one experience on three different locations, but already announced a second game [42]. On the other hand, Dreamscape Immersive is only located in a city mall in Los Angeles, but offers three different experiences, with varying length and multiplayer options, usually from a singleplayer up to a six player group [17]. Unlike any of the games developed by the aforementioned companies, Dreamspace is focusing on the exploration genre rather than a shooter. The pods are ca. 80 square meters large including railings, fans positioned behind the players and similar, leaving the actual play area much smaller.

Lastly, DIVR Labs or shortly DIVR, the collaborator on this project, is also focusing on exploration and puzzles, but unlike Dreamspace, the play arena is very large (250 square meters). The size of the arena allows for more than one group to enter at the same time, which is reflected in increased daily revenue. The area is divided into seven separate rooms or levels. This can mean that free-roaming is limited to a single room, as is the case in *Golem VR*, or a set of adjacent rooms just like in *Arachnoid*, formerly known as *Mission Blue Effect*. These two experiences are both available at the same location in Prague and both are susceptible to collisions.

An overview of all the LBE VR enterprises presented in this section are listed in Table 1.1.

Company (launch)	**Locations**	**Arena**	**Time allocation**	**Players per game**	**More groups co-locate? How is the issue solved?**
DIVR (2016)	1 in Prague	250 m2	25 min	1-4	Yes. Guide hints, solving tasks for the players when time allocation for each room runs out. Next group enters in 5 min.
The Void (2015)	11 - mostly US and Canada, 1 in Dubai	80 m2	ca. 12 min	1-4	Yes. There is a time allocated for each room, the game solves itself, sends more enemies when needs more time. Next group enters after 5 min plus the staff physically pushes people out.
Dreamscape (2016)	1 in Los Angeles	80 m2	varies, ca. 40 min	1-3, 1-6 or 1-5	No. Up to 6 players are in pods, so they do not move around much.
Nomadic (2015)	2 in the US	warehouse scale stage	30 min (ca. 15 without setup)	1-4	Likely not. The reservations can be done by 15 min intervals, which suggests that there is only one group present at a time.

Zero Latency (2012)	23 venues in 13 countries	186 - 372 m2	30 - 45 min	1-8	Likely not. It appears as if the groups can free roam at any point, making it impossible to have multiple groups in the arena.
Spaces (2016)	3 - 2 in the US, 1 in Tokyo	N/A, "fairly large platform"	10-15 min	1-4	No. The platform accommodates one group at a time
SandboxVR (2016)	6 - 1 in the US, 1 in Canada, 4 in Asia	N/A, "fairly large"	30 min	2-6	No. The large green screen area accommodates one group at a time.

Table 1.1: Overview of the state of the art.

1.4 The Academic Field of Location-based Virtual Reality

To understand the empirical material surrounding the problem of collisions in VR, it became important to search the academic field for relevant work. In order to efficiently scout out the relevant academic field, a literature review strategy was adopted. As already anticipated at the beginning of this project, the academic field for LBE VR is very narrow due to its short history. As a commencement point of searching, Aalborg University Library (AUB) was chosen. This allowed for a broad variety of databases and library suppliers to be searched. The first general search term *"location based virtual reality"* yielded 97 search results and after a brief skim, there was a visible tendency of using the phrase in relation to real-world locations, such as cultural or geological sites, or outdoor activities, such as geocaching. This resulted in the decision to search in a database which focuses on digital and technological topics.

1.4.1 Search Domain and Search Method

The ACM (Association for Computing Machinery) digital library became the primary location for further searches due to its focus on technology. When searching through a database, one can search for an exact phrase or a sentence. The phrase search is marked by double quotation marks. Without the quotation marks, all papers that include at least one of the words are found. Another technique for more controlled searching is the usage of boolean operators: *AND*, *OR* and *NOT*. Similarly as in various programming languages, these operators are used when searching for materials that include either: all the keywords (AND), at least one of the searched keywords (OR) or to exclude a specific term (NOT).

A number of search words were selected based on section 1.3. The preferred area of search were papers dealing with virtual reality and since the focus of this paper is upon the IMRS field, the main four keywords became: *immersive*, *multi-player*, *room-scale* and *virtual reality*. Furthermore, the problem area deals with collisions in VE, more specifically its prevention and avoidance. The selected search words and phrases for this project scope are listed in Table 1.2 (see also Appendix A for detailed info on the searches).

location based virtual reality				
flow	AND	virtual reality		
flow	AND	virtual reality	AND	multiplayer
virtual reality	AND	multiplayer	AND	collision
multiplayer	AND	room-scale		
multiplayer	AND	room scale	AND	virtual reality
room-scale	AND	virtual reality		
warehouse-scale	AND	virtual reality		
collision avoidance	AND	virtual reality		
escape room				
immersive	AND	room-scale	AND	multiplayer

Table 1.2: The list of search words and phrases.

1.4.2 Summary of Findings of Literature Review

Found papers were individually examined based on their abstract or, if the abstract was still unclear or missing, on the full text. The papers were selected based on their relevance, that is, if they dealt with one or more of these themes:

- Collision Avoidance
- Physical Locomotion in VR
- Collaboration in Virtual Space
- Methods for Enlarging Virtual Space

Many of the found papers utilized physical locomotion in VR but on a small scale. Such papers were not labeled as dealing with physical locomotion unless the paper would somehow enrich the research field dealing with such topic. The more of these themes could fit a paper, the more relevant. This literature review strategy yielded 20 relevant papers out of which five were found through source chaining (see Table 1.3).

Although not exactly an academical source, it has to be noted that articles published on `https://lbe.news/` were invaluable to the understanding of the LBE VR community and industry area. This platform unites and promotes professionals providing VR, LBE VR and family entertainment products. Furthermore, the site's goal is to become a credible source for industry data and statistical analysis.

Published Article	Author	Year	Theme(s)
Collision Avoidance in Virtual Environments Through Aural Spacial Awareness [1]	Afonso and Beckhaus	2011	Collision Avoidance
How to Not Hit a Virtual Wall: Aural Spatial Awareness for Collision Avoidance in Virtual Environments [2]	Afonso and Beckhaus	2011	Collision Avoidance
Obstacle Avoidance During Walking in Real and Virtual Environments [7]	Fink et al.	2007	Collision Avoidance, Physical Locomotion in VR
Inside looking out or outside looking in?: an evaluation of visualisation modalities to support the creation of a substitutional virtual environment [8]	Garcia et al.	2018	Collision Avoidance, Methods for Enlarging Virtual Space
ARES: An Application of Impossible Spaces for Natural Locomotion in VR [9]	Garg et al.	2017	Physical Locomotion in VR, Methods for Enlarging Virtual Space
Improving Virtual Reality Safety Precautions with Depth Sensing [15]	Huang et al.	2018	Collision Avoidance
Evaluation of Locomotion Techniques for Room-Scale VR: Joystick, Teleportation, and Redirected Walking [22]	Langbehm et al.	2018	Physical Locomotion in VR

Subliminal Reorientation and Repositioning in Virtual Reality During Eye Blinks [21]	Langbehm et al.	2016	Physical Locomotion in VR, Methods for Enlarging Virtual Space
Towards Virtual Reality for the Masses: 10 Years of Research at Disney's VR Studio [25]	Mine	2003	Collaboration in Virtual Space
Interaction Between Real and Virtual Humans During Walking: Perceptual Evaluation of a Simple Device [27]	Olivier et al.	2010	Collision Avoidance
Mutual Collision Avoidance During Walking in Real and Collaborative Virtual Environments [29]	Podkosova and Kaufmann	2018	Collision Avoidance, Collaboration in Virtual Space
Comfortable and Efficient Travel Techniques in VR [34]	Sarupuri	2018	Physical Locomotion in VR
Triggerwalking: A Biomechanically-inspired Locomotion User Interface for Efficient Realistic Virtual Walking [35]	Sarupuri et al.	2017	Physical Locomotion in VR
VR Collide! Comparing Collision-Avoidance Methods Between Co-located Virtual Reality Users [36]	Scavarelli and Teather	2017	Collision Avoidance, Collaboration in Virtual Space
Walkable Self-overlapping Virtual Reality Maze and Map Visualization Demo: Public Virtual Reality Setup for Asymmetric Collaboration [37]	Serubugo et al.	2017	Physical Locomotion in VR, Collaboration in Virtual Space, Methods for Enlarging Virtual Space
Asymmetric Design Approach and Collision Avoidance Techniques For Room-scale Multiplayer Virtual Reality [43]	Sra	2016	Collision Avoidance, Physical Locomotion in VR

MetaSpace: Full-body Tracking for Immersive Multiperson Virtual Reality [44]	Sra and Schmandt	2015	Collaboration in Virtual Space
Estimation of Detection Thresholds for Redirected Walking Techniques [46]	Steinicke et al.	2010	Physical Locomotion in VR, Methods for Enlarging Virtual Space
Impossible Spaces: Maximizing Natural Walking in Virtual Environments with Self-Overlapping Architecture [49]	Suma et al.	2012	Methods for Enlarging Virtual Space
Towards Virtual Reality Infinite Walking: Dynamic Saccadic Redirection [50]	Sun et al.	2018	Physical Locomotion in VR, Methods for Enlarging Virtual Space

Table 1.3: Literature overview showing found literature together with authors, years of publication and matched themes.

1.4.3 Literature Review Analysis

The most fruitful search phrases were *"room-scale" AND "virtual reality"* and *"collision avoidance" AND "virtual reality"*. Together they yielded 13 out of the 21 papers found. In this subsection, the found literature is described in detail.

Fink et al. [7] set out to test if visual-motor behaviour in an immersive virtual environment (VE) is the same as it is in the real world. The way they tested it was to set up a stationary goal and stationary obstacle en route and then compare locomotion paths of participants in VE to those in a matched physical environment. The location of the stationary obstacle varied and the whole setup was in a 12 by 12 metres large room. Most participants deviated a bit further from a straight path to the target in the VE compared to the physical environment. The minimum clearance distance from the obstacle was 0.16 metres greater and also the walking speed was slower in VE. Despite this, it was concluded that the quantitative difference in the deviation around an obstacle was small and thus human paths in real and virtual environments are qualitatively similar in shape.

A similar research was conducted by Podkosova and Kaufmann [29] with the difference of substituting the stationary obstacle with yet another participant. The goal was to compare mutual collision avoidance during walking in three tested conditions: real, virtual co-located and virtual distributed. To explain these terms, the difference between the two virtual conditions is that the co-located means the participants share a common tracking space while in the distributed environment, they share the virtual space but not the tracking space. In the test, the participants got tasks but were not explicitly told to avoid their test partners. Observations showed that testing the co-located condition first made participants avoid collisions in the vast majority of cases also in subsequent tests. On the other hand, when users were presented the distributed condition first, the participants walked through each other's avatar in most cases. From questionnaires, it was clear that participants focused on collision avoidance in the virtual co-located scenario as opposed to focus on the task in the virtual distributed scenario. The conclusion was that there is a significant difference in locomotor trajectories of participants between real and virtual conditions. Similarly as in the research by Fink et al. [7], there was an increase in the clearance distance and a decrease in walking speed in the virtual co-located condition.

Scavarelli and Teather [36] developed three visual feedback mechanisms for preventing physical collisions between a co-located VR user and a stationary dummy. The three mechanisms are a 3D avatar, a bounding box and a camera overlay, which is a live video feed overlaid on the VE. The participants had to walk towards different dots on the ground and there would either not be an obstacle on the path, an obstacle near the motion path or an obstacle right in the motion path. The participants were instructed to avoid the obstacle. It was found that the conditions with camera overlay and avatar had the fastest travel time around an obstacle and it was also the two favourite options by the participants. On the other hand, the bounding box mechanism had fewer collisions, rendering this option the safest.

Staying with the theme of collision avoidance during walking, it is interesting to look into research by Olivier et al. [27]. Even though this research was not conducted in VE but in front of a TV screen, their results might still inform the field of VR. Their goal was to assess whether real humans are capable of accurately estimating a motion of a virtual human and related collision avoidance. The participant was looking at the presented situation from a first person perspective and their virtual avatar was moving forward at constant walking speed. From a side, another virtual human would start approaching. At various times (also called *cut-off time* in the paper), the screen would freeze and the participants had to judge the situation, whether they would give way to the virtual human or not. The results showed that the judgment accuracy was not influenced by the cutoff time, in other words, the participants could very quickly estimate the situation. It was also easier for the participants to estimate the crossing order (aka. who passes first) compared to collision detection (aka. if nobody adjusts their speed, will they collide).

Sra [43] addresses the problem of various sizes and shapes of physical environment for multiplayer scenarios and also presents an automated system for steering the user away from walls and other obstacles by using Galvanic Vestibular Stimulation. The idea is to have cathodal current on one side and anodal current on the other. This shifts the user's balance resulting in swaying in the direction of the anode. The system is still being developed and thus its evaluation is not presented in this paper. Her previous work with Schmandt [44] was focusing on full-body racking for local multiplayer purposes in VR. Their work is once again not tested, but the hypothesis is that representing the participants as full-body avatars controlled by natural movements would lead to greater sense of presence. Similarly as some of the IMRS companies mentioned, the walls and objects in the physical world have their counterparts in VR.

A number of papers focus on the overlapping architecture in VR. Among these papers, the most robust is the research by Suma et al. [49] that introduces the concept of *impossible spaces*. This concept should help to maximize the size of VE that can be explored with natural locomotion. In other words, relatively large virtual space is compressed into a smaller physical arena. This idea works best for interiors but can be also applied for outside if enough buildings or obstacles block the view of the user. Suma et al. conducted two user studies to explore the perception and experience of the impossible spaces. In the first experiment, the users were explained the concept of impossible spaces prior to the test and then they had to speak-out-loud whenever they thought they detected something impossible in the test. The results showed that small rooms may overlap up to 56% before participants would start to notice. Larger rooms (around 9.1m x 9.1m) may overlap up to 31%. In the second experiment, the users were not told about the concept of impossible spaces and instead focused on playing a game which was created as a chain of impossible spaces creating an expansive outdoor scene. The participants moved on a S-curved path with various buildings on the side, which they could enter. In reality, the participants were moving in a figure eight pattern. Out of the 17 participants (out of which 14 had no prior knowledge of the impossible spaces), 12 did not notice the manipulation of space. The subsequent questionnaire and semi-structured interview revealed that even though some participants noticed the change, they seemed indifferent to it. However, participants felt a little dizzy and off-balanced, often during or right after the curvature gain. The curvature gain is when the user is turning slower in the virtual world compared to the physical world. Therefore it was concluded that impossible spaces offer a powerful illusion when users are naive to the manipulation, but it should be used with care in practical situations. Garg et al. [9] illustrate the applied use of impossible spaces in a room-scale VR game. They tested their gaming narrative content on five participants. None of the participants felt lost during the experience and only one of the participants was able to notice and deduce the mechanic of impossible spaces. Lastly, Serubugo et al. [37] tested a walkable self-overlapping VR maze in a public library. Their space was limited to 2.5m x 2.5m. Two or more users could collaborate on solving the maze. One would wear the VR headset while the bystanders could provide instructions where to go based on a visualized map which was stationed near-by. The results showed that none of the HMD users noticed the game updating in VE, but due to the limited space, they could deduce the mechanic. It was also found that the experience was more engaging and faster with guidance as compared to solving the maze alone.

Thanks to quantitative research by Steincke et al. [46], many detection thresholds were estimated that can be used for redirected walking. The research produced three different experiments dealing with virtual and physical rotations, virtual and physical straightforward movements, and path curvature. In the first experiment, the participants had to guess whether the perceived rotation was greater or smaller than the actual physical rotation. In the next experiment, the participants had to guess whether they walked further virtually or physically. In the last experiment, the participants had to estimate a path curvature while walking a curve path in the real world, but a straight line in the virtual world. The results show that users can be turned physically about 49 percent more or 20 percent less than the perceived virtual rotation. Furthermore, virtual distances can be upscaled by 16% and downscaled by 14%. Lastly, it was found that a circular arc with a radius of 22m or greater is necessary to prevent users from detecting redirection, aka. they believe they walk in a straight line.

Yet another field of research deals with relocation and reorientation of a VR user during eye blinks [21, 50]. Sun et al. [50] use eye-tracking technology to improve upon the redirected walking method. The method has three parts: saccade detection, dynamic path planning and subtle gaze direction. Saccade detection is used to identify opportunities to reorient the virtual camera. Dynamic path planning is used to choose the best virtual path the participant can take based on the current location and orientation of the camera. Lastly, subtle gaze direction is used to induce visual saccades by temporarily showing a stimulus in the user's periphery. It was found that by using this method, the rotation gains can be much higher as opposed to prior research without inducing simulator sickness.

Some experimenters are trying to include the real obstacles in their virtual environments, such as the aforementioned work by Sra and Schmandt [44]. Garcia et al. [8] developed a system which would detect an obstacle, for example a piece of furniture, and then substitute it depending on its dimensions by a virtual asset. This method can potentially increase the space that the user can move in. They tested two visualization methods to aid in the creation of the virtual representations of the physical environment. The first method is to view the physical environment while immersed in VE and the second is to view VE through external device, such as a tablet. The experiment had two phases, volume drawing and object spawning. It was found that the immersive option had better accuracy and the highest preference rating, but it was slower. However, there was not a statistical difference in errors made and time and only a small difference in accuracy and preference. Research by Huang et al. [15] reports on their work dealing with two augmented virtuality interfaces that ingrate the depth sensing of surroundings in the VR scene for safety precautions. The two interfaces are grids, one in monochrome and the other with colours based on depth values. The paper does not present any results of a user study.

Langbehn et al. [22] conducted an experiment to analyze effects of three different locomotion techniques on the user's cognitive map building as well as effectiveness, motion sickness, presence and user preference. The three locomotion techniques are joystick, teleportation and redirected walking. The participants had to reach four different targets in an indoor VE. After they reached the last one, they had to point in the direction of the targets in order of appearance. Their HMD went black and the users had to estimate the size of the room in meters. Finally, they could take off the HMD and were asked to draw a 2D map of the VE. The final task was to arrange the room from memory by the use of paper cutouts of the furniture and objects in the room. The results suggest that redirected walking performs best regarding the user's ability to unconsciously acquire spatial knowledge about VE. Furthermore, redirected walking and teleportation were subjectively preferred. Joystick movement performed the worst in most tests and induced motion sickness. Since teleportation and redirected walking were not significantly different, both methods are recommended for use as compared to joystick movement.

A whole area of research deals with other ways of locomotion in VR, something that would fit in-between natural walking and teleportation [34, p. 232]. Some of the methods use the natural swinging movement of arms which simulate walking in the direction of the user's gaze [48] or even uses the triggers as natural bi-pedal steps [35]. The former method moves the participant by a step every time a trigger is pressed, but tends to work less efficiently for longer distances as the participants might start experiencing finger fatigue [34]. Sarupuri et al. [35] analyzed head oscillations of VR users while they walked with an HMD and used the data to simulate realistic walking motion with respect to the trigger pulls. Evaluation of the triggerwalking technique showed that it can be efficiently used while still benefiting from the advantages of real walking. Further studies conducted by Sarupuri [34] focused on developing a locomotion system which would be a set of locomotion techniques which could be used for seated, standing and room-scale VR. The goal was to develop a locomotion technique that would fit for short, medium and long distances. The proposed evaluation is to have the participant either sit or stand and test out four different locomotion techniques: joystick, teleportation, triggerwalking and comprehensive locomotion. The comprehensive locomotion is a set of the three above mentioned techniques, teleportation for long distances, joystick for medium and triggerwalking for short. The evaluation was not yet conducted.

Two papers published by Afonso and Beckhaus [2, 1] deal with collision avoidance in relation to aural spatial awareness. Their system is based upon the idea of constantly informing the users of their proximity to the surrounding walls through playback of directional sounds. The setup would mimic eight surround loudspeakers, located always in front, back and three on each side of the user. The volume of the playback sound would increase when the user would get closer to the wall. Their initial pilot study showed that on average, the user collided only half as often when they had a full collision avoidance feedback as opposed to only having a collision notification feedback [1]. Their subsequent study showed confirmed this result but gave rise to new questions which are yet to be answered [2].

Lastly, a paper by Mine is not necessarily informing the academical field, but it does provide reflections and knowledge acquired during a 10-years work at Disney VR studio dealing with location-based VR [25]. There are not any empirical findings per se but even then this paper became invaluable for the design phase of this research (see chapter 2).

1.4.4 Conclusion of the Literature Review

As can be seen, the academic field has not yet worked with collisions in the same context as this project is proposing. There are papers that consider collisions in terms of enhancing in-home VR stations and trying to make the physical space larger, for example by including the nearby furniture in the virtual world [8]. An interesting method for collision avoidance is the usage of electric current as shown by Sra [43]. The current has to be low, which makes this method less reliable when people move at a higher speed in VR. However, it remains a promising tool for further development or as an addition to existing systems for collision prevention. The same situation can be said about the aural awareness method as tested by Afonso and Beckhaus [2, 1], though having additional audio in a virtual game or experience might be too distracting.

Several papers dealt with *tricking* the minds of the players by making the virtual area seemingly larger [49, 9, 37, 46]. These projects showed a promising field of research, however, their findings are not relevant to the research problem outlined in this report as it does not deal with large physical multiplayer areas or collisions.

Perhaps the most informative finding was presented by Podkosova and Kaufmann [29], who found that the choice to avoid obstacles in the *virtual distributed* scenario was seemingly influenced by the order, in which the virtual scenarios were presented. Participants who were exposed to the virtual co-located condition first had a tendency to avoid collisions in the virtual distributed environment, suggesting a pre-conditioning effect. Even people who found themselves in their first virtual experience did not always try to avoid collisions as discussed by the authors of the experiment [29]. However, as can be seen from the study by Olivier et al., people are able to correctly assess the situation and avoid colliding with a virtual character [27]. This suggests that when people did not try to avoid collisions, as in the experiment by Podkosova and Kaufmann, it was not because of their inability to do so. A similar thought was expressed by Scavarelli and Teather, who expressed a limitation to their study of collision-avoidance methods in co-located VR:

> "Participants may behave differently when they know that no collision is actually possible, as the obstacle was simulated." [36]

Research by Sun et al. [50] shows a promising way of enhancing redirected walking as their method requires less physical tracking space. In the case of IMRS, the typical VR experience would also include physical props which would be aligned with the virtual ones. As argued by a number of researchers [44, 14], this is a powerful way of enhancing the feeling of presence. This is why the subliminal reorientation and re-positioning would not work with the physical props as the virtual and the physical worlds would not align. Therefore the issue of not having a clear solution to the collision problem appears as an unexplored gap in the academic field.

1.5 Research Question

There are some precautions the companies can take in order to minimize the risk of colliding, but there is not a solution that would be universal or academically validated, therefore their efficiency is unknown. The problem is thus not only theoretical, but also practical, because the solution is not as simple as having fewer groups in the arena, as then the company cannot use the full capacity of the arena, which generates lower revenue. As shown in the previous sections, there are some solutions to this problem, but they are often recognizable as forceful slowing down or speeding up, which then breaks the illusion of virtual reality. In the arena in Hamleys as well as the ones operated by The VOID, there already are precautions to this such as allowing new groups to enter an arena with a time delay. This allows the first group to get a head-start before the second group enters, then after five more minutes a third group gets in etc. Another precaution is scalable puzzles. This allows for different difficulty levels of a puzzle depending on the size of the group playing it, ranging from a full four-player group to a single player, as in the case of Golem VR. The VOID's main type of interaction is shooting and thus their way of prolonging a stay in a room is to send in more enemies than the players need to deal with or have them run away if the time is up. In case of Golem VR, these precautions were not enough to stop the groups from occasionally colliding, as reported by Hamleys employees, especially in extreme cases when the first group is very slow, while the group that follows them is very fast. In the worst case scenarios, the groups might collide again in subsequent rooms. The VOID, apart from the precautions mentioned above, has an employee inside the area, who pushes people out of the rooms if they linger for too long. This once again breaks the immersion.

To sum this problem description up, the optimal solution would be a balance between having a full capacity of the arena while at the same time avoiding groups of players colliding with each other. In the VR scope, this problem is exclusive for IMRS VR, as the players are stationary or confined to a small tracking space otherwise. Modular or small-sized IMRS VR arenas also very often avoid this problem as there can be only one player or one group of players present at a time. The goal of this research is to avoid players getting injured, getting equipment damaged and also having players lose their presence which leads to not enjoying the experience. Furthermore, the findings from this research might help large-scale multiplayer VR experiences with estimating how many users can fit into a physical tracking space at the same time while avoiding collisions. Therefore the overall research question is:

> **How can virtual reality experiences be designed so that the potential collisions of groups of players in an immersive multiplayer room-scale arena are eliminated while not sacrificing the size of the arena and the nature of the gameplay?**

Chapter 2

Design of Collision Detection Solutions

The design chapter describes the progress of going from design constraints and state of the art summary to more concrete ideas for collision-detection methods. Some of the ideas are tested through a low fidelity prototype and further modified as preparation for subsequent implementation and testing.

2.1 Design Constraints

When designing an arena for a location-based virtual reality game or an experience, there are a couple of factors one should consider. First of all, as already described, there are Impulse-Driven and Destination-Driven LBE. Realizing where on the scale the experience is can be a big help as it can answer questions such as, who is the primary target group, how long the experience should be or how to price it. Other main factors or questions new LBE enterprises should ask themselves are: Is the experience multiplayer or singleplayer? How are the players moving and interacting in the world?

At the very start of this project, there were a few design constrains that were agreed upon with Ondrej Bach, a co-founder and CPO at DIVR Labs. These constraints are a reflection of the questions asked above and also the company's history and vision for the future. As DIVR is the leader of the Czech immersive multiplayer room-scale VRE industry, there is a number of things that should not be modified:

A) Ability to have multiple groups in the arena

B) Having a large sized-arena

C) Having a virtual environment mapped onto the physical one and also physical props

To put this into perspective of the conducted research, a list of collision-avoidance techniques was compiled and checked against the design criteria (see Table 2.1). The collected list is based on already existing solutions that are being used by aforementioned IMRS VR enterprises as well as ideas which emerged from a private brainstorming session and a number of design-oriented talks with the game designer working at DIVR.

	A	B	C
1 Game adaptation	Yes	Yes	Yes
2 Voiceovers	Yes	Yes	Yes
3 Entry intervals	Yes	Yes	Yes
4 Small arena	No	No	Yes
5 Watcher	Yes	Yes	Yes
6 Perceived large arena	No	Yes	No
7 HUB	Yes	Yes	Yes, but the story would have to be non-linear
8 Open-space	Yes	Yes	No
9 Detour	Yes	yes	Yes, in some variations expect for nearby rooms affected by the detour, which would add an extra room and also change the order of the entered rooms (see caption for Figure 2.9).

Table 2.1: A list of collected solutions and how they fulfill the criteria.

Further details to each solution is provided below:

1. **Game adaptation** This collision-avoidance technique is very popular with The VOID company. The basic idea of this technique is to have the game adapt to the amount of time the group has available. For example, if the group needs to slow down, aka. prolong their stay in the room, more enemy ships or soldiers will come and attack the players (see Figure 2.1). On the other hand, if the group needs to hurry up, the enemies can run away or be eliminated by a stray bullet or similar. This technique works well for shooters or scenarios in which an interaction does not have a definitive ending.

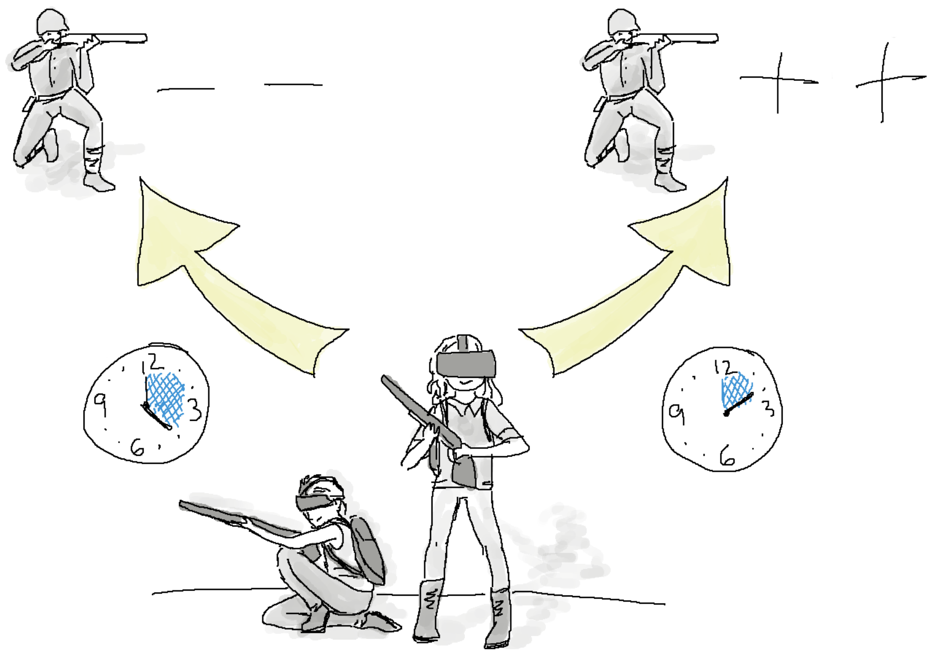

Figure 2.1: The game continuously checks time. If the group is too fast, more enemies are added. If the group is too slow, the challenge decreases.

2. **Voiceovers** A similar technique to game adaptation but used with game genres other than shooters or in scenarios, where game adaptation is not possible. When there is a group who performed fast in a room, an additive voiceover or dialogue will play in a subsequent room (see Figure 2.2). The goal of this is to compensate for extreme cases and try to even out the average completion time of the full game. The default state does not have additional voiceovers, but the story should not be affected by this change. Therefore, extra care needs to be put into making the voiceover versions, so that each communicates the same thing, even if they use different words.

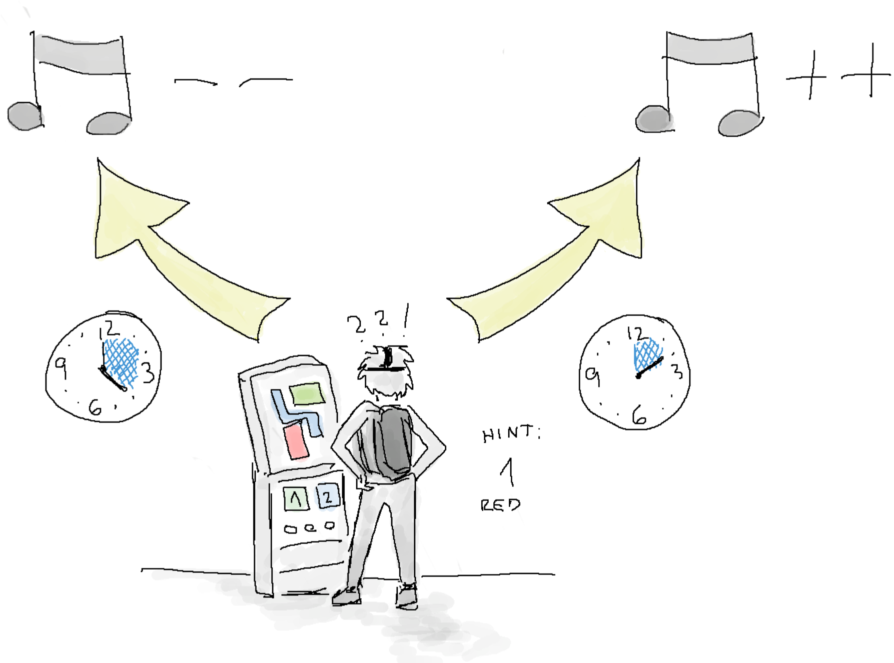

Figure 2.2: The game uses additional voiceovers in case the group performs slowly.

3. **Entry intervals** Having individual groups enter the arena after certain amount of minutes is an already existing and helpful precaution (see Figure 2.3). Even though it does not solve the problem completely, it should be always used in standard IMRS experiences. The longer the interval is, the lower the chance for collisions. However, there must be a certain trade-off between the time interval and the number of groups that can be in the arena at a time otherwise the company could have lower revenue.

Figure 2.3: Groups are allowed to enter the arena in 5 minutes intervals.

4. **Small arena** The perfect case would be to have one group per large arena with a variety of physical props. However, the price of such experience would be either too high for the potential customers so that it would compensate for the cost of the rented space or the revenue would be too low for the company because of the same reason. Therefore, this solution proposes a small area accommodating one group (2.4). The group can take all the time they need and they will never collide with anyone. The downside of this is the lack of various physical props, because such arenas could be only one or two rooms large. As an example, an arena of 250 square meters could be divided into 4-5 rooms, rendering the final arena size only around 50 - 60 square metres large.

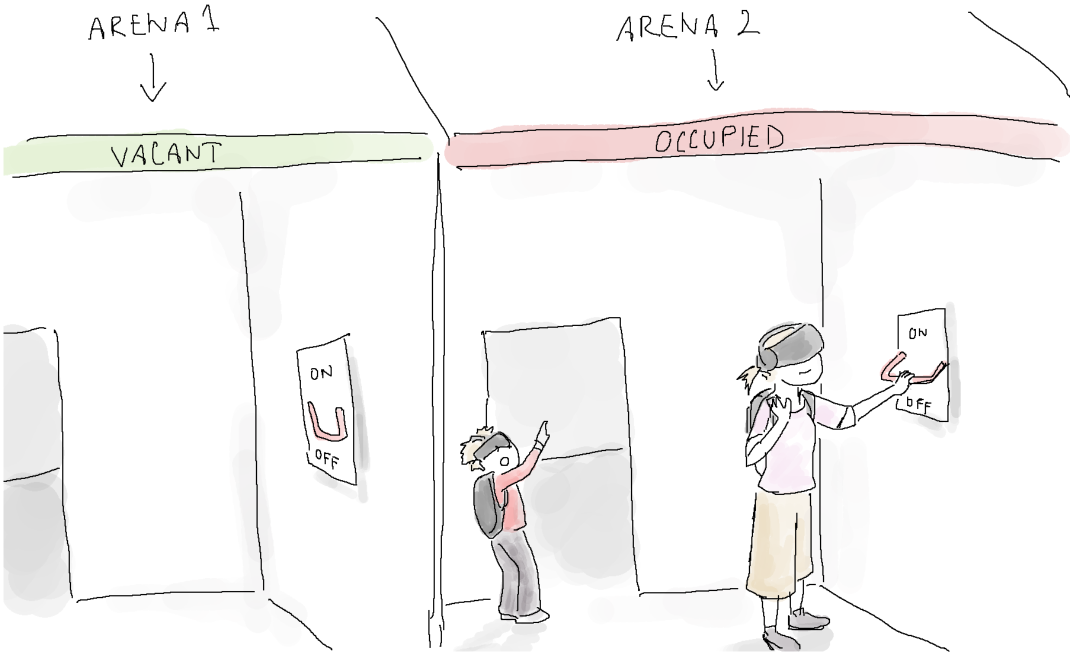

Figure 2.4: A number of small identical arenas each allowing only one group to enter.

5. **Watcher** Another technique popular with The VOID. The idea is to have a physical person inside the arena who watches over the groups moving about the arena (see Figure 2.5). Even though this can be very effective when it comes to collision avoidance, as the watcher can push people out of the rooms when they linger for too long or can simply grab someone before they can crash into another group, it breaks the presence immediately. Once groups realize there is another person in the room with them they might become self-conscious and would not fully immerse themselves in the game again. Therefore, this technique, however effective, is strongly disadvised.

Figure 2.5: A physical person watching over the groups and preventing collisions.

6. **Perceived large arena** Similarly as the small arena, this arena would accommodate only one group at a time. The main difference would be the perceived size which would feel larger than what it actually is, for example by utilizing redirected walking (see section 4.1.2) or impossible spaces (see Figure 2.6). However, since space would have to be reused, physical props would have to be very limited or missing altogether.

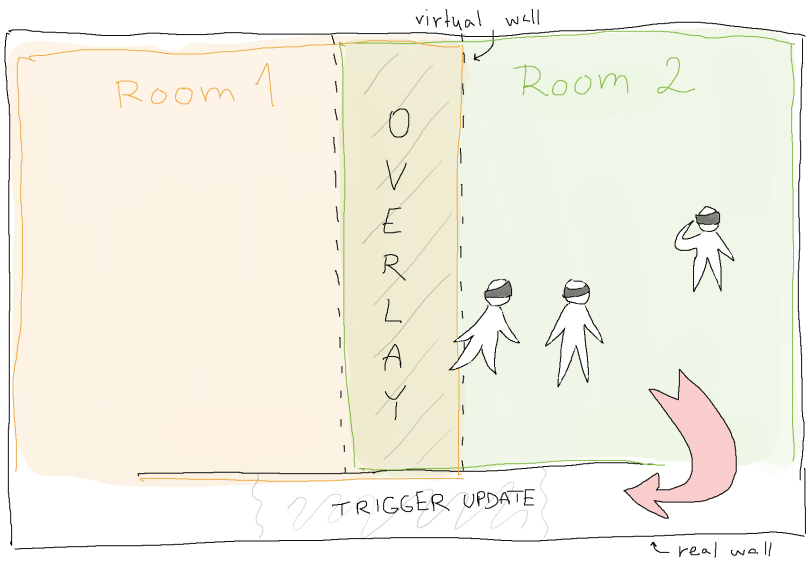

Figure 2.6: The impossible spaces. The idea is to reuse the available space by overlapping the rooms up to 56% in case of small virtual rooms or 31% in case of large virtual rooms [49].

7. **HUB** The idea of having a number of separate rooms connected by another single shared room, a HUB, is very promising (see Figure 2.7). Not only does it allow for having multiple groups in the arena but also allows for having the virtual world mapped onto the real world. The only two downsides could be the non-linearity of the story and the chance of meeting other groups in the HUB area, which might not fit well with certain experiences.

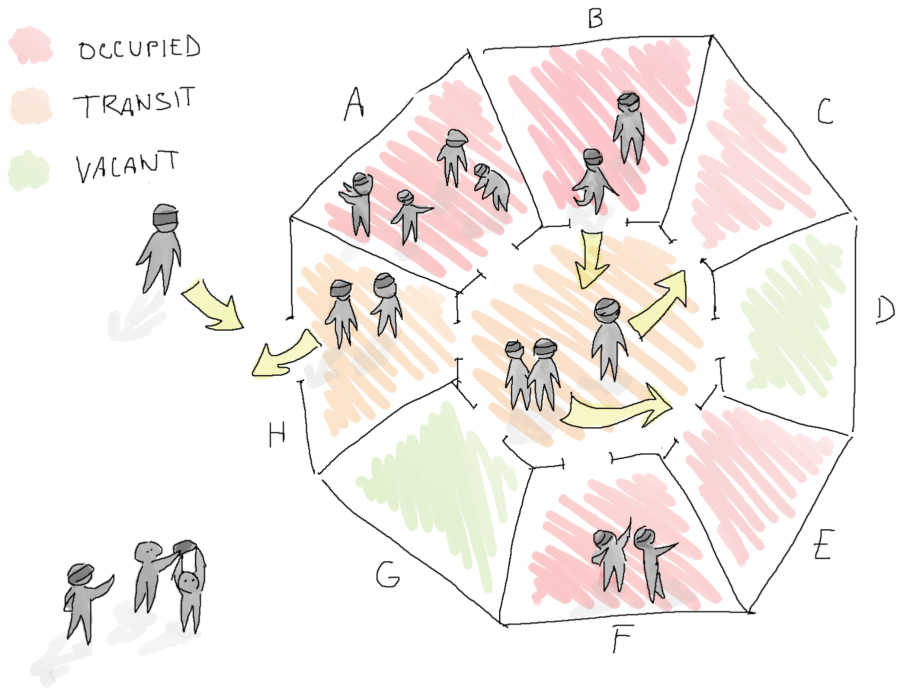

Figure 2.7: HUB area with adjacent rooms colour-coded depending on their availability. The arena should be able to accommodate n - 1 groups, where n is the number of rooms excluding the HUB area.

8. **Open-space** This version is similar to the HUB but without having physical rooms filled with props. The groups or individuals can see each other in a large open-space arena but have a different instance of the game (see Figure 2.8). Another example is an open-space area filled to its maximum capacity with players who share the same instance. In other words, there is only one game per arena, the only two downsides are the large number of players playing at the same time and also that the players are strangers to each other. Similarly as with HUB, the public open-space might only fit certain experiences or games, especially in relation to the story.

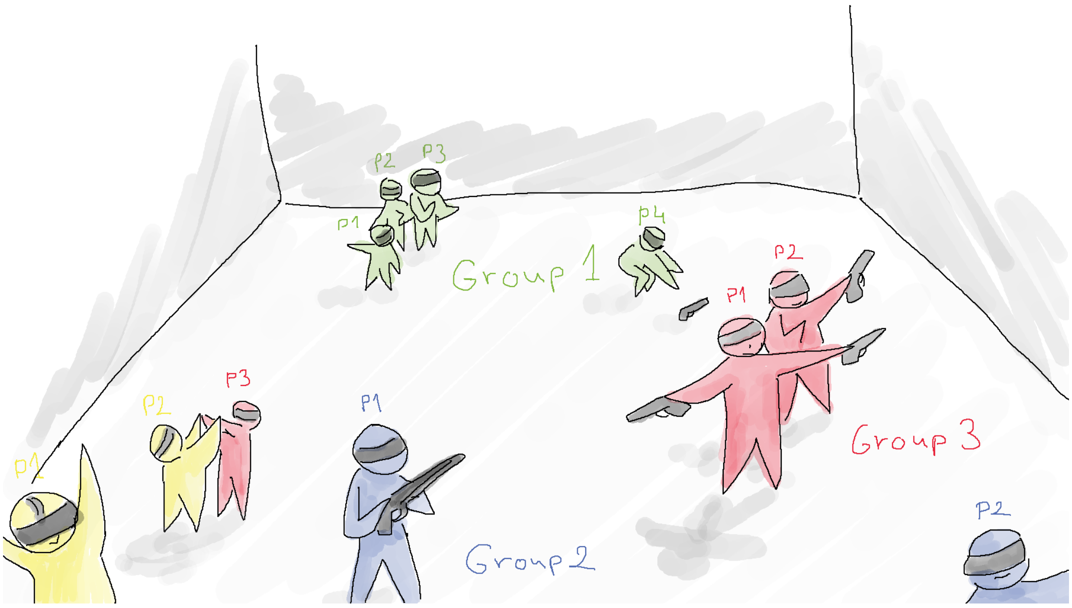

Figure 2.8: Open-space shared by a number of groups. In other scenarios, all players could share the same instance, forming one large group.

9. **Detour** Inspired by airport ground system, which would send a group through a detour when a potential collision would be detected. There is a certain trade-off between having virtual rooms mapped onto the physical space and the number of available detours (see Figure 2.9). The idea for this design is to test out if one detour in the place of highest risk of collision is enough to radically lower the number of collisions. However, the detour might happen again in subsequent rooms.

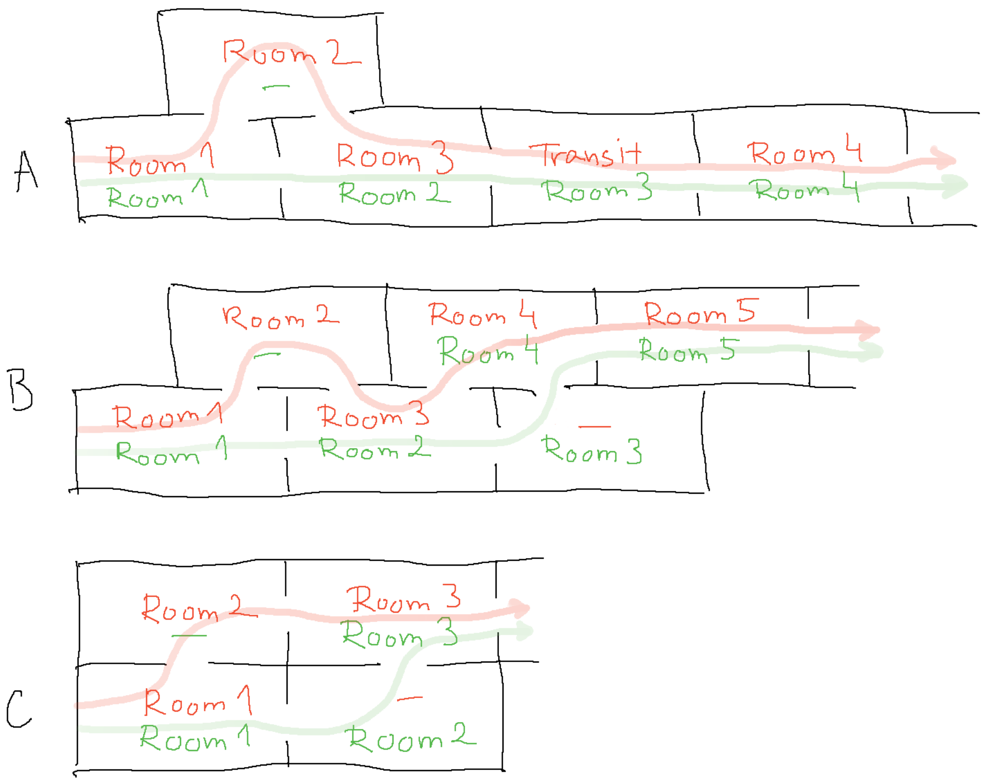

Figure 2.9: Different examples of how detour could be executed in IMRS VR scenarios. Green group entered the arena first. Detours would be used in cases of having green group extremely slow and/or red extremely fast. Variation A shows how red group detours and then returns to the right track one room behind the green group. The transit room can be used for additional fail-safe procedures, if necessary. Variation B offers two detours and does not include a transit room. In extreme cases, red group might even be able to get past green group when they are in room 3. Variation C shows how to execute detours while keeping all the physical to virtual mapping of the room, as well as props inside the rooms, present. Room 2 for both groups would have to have identical equipment and adjusted placement of doors and other elements, if needed.

It has to be noted that for solutions *HUB* and *Open-space*, the players would have to be warned about the possibility of meeting other groups. As was seen in an experiment by Podkosova and Kaufmann [29], people did not always try to avoid collisions, which might be a behaviour that emerged with virtual games [36]. Therefore it would have to be stressed out before the start of the experience, that the arena is filled with actual physical people. A similar warning is used in Hamleys arena in relation to the physical environment in order to prevent people from trying to walk through walls and similar. The remark is repeated again in an instructional video in the first room of the experience.

Apart from the experience acquired during my three-months-long internship at DIVR, inspiration for good principles and practices in an interactive VR entertainment was also taken from Mark Mine's lessons learned during his 10 years of building interactive virtual worlds at Disney studio. One of the most important lessons is the importance of using physical interfaces. Interface devices such as canons or steering wheel on a ship immerse players much more than if they had to use a controller for interaction [25, p. 15]. The usage of physical interface devices also takes advantage of real-world skills and is therefore naturally intuitive. This also supports designs with virtual rooms mapped onto the physical ones, because that naturally leads to also having physical interface devices, such as winch, levers, buttons etc. Another thought needs to be given to the utilization of all the available time, such as waiting time in queues or wandering around the HUB when there is not a new room available. In the paper, Mine proposes setting up the mood in the queue already or introduce parts of the backstory to help the players to ease-into the game [25, p. 15]. Mine further proposes to have glass doors leading to the room, so that the players can learn the interaction from players inside or rough layout of the room. However, this might not be a good idea, because it can ruin the experience by showing its back stage. For example, if the players are riding a virtual elevator, they might not feel as immersed if they already knew there is no elevator and it is just their mind tricked.

To paraphrase and simplify the problem formulation, the goal of the project is to explore and compare solutions in which groups of players would not collide with each other while keeping the physical arena intact. In section 2.1, design constraints were presented, which are also considered in the selection of relevant solutions. Therefore out of the nine suggested solutions, only four are going to be further worked on and evaluated. Reasons for inclusion or exclusion of each of the proposed solutions is provided below:

1. Game adaptation - This is probably the most effective and error-free method on this list. It works by checking the room ahead and then either adding more enemies to prolong the stay in the room or, contrary, removing enemies

to hasten the group. Removing enemies might not be necessary, but even if it is, it can be done in two ways. Enemies can flee in terror or be killed by a stray bullet even if the players aimed at a different place.

2. Voiceovers - The ability of the game to average-out completion times based on current performance data is an important part of the evaluation.

3. Entry intervals - As already mentioned, this precaution is already being used by most of the IMRS VR enterprises, therefore it is also part of the test.

4. Small arena - In small arenas, scenarios with collisions can never emerge plus this method does not fulfill all the design constraints. Therefore it is not included in the test.

5. Watcher - This method is presence-breaking and is ill-advised. The presence is the key, as also implied by Ondrej Bach:

   > "We want to control what goes on in the arena... and for how long, but we don't want people to know."

   This method is therefore excluded from the evaluation.

6. Perceived large arena - Similarly as with small arenas, scenarios with collisions can never emerge and the usage of physical props or mappings is limited, therefore it is not included in the test.

7. HUB - Since the players are able to see each other inside the HUB, there can be no collisions. However, this method is part of the test in order to see how well the arena can handle assigning rooms so that there is little to no waiting time in the HUB itself.

8. Open-space - Players would be warned of shared space and would be able to see each other across instances, therefore this method does not need to be tested.

9. Detour - Included in the evaluation.

2.2 Low Fidelity Prototype for Linear Arenas

The design of the last solution, *detour*, is based on ground control at airports. This would require having a floor plan in which there would be duplicated rooms, which would serve as an alternative route. These alternative routes would be used once a clearance zone of two groups would get too small. To put this back into the perspective of an airport and planes, the aircraft needs to keep a safe distance from other aircrafts. This is called separation minima and once the aircrafts lose this minimal distance, they are said to be in conflict [16]. Conflict is the last stage before an actual collision. In VR, the system would track those distances and suggest routes in order to keep this distance reasonably high, but at the same time trying to not delay groups behind. Also, if the separation minima would be breached, that is if the groups would be in conflict, some other event could take place, such as the fall of a roof that would split the room into two. The group behind would have to spend extra time to find a way through it while the group in front would be urged to move away.

A new design challenge was to remodel the original Hamleys arena so that it could encompass existing levels while allowing a detour option for fast groups of players. At first, a low fidelity prototype was constructed which was based on scaled-down measurements of Hamleys VR arena. For ease of manipulation, the rooms were estimated to form a rectangle or a square, so that there would be only two types of rooms - small and large (see Figure 2.10). These simple paper cut-outs allowed for rapid prototyping and easy visualization (see Figure 2.11).

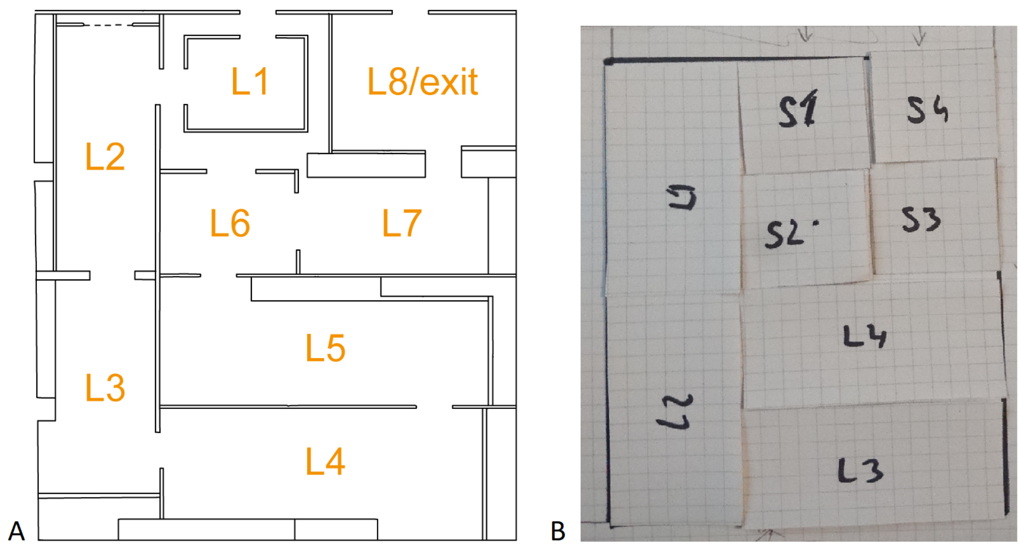

Figure 2.10: The conversion of Hamleys floor plan (A) into a lo-fi (B) with only two types of rooms: small (S1 - S4) and large (L1 - L4).

Another version was created which utilized three types of rooms instead of two: small, medium and large. The addition of one more type was meant to enhance the variety of the arena. However, after further discussion with the project owner, it was decided to discontinue the idea of having only a small number of room types as it would severely limit the experience. Therefore detours have to happen

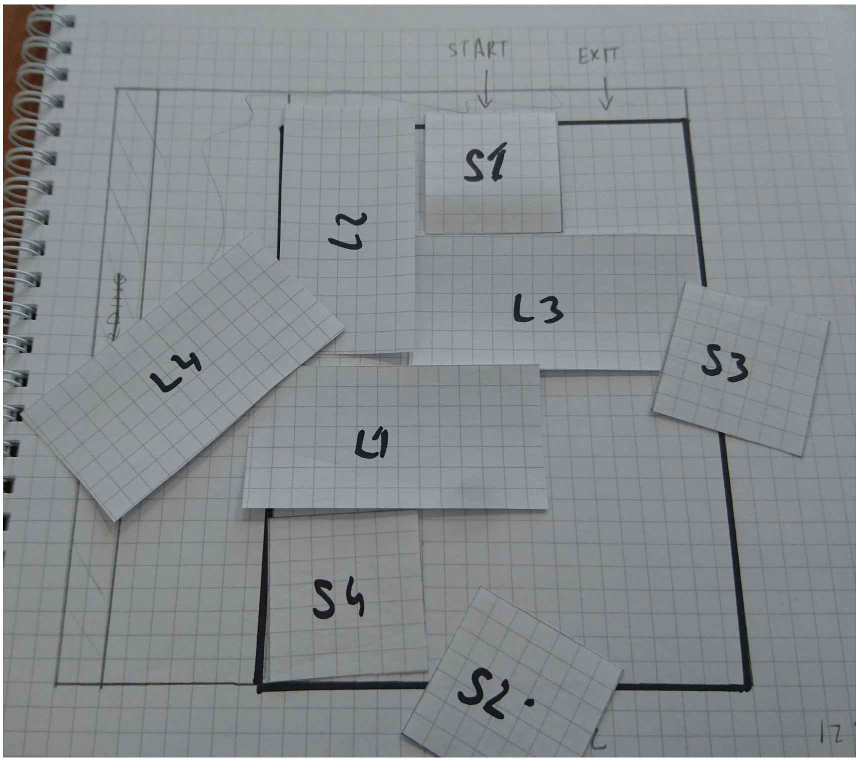

Figure 2.11: A low fidelity prototype which served as a tool for quick readjustments to current Hamleys arena floor plan.

with minimal impact on the physical arena, which also means that there can only be very few detours. As reported by DIVR staff at Hamleys, collisions usually happen in room number four, which is why it was chosen as a spot for a detour. If there are groups that collide, the staff and the players try to do their best to avoid subsequent collisions. By implementing a detour option in this point of high-risk it might be possible to avoid the majority of collisions (see Figure 2.12).

2.3 Summary of the Design Chapter

Manipulation of time through *voiceovers* and *entry intervals* are easy to implement into existing experiences or games. These two methods are evaluated in simulated scenarios in combination with other methods, when applicable. HUB floor plan can be random as long as there are n + 1 rooms, where n is the number of groups inside the arena and all the rooms lead directly to the HUB. In the case of GolemVR, there are seven levels and an extra off-boarding room. The evaluation is based on existing statistical data recorded in GolemVR, which is why similar scenarios must be used in order to get roughly comparable data. What it means

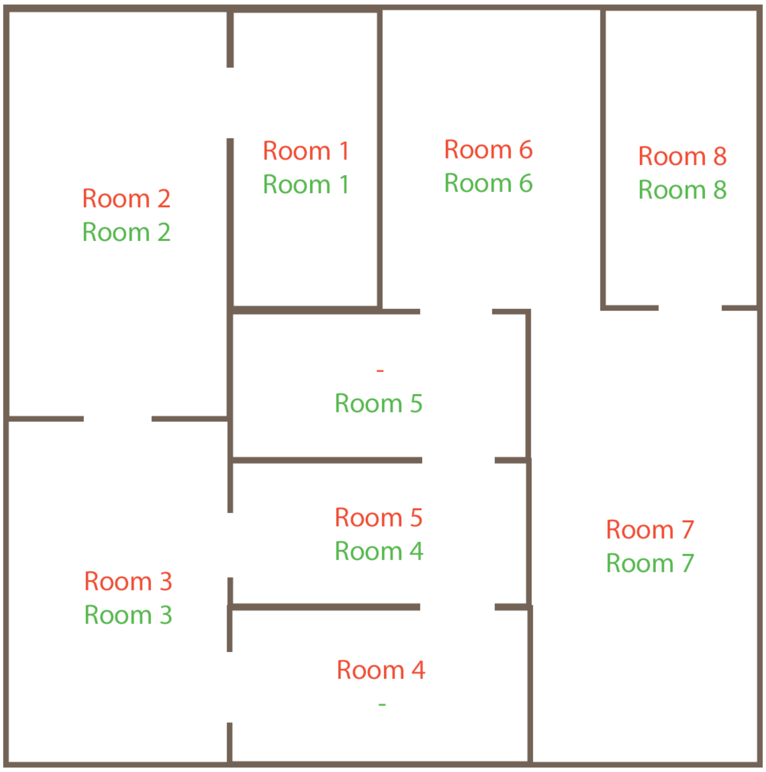

Figure 2.12: Detour option in the spot of the highest risk of collision. Green and red each represent the two different paths the group can take. The path will be chosen depending on the current condition in the arena when the group is in room 3.

is, that there must be an identical amount of levels and players have to spend the same amount of time playing them. In the case of HUB, an octagon is used as floor plan, since all the rooms need to have access to the middle HUB area (see Figure 2.7). Seven rooms are used as the levels and the extra room as the on-boarding and off-boarding area. Since the capacity of the arena is six groups, the staff needs to first off-board a group before sending another one in, which prevents the room from crowding. Even if more than one group happens to be in the off-boarding area, it is still part of the HUB and therefore the groups would see each other and would not collide (see orange marked HUB area in Figure 2.7).

The floor plans for the original Hamleys arena and the detour arena are based upon the results from the low fidelity prototyping (see Figures 2.10 left and 2.12).

Chapter 3

Implementation of The Simulation

This chapter presents how a computer simulation was built in Unity game engine based on the ideas and floor plans presented in chapter 2. The first section introduces the implementation environment and provides further argumentation for why a simulation was chosen over testing with real people. Each subsequent section deals with one aspect of the program, explaining its function and how it was implemented.

3.1 Why a Simulation in Unity

Unity game engine is a multi-purpose development platform, which allows for creation of 2D or 3D multimedia content. Unity is using other engines and libraries, such as physics engines used for simulating real physics, audio, render engines etc. Projects created in Unity can be deployed on a large selection of platforms, such as Windows, Android, Mac OS, Linux etc.

A high fidelity 3D prototype with various room plans or scenarios was built using Unity engine in order to serve as a simulator for the evaluation. Even though cooperation with DIVR was established for this project, it would be very expensive to rebuild the physical arena or test in the arena for a prolonged amount of time. Therefore it was decided that a virtual simulation would be a better option. Not only does it cost a fraction of time and energy but also allows for rapid testing of extreme cases. Most importantly, virtual representation can be used for exploring crowd flow issues and rescue and evacuation scenarios [25], which are closely related to the collision-avoidance and flow problems presented in this report. The implemented logging system also allows for recording of all the activity in the arena, so that any situation can be recreated for further inspection.

3.2 Setup with Gizmos

Since there can be no collisions without movement, empty game objects were used as waypoints marking out a path that the players take inside an arena. The game object is basically an empty container, which can hold other objects or scripts. By default, an empty game object has only one component: a Transform, which consists of the object's position, rotation and scale. Since waypoint is basically a stop or a certain point on a path, only the positions are necessary. The empty game objects, therefore, look like invisible points in space, which is why it was necessary to make them visible for further manipulation. In order to do so, Gizmos can be used. Gizmos are objects in Unity engine, which can be used for visual setups only the developer can see because by default they cannot be seen during runtime of the program. Waypoints are drawn as circles and connected by lines, both drawn by Gizmos. In other words, each Gizmo draws a line between two positions (see Figure 3.1). Each waypoint can be used more than once, which allows the path to split. This is important later on for the detour arena.

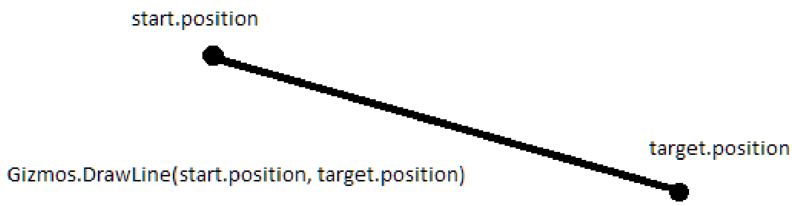

Figure 3.1: An example of how lines are drawn between two different positions through Gizmos.

In order to further enhance the visual feed of the simulation, simple 3D shapes were used to build a 3D representation of an arena. Three different arenas were built:

- Hamleys existing arena (see Figure 3.2)
- Detour idea based on the low fidelity design (see Figure 3.3)
- HUB (see Figure 3.4)

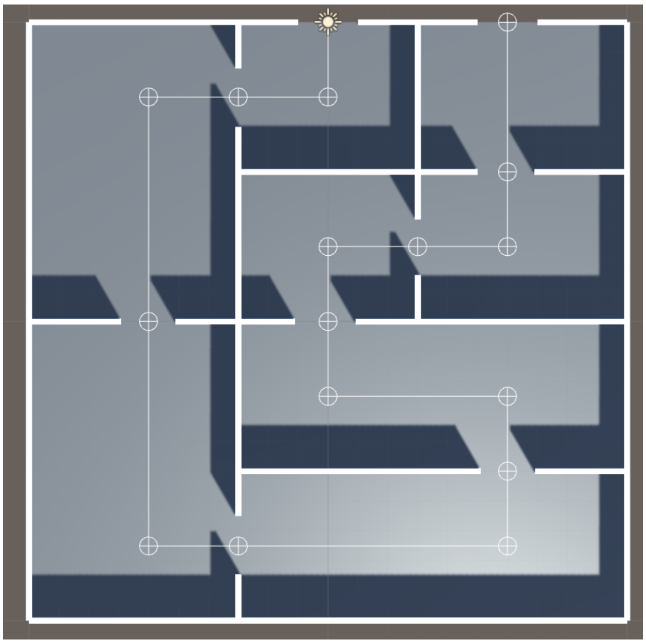

Figure 3.2: Floor layout for the original Hamleys arena. Waypoints are depicted as small circles with lines in-between.

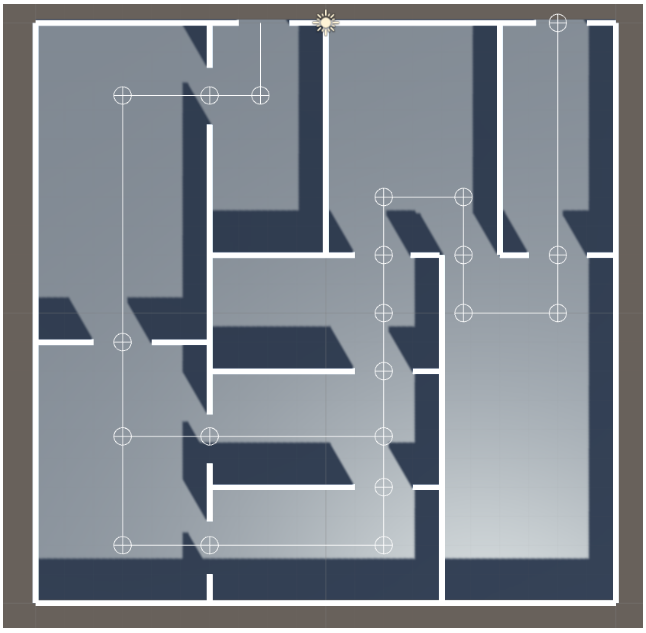

Figure 3.3: Floor layout for the detour arena. Waypoints are depicted as small circles with lines in-between.

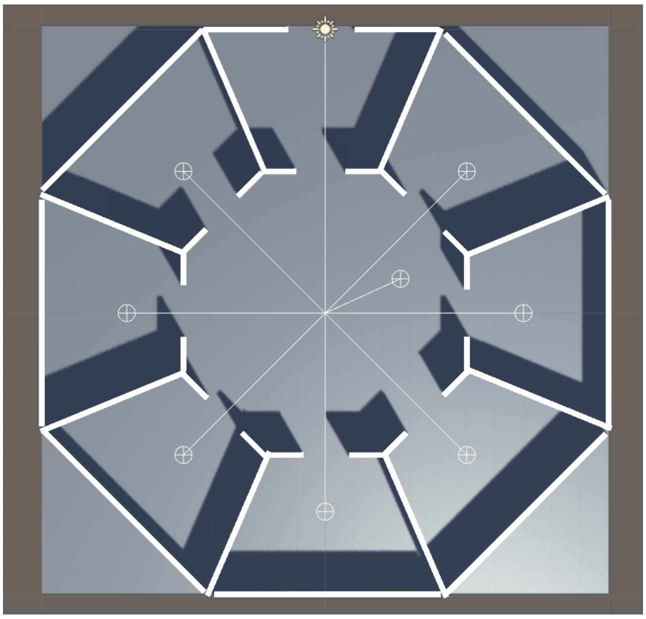

Figure 3.4: Floor layout for the HUB arena. Waypoints are depicted as small circles with lines in-between.

3.3 Spawning

The simulation is set to be as busy as possible so that it performs equally well or worse than a real arena. This means that in reality, the situation can never be as extreme as the arena does not fully use its capacity all the time. For the purpose of simulating extreme cases, a spawn system was created where groups can enter the arena under different conditions. The two main conditions for entering the arena are going to be time intervals between groups and room clearance for the case of original and detoured floor plans and time intervals and arena capacity in the case of the HUB. Time interval is the time before the next group can enter, so that the time interval of zero means all groups enter at the same time. In Hamleys, the time interval is five minutes, which is also replicated for the detour design as it has a similar structure as the original Hamleys arena. In the case of the HUB, the time interval can be much shorter. In theory, all groups can enter the HUB at the same time, but for the sake of easier flow and distribution into the rooms, the minimal interval is set to five seconds. This puts additional load on the system, but as already explained, it only means that in reality, the system is going to perform even better. Additionally, the interval would be based on how fast the group can get through on-boarding.

In the case of linear layouts such as the original Hamleys and its detour version, the system can additionally wait for the previous group to clear room two, which usually adds up to just over five minutes as well. Even though this might not revolutionize the system, it can help detecting slower groups as early as in the second room, resulting in extra few seconds before another group can enter.

In the case of non-linear layouts such as the HUB, the most important factor is the capacity of the arena. As stated before, there could be always one group less compared to the number of rooms. The reason behind this is that whenever a group finished a level, they can immediately enter a new one unless it has already been cleared. In case there is not an available room for a long time, the group might get bored in the HUB arena, which is why there should always be some activity they can do. The best activity would be a one with an undefined ending, such as the given example with shooting soldiers.

3.4 Movement and Distribution

Movement around the Hamleys arena is the simplest of the three because it can just keep increasing the waypoint identification number (ID) and then move from the group's current position to the current waypoint. Once the distance between the group and the waypoint is lower than a reach distance of the waypoint (in this case, it is set to zero), the ID increases again, the group moves towards the new waypoint ID and so on (see Figures 3.5 and 3.6).

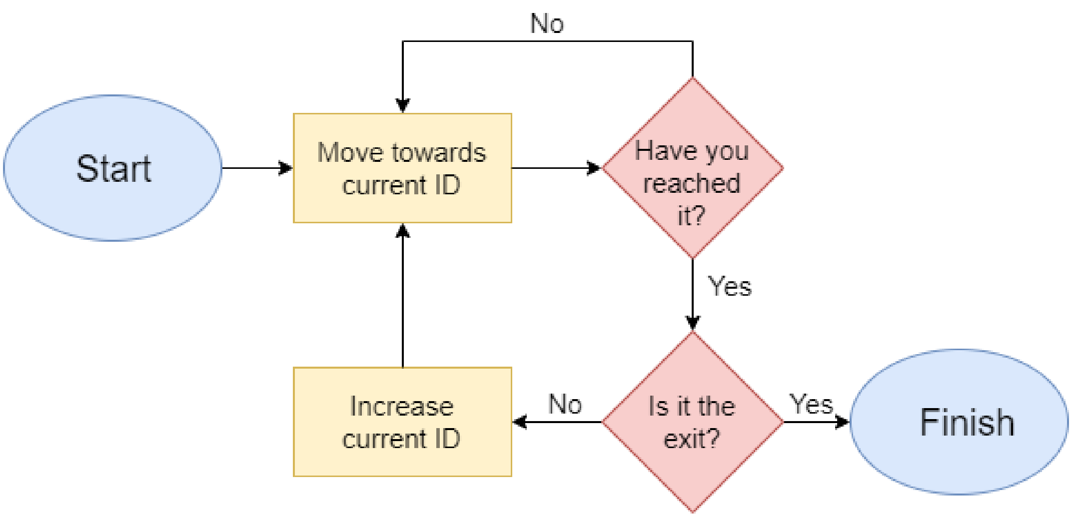

Figure 3.5: A flowchart depicting a linear movement system which works for the original Hamleys arena and with a few exceptions also for the detour arena.

```
void Update ()
{
    float distance = Vector3.Distance(PathToFollow.path_objs[currentWaypointID].position, transform.position);

    transform.position = Vector3.MoveTowards(transform.position, PathToFollow.path_objs[currentWaypointID].position, speed);
    timer += Time.deltaTime;

    if (distance <= reachDistance && reachedEnd == false)
    {
        if (currentWaypointID != PathToFollow.path_objs.Count)
        {
            currentWaypointID++;
            checkedForCollision = false;
            collisionDetected = false;
            UpdateSpeed();
        }
    }
    if (timer >= roomCountdown)
    {
        speed = 0.05f;
    }
```

Figure 3.6: Code snippet for the movement in Hamleys arena. The distance is calculated between the group and the current ID. The group keeps moving towards this location and once it gets to its reach distance, the ID increases again.

The only modification between the two linear movements is the presence of a detour. As can be seen in Figure 3.7, once a countdown in room 3 expires, the group can either follow the original path or the detour. If the system suggests taking the detour, the waypoint changes and thus the group goes around. The group remains marked as *detoured* until room 6 so that the system knows which room to load even when the group reconnects to the original path once clearing room 4 coloured red. The flowchart for the movement is generally the same as the one for Hamleys (see Figure 3.5) with the small exception of setting the IDs to a specific number instead of just increasing them by one.

```
if (timer >= roomCountdown)
{
    speed = 0.05f;
    if (currentWaypointID == 6 && detour == true)
    {
        currentWaypointID = 18;
    }
    else if (currentWaypointID == 6 && detour == false)
    {
        currentWaypointID = 7;
        UpdateSpeed();
    }
}
```

Figure 3.7: A slight modification to the movement in detoured arena. At certain waypoints, if the group is scheduled for detour, is set to different waypoint before returning back onto the original path.

Path in the HUB arena is not linear, therefore the group can go to any waypoint available. Available waypoints are stored in a list and once the group reaches the centre of the HUB, a random waypoint is selected from the list. In order for this to work, there are four lists:

- **List<int> visited** This list is empty when the group enters the arena for the first time. Once a room is cleared, the room ID is stored in this list. Once the group visited all the rooms, the bool reachedEnd becomes true and the group can proceed to waypoint 1, which is the exit (see Lines 146 and 172-177 in Figure 3.9).

- **List<int> waypointList** List of all the occupied rooms at the moment.

- **List<int> available** This is a list of all the available rooms that the group can visit. All rooms are included when the group enters the HUB for the first time and then whenever the group clears a room, it is removed from this list. It is basically a reversed **visited** list.

- **List<int> copyAvailable** A local copy of the list **available**.

The difference between the last two lists is that the **copyAvailable** list can be depleted even if the group has not visited all the rooms yet. For example, if the group has two rooms left in the **available** list and reaches the centre of the HUB, the **copyAvailable** is created and it is identical. The system then selects a random number of the room to visit, removes this number from the **copyAvailable** and checks if it was already visited or if it is occupied. If at least one of those conditions is true, the system selects a new number. In case the second room cannot be used as well, the **copyAvailable** is empty and thus the group is sent to waypoint 9 to wait a few seconds, then return to the HUB and once try again (see Figures 3.8 and 3.9). If the system was to use the original **available** list, it would be stuck in an infinite loop unless it would remove the room numbers just like what the **copyAvailable** does. However, it would be more difficult to retrieve or calculate the missing room numbers again from the **visited** list, therefore this is preferred due to its easier implementation.

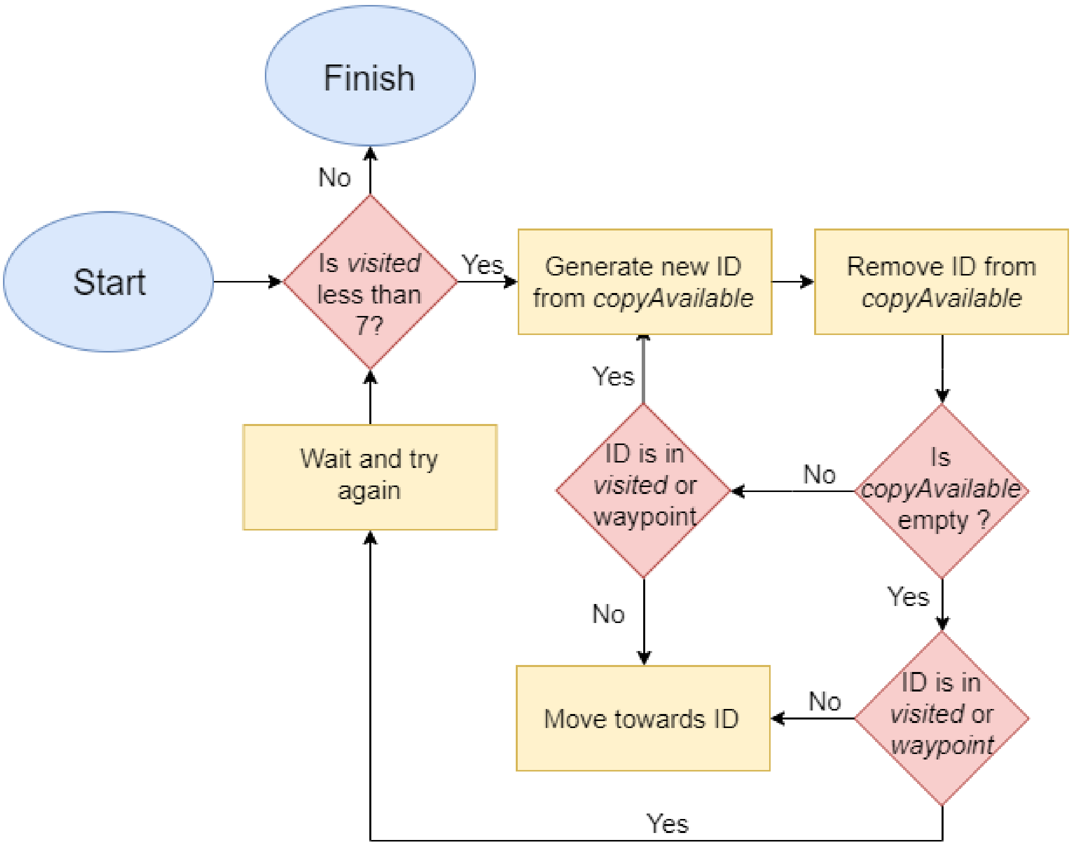

Figure 3.8: A flowchart showing the movement in the HUB in terms of selecting an ID.

```csharp
if (distance <= reachDistance) // && reachedEnd == false)
{
    if (currentWaypointID != PathToFollow.path_objs.Count && returnToHUB == false)
    {
        distribution.ClearWaypoints();
        checkedForCollision = false;
        collisionDetected = false;
        UpdateSpeed();
    }
    else if (transform.position == PathToFollow.path_objs[0].position)
    {
        waitingTime = 0;

        if (visited.Count < 7)
        {
            List<int> copyAvailable = new List<int>(available);
            int randomIndex = UnityEngine.Random.Range(0,copyAvailable.Count);
            currentWaypointID = copyAvailable[randomIndex];
            copyAvailable.RemoveAt(randomIndex);
            while (copyAvailable.Count != 0 && (visited.Contains(currentWaypointID)
                || waypointList.Contains(currentWaypointID)))
            {
                randomIndex = UnityEngine.Random.Range(0, copyAvailable.Count);
                currentWaypointID = copyAvailable[randomIndex];
                copyAvailable.RemoveAt(randomIndex);
            }
            if (copyAvailable.Count == 0 && (visited.Contains(currentWaypointID)
                || waypointList.Contains(currentWaypointID)))
            {
                Debug.Log("The group has nowhere to go!");
                currentWaypointID = 9;
                returnToHUB = false;
            }
            else if (available.Count != 0)
            {
                visited.Add(currentWaypointID);
                available.Remove(currentWaypointID);
            }
        }
        else
        {
            reachedEnd = true;
            currentWaypointID = 1;
        }
        returnToHUB = false;
    }
}
```

Figure 3.9: A code snippet showing the selection of a new waypoint.

3.5 Behaviour When Entering and Exiting a Room

The system has two basic behaviours which depend on its ID and these behaviours trigger once the UpdateSpeed() method is called when the group reaches a waypoint. The first behaviour is to stop the movement and start a countdown, which is a random number between a minimum and maximum amount of time the group can spend in the room (see Lines 128 - 132 in Figure 3.10). This behaviour is basically a simulation of the time spent playing the game in each room. The second behaviour is to increase the roomID, log the time it took to clear the previous room, reset this timer and also set the speed back to normal (see Lines 133 - 140 in Figure 3.10). This behaviour is a simulation of the group entering a new room, therefore it is only a transit waypoint before a group stops due to the first behaviour.

```
128         if (currentWaypointID == 4)
129         {
130             speed = 0f;
131             roomCountdown = UnityEngine.Random.Range(90,270);
132         }
133         if (currentWaypointID == 5)
134         {
135             roomID = 2;
136             collection[groupID].roomID = roomID;
137             collection[groupID].time2 = timer;
138             timer = 0.0f;
139             speed = 0.05f;
140         }
```

Figure 3.10: Code snippet showing the two different behaviours (example taken from the linear Hamleys arena).

3.6 Collision Detection and Prevention

In order to react early to a potential collision, a system of collision detection was implemented. Once again the system for both linear arenas is similar, while the HUB does not need such system at all as collisions cannot happen.

First of all, the system needs to know how many and which groups are present in the arena and so it finds all objects that are classified as a group (see Lines 37 - 49 in Figure 3.11). If the group leaves the arena, it is also removed from the list of active groups (see Lines 50 - 54 in Figure 3.11). Once there is more than one group in the arena, the detection is active (see Figure 3.12). If there is only one group in the arena, there cannot be any collisions, therefore the system does not need to be alert. Whenever a group moves to a new waypoint, the system checks the group ahead and compares the room ID to the current group's room ID *plus one*. That is, the system checks if the rooms would be identical in case the second group moved into the room. Since the detour waypoints are taking care of the room IDs, the system works exactly the same for both types of linear arenas. If the IDs are identical, a potential collision is reported and a boll *IsAboutToCollide* is set to true (see Figure 3.12). Depending on the state of this bool, the system of additional voiceovers might trigger.

```
        for (int i = 0; i <= 99; i++)
        {
            group = GameObject.Find("Group" + i);
            if (groupList.Contains(group))
            {
                // Do nothing
            }
            else if (group != null)
            {
                groupList.Add(group);
            }
        }

        for (int i = groupList.Count - 1; i > -1; i--)
        {
            if (groupList[i] == null)
                groupList.RemoveAt(i);
        }
        if (groupList.Count >= 2)
        {
            for (int i = 0; i < groupList.Count-1; i++)
            {
                collisionGroup1 = groupList[i].GetComponent<MoveOnPath>().groupID;
                collisionGroup2 = groupList[i+1].GetComponent<MoveOnPath>().groupID;
                tempRoom1 = groupList[i].GetComponent<MoveOnPath>().roomID;
                tempRoom2 = groupList[i + 1].GetComponent<MoveOnPath>().roomID + 1;
                if (tempRoom1 == tempRoom2 && groupList[i].GetComponent<MoveOnPath>().checkedForCollision == false)
                {
                    Debug.Log(tempRoom1 + " " + tempRoom2 + "Collision detected!");
                    // The program should react to the collision here!
                    groupList[i].GetComponent<MoveOnPath>().checkedForCollision = true;
                    groupList[i + 1].GetComponent<MoveOnPath>().isAboutToCollide = true;
                }

                if (tempRoom1 == groupList[i + 1].GetComponent<MoveOnPath>().roomID
                    && groupList[i].GetComponent<MoveOnPath>().collisionDetected == false)
                {
                    Debug.Log("Collision");
                    Save();
                    groupList[i].GetComponent<MoveOnPath>().collisionDetected = true;
                }
            }
        }
```

Figure 3.11: The system updates a list of active groups and every time a group moves to a new waypoint, the system checks the group ahead. If the room ahead is empty, nothing happens. If there is a group in the room, the system logs a potential collision.

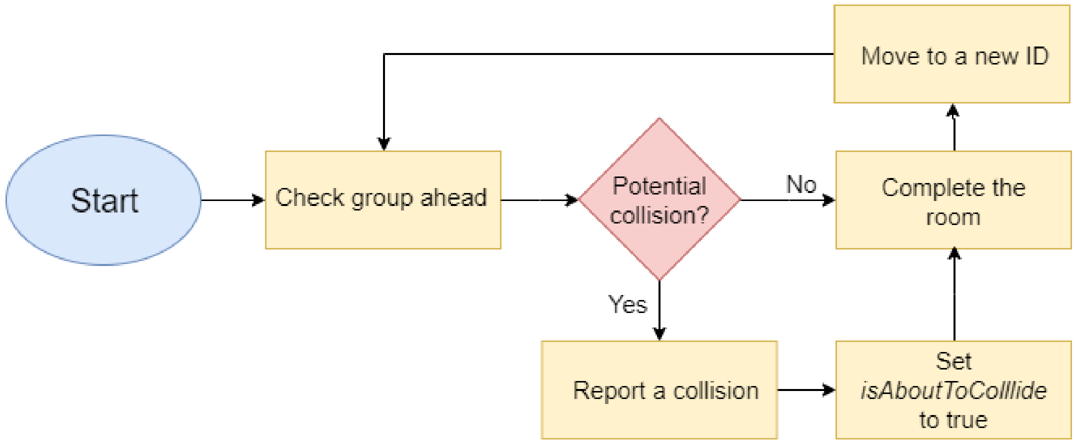

Figure 3.12: A flowchart showing the collision detection system.

3.6.1 Triggering Additional Voiceovers

The system of additional voiceovers works in a way so that it tracks the time each group spends in each room. If the time spent in a room is below a certain threshold, the next room is going to include the additional voiceovers, which eventually averages out total completion times per group. For example, if a group uses only 90 to 110 seconds in room 2, they get extra twenty seconds in room 3 to average out the time spent in the room. Similarly, if a group is too fast in room number 4, they get additional 30 seconds of dialogue in room number 5. The numbers for the thresholds were chosen based on the provided data by DIVR so that the top 20-25% fastest groups would get the additional voiceover. Same goes for the detour arena but does not apply for the HUB.

3.7 Logging System

In order to get quantitative data, which can be used for the evaluation of the collision detection methods, two different events are logged. First is the data about each group's play session in the arena and the second is when a collision happens. The logging system is necessary in order to keep track of what is happening in the arena during the simulation. Not only that, but it also saves the data into readable files which can then be used for further analysis.

It goes without saying that video recording of the screen or observations could also work instead of logging. However, in case of observations, a human error could potentially affect the results. In the case of the video recording, the data gathering would be lengthy. Therefore it was decided that logging is indeed the best way to go around it.

3.7.1 Group report

A log with all of the group's data gets created when a group enters the last room, that is, waypoint 17. Since the last room is not technically a level, the group only spends a few moments there. Due to this, the logging time for this room is not important, but it can still be used for real life scenarios, for example for knowing how long the groups have to wait before the staff comes to help with off-boarding. The Save() function is called, creating a new log file and the group leaves. The information that gets recorded is the name of the group, the exact time they entered and left the arena and also the time in seconds for clearance of each room (see Figure 3.13). The data is saved as a JavaScript Object Notation (JSON) file, which can also be used in Excel for further analysis or for re-construction of the play-through.

```
        if (currentWaypointID == 17)
        {
            reachedEnd = true;
            roomID = 8;
            collection[groupID].roomID = roomID;
            endTime = DateTime.Now.ToString("HH:mm:ss");
            collection[groupID].time8 = timer;
            collection[groupID].endTime = endTime;
            timer = 0.0f;
            currentWaypointID = PathToFollow.path_objs.Count - 1;
            Save();
            Destroy(gameObject);
        }
    }

    void Save()
    {
        JSONObject dataJson = new JSONObject();

        int i = groupID;
        JSONArray coll = new JSONArray();
            coll.Add(collection[i].groupID);
            coll.Add(collection[i].startTime);
            coll.Add(collection[i].endTime);
            coll.Add(collection[i].time1);
            coll.Add(collection[i].time2);
            coll.Add(collection[i].time3);
            coll.Add(collection[i].time4);
            coll.Add(collection[i].time5);
            coll.Add(collection[i].time6);
            coll.Add(collection[i].time7);
            coll.Add(collection[i].time8);

            dataJson.Add("Group " + i, coll);

         //SAVE JSON IN COMPUTER
        string path = Application.dataPath + "/arenaData" + groupID + ".json";
        File.WriteAllText(path, dataJson.ToString());
        Debug.Log("Save successfull.");

    }
```

Figure 3.13: The Save function creates a JSON file, which logs time duration of each room for each group.

3.7.2 Collision report

The second event that is logged is when two groups happen to collide, that is, if two groups are in the same room at the same time. The only three things that get logged are the two group IDs and the location of the collision (see Figure 3.14). With this information, it is possible to look up the two groups and analyse why the collision could have happened based on the logged data.

```
void Save()
{
    JSONObject dataJson = new JSONObject();

    JSONArray coll = new JSONArray();
    coll.Add(collisionGroup1);
    coll.Add(collisionGroup2);
    coll.Add(tempRoom1);

    dataJson.Add("Collision", coll);

    //SAVE JSON IN COMPUTER
    string path = Application.dataPath + "/collisionReport" + collisionGroup1 +
        collisionGroup2 + tempRoom1 + ".json";
    File.WriteAllText(path, dataJson.ToString());
    Debug.Log("Collision reported.");

}
```

Figure 3.14: The Save function creates a JSON file, which logs which two groups collided and where.

Chapter 4

Evaluation

The simulation presented in the previous chapter was used as a tool for this evaluation. The implemented collision avoidance techniques are tested under various conditions and in various combinations to find the best result. Furthermore, the evaluation uses two sets of data, both courtesy of DIVR.

4.1 Original Hamleys Simulation Results

The first round of testing is using the existing Hamleys arena. Solutions which are tested and proposed in this section would be the cheapest to implement, as the arena would not have to be changed in any way. The knowledge acquired from these tests can also be applicable to other linear VR experiences. The first few tests are focusing on gathering empirical evidence showing how severe this collision problem can be.

4.1.1 Test 1: The Worst Case Scenario (data set 1)

The first test used statistical data provided by DIVR (see Figure 4.1 and Table 4.1). This data is based on 1000 samples of real players playing GolemVR in the existing Hamleys arena. The test uses all the available data, whenever possible, which means also outlier data to fully reflect the situation at Hamleys original arena. The distribution of the data shows that outliers are more common for times when players have to spend more time in the arena rather than less 4.1. However, it has to be noted that this first set of data only includes outlier data in rooms nr. 2 to 6. Room nr. 1 and 7 are already without outlier data. All other tests presented in this chapter are using a newer data set (see Table 4.2), where outliers are complete for all the rooms. This test was however kept for comparison of the old data and new data.

In the first test, the program does not react to groups colliding. If a collision happens, both groups stay in the room as if the room was empty and carry on with their experience. The only prevention mechanism is to let groups inside after 5 minute intervals. Once again, this is done only to show how severe this collision problem can be.

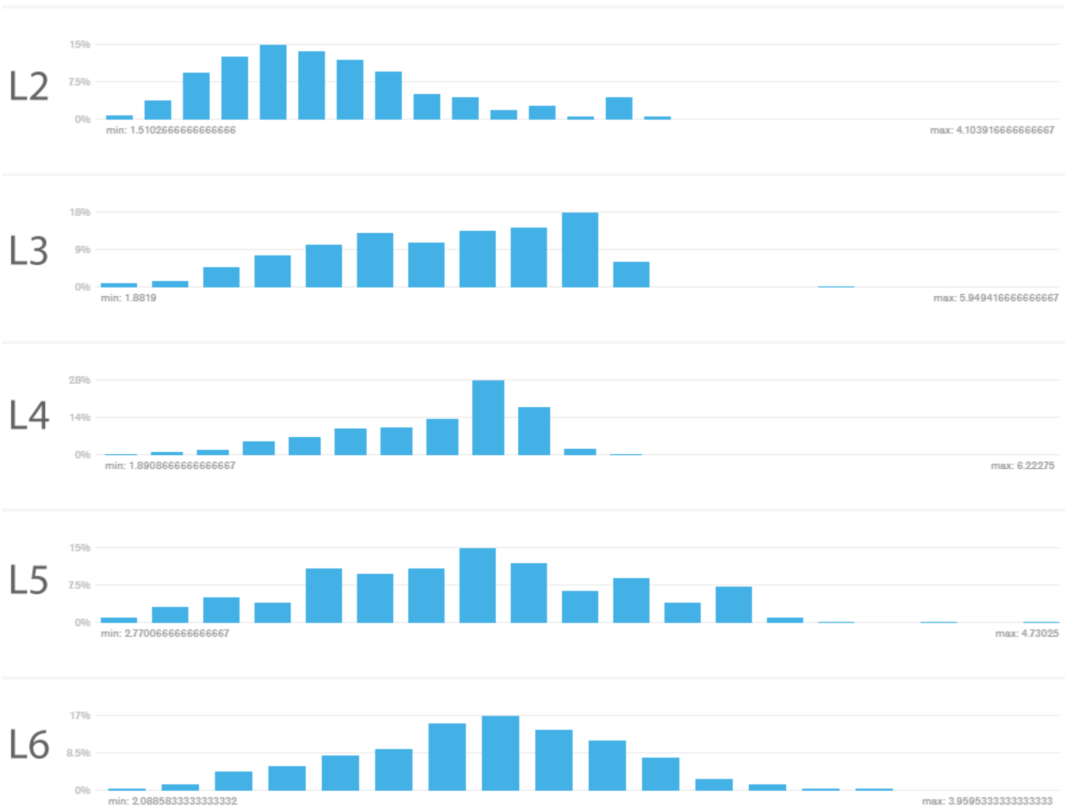

Figure 4.1: Data set 1. Distribution of completion times per each level. Courtesy of DIVR.

The last room (room nr. 8) logs time between the group entering the room and closing the game by the Hamleys staff. This means that the reported times include the off-boarding time and do not reflect the actual time spent in the room. Groups cannot collide in this room, however, since the clearance time is much lower than in the room before. In the simulation, this room is simply as long as the time it takes for the group to pass from its entrance to its exit.

Room Number	Time in Minutes (min to max)	Time in Seconds (min to max)
1	3.2 - 3.4	192 - 204
2	1.5 - 4.1	90 - 246
3	1.88 - 5.95	113 - 357
4	1.89 - 6.22	113 - 373
5	2.77 - 4.73	166 - 284
6	2.088 - 3.95	125 - 237
7	2.8 - 3	168 - 180
8	N/A	N/A

Table 4.1: Data set 1. Note that only rooms nr. 2 to 6 are with outlier data, while 1 and 7 are without.

Results:

- 30 groups tested
- 38 unique collisions reported
- 13 unique pairs of groups collided at least once
- Elapsed time approximately 2 hours 50 minutes

4.1.2 Test 2: The Worst Case Scenario (data set 2)

The new data set includes complete data for all the rooms except the last room (see Figure 4.2 and Table 4.2). However, as it was already established, the last room is not considered to be a playable level, so every group spends the same amount of time minus the factor of staff coming over to help the group off-board. The data is newer and also based upon 1000 samples of real player data.

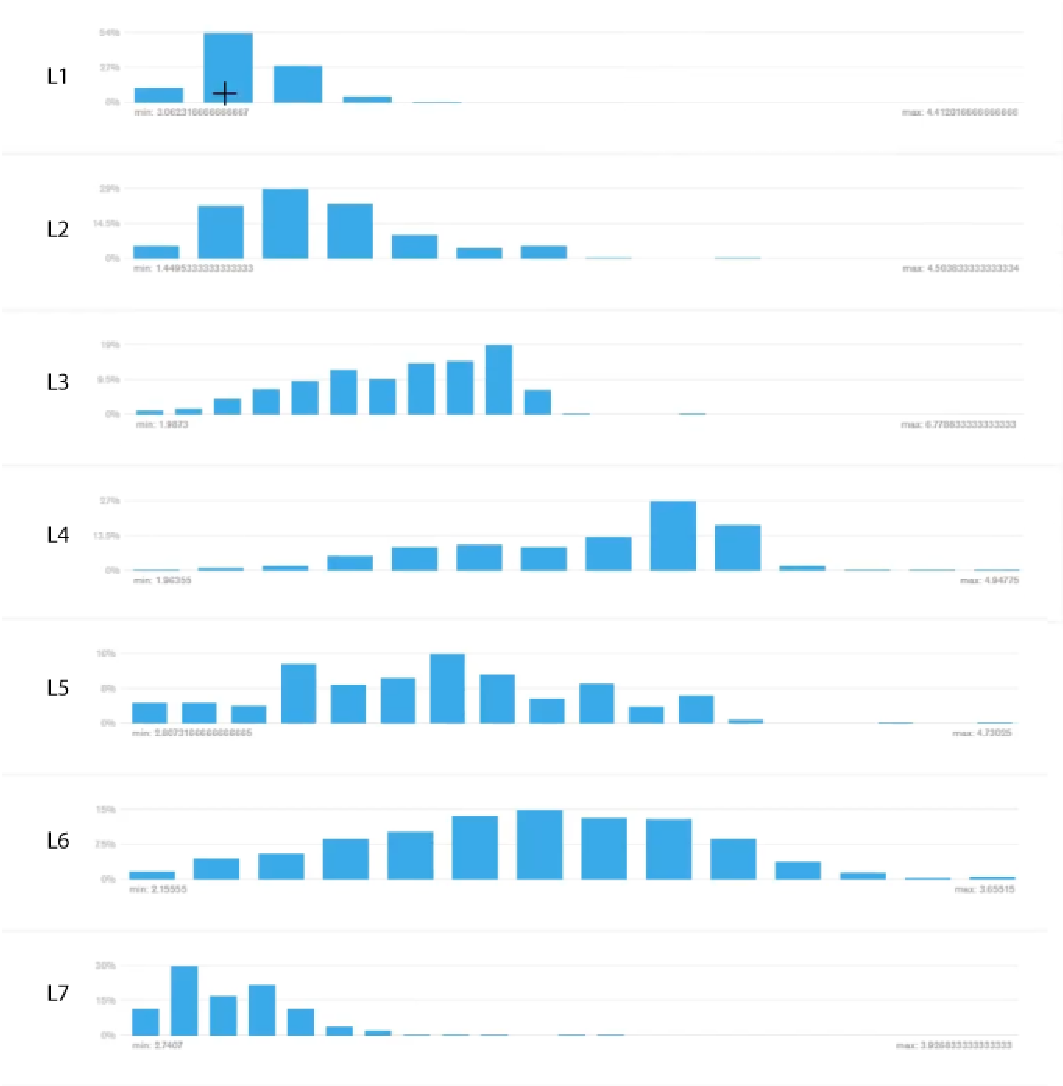

Figure 4.2: Distribution of level completion times from GolemVR (including outliers). For exact numbers, see Table 4.3. Courtesy of DIVR.

Room Number	Time in Minutes (min to max)	Time in Seconds (min to max)
1	3.06 - 4.4	184 - 264
2	1.45 - 4.5	87 - 270
3	1.99 - 6.78	119 - 407
4	1.96 - 4.94	118 - 296
5	2.8 - 4.73	168 - 284
6	2.16 - 3.66	130 - 220
7	2.74 - 3.9	164 - 234
8	N/A	N/A

Table 4.2: Data set 2. This time all the room times include outliers.

Results:

- 30 groups tested
- 44 unique collisions
- 14 unique pairs of group collided at least once
- Elapsed time approximately 2 hours 50 minutes.

The results show that there is one more unique pair of groups that collided compared to the old data and a higher amount of total collisions. The higher amount of collisions can be explained by having more outlier data compared to the first data set.

4.1.3 Test 3: Data Without Outliers

Since some outlier data are cases where technical difficulties, internal testing or collisions happened, the data also includes unrealistic time stamps. By looking at the Table 4.2, it can be seen that, for example, room nr. 3 has a very high time stamp around 7 minutes. This is very unrealistic, as the experience itself takes around 20 to 25 minutes. By looking at the distribution of time duration for each level (see Table 4.3), it can be seen that over 99% of the time duration stamps for level 3 is below 4.2 minutes. Do note that the statistics are rounding up the percentage numbers (for example 4.67% would be rounded up to 5%), which results in reporting the total distribution as 100% in level 3, even though clearly there is at least one player, who reported spending up to 7 minutes in said level. Furthermore, there are mechanics in the game that solve the puzzles after a certain amount of time elapses. This time is usually up to five minutes but varies for different rooms. With all this in mind, it was decided to exclude the outlier data, that is, time stamps that got reported fewer than in 1% of the cases (see Table 4.4). Presumably, the data is either faulty or was created during testing sessions by DIVR.

L0

<1	1 - 1.5	1.5 - 2	2 - 2.5	2.5 - 3	3 - 3.5	3.5 - 4	total
42%	19%	16%	11%	6%	3%	2%	99%

L1

<3.2	3.2 - 3.3	3.3 - 3.4	3.4 - 3.5	3.5 - 3.6	total
11%	54%	29%	5%	0.50%	100%

L2

<1.8	1.8 - 2	2 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3	total
5%	22%	29%	23%	10%	4%	6%	99%

L3

<2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3	3 - 3.2	3.2 - 3.4	3.4 - 3.6	3.6 - 3.8	3.8 - 4	4 - 4.2	total
1%	2%	4%	7%	9%	12%	10%	14%	15%	19%	7%	100%

L4

2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3	3 - 3.2	3.2 - 3.4	3.4 - 3.6	3.6 - 3.8	3.8 - 4	4-4.2	total
1%	2%	6%	9%	10%	9%	13%	27%	18%	2%	97%

L5

<3	3 - 3.1	3.1 - 3.2	3.2 - 3.3	3.3 - 3.4	3.4 - 3.5	3.5 - 3.6	3.6 - 3.7	3.7 - 3.8	3.8 - 3.9	3.9 - 4	4 - 4.1	4.1 - 4.2	total
5%	5%	4%	14%	9%	10%	16%	11%	6%	9%	4%	6%	0.90%	100%

L6

<2.3	2.3 - 2.4	2.4 - 2.5	2.5 - 2.6	2.6 - 2.7	2.7 - 2.8	2.8 - 2.9	2.9 - 3	3 - 3.1	3.1 - 3.2	3.2 - 3.3	3.3 - 3.4	total
2%	4%	6%	9%	10%	14%	15%	13%	13%	9%	4%	2%	101%

L7

<2.8	2.8 - 2.85	2.85 - 2.9	2.9 - 2.95	2.95 - 3	3 - 3.05	3.05 - 3.1	total
12%	30%	17%	22%	12%	4%	2%	99%

Table 4.3: Distribution of level completion times from GolemVR (including outliers). Due to rounding up percentage numbers, the total percentages do not always add up to 100%.

Room Number	Time in Minutes (min to max)	Time in Seconds (min to max)
1	3 - 3.5	180 - 210
2	1.5 - 3	90 - 180
3	2.2 - 4.2	132 - 252
4	2.4 - 4.2	144 - 252
5	2.8 - 4.1	168 - 246
6	2.1 - 3.4	126 - 204
7	2.7 - 3.1	162 - 186
8	N/A	N/A

Table 4.4: Data set 2 without outliers.

The program does not prevent groups from colliding and just as in the first two tests, the only prevention mechanism is to let groups inside after 5 minute intervals.

Results:

- 30 groups tested
- 16 unique collisions reported
- 6 unique pairs of groups collided at least once
- Elapsed time approximately 2 hours 25 minutes

4.1.4 Test 4: Voiceover Conditions and Modified Entry Interval

Test number 4 was also based upon data without outliers. New changes to the program allow new groups into the arena if 5 minutes elapsed **and** the previous group left room nr. 2. Furthermore, if a group is too fast in room nr. 2, they get additional 20 seconds of dialogue in room nr. 3. Similarly, if a group is too fast in room nr. 4, they get additional 30 seconds of dialogue in room nr. 5.

Results:

- 50 groups tested
- 2 unique collisions (group 21 and 22 in rooms nr. 5 and 7)
- 1 unique pair of group collided at least once
- Elapsed time approximately 4 hours 52 minutes for all tested groups, 3 hours 2 minutes after 30 groups

4.1.5 Test 5: Modified Both Entry Intervals and Voiceover Conditions

Similar conditions as in Test 4, with the difference of allowing groups to enter after 5 minutes **and** the previous group left room nr. 2. Furthermore, if a group is too fast in room nr. 2, 4, **or** if there is a potential collision in the next room, they get additional time, similarly as in the previous test.

Results:

- 90 groups tested
- 16 unique collisions (11x L5, 3x L6 and 2x L7)
- 11 unique pairs of group collided at least once
- Elapsed time approximately 9 hours 41 minutes for all tested groups, 3 hours 6 minutes for 30 groups

4.2 Airport-inspired Detour Simulation Results

Following three tests are run in the airport-inspired detour arena as depicted in Figures 2.12 and 3.3.

4.2.1 Test 6: The Airport Detour

Testing without outlier data (data set 2). The program has an alternative route for room nr. 4 + 5 (red path in Figure 2.12). If a group detects another group in room nr. 4 (green or red, aka. original or detour), then they are also taking a detour. The reason for that is, that if the system would ignore groups coming in from the detoured path, it would be likely that the groups would collide in green room nr. 4 once the detoured group would finish red room nr. 4. Furthermore, just as with the Hamleys arena, there is still the prevention mechanism of letting groups inside the arena after 5 minute intervals.

Results:

- 30 groups tested
- 16 unique collisions
- 7 unique pairs of groups collided at least once
- Elapsed time approximately 2 hours 46 minutes.

4.2.2 Test 7: Voiceover Conditions and Modified Entrance Intervals

Same testing conditions as in Test 6, with the exception of adding new rules about the entrance intervals and voiceover management. The program only allows new groups inside the arena if 5 minutes elapsed **and** the previous group left room nr. 2. Furthermore, if a group is too fast in room nr. 2, they get additional 20 seconds of dialogue in room nr. 3. Similarly, if a group is too fast in room nr. 4, they get additional 30 seconds of dialogue in room nr. 5.

Results:

- 40 groups tested
- 4 unique collisions
- 1 unique pair of groups collided four times
- Elapsed time approximately 4 hours after all 40 groups, 3 hours 6 minutes after 30 groups.

From the recorded screen capture, it was clearly visible that there was a considerable stacking on the detour path since nearly all of the groups took the detour, even though sometimes they did not have to. The issue was solved by greatly increasing the frequency of triggering collision detection for the last test.

4.2.3 Test 8: Checking for Collision Every Frame

The last test in the detour arena has the same conditions as Test 7 with the exception of detecting potential collisions every frame, which allows for last-second modifications to the path.

Results:

- 40 groups tested
- 5 unique collisions
- 3 unique pairs of groups collided at least once
- Elapsed time approximately 4 hours after all 40 groups, 3 hours 7 minutes after 30 groups.

4.3 HUB Simulation Results

The last arena to be tested is the HUB. Unlike the two previous floor plans, it is not linear and allows players to see each other in the central part of the arena.

4.3.1 Test 9: The HUB

This arena is the only one out of the three presented, where collisions are not possible thanks to its non-linear nature. The system would simply not open a door to an already occupied room. The HUB is therefore a great solution for VR experiences, where linearity is not a requirement. For the sake of comparison, the HUB has exactly the same room designs as in the existing Hamleys experience, that is, using the same time duration data and room equipment. For the group to be able to finish the experience, they need to finish all the rooms.

Results:

- 50 groups tested
- 0 collisions
- Elapsed time approximately 4 hours 3 minutes after all 50 tested groups, 2 hours 23 minutes after 30 groups.

4.4 Statistical Analysis of the Results

One way of looking at the results is calculating how many groups collided out of all the groups tested (see Table 4.5). In other words, it shows how many groups out of the total in each test are affected by the collisions. This means that if one unique pair of groups collided, it is actually two affected groups. However, if a group collided with a different group the second time, only the new group is added to the total. However, this only happened once out of all tests, in Test 6.

	Total number of collisions	Number of affected groups/total	Mean
Test 1	38	26/30	0.86
Test 2	44	28/30	0.93
Test 3	16	12/30	0.4
Test 4	2	2/50	0.04
Test 5	16	22/90	0.24
Test 6	16	16/30	0.53
Test 7	4	2/40	0.05
Test 8	5	6/40	0.15
Test 9	0	0/50	0

Table 4.5: Results for each of the nine tests.

The means are on the scale from zero to one, with zero being no collisions and one meaning all groups collided at least once. Test 1 and 2 were further excluded from the statistics since they included outlier data which were, for the reason stated before, incorrect. Similarly, Test 5 was a drastic step down from the previous test (Test 4), which is why it was also excluded from further analysis.

The means show that HUB has the best results and it is closely followed by Test 4 and then Test 7. By looking at the conditions of each test, it can be seen that Tests 3 and 6 are comparable. They had the same conditions and the only variable that changed was the arena type. Same situation happened with Tests 4 and 7. Tests 3 and 4 were from the original arena while 6 and 7 were from the detour arena.

The chosen statistical method is called one-way analysis of variance (one-way ANOVA) and it can be used for comparing two or more means from two unrelated groups or tests. *One-way* means that there is only one independent variable, in this case the floor plan (original versus detour). The null hypothesis for the test is that the two means are equal. Therefore a significant result indicates that the two means are not equal. Since Tests 3 and 6 are comparable, one-way ANOVA can tell whether their means are significantly different. The same statistical analysis is conducted for Tests 4 and 7.

4.4.1 ANOVA Results for Tests 3 (original) and 6 (detour)

Input for this analysis is the total number of collisions per group for each of the two tests. For example, if groups 2 and 3 collided, both groups are marked as having one collision. If group 3 collides with group 4, it means that group 3 has now two collisions while group 4 only one, etc. The total number of inputs is 30 for each test (aka. 30 groups per treatment).

Closer look at Tests 3 and 6 shows that there were 32 collisions in total in each Test (see Table 4.6), which resulted in an identical mean value. Standard deviation shows how much the reported collisions of each group in a test differ from the mean value of the entire test.

	Test 3	Test 6	Total
N	30	30	60
$\sum X$	32	32	64
Mean	1.0667	1.0667	1.067
$\sum X^2$	100	100	200
Std.Dev.	1.5071	1.5071	1.4942

Table 4.6: One-way ANOVA of Tests 3 and 6.

One-way ANOVA test was run at significance level of 0.05. This number can be explained as the probability of rejecting the null hypothesis when it is true. In other words, there is a 5% chance that the results are incorrectly labeled as significantly different even though they are not. Figure 4.3 shows that the f-ratio value is zero which further supports the claim that the two means are exactly equal to each other. The calculated p-value is 1 and since 1 is not smaller than 0.05, there is weak evidence against the null hypothesis, so the hypothesis cannot be rejected.

Source	*SS*	*df*	*MS*	
Between-treatments	0	1	0	*F* = 0
Within-treatments	131.7333	58	2.2713	
Total	131.7333	59		

Figure 4.3: Detailed one-way ANOVA results for Tests 3 and 6.

4.4.2 ANOVA Results for Tests 4 (original) and 7 (detour)

In the case of Test 4 and 7, the ANOVA is unbalanced because the sample size for the tests is not equal (see Table 4.7). This might make the result less reliable. Once again, the one-way ANOVA test was run at significance level of 0.05. Figure 4.4 shows that the f-ratio value is 0.7395. The calculated p-value is 0.392159 and since it is not smaller than 0.05, the hypothesis cannot be rejected in this case either.

	Test 4	Test 7	Total
N	50	40	90
$\sum X$	4	8	12
Mean	0.08	0.2	0.133
$\sum X^2$	8	32	40
Std.Dev.	0.3959	0.8829	0.6569

Table 4.7: One-way ANOVA of Tests 4 and 7.

Source	*SS*	*df*	*MS*	
Between-treatments	0.32	1	0.32	*F* = 0.7395
Within-treatments	38.08	88	0.4327	
Total	38.4	89		

Figure 4.4: Detailed one-way ANOVA results for Tests 4 and 7.

4.5 Summary and Discussion of the Results

As statistically proven, there is not a significant difference between the original and detoured arena. The best three results can be listed based on the ratio of the total number of affected groups out of the total of all group in a test (see Table 4.8). Generally, HUB seems to be the safest and most efficient solution. It takes about two and half hours for 30 groups to play through the experience, while the best results for original and detour arenas, Tests 4 and 7, both took over three hours individually.

Best results	Mean	Test number (description)	Completion time (30 groups)
1	0	Test 9 (HUB)	2 h 23 m
2	0.02	Test 4 (original)	3h 2 m
3	0.025	Test 7 (detour)	3 h 6 m

Table 4.8: The top three results listed with details.

One of the downsides of the HUB design was that it could potentially take a long time to finish the experience, in case players had to wait for the right rooms to unlock. However, as can be guessed from the total time of 2 hours 23 minutes, the waiting time was minimal. Adding extra voiceover time or waiting for groups to leave room nr. 2 works reasonably well with only two collisions reported (see Test 4), but at a cost of about 40 minutes of gameplay per 30 groups. However, it has to be noted that the simulated conditions were at the highest peak possible, which allows to make the following two important assumptions:

- A situation like this rarely happens in real life. Generally, weekends, afternoons or in the summertime, the arena is busier compared to weekdays, early mornings or winter. It has to do with tourism, naturally, but also working hours or public holidays.

- Because of point one, it can be safely assumed that the risk of colliding is in reality much lower than demonstrated in this report, making Tests 4 and 7 very good alternatives, if linear design is desirable.

In the simulation, the groups would enter a room and then the system would generate a random duration time from a poll available for each room. This allows for very extreme cases, often switching between fast and slow level completion time in the frame of a single play-through. However, in reality one might often see groups that are either slow or fast across the whole experience. That is, some groups like to storm through the experience while others want to focus more on the visuals, rather than the gameplay resulting in increased total play time. Detecting these groups can be a big help as the system might suggest a larger entry interval after a slower group.

The first tests in the evaluation did not respond to a collision. This means that if a collision happens, both groups stay in the room as if the room was empty and carry on with their experience. Once again, this can never happen in real life, as people crash, stop to take down their helmets, wait for the other group to leave first etc. The results of these tests, namely Tests 1 to 3, are therefore only illustrative and serve as a proof of the collision problem truly existing.

By analyzing the log files of Test 4, it can be seen that group 21 was fast in room nr. 2, which granted the players extra seconds in room nr. 3. The two colliding groups, 21 and 22, overlapped in room nr. 5 for 6 seconds, from 17:08:34 to 17:08:40, and then again in room L7 for 26 seconds, from 17:14:31 to 17:14:57 (see Table 4.9). The idea was to see if the collision could be avoided if the times were increased for group 22 in both rooms. Thus the system was changed so that the extra time would also be added in case of a potential collision in the next room (see Test 5). However, it only resulted in groups stacking up in the second part of the experience and colliding with each other.

In Test 7, one unique pair of groups collided four times. It was groups 28 and 29 and as can be seen from the log files, it was the very extreme case with maximum time duration for group 28 and low duration for group 29. After further inspection, it turns out that group 29 had extra 20 seconds in room nr. 3, but did not have those extra 30 seconds in room nr. 5, because it was a few seconds above the time limit when the delay triggers. The groups first collided in room nr. 4 and then continued colliding in each subsequent room until the exit.

Lastly, the number of groups tested needs to be addressed. Generally, all tests

	Group 21 entered 16:52:17	Group 22 entered 16:57:17
L1	16:55:28	17:00:31
L2	16:57:13	17:02:51
L3	17:01:33	17:05:51
L4	17:05:32	17:08:34
L5	17:08:40	17:12:07
L6	217:11:55	17:14:31
L7	17:14:57	17:17:36
	Group 21 left 17:14:59	Group 22 left 17:17:38

Table 4.9: Test 4 - analysis of duration time for each of the two colliding groups - 21 and 22.

had to have a minimum of 30 groups that would finish the experience. That time was usually enough for getting an overview of how well the test settings perform. However, in some cases, when the performance was unclear, the simulation was testing more groups, so that it would be easier to judge the performance based on more data.

Conclusion

At the start of the project, the goal was to find a balance between having a full capacity of the arena while at the same time avoiding groups of players colliding with each other. The research question was formulated to reflect this goal:

> How can virtual reality experiences be designed so that the potential collisions of groups of players in an immersive multiplayer room-scale arena are eliminated while not sacrificing the size of the arena and the nature of the gameplay?

Through virtually-simulated testing, it was found that the HUB floor layout is the most effective out of the suggested designs for multiple reasons. Not only it is the safest option as collisions are impossible in this setup, but it also performs well in regards to the amount of time the players spend in the arena. The HUB is much more forgiving in regards to extreme cases, that is, towards fast or slow groups. It also fulfills the three design constraints:

A) Ability to have multiple groups in the arena

B) Having a large sized-arena

C) Having a virtual environment mapped onto the physical one and also physical props

The only downside of the HUB design is the fact, that players can meet other players in the HUB arena and the experience might not be linear. For strictly linear gameplay, the HUB is not advised as the experience would more likely profit from using a combination of collision avoidance techniques presented in this report. These conditions involve having a modified version of the entry interval and additional voiceovers or other modifications that can increase time spent in a room. Despite that, linear experiences could also work with the HUB, but at the cost of sacrificing the physical mapping of the virtual world. Physical props could still be used, but not the ones that are stationary, or they would have to be present in each of the rooms and only be active when needed.

All in all, the HUB is not *the* perfect solution to the problem formulation, but it is a very promising floor design and its uses should be explored fully by the academic community. As of the date of writing this report, the HUB design is not used by any of the IMRS or LBE VR experiences in the world.

Acknowledgement

I would like to give a special thanks to my supervisor Kasper Rodil and Ondrej Bach from DIVR Labs for their invaluable help with this project. I would also like to thank all the other members of DIVR Labs for their help and willingness to answer all my inquiries.

Bibliography

[1] Christian Afonso and Steffi Beckhaus. "Collision Avoidance in Virtual Environments Through Aural Spacial Awareness". In: *CHI '11 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '11. event-place: Vancouver, BC, Canada. New York, NY, USA: ACM, 2011, pp. 1369–1374.

[2] Christian Afonso and Steffi Beckhaus. "How to Not Hit a Virtual Wall: Aural Spatial Awareness for Collision Avoidance in Virtual Environments". In: *Proceedings of the 6th Audio Mostly Conference: A Conference on Interaction with Sound*. AM '11. event-place: Coimbra, Portugal. New York, NY, USA: ACM, 2011, pp. 101–108.

[3] Bryan Bishop. *With Star Wars: Secrets of the Empire, virtual reality is finally ready for prime-time*. Nov. 2017. URL: `https://www.theverge.com/2017/11/20/16678438/star-wars-secrets-of-the-empire-virtual-reality-disney-the-void-ilmxlab` (visited on 05/16/2019).

[4] Alexander E. I. Brownlee et al. "A fuzzy approach to addressing uncertainty in Airport Ground Movement optimisation". In: *Transportation Research Part C: Emerging Technologies* 92 (July 2018), pp. 150–175.

[5] Boris Fedotov. *VR LBE MARKET LANDSCAPE AND TRENDS*. Oct. 2018. URL: `https://medium.com/@bfedotov/vr-lbe-market-landscape-and-trends-22ac9a245316` (visited on 01/17/2019).

[6] Charlie Fink. *The Free Roam VR Cage Fight*. en. 2018. URL: `https://www.forbes.com/sites/charliefink/2018/09/18/the-free-roam-vr-cage-fight/` (visited on 01/22/2019).

[7] Philip W. Fink, Patrick S. Foo, and William H. Warren. "Obstacle Avoidance During Walking in Real and Virtual Environments". In: *ACM Trans. Appl. Percept.* 4.1 (Jan. 2007).

[8] Jose F. Garcia et al. "Inside looking out or outside looking in?: an evaluation of visualisation modalities to support the creation of a substitutional virtual environment". In: ACM, May 2018, p. 29.

[9] Amit Garg et al. “ARES: An Application of Impossible Spaces for Natural Locomotion in VR”. In: *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’17. event-place: Denver, Colorado, USA. New York, NY, USA: ACM, 2017, pp. 218–221.

[10] Nikki Gillil. *Why are VR headset sales declining?* en. Aug. 2018. URL: `https://econsultancy.com/why-are-vr-headset-sales-declining/` (visited on 01/17/2019).

[11] Charlie Hall. *Welcome to The Void*. en. May 2016. URL: `https://www.polygon.com/features/2016/5/5/11597482/the-void-virtual-reality-magician-tracy-hickman` (visited on 01/31/2019).

[12] Morton L. Heilig. “Sensorama simulator”. en. Pat. US3050870A. Aug. 1962. URL: `https://patents.google.com/patent/US3050870A/en?q=sensorama&oq=sensorama` (visited on 01/17/2019).

[13] Morton L. Heilig. “Stereoscopic-television apparatus for individual use”. Pat. US2955156A. Oct. 1960. URL: `https://patents.google.com/patent/US2955156A/en` (visited on 01/17/2019).

[14] H. G. Hoffman. “Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments”. In: *Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. No.98CB36180)*. Mar. 1998, pp. 59–63.

[15] Shaoyan Huang et al. “Improving Virtual Reality Safety Precautions with Depth Sensing”. In: *Proceedings of the 30th Australian Conference on Computer-Human Interaction*. OzCHI ’18. event-place: Melbourne, Australia. New York, NY, USA: ACM, 2018, pp. 528–531.

[16] ICAO. *Separation Standards - SKYbrary Aviation Safety*. URL: `https://www.skybrary.aero/index.php/Separation_Standards` (visited on 04/11/2019).

[17] Dreamscape Immersive. *Dreamscape. A VR experience like no other.* en. URL: `https://dreamscapeimmersive.com/` (visited on 02/01/2019).

[18] iVROX. *A Brief History of Virtual Reality*. en-US. 2018. URL: `https://www.vrfocus.com/2018/05/a-brief-history-of-virtual-reality/` (visited on 01/18/2019).

[19] Jason Jerald. *The VR Book: Human-Centered Design for Virtual Reality*. New York, NY, USA: Association for Computing Machinery and Morgan & Claypool, 2016. ISBN: 978-1-970001-12-9.

[20] DIVR Labs. *Golem VR - the biggest VR experience in Europe*. en. URL: `https://www.golemvr.com` (visited on 01/17/2019).

[21] Eike Langbehn, Gerd Bruder, and Frank Steinicke. "Subliminal Reorientation and Repositioning in Virtual Reality During Eye Blinks". In: *Proceedings of the 2016 Symposium on Spatial User Interaction*. SUI '16. event-place: Tokyo, Japan. New York, NY, USA: ACM, 2016, pp. 213–213.

[22] Eike Langbehn, Paul Lubos, and Frank Steinicke. "Evaluation of Locomotion Techniques for Room-Scale VR: Joystick, Teleportation, and Redirected Walking". In: *Proceedings of the Virtual Reality International Conference - Laval Virtual*. VRIC '18. event-place: Laval, France. New York, NY, USA: ACM, 2018, 4:1–4:9.

[23] Zero Latency. *Zero Latency*. en-au. URL: https://zerolatencyvr.com (visited on 01/17/2019).

[24] Tom Mainelli, Jitesh Ubrani, and Michael Shirer. *Augmented Reality and Virtual Reality Are on the VRge of Growth, Says IDC*. June 2018. URL: https://www.idc.com/getdoc.jsp?containerId=prUS44001618 (visited on 01/17/2019).

[25] Mark Mine. "Towards Virtual Reality for the Masses: 10 Years of Research at Disney's VR Studio". In: *Proceedings of the Workshop on Virtual Environments 2003*. EGVE '03. event-place: Zurich, Switzerland. New York, NY, USA: ACM, 2003, pp. 11–17.

[26] Nomadic. *Make Believers*. en. 2018. URL: https://blurtheline.com/ (visited on 01/31/2019).

[27] Anne-Hélène Olivier et al. "Interaction Between Real and Virtual Humans During Walking: Perceptual Evluation of a Simple Device". In: *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*. APGV '10. event-place: Los Angeles, California. New York, NY, USA: ACM, 2010, pp. 117–124.

[28] B. Joseph Pine Pine II and James H. Gilmore. "Welcome to the Experience Economy". In: *Harvard Business Review* July–August 1998 (July 1998).

[29] Iana Podkosova and Hannes Kaufmann. "Mutual Collision Avoidance During Walking in Real and Collaborative Virtual Environments". In: *Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*. I3D '18. event-place: Montreal, Quebec, Canada. New York, NY, USA: ACM, 2018, 9:1–9:9.

[30] Albert B. Pratt. "Weapon". Pat. US1183492A. May 1916. URL: https://patents.google.com/patent/US1183492A/en (visited on 01/17/2019).

[31] International Society for Presence Research. *Presence defined*. en-US. Oct. 2009. URL: https://ispr.info/about-presence-2/about-presence/ (visited on 01/17/2019).

[32] Janko Roettgers. *Location-Based VR Predicted to Surpass $800 Million by 2022*. en. Apr. 2018. URL: https://variety.com/2018/digital/news/location-based-vr-revenue-forecast-1202776212/ (visited on 01/17/2019).

[33] Anshel Sag. *Location-Based VR: The Next Phase Of Immersive Entertainment*. en. Jan. 2019. URL: https://www.forbes.com/sites/moorinsights/2019/01/04/location-based-vr-the-next-phase-of-immersive-entertainment/ (visited on 01/17/2019).

[34] Bhuvaneswari Sarupuri. "Comfortable and Efficient Travel Techniques in VR". In: *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*. UIST '18 Adjunct. event-place: Berlin, Germany. New York, NY, USA: ACM, 2018, pp. 232–235.

[35] Bhuvaneswari Sarupuri et al. "Triggerwalking: A Biomechanically-inspired Locomotion User Interface for Efficient Realistic Virtual Walking". In: *Proceedings of the 5th Symposium on Spatial User Interaction*. SUI '17. event-place: Brighton, United Kingdom. New York, NY, USA: ACM, 2017, pp. 138–147. (Visited on 02/14/2019).

[36] Anthony Scavarelli and Robert J. Teather. "VR Collide! Comparing Collision-Avoidance Methods Between Co-located Virtual Reality Users". In: *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA '17. event-place: Denver, Colorado, USA. New York, NY, USA: ACM, 2017, pp. 2915–2921.

[37] Sule Serubugo et al. "Walkable Self-overlapping Virtual Reality Maze and Map Visualization Demo: Public Virtual Reality Setup for Asymmetric Collaboration". In: *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*. VRST '17. event-place: Gothenburg, Sweden. New York, NY, USA: ACM, 2017, 91:1–91:2.

[38] William R. Sherman and Alan B. Craig. *Understanding Virtual Reality - Interface, Application, and Design*. Vol. 12. Aug. 2003.

[39] Jonathan Shieber. *Location-based virtual reality is increasing its footprint in the U.S.* en-US. 2018. URL: http://social.techcrunch.com/2018/05/26/location-based-virtual-reality-is-increasing-its-footprint-in-the-u-s/ (visited on 01/17/2019).

[40] SkyVector. *TMB - Miami Executive Airport | SkyVector*. URL: https://skyvector.com/airport/TMB/Miami-Executive-Airport (visited on 02/20/2019).

[41] Mel Slater and Anthony Steed. "A Virtual Presence Counter". In: *Presence: Teleoperators and Virtual Environments* 9.5 (Oct. 2000), pp. 413–434.

[42] Spaces. *SPACES - VR - Go Anywhere Do Anything*. en-US. URL: https://www.spaces.com/ (visited on 02/01/2019).

[43] Misha Sra. "Asymmetric Design Approach and Collision Avoidance Techniques For Room-scale Multiplayer Virtual Reality". In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16 Adjunct. event-place: Tokyo, Japan. New York, NY, USA: ACM, 2016, pp. 29–32.

[44] Misha Sra and Chris Schmandt. "MetaSpace: Full-body Tracking for Immersive Multiperson Virtual Reality". In: *Adjunct Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST '15 Adjunct. event-place: Daegu, Kyungpook, Republic of Korea. New York, NY, USA: ACM, 2015, pp. 47–48.

[45] Statista. *VR device shipments by vendor worldwide 2017-2019 | Statistic*. en. URL: `https://www.statista.com/statistics/671403/global-virtual-reality-device-shipments-by-vendor/` (visited on 01/17/2019).

[46] F. Steinicke et al. "Estimation of Detection Thresholds for Redirected Walking Techniques". en. In: *IEEE Transactions on Visualization and Computer Graphics* 16.1 (Jan. 2010), pp. 17–27. (Visited on 05/07/2019).

[47] Dragoş Stoica, Sergio Gonzalez-Rojo, and Félix Mora-Camino. "Airport Ground Traffic Scheduling and Control". In: *IFAC Proceedings Volumes*. 10th IFAC Symposium on Control in Transportation Systems 2003, Tokyo, Japan, 4-6 August 2003 36.14 (Aug. 2003), pp. 95–99.

[48] Niels Anders Beckmann Stok et al. "The Jackal and the Wolf: Adapting a Namibian Cautionary Tale Into a Virtual Reality Game". English. In: *Kultur und Informatik : Hybrid Systems*. Verlag Werner Hülsbusch, Apr. 2018.

[49] E. A. Suma et al. "Impossible Spaces: Maximizing Natural Walking in Virtual Environments with Self-Overlapping Architecture". In: *IEEE Transactions on Visualization and Computer Graphics* 18.4 (Apr. 2012), pp. 555–564.

[50] Qi Sun et al. "Towards Virtual Reality Infinite Walking: Dynamic Saccadic Redirection". In: *ACM Trans. Graph.* 37.4 (July 2018), 67:1–67:13.

[51] Ivan E. Sutherland. "A Head-mounted Three Dimensional Display". In: *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I*. AFIPS '68 (Fall, part I). New York, NY, USA: ACM, 1968, pp. 757–764.

[52] *The Butcher of Prague | The scariest escape game Prague*. URL: `https://strachpodprahou.cz/en/butcher/` (visited on 02/19/2019).

[53] Triotech. *VR Maze Attraction - Virtual Reality Attraction*. en-US. URL: `https://trio-tech.com/products/vr-maze/` (visited on 01/17/2019).

[54] Adam Turner. *Virtual reality offers tantalising taste of brave new world*. en. Aug. 2015. URL: `https://www.smh.com.au/technology/virtual-reality-offers-tantalising-taste-of-brave-new-world-20150820-giyhv3.html` (visited on 01/31/2019).

[55] THE VOID. *THE VOID - Step Beyond Reality*. 2016. URL: https://www.thevoid.com/ (visited on 01/31/2019).

[56] Sandbox VR. *Escape Together*. en-US. URL: https://sandboxvr.com/ (visited on 02/22/2019).

[57] Wareable. *All You Need To Know About Location-based VR*. en. Jan. 2018. URL: https://vrroom.buzz/vr-news/guide-vr/all-you-need-know-about-location-based-vr (visited on 01/11/2019).

Appendix A

Literature Review Search Results

Please note that the following table is split over two pages. The total amount of relevant papers found is 20 out of which five were found through source-chaining. The two databases used are Association for Computing Machinery (ACM) and Aalborg University Library (AUB).

Portal	Search word	All results	Relevant results	Relevant papers	Notes
AUB	"location based virtual reality"	97	?		Generally for LBE VR: very often, location-based means it's not VR at the location, but something more along the lines of geo-caching
ACM	"location based virtual reality"	2	1	Mine [25]	Identical search results for "location-based virtual reality"
ACM	"flow" AND "virtual reality"	183	?		Browsed through a couple of first pages, but decided the search words were misleading
ACM	"flow" AND "virtual reality" AND multiplayer	6	0		

ACM	"virtual reality" AND multiplayer AND collision	4	1	Sra [43]	
ACM	multiplayer AND "room-scale"	4	0 (1 identical)		Same as if searching for multiplayer AND "room scale" AND "virtual reality"
ACM	multiplayer AND "room scale" AND "virtual reality"	2	0 (see note above)		
ACM	"room-scale" AND "virtual reality"	20	7 (8 - 1 identical)	Garcia et al. [8], Serubugo et al. [37], Garg et al. [9], Langbehn et al. [21], Sun et al. [50], Langbehn et al. [22]	
ACM	"collision avoidance" AND "virtual reality"	27*	6 (9 - 3 identical)	Olivier et al. [27], Huang et al. [15], Podkosova and Kaufmann [29], Scavarelli and Theather [36], Afonso and Beckhaus [1], Afonso and Beckhaus [2]	Quite a lot of crowd simulation papers, * two of the results were almost identical, just published at two different conferences
ACM	"escape room"	6	0		Found papers often dealt with collaboration in a group
AUB	immersive AND room-scale AND multiplayer	36	0 (2 identical)		

Table A.1: Keywords search results.