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Visualization Vechniques and Haptic Feedback in Virtual Reality Learning Environments

Final Research Paper

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Abstract

Immersion, interactivity and especially interactive visualization are some of the most valuable aspects that virtual reality learning environments (VRLEs) have over conventional learning methods. Even though Virtual Learning Environments have been adopted in several, mainly educational, institutions, some factors of their advances relative VRLE and their effective influence still remain unknown. In order to clarify certain attributes like visualization of complex theories and the influence of haptic feedback, we conducted two separate studies with overall almost 100 study participants. (For this reason several chapters of this paper are split into two sub categories where each of the two approaches is discussed in detail.). Our VRLE concerning haptic feedback in virtual reality (VR) showed already promising results in terms of influence of mixed reality systems, bolstering our assumption of their importance. Though we decided that for this paper we need additional further work to fortify the first insights, as they were heavily influenced by our makeshift setup. The second work, concerning gravitational waves and their visualization, showed strikingly good results in terms of increased understanding of abstract physics theories. We were able to indicate an average increase in understanding of the basic attributes of gravitational waves of more than 55% in 5 questions of the connected pre and post survey user study.

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1 Introduction

In this chapter the motivation for this thesis and the separate project, their respective contribution to general research in the topics as well as the general structure of this work is described.

1.1 Motivation

Education and teaching and how to approach it reasonably well it a field of study that has been of general interest for a very long time and is in need of constant evolution in order to stay up to date with the worlds developments. Especially in terms of Science, Technology, Engineering and Mathematics (STEM) education this is of significant interest, as teaching and learning in these fields can be particularly challenging. This is also reflected in developments of the number of graduates in these areas. They urgently need to be increased, be that via increase of motivation for the students, raising their general interest in the topics, or providing better explanations or increased insight into the long term values, among many other possibilities to be found (Olson & Riordan, 2012).

As one of many possibilities to solve several potential problems in these fields of education, Virtual Learning Environments (VLE) frequently proved to be an appropriate solution. It provides countless possibilities to engage learners more actively into abstract or complicated theories and phenomena. It can create interactive simulations where realistic and true to life situation can be experienced and trained hands-on. Additionally to these possibilities there is also the combination of gaming elements to further increase engagement and motivation that is being actively researched and already showed promising results in several occasions. This is exactly where the basic ideas of both projects started, to find ways of increasing engagement and improve learning behaviour in VLEs. While there is also an important other side of the coin, the expertise and know-how of educators, the focus over the course of this work will for the biggest part be on the learners point of view. As a more specialized application we also decided to look into visualization techniques used for complex theorems, where classical commonly used approaches often produce visual information overload and where alternative methods are urgently necessary.

Furthermore, not only STEM education but any other field of study can profit from developments and insights towards VLEs, as various applications, especially in training of potentially dangerous situations, have been found already and mostly all still require further development and new approaches.

1.2 Contribution

This work contributes into two separate specialized research topics in VRLEs with two separate projects. Firstly an extensive study on user study with 56 participants has been conducted in order to research general effects on learning behaviour and immersive well-being in virtual environments. This user study consisted of a detailed investigation using a hybrid approach with a mixed reality and a virtual reality part. Secondly an analysis of alternative visualization methods for gravitational waves representations in an interactive VRLE, providing better intuitive understanding compared to previous approaches taken. This analysis was done with a user study in which 35 participants confirmed initial assumptions about the positive influence of our approach taken with striking results.

1.3 Structure of the Work

This thesis is separated into three main parts with two different concerns, haptic feedback and visualization techniques in VRLEs. Firstly in Chapter 2 a general informative background and corresponding related approaches to both concerns is given. Next the thesis is split into two big chapters concerning each separate topic in a similar structure, these being Chapter 3 and Chapter 4. These chapters both start with a deeper insight in the initial idea for the respective project and why it was chosen, then go over the development part with explanations to the most important steps taken during the implementation phase of the practical part. Finally both chapters finish with an evaluation of the taken approaches and the gained insights via the recorded data and what exactly the data tells. After both main chapters are closed up, in Chapter 5 conclusions about the overall approach and its results are given as well as future perspectives of each projects are outlined.

2 Background and Related Work

In this chapter literature findings and related work to each project as well as the overall idea for the projects in further chapters will be discussed. First the focus will be on education, specifically STEM education, why it is urgently important and how teaching as well as learning in these subjects can be improved. Then we will focus on virtual learning environments and virtual reality as a learning aid, supporting especially aforementioned topics. Afterwards more details on related ideas regarding haptic feedback and it's effects on learning behaviour, as well as further visualization techniques and other approaches for Physics and Astrophysics in Virtual Reality Learning Environments will be discussed.

2.1 Education and Learning

Innovation and development of "new-to-the-world" technologies have been seen as fundamentally important part of sustained growth and competitive advantages of industrially developed economies, ultimately leading to higher living standards.To achieve this, it would not suffice to imitate or adapt to approaching technologies but they must be pushed from inside, which requires a corresponding mindset of everyone involved (Milbergs, 2004).

Science, Technology, Engineering and Mathematics (STEM) education could be the key towards this goal and if properly utilized should create a society of sufficiently educated citizens in these important core areas. Unfortunately while being ubiquitously used in corresponding discussions, it has been confirmed several times that the ongoing approaches are very often fruitless and at times even counterproductive, thus making it an incremental process of improvement of the overall education system (Bybee, 2010). Kuenzi (2008) confirms this in their work and claims, that a world leading country in innovation should correspondingly also lead in maths and science proficiency, which is unattainable for pupils if their teachers are already lacking adequate knowledge. He shows up how much effort and money flows into these education areas, how it's still evidently producing inferior results and focuses on how the overall infrastructure in the US could and should be improved to tackle this approaching deficit in an appropriate manner.

Zeidler (2016) found, that many current approaches on the topic are inadequate starting in their roots and a fundamentally different approach would be required. She claims that the base ideas about STEM education which became very popular are only creating an inherently deficit framework. STEM education needs to be integrated in a holistic sociocultural model and doing so would create a system, where an educational surplus instead of another generation of uninvolved, unengaged and uninformed citizens are created (Zeidler, Sadler, Simmons, & Howes, 2005). Nonetheless, a thorough analysis on latest developments in journals about this topic has shown various approaches and opinions on the current status , thus making it hard to get a general statement about it. Especially since 2016 there has been a continuously raising number of publications on the subject, and the acceptance of the first dedicated STEAM education journal in 2019 with *International Journal of STEM Education*, highlights the tremendous interest in research about both teaching and learning STEM (Li, 2019; Li, Wang, Xiao, & Froyd, 2020).

Chai (2019) focused on the importance of STEM teachers professional development (TPD) as a fundamentally important aspect in solving apparent problems in current STEM education. While not being directly related to this works approach, TPD is a generally important aspect of educational studies and there has been discovered a lack of corresponding studies and thus educated and founded insights. Even though future research is needed on the topic, STEM-TPD frameworks are proposed to be a solution to possible lack of teachers with the necessary inter disciplinary knowledge.

While we see that various problems with the education process from start to finish lie in many different areas, what mostly all works on STEM agree on is, that it needs to become more interesting, relevant and engaging for the learner (Duncan, 2009). This insight leads to many of the further approaches taken over the course of this work and will be focused on time and again.

2.1.1 Traditional and Blended Learning Approaches

Traditional learning commonly includes attending lectures and conventionally conveying didactic material in a face to face manner from teacher to learner. This concept makes it necessary for everyone to be in the same physical space at the same time, which in turn enables social behaviour and cultural effects as people can learn from and with each other. However this also inevitably leads to one of the major disadvantages of traditional learning, which proves to be challenging with increasing numbers of students and involves a lot of travelling (Alaneme, Olayiwola, & Reju, 2010). While the temporal and locational challenge might be only an inconvenience at times, another identified problem with traditional learning is the lack of actual gained knowledge and understanding from learners within the given modus. Tynjälä (1999) described a troublesome situation in common higher educational institutions, where experts should be educated and given an environment for knowledge building. They found that, for example in many universities, the education process resembles knowledge transmission instead, relying on traditional learning methods for the biggest part. This sequentially leads to acquisition of inert knowledge and the creation of non-experts, consumers of expertise rather than experts themselves. Procedural instructions without further explanation, in comparison to conceptual instructions, lead to conceptual understanding and adoption of some extend but also to less transferred knowledge about the procedure and thus understanding (Rittle-Johnson & Alibali, 1999).

One commonly approached solution to some of the issues encountered with traditional learning is a mixed approach in the manner of a blended learning mode. Without completely replacing all the known and trusted processes that people learned to trust over centuries, this frequently includes technology support in proven methods to enhance and expand possibilities in knowledge acquisition, as well as completely different approaches in certain aspects to enable critical thinking and problem solving techniques. While most blended learning approaches are somehow connected to new technologies or e-learning, more details about how different variants are actually implemented will be discussed in later chapters and here focus will be more on their effects and outcomes. Several different research works have shown that an overwhelming amount of students feedback was positive with often more than 95% of approval of the tested blended methods, which was also confirmed in corresponding test results (Nazarenko, 2015). What has to be kept in mind in any introduction of new methods is also that teachers and tutors need to be appropriately trained in the used technologies for a blended approach in order for the results to be conclusive. One identified problem was often also too high expectations promised to the students that could not be fulfilled and after all induced negative effects instead of improvements (Adelsberger, Bick, & Pawlowski, 2000; Hameed, Badii, & Cullen, 2008). Alaneme et al. (2010) also found, that most students prefer a blended approach as combination of traditional and electronically supported learning over a pure traditional approach, which is confirmed also in more in recent works (Castro, 2019; Sahni, 2019).

While there have been several successful attempts, there still remains a lot to be found in research and analysis on the topic and thus it continues to be an active research field on its own. However, already thousands of years ago the famous philosopher Confucius (511 BC - 479 BC) said: *"I hear and I forget. I see and I remember. I do and I understand"*. Until today these words remain to be an inspiration in interactive learning approaches and many a work in education have even been titled with it.

2.1.2 Exploratory Learning

While the topic of exploratory learning is not compulsorily connected to computer media, it is very frequently used in combination with digital environments (Bliss & Ogborn, 1989). Edwards (2012, p. 1) defined the term exploratory learning as a family of approaches that share several common principles, like the ability of the learner to control their own learning, the non necessity of following narrow paths to enlightenment, the diversity of learners and their own intellectual styles and finally the fact, that an appropriately designed context can make learning feel easy and natural. While these principles are not some of the latest insights, the development and usage of computers and modern technologies made it easier for them to be adopted as educational approaches and finding their way into mainstream education.

Already in 1993 Njoo and De Jong (1993) conducted research on exploratory learning behaviour in computer supported learning environments in two separate approaches with group of 17 and 91 students respectively. While the first group was analysed with thinking-aloud protocols, the second bigger group was tasked to fill out open ended assignment sheets with some instructional support in the form of hints on the forms. Interestingly they identified twenty-two different learning processes, where students of both studies were generally reluctant to apply processes that could be tied to exploratory learning, specifically generating hypotheses, interpreting data, and drawing conclusions.

Rieman (1996) on the other hand confirmed the effectiveness of exploratory learning behaviour, especially in task oriented exploration. Although they also identified the necessity for further instructional material and support and the need for a social support aspect from other users at times and additionally non-task related exploration was perceived as inefficient.

de Freitas and Neumann (2009) created a five-step model of Exploratory Learning (Figure 2.1) based on Kolbs model of Experiential Learning (Kolb, 1984). They added an important fifth intermediate-step in the model with immersive exploration. The explorative aspect, especially in an immersive environment, grants learners the possibility to gain a lot more self-consciousness about the learned topic and additionally enables them to socially interact with each other. The process according to their adapted model also starts with previous experience, goes over a reflection phase, the forming of abstract concepts and testing of the insights which in turn become further experiences. But the new possibility of exploration in between step one and two of Kolbs model leads learners to experience and digest provided material and information at their own pace and with their own habits, giving them full jurisdiction over the process and thus providing an appealing environment and positive reflection.

Bunt, Conati, and Muldner (2004) found that an additional important part of exploratory learning environments is self-explanation of the learner, next to necessary meta-cognitive skills such as systematic approaches towards exploration and the creation and confirmation of hypothesises. They found that results of a frequently used framework, the Adaptive Coach for Exploration(ACE), were frequently flawed, as students answers and actions were taken as positive explorative behaviour, while it was not distinguished between merely performed actions and actually self-explained actions. By adapting the framework to theirs needs and enabling additional interfaces for the measurement of self-explanation of a student, they identified results of the students self-explanation and also of its evolution in regard of ACEs coaching, which supported their hypothesis of its importance.

2.1.3 Increasing Interest and Engagement further with Gamification

Even though it's not strictly connected to exploratory learning, the concept of Gamification appears often during research on that subject. Often enough to be a whole separate topic on its own. Research done in this specific area focuses a lot on improving the learners engagement and interest in the concerning matter via adding game elements into non-game settings. When employed properly, these give the power to engage, inform and educate the learner in so far unknown dimensions (Kapp, 2012). Now this

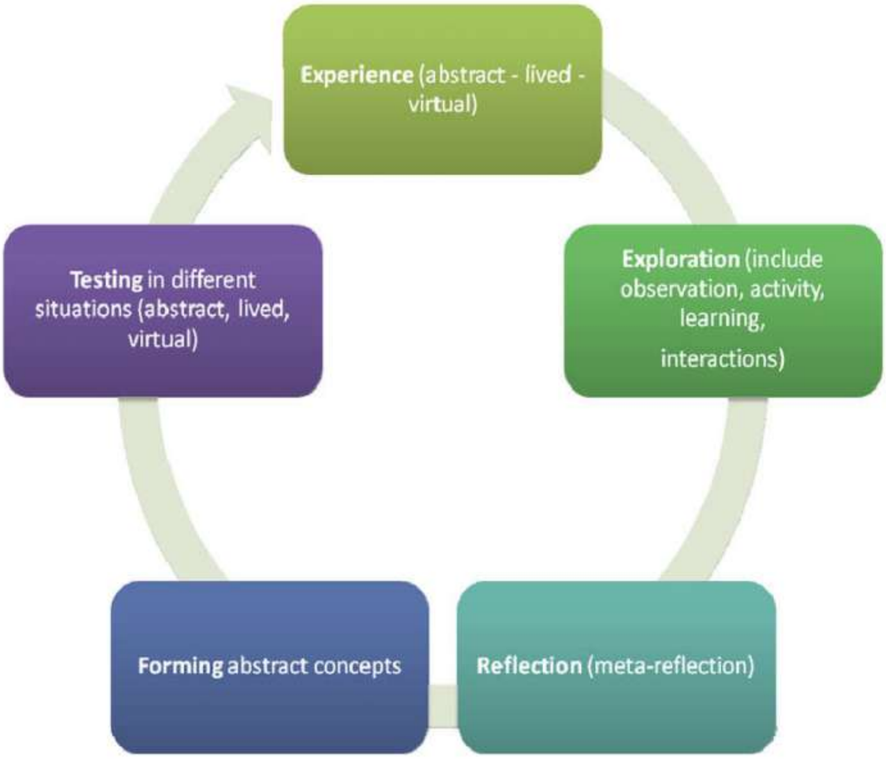


Figure 2.1: Exploratory Learning Model, (taken from de Freitas and Neumann (2009))

leads to a big question about how to introduce game elements appropriately in an educational setting.

Kiryakova, Angelova, and Yordanova (2014) built up on Kapps definition of gamification and analyse important differences between serious games and gamified education contexts and discuss suggestions on how to appropriately implement those. One possible mechanic that is easy to apply is the rewarding factor of games and thus including positive reinforcement. Further similar possibilities are the accumulation of points, leader boards and level achievements as possible learning rewards. In environments with multiplayer elements they can also induce a friendly competitive engagement between learners and thus additionally increase individual motivation. They identified e-learning settings to be an particularly suitable environment for game elements to be added, especially for nowadays digital natives, and also found an increased overall ability to learn new skills by up to 40% (Paisley, 2013). While gamification is found to be used often to enhance learners experiences in a learning environment, there are also approaches taking this principle even another step further by creating dedicated games in the means of game-based learning (Mosquera, Steinmaurer, Eckhardt, & Guetl, 2020)

J. T. Kim and Lee (2015) developed a dynamic gamification model around four basic characteristics (curiosity, challenge, fantasy and control), that helps to understand the underlying factors for the positive impact of game mechanics inclusion (Figure 2.2). While having a somewhat steeper entry curve, their results showed that after the initial adaption phase a gamified environment can show greatly superior curve development compared to traditional proven approaches, that resulted in solid but steadier results.

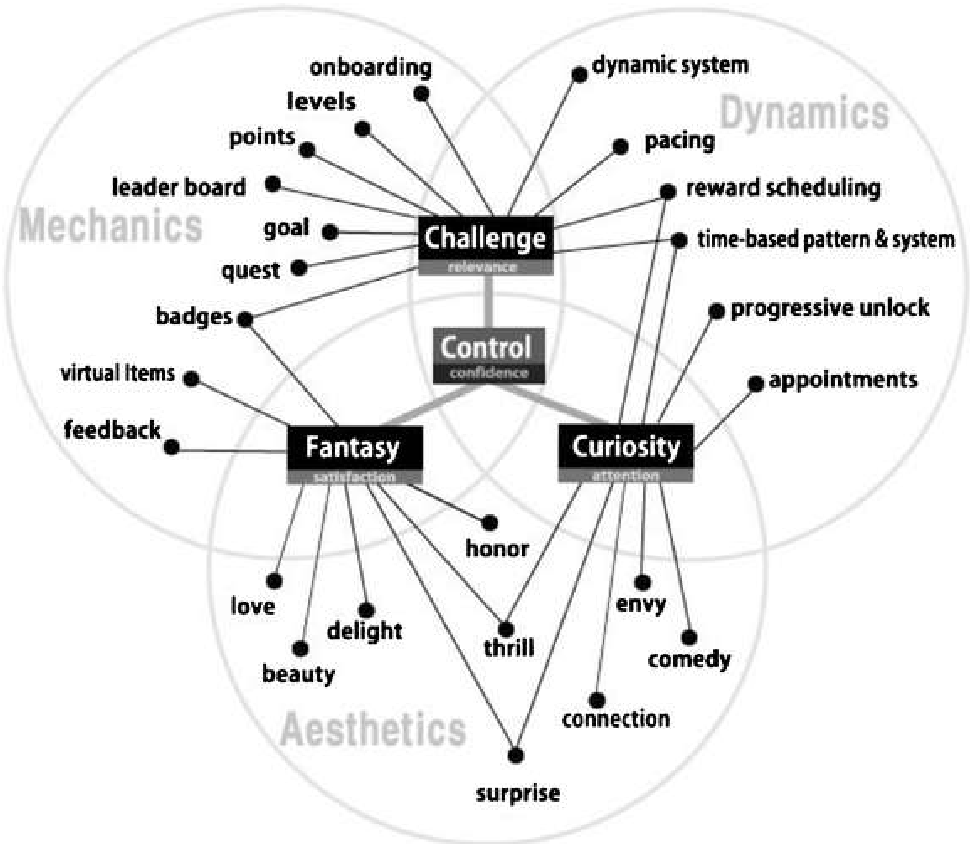


Figure 2.2: Fundamentals for Dynamic Model for Gamification (taken from J. T. Kim and Lee (2015))

Even though it has been shown that adding gamification to educational environments can improve overall learning outcome in many circumstances, only a small percentage (11.3%) of teachers use it on a regular basis. While the attitude on average seems to be positive towards gamification, lack of time, training and financial support have been identified as main reasons for this attitude-use gap, which provides a few more aspects to take care of when introducing such (Martí-Parreño, Seguí-Mas, & Seguí-Mas, 2016).

2.2 Virtual Learning and Learning in Virtual Reality

In this section different approaches on Virtual Learning Environments (VLE) will be discussed, as an introduction into more specialized learning environments that present a big part of the base for some approaches taken and decisions made in both practical projects of this thesis. As a specialized type of VLE, more details will be discussed about Virtual Reality and its influence and applications in VLEs.

2.2.1 Virtual Learning Environments

VLEs are modern possibilities to enhance and support educational methods and processes with technology that has not been available for the biggest part of the history of education. Most of the time they include web based applications that improve communication between participating parties, engagement of the learning party and time and space constraints between all members of the corresponding courses, to name only a few potential improvements towards their alternatives and counterparts. Their focus in the first place is to support and enhance the overall process of transferring knowledge (Trafford & Shirota, 2011). While many applications already exist and can be found in literature, there are still plenty more unresearched aspects of VLEs and in the further discussion we will focus on the ones concerning the projects included in the main chapters of this work.

VLEs have become frequently used ways to enhance traditional non-digital learning approaches inside and outside of the classroom of countless educational institutions. While they are not meant to fully replace other classic methods it is important to analyse an appropriate way of application for VLEs in a course. If one does not pay enough attention to the perks of VLEs in terms of format, content and the corresponding utilization, it can essentially be rendered useless as it would not add any contribution to an improved experience for the learners (Demian & Morrice, 2012). Thus VLEs have been proven to be an appropriate alternative to traditional learning approaches in certain circumstances and events. They can be means of creating stimulating and enhancing environments that increase a learner's understanding of specific events and mechanics (Pan, Cheok, Yang, Zhu, & Shi, 2006a). Though, it is important to note that, while showing advantages in certain setups, virtual environments should not be seen as a full replacement of conventional learning methods. Rather should it be analysed when and where their implementation provides the greater benefit compared to other options (Cook, 2007).

In an analysis of recent publications and studies on VLEs, learning support, simulations and games were found to be the most used design and collaborative as well as exploratory based strategies the most used learning approaches (Reisoğlu, Topu, Yılmaz, Yılmaz, & Göktaş, 2017).

Further chapters are focusing on some more specialized applications of VLEs, especially some that led to decision being made in the practical part of this work.

2.2.2 Virtual Reality in Virtual Learning Environments

While VLEs already show a considerable number of potential improvements, Virtual Reality (VR) provides another aspect to further enhance some of these effects. It does so by creating the possibility to involve the learner into a VLE that introduces interactivity and immersion in dimensions previously unthought of (Abdoli Sejzi, 2015; Kondo, 2006). Interactive VLE's have shown the ability to transmit physical phenomena surpassing traditional learning methods and thus the focus of this work will be on the combination of those in the form of Virtual Reality Learning Environments (VRLE) (Brown, Lomsdalen, Humer, & Eckhardt, 2019; Chu, Humer, & Eckhardt, 2019; Schmidt & Stewart, 2009; Thorsteinsson & Shavinina, 2013).

Checa and Bustillo (2020) approached an analysis on the effectiveness of VRLE in a comparison of two environments in regards to visual learning of historic facts and information. They created a VR representation of the Spanish city Briviesca in medieval times with 3D models. One group was tasked to gain information in a semi-guided VR tour and a testing group that received the effectively same information in a video of the renderings. While theoretically the available information was the same, they could identify a greatly increased in understanding of the cities structure and visual information of houses for the VR group, while facts received via a video narrative channel was remembered better for the pure video group. What has to be kept in mind is still the influence of the comparable novelty of VR for many users, thus increasing their interest and satisfaction with the new experience for them. Nonetheless it is another aspect to keep in mind when designing VRLEs, as distraction can be a diminishing factor towards the learning experience and thus, learners should be guided properly through the experience to avoid missing critical information, while still leaving enough freedom for self exploration.

While VR was not that commonly available in the last century, Pan, Cheok, Yang, Zhu, and Shi (2006b) already analysed the applicability of VRLE and mixed reality in VR as teaching environments in a more comprehensive study. Focusing on some if the main identified advantages of VLEs, namely enhancing, motivating and stimulating the learners understanding, they even then identified strong indications of VLEs in combination with VR or Mixed Reality (MR) to be appropriate enhancements to support learning processes. Analysing several applications, for example in Chinese elementary schools, they found common demands to be satisfied. Mixed Reality is going to be focused on more in the next chapter and is basically defined via it's three main characteristics, being a combination of the real and the virtual in any manner, in three dimensional space and interactive (Azuma, 1997).

Engineering studies provide popular applications for VRLE implementations to increase learners comprehension, especially because often spatial understanding of diagrams is difficult. In a specialized application with two variations of ternary phase diagrams, Vergara, Rubio, Lorenzo, and Rodríguez (2020) showed generally positive effects of the virtual interactive environment, but especially reported importance of its appropriate design. Functionalities that are not necessarily unique to VR VLEs but general computer applications, like exploding views, rotation and application of transparency, were recognized to be even more useful in VR, according to participants feedback.

In a very recent approach Madden et al. (2020) compared three different implementations of teaching moon cycles: hands-on, desktop and VR. While they could not indicate any strong correlation for improved learning in any of the settings during their approach, they could show better results connected to previous gaming experience of the users and also gender. This got confirmed with related literature. Nonetheless they also reported utterly positive response towards the VR setting and user enjoyment, which they also ascribed to VR novelty.

2.2.3 Different Virtual Reality Devices

In order to experience a VRLE, some kind of immersive interface is necessary. Here most commonly some sort of Virtual Realtiy Headset or Head Mounted Display (HMD) comes into play. These devices contain as their core functionality some kind of screen that lets a user see a three dimensional world with appropriate depth effect, as well as gyro sensors that allow the device to recognise head movements and respond accordingly with changing the image shown on the screens appropriately. The industry has found several different ways to realize these features and is constantly developing new advancements, with Oculus, HTC, Microsoft and Google as some of the top players in this branch.

Although there are various potential benefits of using VRLEs for educational purposes, one main problem next to the restricted usage for specific applications remains to be accessibility and financial issues with the required hardware. While both Oculus and HTC, as well as other Head Mounted Display (HMD) manufacturers, provided several high end devices for the end customer already, low end and stand alone hardware are still only approaching easy and affordable access for private users (Belleman, Belleman, Stolk, & Vries, 2001). This leads to the assumption that while it seems inconvenient at times for personal use, VRLE applications might be a potentially solid opportunity for businesses and facilities to include in their learning environment and knowledge transfer and training processes. Furthermore this assumption also brings about some further studies on the topic in the later chapters of this work, as the application generally is intended for classrooms in educational facilities. While higher end hardware is out of reach for many people, there has been research on lower end hardware, which could be affordable for a much bigger part, that showed their ability to produce as almost as good results as their very much more costly counterparts (Díaz, Zarraonandía, Sánchez-Francisco, Aedo, & Onorati, 2019). Therefore even for private usage the opportunities are given, as lower resolution and frame rate do not show significant impact on learning results and the users experience. Moro, Štromberga, and Stirling (2017) confirms this assumption in a separate approach, comparing the Oculus Rift desktop-based HMD to the Gear VR mobile HMD. While with cheaper versions, more often some complaints like motion sickness and nausea are reported, the end results of learning outcome and user experience are almost equal.

While it does not help with the accessibility issue, CAVE VR environments need to be mentioned here as well, as their immersion is often incomparably to other VR approaches. CAVEs are room scale VR setups that consist of many projectors, big screens and powerful computers to control all components. One of the biggest advantages of a

CAVE is the unrestricted access of the user in the environment as the only necessary direct accessory are light shutter glasses. Cruz-Neira, Sandin, and DeFanti, 1993 This makes it very easy and realistic to experience for the user while also being absolutely aware of their own body and presence inside the simulation. The usefulness of CAVE environments has been proven in several VLE applications. Yuen, Choi, and Yang (2010) approached this with a focus on their used infrared motion-tracking technology to interact with the simulation, showing enhanced driving operations and user experience in their gained results.

Table 2.1 contains a summarized explanation and the corresponding sources of most important terms and abbreviations used in this work.

Term/Abbreviation	Definition	Source
VLE	*Virtual Learning Environment* Technology enhanced setting to positively influence learning attributes	Trafford and Shirota (2011) Pan, Cheok, Yang, Zhu, and Shi (2006a)
VR	*Virtual Reality* Immersive and Interactive three dimensional environment	Abdoli Sejzi (2015) Burdea and Coiffet (2003)
XR, MR or AR	*Augmented* or *Mixed Reality* Combining the real and the virtual world	Azuma (1997)
VRLE	*Virtual Reality Learning Environment* Combination of VLE and VR	Thorsteinsson and Shavinina (2013)
HMD	Head Mounted Display[12]	Belleman, Belleman, Stolk, and Vries (2001)
CAVE	*Cave Automatic Virtual Environment* A room-scale VR environment Very high resolution multi-screen setup	Cruz-Neira, Sandin, and DeFanti (1993)
Haptic Feedback	Combination of force, tactile, vibrotactile and proprioceptive Feedback	Cichocki et al. (2007) Bark et al. (2015)

Table 2.1: Commonly used Terms and Abbreviations and their definition

2.3 Haptic Feedback in Virtual Learning Environments

2.3.1 Haptic Feedback

Burdea and Coiffet (2003) describe Virtual Reality as I^3 for Immersion-Interaction-Imagination. As part of each of those pillars of VR, haptic feedback, next to visual and auditory interfaces, has been of general interest since the dawn of VR environments itself (Callaghan et al., 2008; Dattalo et al., 2018).

Haptic feedback encompasses the modalities of force feedback, tactile feedback, and the proprioceptive feedback (G. Burdea, 1999). Force feedback integrated in a VLE provides data on certain properties of a virtual object such as hardness, weight, and inertia. Tactile feedback is used to give the user an impression of the virtual object surface contact geometry, smoothness, slippage and temperature. Finally, proprioceptive feedback is the sense of the user's body position.

2.3.2 Application and Influence

In various simulation systems, haptic feedback has become an integral component. For example, in systems designed for gaining and upgrading surgical skills (Raison, Ahmed, & Dasgupta, 2015; van der Meijden & Schijven, 2009; Våpenstad, Hofstad, Langø, Mårvik, & Chmarra, 2013), haptic feedback is considered to be essential to conceptualize and segment most surgery procedures into critical task components. Haptics in nearly all such VLEs have been designed to realistically replicate the real-world forces relevant to a particular task. Earlier works also suggest that haptics in a VLE contribute positively to the users' learning outcome and perception of virtual object shapes (Crespo & Reinkensmeyer, 2008; Song, Dan Morris, Colgate, & Peshkin, 2005). Furthermore, the methodology in the work of Covaci, Postelnicu, Panfir, and Talaba (2012) suggests positive influence of virtual visual haptic feedback in the implementation of a virtual free throwing basketball simulation in a CAVE XVR environment. In that work the conclusion was drawn that haptic feedback in any form is essential in such projects. This claim was also supported by feedback of professional players that achieved results similar to the ones in real world inside the simulation. Contrary to that, Adams, Klowden, and Hannaford (1999) found no significant learning benefit from haptic feedback for simple manual assembly task, but an overall benefit from training in a virtual environment.

2.3.3 Controls and Implementation

One aspect of haptic feedback in VR that comes up inevitably is the issue with controls. While visual methods of simulating haptic feedback like delayed movement of virtual objects can only provide so much realism, many applications also require actual force feedback to create an environment that is close enough to reality to analyse certain properties. Standard equipment like the default controllers that come with an HTC

Vive HMD [3] are not designed to provide any more haptic feedback than the weight of the actual controller, which often is not corresponding to what is desired in a VLE. While some applications work with this constraint, analysing haptic feedback influence on interactions with the VR world quickly run into its borders and thus customizations are often a valid solution to this.

Bouzit, Burdea, Popescu, and Boian (2002) analysed such an approach with a custom haptic feedback glove. The Rutgers Master II (See Figure. 2.3), created already in 1999, was designed for dextrous interaction with virtual environments and is upgraded by pneumatic actuators that provide force feedback of up to 16NM on each finger. Successful applications for this glove ranged from medical rehabilitation to military command and control, thus confirming the advantage of a physical interface for such applications. The RS232 line to a connected PC recorded up to 346 complete hand position datasets per second and enabled many possibilities for further analysis.

Yoshikawa and Ueda (1996) approached the issue similarly with an interface consisting of several link components attached to the operators fingertips. This device allows the user to feel various dynamic force components (such as the inertial, centrifugal, Coriolis, and gravitational forces) and surface slippage of virtual objects. Verifying the validity of the technique they used with a "measuring motion and displaying force" approach with a two-fingered display device that allowed the user to get a feeling of manipulating dynamic virtual objects and even the perception of the slippage in regard to object's surface. . While intuitively the assumption of actual vibrotactile haptic feedback with any sort of appropriate controls yielding superior results to any visual or otherwise simulated sort, Kreimeier et al. (2019) conducted a comprehensive user study to investigate the matter in more detail. Comparing results of various tasks like throwing, stacking and object identification, they found strong indications of the connection between different tasks in VR and the corresponding type of haptic feedback. This implies at least a tendency for MR setups to provide stronger positive effects than purely simulated haptics in just VR.

Cichocki et al. (2007) investigated specifically vibrotactile feedback in connection with brain computer interfaces. Their studies showed the feasibility of the vibrotactile haptic channel in general and especially its advantage over the visual one, notably even more when the visual channel was occupied with a complex task. Bark et al. (2015) confirms the effectiveness of this kind of haptic interface with a several day long study concerning a movement guidance system measuring arm motions while indicating deviation from the desired trajectory with vibrations.

2.3.4 Medical Simulations

Coming to an especially important application for haptics in VR environments, medical simulations can be found frequently during corresponding research. This also led to some of the later assumptions taken for future work in this topic, where the project described in chapter 3 serves as a starting point, and will be discussed in more

[3] https://www.vive.com/

Figure 2.3: Rutgers Master II and Rutgers Master II-ND. ©Rutgers University (retrieved from Bouzit, Burdea, Popescu, and Boian (2002))

detail in regards to other approaches here. The possibilities for possible advantageous applications of different forms of force feedback in surgical simulations are actively researched. Various different medical applications have identified an urgent need for sophisticated simulations of haptics in simulated training environments.

Khaled et al. (n.d.) found the immediate necessity for adequate implementation of force feedback for palpation, as a core diagnostic approach for surgeons for identification of tissue and corresponding attributes. While in praxis there exist alternatives for identification, even those can not provide the important information about tissue elasticity. In their study they analysed the usage of a customised haptic system using ultrasonic elastography and showed its potential to induce real-time forces. While their main intention of the research was proceedings in medical simulations, they stated also other useful applications in navigation, telemedicine, teaching and telecommunication (Ullrich & Kuhlen, 2012).

(Basdogan, Ho, & Srinivasan, 2001) developed a training system for laparoscopic procedures with two haptic feedback devices. With the simulated insertion of a catheter into the cystic duct it provides an environment where tactile sensing and haptic feedback proved essential cues to the users to appropriately accomplish the task, without damaging any tissue or devices, which would otherwise be close to impossible. They themselves and several sources they cited believe that providing users with appropriate haptic cues can be powerful ways to enhance medical training and performance of and in corresponding visualisations.

(van der Meijden & Schijven, 2009) also states the intuitive advantage of feedback, but analysed the actual outcome of adding haptic interfaces to virtual simulations. While VR on its own is essential and medical simulations without it would be unimaginable, developing an appropriate interface for corresponding force feedback in an acceptable way proved to be a challenge. Unfortunately many institutions also refrain from investing into development or even research into the topic before a conclusive confirmation for its advantage is shown. The results of their study are lamentably also inconclusive and unanimous. They indicate a positive assessment in the majority of analysed cases, but concentrating on minimal invasive and robot supported surgery, they lacked research data for any solid confirmations. In general applications like knot tying the advantage could already be confirmed and thus the active research on the topic continues.

2.4 Physics in Virtual Learning Environments

2.4.1 General Physics

Already in the early 90s scientists discovered benefits of using virtual reality for physics education (Loftin, Engleberg, & Benedetti, 1993). Interactivity as a core element of VR simulations proved to be a main contributor to increased understanding of physics phenomena and attributes, where adjustable factors of the environment or specific objects, like gravity, surface friction or atmospheric drag were used as a tool for users to increase immersion. Other approaches showed benefits also for further physics concepts like wave propagation, ray optics and more. Especially the high degree of reality that is provided by the interactive simulation and is unattainable in traditional two dimensional interfaces is ever again identified as one of the main advantages. These approaches proved to enhance the intellectual stimulation and understanding at a high school or college level (J. H. Kim, Park, Lee, & Yuk, 2001). Also game mechanics, which is very often a popular aspect to include with VR simulations, showed significantly improved results in understanding of concepts like electromagnetism (Squire, Barnett, Grant, & Higginbotham, 2004). Not only was an increased understanding identified, but that game mechanics could help battling weakness in understanding from previous approaches on the topic.

Combining advantages of VRLEs, Exploratory Environments and Gamification, MaroonVR ("MaroonVR," 2020) is an interactive and immersive Virtual Reality Platform designed to represent a physics laboratory. There have been several studies conducted in and with the virtual environment and its effectiveness has been shown in various aspects. The virtual laboratory teaches physics concepts to the user in an engaging way, currently focusing on electromagnetism principles, and is being actively developed. Results of corresponding studies showed unanimously a positive feedback on increased engagement and understanding for theories and physics laws taught in the simulation, especially such that would be too dangerous, expensive or simply not visible in real life (Pirker, Holly, et al., 2018; Pirker, Lesjak, & Guetl, 2017; Pirker, Lesjak, Parger, & Gütl, 2018).

2.4.2 Astrophysics and Gravitational Waves

Looking more specifically into gravitational waves as the topic we used for our simulation, we found they were already first discussed by Laplace in 1805 (Hammesfahr et al., 2000), proposed in 1905 by Henri Poincare (Poincaré, 1905) and predicted by Albert Einstein in 1916 (Cervantes-Cota, Galindo-Uribarri, & Smoot, 2016). Gravitational waves carry the gravitational force from accelerated objects infinitely through the universe. From general relativity, gravity can be expressed as space-time curvature caused by the presence of mass. Quadrupole accelerations of mass distributions will produce ripples in space-time(Weber, 2004). These ripples propagate at the speed of light, and are known as gravitational waves. They were not widely studied until the 1950s, when it was proved by Hermann Bondi that gravitational waves are physically observable and in fact carry energy (Bondi, 1960; Bondi, Van der Burg, & Metzner, 1962).

The first confirmed evidence for gravitational waves, so far, was in in 1974: Russell Alan Hulse and Joseph Hooton Taylor, Jr discovered a binary pulsar system(J. M. Taylor, 1982). Over the course of the following 8 years, the loss of orbit distance of these pulsars was measured and satisfied Einsteins prediction precisely and was an indirect, calculated proof of the existence of gravitational waves (J. M. Taylor, 1979; Weisberg & Huang, 2016). A Nobel Prize was awarded in 1993 for this discovery.

For more than 20 years there were several ongoing efforts, but gravitational waves have not yet been directly detected until in 2015: The Laser Interferometer Gravitational-Wave Observatory (LIGO) at Cal Tech directly sensed the distortions in space time caused by passing gravitational waves generated by two colliding black holes nearly 1.3 billion light years away, gaining the general interest of the public (B. P. Abbott et al., 2016; B. Abbott et al., 2004; Castelvecchi & Witze, 2016).

Newton mechanics cannot predict gravitational waves, due to the instantaneous force distribution. According to general relativity, no force can expand faster than the speed of light which includes gravity(E. F. Taylor & Wheeler, 1975; Yarman, 2006). Under normal conditions, the distance to massive objects is relatively constant or subject to a linear velocity. Should a massive body change the distance to an observer regularly (sinusoidal or pulsating), would result in a periodical difference in gravity force(Allen, Andersson, Kokkotas, & Schutz, 1998). Since the gravity force expanses with the speed of light, this periodical force shift propagates as waves. Moreover cosmological catastrophic events such as supernovae but also great moving masses can produce observable gravitational waves(Yakunin et al., 2010). One commonly described source are binary star systems, as was observed by LIGO, due to their orbit towards each other and the oscillating change of position relative to an outside observer in the orbit-plane.

2.4.3 Visualization of Gravitational Waves

The illustration of gravitational waves is subject of cosmology and theoretical physic lectures as well as popular science media in order to satisfy the general demand in exposition. The common methods are static images on whiteboards and visualized 3D simulations. Since in both cases depth impression is absence, the illustration is often reduced to a two dimensional representation in order to not overload the visuals. Furthermore the absence of interactivity is evident. Virtual Reality (VR) makes it possible to immerse the learner into a Virtual Learning Environment (VLE) (Callaghan et al., 2008; Dattalo et al., 2018; Pan, Cheok, Yang, Zhu, & Shi, 2006) that is enhancing, motivating and stimulating learners' understanding of certain events (Abdoli Sejzi, 2015; Kondo, 2006). Interactive VLE's have shown the ability to transmit physical phenomena surpassing traditional learning methods(Brown et al., 2019; Chu et al., 2019). Kitagawa et al. (2017) approached a study with the simulation of gravitational waves with a black hole as its source in their VR environment VIGOR. Similar to the project contained later in this work, they visualized the effects of their simulated gravitational waves on objects known to the user, in this case a human avatar and an earth-resembling planet. The learner is able to change properties of the gravitational waves according to will and thus intuitively learns from a causal relationship. One mentioned concern is that the visual overload can be overwhelming, especially for first time users of the simulation. Thus bimodal approaches are considered, with for example audio as a second channel, which has proved to be a good application for high volume information transition, as it improves the users information processing time.

2.4.4 Visualization Techniques with OpenGL

Due to the often complicated calculations that are necessary in order to determine truthful results in physics simulations, graphics frameworks or interfaces are required to ensure performance being satisfactory, especially in live simulations. While there are several possibilities to choose from, such as Vulkan[4], Apples Metal[5] or Microsofts DirectX[6], in the further part of this work the focus is going to be on OpenGL[7], due to portability and provided functionalities.

Already in 1997 the advantages of using OpenGL for sophisticated 3D visualization approaches have been brought up, especially due to the fact that the entrance barrier is less than other in depth graphics programming might require (Carr, 1997). While talking about *how* to implement appropriate visualizations we also have to keep in mind a quote of a very important physicist that brought up many underlying theories for the area of astrophysics about *why* proper visualizations are required: *"If I can't picture it, I can't understand it"* - Albert Einstein.

Especially in astrophysics, where simulations range often in multiple dimensions and contain enormous ranges of physical quantities, researchers found the necessity for appropriate calculation approaches and the utilization of graphics cards as a way

[4]https://www.khronos.org/vulkan/

[5]https://developer.apple.com/metal/

[6]https://docs.microsoft.com/en-gb/windows/win32/directx

[7]https://www.opengl.org/

to overcome some performance issues that appear in numerical simulations, which becomes most important in real time applications. Even the finite speed of light needs to be taken into account in such simulations, because the time it takes for the light in the virtual environment to reach the virtual observer sometimes has a big impact (Kapferer & Riser, 2008).

In a multi step approach on the analysis of OpenGL visualization various techniques of the framework and their advantages and applications have been researched in detail (Bailey, 2009, 2011, 2013). While important techniques like point cloud visualization or a discussion about the increase of depth impression with discarding pixels or manipulating alpha values are explained, it is pointed out that OpenGLs GPU shaders are not only usable for visual effects alone. While this might be the first thing that comes to ones mind while talking about shaders, next to glossy special effects they also can be used in order to further increase calculation performance due to the parallel computing nature of GPUs. Especially in part three of his analysis approach Bailey focuses on compute shaders, that can be used to enable two-way communication between CPU and GPU, thus introducing the possibility to outsource expensive calculations onto the GPU while using the results on the CPU.

Next to calculation time and performance impact the outcome resolution is of great importance for desired visual effects to be conceived appropriately by the viewer. For this often not only simple rendering concepts need to be adapted but a vital aspect of graphics programming needs to be taken care of, post processing. While Multisample Anti-Aliasing (MSAA) has been a tool most popular for a long time to do this important job, Jimenez et al., 2011 analysed upcoming alternatives and promising new approaches. This presents its very own specialized active research topic though and thus is not going to be further pursued in this work.

2.5 Summary

A great many developments are happening at a very frequent pace in all the different areas of education and while being an old research topic on its own, nowadays rapid changes in technology developments introduced whole new specialized disciplines with Technology-Enabled Active Learning(TEAL). STEM education requires increased attention and active development both on the sides of learners and educators the same. While not only different approaches from and towards the actively participating individuals in such learning processes are required, also whole new mindsets or a least changes of old ideas need to be introduced, as well as awareness to be created in order to make innovations in corresponding infrastructure possible.

VRLs are providing popular alternatives to the sometimes lacking traditional learning approaches and especially in an even more focused approach with VRLEs showed promising developments and positive influence where they are already in use. More and more the awareness of the potentials of TEAL and VLEs is raising but still requires more research and improvements. Technology in the industry is steadily improving and innovations are brought up frequently, thus also alternatives for lower cost systems are being more affordable and it could be indicated that even those would provide a vast array of positive effects if applied properly, with only slight disadvantages compared to more costly systems.

With several attributes being indicated that would benefit of further analysis, both the influence of haptics on learning effectiveness as well as visualization techniques in physics have been found to be of special interest. While both aspects are analysed in fairly specific applications, insights in both might lead to beneficial insights for the general topic of VRLEs. Haptic feedback in that sense is seen to be especially important in different high precision applications in medical and surgical simulations, where only visual feedback in virtual environments would not provide enough feeling and information to the user to create experience that could be translated into real world application. Even though there have been strong indications for the importance of haptics, a general consensus has not been found and a valid answer towards this questions is still required. Representing a prime example of complicated theorems and formulas, physics has already for a longer time looked into virtual representations of such and showed much success at that as well. Already many theorems of classical physics have gotten appropriate representations and their effectiveness has been proved. Thus, the assumption lies near, that new insights and breakthroughs could be appropriate applications for new VRLE approaches, specifically in more specialized areas like astrophysics. In such areas in the first place visualization techniques have a great impact on their performance and as such graphics libraries like OpenGL are frequently used, and their possibilities are looked at in much detail.

In the next chapter the first of these two mentioned projects is going to be discussed in a three part structure, explaining the corresponding design, its indicated requirements, the development of the resulting practical project and finally the accompanying user study and insights into the recorded data.

3 Haptic Feedback in Virtual Learning Environments

Due to the nature of this work being split into two separate approaches, concerning different aspects, the following chapter will focus on the first of those aspects: Haptic Feedback and it's influence in Virtual Learning Environments and details of the approach described in this work. First the focus will be on system requirements and design decisions for the approach. Then there will be details on the actual development of the project and finally the assessment and evaluation of the gained data and insights.

Some parts in the following chapters are taken directly or in a slightly adapted version from Lontschar, Deegan, Humer, Pietroszek, and Eckhardt (2020), as this was the corresponding scientific publication. These parts are indicated separately and contain parts of the original documentation and implementation of the project described over the further course of this chapter.

3.1 Concept and Design

This section is covering the main idea behind the approach chosen in this work, why these specific approaches were picked, the conceptual design of the system to be established and our identified requirements to it. The main idea for this project, that came out of corresponding literature research, was to find an appropriate setting, which allowed a certain mechanical task to be carried out in two equivalent ways, with (MR) and without(VR) haptic, to get a meaningful comparison of haptics effects. This basic idea also represents the main research question analysed over the course of this first project in this thesis.

3.1.1 Motivation and Goals

In Chapter 2.3 we identified uncertainty about the positive, negative or any effect at all of haptic feedback in VRLEs. Considering the fact that the intuitive idea about it is very appealing and there are some even contradicting opinions about it, we decided to analyse the matter in more detail. While various approaches on this topic have been tested already, some of them with very sophisticated hardware assistance, we took the decision to approach this in an affordable, simplified and specifically more generalized manner. Thus we concentrated mainly on finding an application that focuses less on very precise movements on a small scale, like for example explained in Chapter 2.3.4, but more on giving the user a feeling of weight and inertia of a body when interacting with virtual objects. The basic idea behind this evolved into creating a possibility to observe and draw conclusions on how an interface for learners, which feels natural to them, influences their behaviour and especially their development and progression inside a virtual environment. In order to create such possibility in a dual setting that yields comparable results, we found the necessity for our setup to be usable in virtual as well as in mixed reality. The specific requirements for this setup are going to be specified in the following chapters.

3.1.2 Requirement Analysis

In this section we discuss a fundamentally important aspect of software development projects. Defining the requirements of a project provides the possibility to consider the needs of a user from the application in terms of system operation as well as system behaviour (Chen, Ali Babar, & Nuseibeh, 2013). Additionally, we also have to take into consideration the need for an environment capable of providing means of comparison and measurement of various influences and different factors. Thus this section is split into functional and non-functional requirements, each concentrating on the respective aspect.

Functional Requirements

The main reason for this project is to analyse the effect of haptic feedback on learning behaviour of the user. Therefore the system has to provide an environment, where the user has the possibility to interact with the virtual world while at the same time experiencing the corresponding physical stimuli in the real world. For this to be feasible, a task has to be thought of, that can be carried out with and without haptics in the exact same manner, just with or without the added stimuli. In order to get comparable data, the task hast do be measurable and the corresponding information has to be processed and saved by a system for further analysis. The following list shows the determined requirements as follows:

1. Experiment Specific
    a) The experiment has to be usable in VR and MR
        i) Both variations need to be equivalent, safe for the haptic stimulus
    b) The user should be able to control the pace of the experiment
    c) It has to be possible for a supervisor to start, stop and reset the experiment, without making the user leave the environment.
    d) Information regarding their current performance have to be displayed to the user
2. Setup Specific
    a) The setup needs to be usable inside and outside, in order to have enough space for a wide area of interaction

b) It has to be mobile and possible to be transported
c) There have to be no obstacles in the way of any potential movements of the user
    i) If not avoidable, the virtual world should also display corresponding obstacles
d) The default view has to be directed towards the task to enable easier orientation

3. Task Specific
    a) The task needs to be in a way repetitive to be comparable but at the same time not boring for the users.
    b) It has to be clear for the user what to do at any time during the experiment.
    c) Every intractable object needs to be in range for the users without moving too much
    d) It needs to be possible to carry out the task with and without haptic feedback in an equivalent manner
    e) the objects need to be intractable equivalently in VR and MR
    f) The user has to have the possibility to reset the current task if against all safeguards something goes amiss

Non-Functional Requirements

As opposed to functional prerequisites, non-functional requirements are concerning system behaviour that is not directly connected to available functions. They are generally including software requirements such as usability, reliability, safety and availability. In the following list the required traits are defined as such:

1. Usability
    a) The simulations should be intuitive to use
    b) The task and aim should be clearly visible
    c) Feedback regarding the users performance should be distinctively shown without being distracting
    d) The behaviour of the simulation should be realistic and corresponding to the real world
2. Reliability
    a) All necessary data has to be saved and no information should be lost
    b) Fallbacks must ensure recovery of any potential problem
    c) The users experience be influenced as little as possible if something goes amiss
3. Performance and Responsiveness
    a) There should be no kind of lag or frame rate drops to prevent motion sickness
    b) The system has to be usable smoothly on a laptop

3.1.3 Design

Design Basis As we identified the need for an appropriate task and virtual environment for study participants during our analysis on haptic feedback effects, we decided to take a previous projects that concerned a similar matter as a starting point. This project involved a learning environment for understanding Newtonian mechanics in different planetary environments, specifically in terms of projectile motion caused by a throw. With this approach they managed to show an improvement in intuitive understanding of scale and order of Newtonian Mechanics in different conditions like gravity and air density (Brown et al., 2019).

Based on this first project and our identified requirements we decided on a first conceptual architecture as seen in Figure 3.1.

Approach Design Based on the idea of this project and to further expand on the question whether haptic feedback contributes to the learning outcome, as well as to assess the immersion in comparison with plain virtual feedback, we decided to develop a VR test environment which encompasses a simple mechanical task to throw objects towards a target. Over the course of the testing process, the object shape and weights, as well as the target distance should change for two separate groups of testers; both participating in the same VLE, but one group handling with real objects in MR, while the other one just using a virtual representation of such in VR.

Our basic premise was to identify a simple task which can be employed into a VLE. There we could introduce haptics for one group and non-haptics for a control group without changing any other simulation components. For that, a throw-and-hit assignment for VLE participants was conceptualized, where we are able to utilize haptics by having virtual objects for one testing group and real objects for the other one: Both groups use a VR headset and find themselves in a virtual environment. One group, referred to as mixed reality group (MR group) should throw real weights, with a trigger on the VR controller to check when they release the weight. The other group, referred to as virtual reality group (VR group), on the other hand, should have virtual weights only (Lontschar, Deegan, et al., 2020). Ensuring appropriate insights regarding the users experience and the corresponding operation inside the VLE we also require a questionnaire before and after the practical participation.

Implementation Design Having decided on the general approach and activity we can now focus on the design of the overall setup. In contrast to the previous project (Chapter 3.1.3), our approach is supposed to be connected to a known environments for the users. Therefore the visual environment has to be created in a manner that the users can relate to. The same counts for the objects which the users are going to interact with.

We identified the need for these objects to provide certain functionalities in order to be properly intractable for the user and also to be recognised appropriately by some

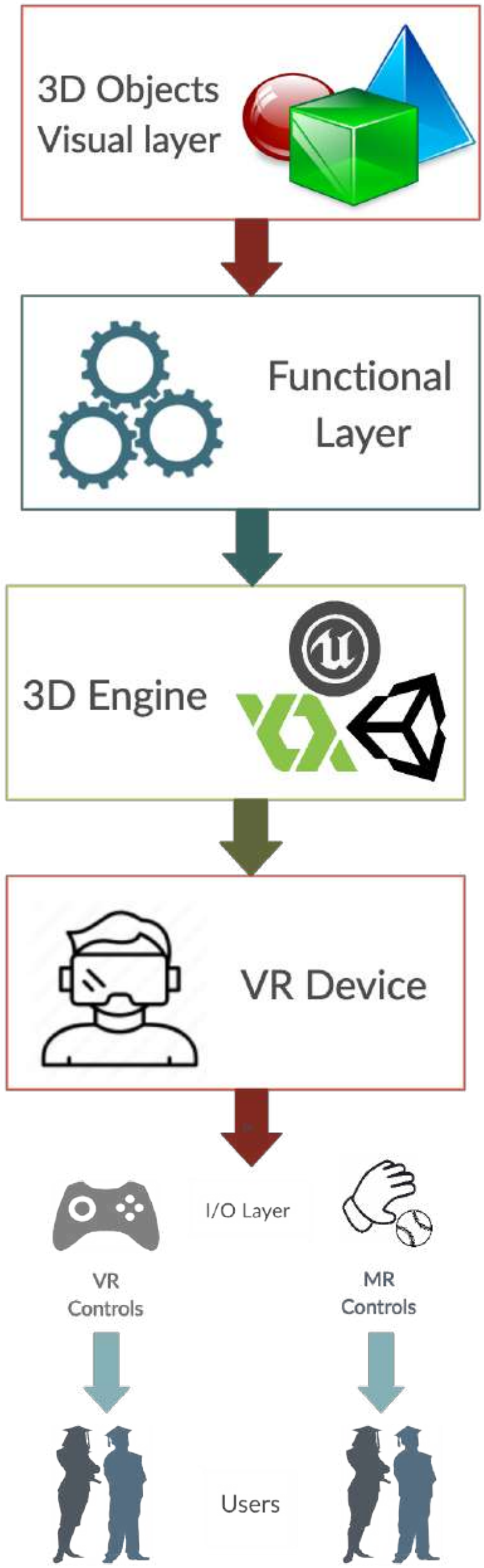


Figure 3.1: Conceptual Design

management and control system in the described environment. Therefore specific management or supervisor classes need to be developed, which control the whole study procedure functionally. They also need to provide some kind of informative feedback to the users, while saving different kinds of data in the background for later analysis by study supervisors.

Because three dimensional environments with customised settings can be created easily in a modern 3D engine, a least one scene in such engine is needed for assembling and representation of a corresponding environment.

User Interface As main concern in this project the users also need a way to interact with the setting actively that provides them with haptic feedback. Therefore a customised controller interface is required that allows the user to grab and hold on real world objects, which in turn has to be recognised by the corresponding virtual object. As users are inside the VLE they also need some kind information about what to do and how they are doing in VR. Therefore the environment needs to have some kind of display mechanism that shows the participant what they are supposed to do as well as what the progress status and their performance so far is.

Finally to differentiate distinct users and their corresponding data, there needs to be some kind of login screen in order to ensure appropriate connection of questionnaire and practical approach.

Data Acquisition Users have to be uniquely identified without any connection to their person, therefore random IDs have to be created before the testing. One of these IDs should be assigned to each participant which allows the connection of pre-, practical- and post-step of the study. Therefore, this approach includes several different aspects of behaviour of the user that all have to be recorded for further analysis. Thus, a general data acquisition and management system has to be implemented in the scene. Corresponding data has to be written to files with the appropriate user identification, so it can be further processed in the data analysis.

3.1.4 Tools and Frameworks

This subchapter introduces the most important technologies and why they were chosen over alternatives if applicable.

Python Because each separate study led to a many data sets being produced, it was not feasible to analyse the data by hand. To support the process of data analysis we decided to use Python 3 (G. Van Rossum & Drake, 2009) because we were familiar with the language and it provides a large built in choice of functionality that we could use, as well as many frameworks supporting further functionality. Additionally with some data sets we required and additional preprocessing step and this was done with C++ version 11 (Stroustrup, 2000), as here we could rely on some functionalities that was already used in previous projects.

Python Libraries To support reading data from raw CSV files in an appropriate format, we used the python CSV library as well as pandas, because of it's straightforward approach and easy access of the read data (McKinney et al., 2010; Shafranovich, 2005; Guido Van Rossum, 2020). For various calculations with the gained data and to further process it, we decided to make use of Numpy and SciPy as a first choice, as they provided all necessary functions in the shortest and least complicated way of turning raw data into what we wanted to know from it (Oliphant, 2006; Virtanen et al., 2020). Finally in order to create meaningful visual representations MatPlotLib was used , as the standard configuration of it's created plots was already very similar to what we planned to create and thus saved time in the visualization part (Hunter, 2007).

Head mounted displays All our experiments with user study participants were conducted with the head mounted display HTC Vive. This HMDs was chosen due to it's comparably high performance and wearing comfort over similarly price competitor models as well as the controller structure as this was an essential part for the adaptions taken in the study approach to enable optional haptic feedback.

Processors and Graphics Cards Each device used to run our projects was driven by Nvidia graphics cards and Intel or AMD processors. The PC we used in the lab environment used a GTX 1080Ti graphics card and an AMD Ryzen 7 CPU. Because one part of the project was carried out in the outside, we were also using a Laptop to run the respective software, which was equipped with an Intel Core i7 4770K processor and a NVidia GeForce GTX 1070 graphics card.

Unity Providing an incredibly large array of functionalities and countless community driven packages for various different visual and interactive applications, we decided to combine functionality and visual representations in this project in Unity (Haas, 2014; Technologies, 2019). Expertise and given functionality for the game engine was main factor for the choice over alternatives like Unreal Engine, GameMaker or others[1].

SteamVR In order to access the HMDs with our software we used SteamVR [2] and the SteamVR package in Unity. In Unity's environment the SteamVR package provided all data handling from and to our program and thus made this part of the project trivial, therefore it was an easy choice. Alternatives exist in the form of libraries from different alternative providers, but as previous experience with SteamVR was given and it's functionality was sufficient, there was no need found to experiment with alternatives.

Miscellaneous In this paragraph some more important tools for the study are explained, which are not necessary in any defined variation and thus not further specified, but crucial for the overall approach.

[1]https://www.gamedesigning.org/career/video-game-engines/

[2]https://store.steampowered.com/steamvr

In order to create a sustainable way of mounting the modified controller of the HTC vive we used a conventional fabric glove, stitched to the controller to fixate its position and held in place with medical bandage tape.

A power supply was necessary for the outdoor setup. For this we used a conventional gasoline driven, portable, electrical generator unit. The only important part here is that it provides enough power to ensure continuous functionality for both the VR headset and the laptop; a generator with maximum output of 3000W was comfortably sufficient in our case.

3.1.5 Summary

In this chapter the intended design and concept for this project were discussed, followed by it's identified requirements and the used tools to achieve the desired outcome in the further development of the corresponding project. There was no specific target group in mind but the intention for this project was to provide a foundation for further and more specialized analysis approaches, while already leading to first insights and confirmations of initial assumptions. The main idea of this implementation was to develop an task in a gamified environment that could be carried out in a VR and an MR environment equivalently in order to create comparable data on the influence of actual real world haptics. Due to this fact a very important aspect in the requirements to pay attention to was participants safety, as handling with real world objects in VR while not actually seeing them provides potential risks to be taken care of. The resulting design in compliance with the indicated requirements provided the baseline for such VRLE that could provide the desired results.

3.2 Development

To gain a measurable outcome we created a Virtual Learning Environment resembling a soccer stadium (see Fig. 3.2). "Learning" in the further course of this chapter relates to the improvement of accuracy and so the gain of intuitive experience of each participant. In this virtual stadium all participants were given the general task of throwing objects into targets multiple times while trying to improve themselves to the best of their ability. In this chapter the final system architecture is described shortly, followed by an explanation of the implemented user interface for test users and supervisor, a detailed view on throwing mechanics, followed by an insight into the points calculation. For further insights on how the immersion is being influenced by haptic feedback we had each participant complete a survey before and after the VLE experience (see Section 3.3.2).

Figure 3.2: View of the participant in the VLE with example objects on the left, current target in front and information blackboard on the right.

3.2.1 System Architecture

Based on the initial design and after analysing requirements and deciding on implementation details, we created a conceptual architecture representing the experiment workflow (See Figure 3.3). Most of the physics behaviour was taken as-is from unity built in physics, as this provided sufficiently realistic behaviour which was in line with the real world equivalent in MR. In order to create a non-blocking workflow, we split the practical and questionnaire part onto two devices, enabling parallel runs for two users; here we only concentrate on the practical part. To ensure proper data flow and preservation of all important information, we created an observer class, which listened to trigger events in the scene in order to evaluate current object and user positions, thus saving corresponding data on grab, release and impact. Each object, throwables and targets, had their own minor functionality and were managed by throwable- and target-spawner classes respectively. The billboard class was reading data gained from the observer and handled any display of information towards the user, more details on that in the corresponding section. The controller class was designed to evaluate the users hand position and translate it into the game appropriately. Additionally the controller only served one interaction mechanic for the user, which was a grab event that was technically translated into a trigger press, more details on that in the controls section (Section 3.3.2).

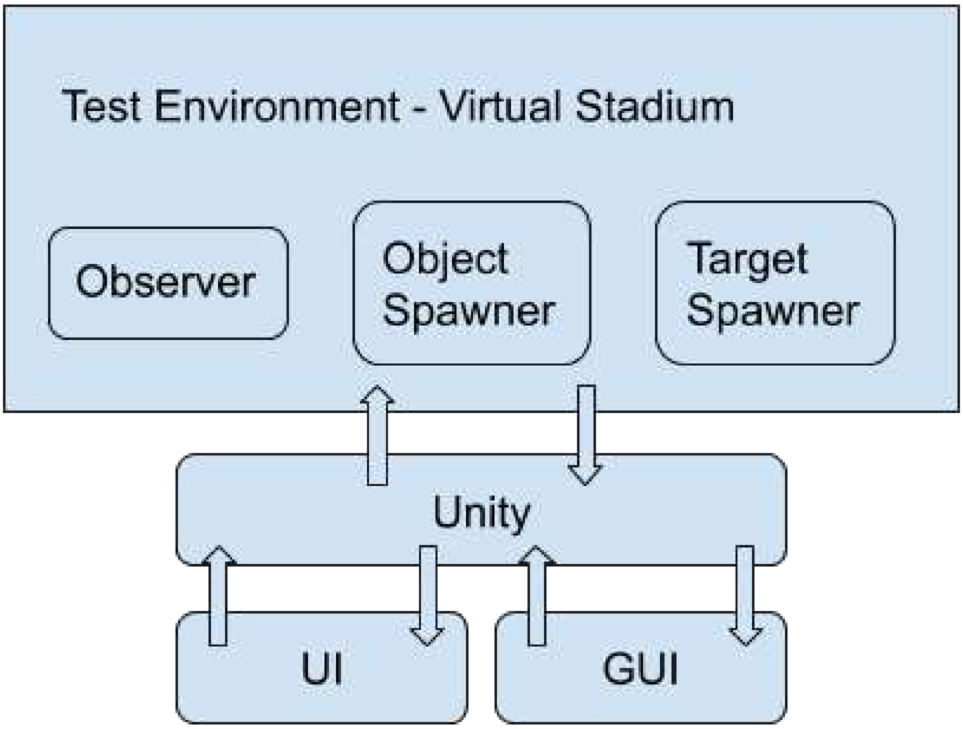


Figure 3.3: System Architecture

3.2.2 Spawners

Because our chosen task includes repeatable behaviour we needed to implement some kind of spawning management for both throwable objects and targets to hit. The resulting ObjectSpawner and TargetSpawner classes have been implemented as prefabs and work automatically during the test process with internal counters in order to stay aware of the current test progress. Both spawner prefabs had all spawnable objects assigned in the prefab interface and follows a process according to our designed test procedure. Thus spawning targets at slightly increasing distances for each throw. Additionally a throwable object is spawned upon throw initiation, in our case a grab movement (See Figure 3.4). After recognition of an objects impact on the ground after a valid throw, the next target is automatically spawned as soon as the next grab movement is made. After five throws with each object, the ObjectSpawner increments a counter and spawns the next object in list, while the target spawner resets the distance to initial and starts increasing again. This procedure is repeated five times, resulting in 25 throws. Afterwards the user can spawn the latest object and repeat throws without any data being recorded any more until supervisor interaction.

Figure 3.4: All available throwables. Normally they are only visible on task engagement.

3.2.3 User Interface and Interaction

Information flow to and from the user is split into user interface (UI) and graphical user interface(GUI) as a specific subset of UI, and this separation is important in this project; each of those are explained in the following subsections.

GUI

The GUI contains all visual information for the user. This encompasses informative data as well as visual feedback in the form of effects and system behaviour that reflects the users actions. As an entry point, a main menu scene represents the first GUI, which is only visible to the supervisor. Here is the possibility to enter the study participants ID number and choose between VR and MR version of the virtual environment. The user him- or herself does not have the possibility for any alphanumeric input whatsoever because it is not required in any way In the conventional sense GUI in this project in game is represented in an implementation of a dynamic blackboard. This blackboard stands in the scene and contains an empty grid which is ordered according to the test process, six rows and columns, containing a header row and column each, along with five associated data cells (3.5). See Section 3.2.4 for further information on how this information was calculated.

Figure 3.5: Ingame view on the information blackboard with scores achieved in four throws

UI

User Interface represents every possibility how information can flow between the user and the virtual environment. This includes textual information, visual representations and also interactions. The environment has been designed so that the only necessary user interaction is grabbing and throwing objects as required by the designed task. Thus the only active interface for the user is the modified controller (See Figure 3.7).

Throwing mechanics The design of this controller allows the system to work equivalently with or without throwable objects in the real world. The copper conductors on thumb and index finger serve as trigger and can simply be pressed together, thus initiating a grab event that is registered by the environment. The objects behaviour in the game is designed to behave like a real object to make the feel upon release as natural as possible. In order to achieve this, the virtual object was fixed onto a position as close as possible to where it would be in the real world, relative to the users hand position. For each frame, position and velocity of the controller and object were recorded and upon release a corresponding release velocity and direction calculated, thus enabling a natural behaviour with the help of built in unity physics.

3.2.4 Points System

To keep the testing process engaging and to enhance some motivation, a scoring system was implemented, therefore creating a game of sorts. The scores calculated with this system were represented on the in game blackboard. This was to provide some meaningful feedback and possible feeling of accomplishment for the participants. Each throw was allotted a certain number of points, representing the inverse distance from the centre of the target to hit, with the target being separated in four areas worth four to one points, starting from the middle. Every object that hit the ground without any target was counted as failed throw and assigned zero points. For each of the five throwable objects there was a sum of points to represent the set and also there was an overall sum at the end, that was used to have some kind of high score system.

The points system was purely an abstraction of some recorded data which was saved for further analysis. The distance of the targets middle point towards the thrown objects impact point was calculated. We defined a length of the radius of the target as maximum distance to be eligible for points and linearly increased them starting from one to a maximum of four, in steps of four. Even though the representation was only an abstraction it still posed an essential part to increase participants motivation and engagement with the added gamification.

3.2.5 Summary

In this chapter the actual development process of this project was described. After a short introduction the system architecture was looked at in detail to get an overview understanding of the process taken. Here it was suggested, how the choices taken in Chapter 3.1.3 were leading towards an system that could be used in two settings that made a meaningful comparison of haptics in VR possible. Then the most important steps of this development process were described, with them being especially the designed user interface and controls, devised to enable this hybrid system, the implemented spawner system used to create a half automated testing process and finally the high scores, which included an essential gamification element.

Everything during the implementation phase has been made in Unity3D with the used scripts written in Visual Studio. Both variants, in MR as well as in VR, used an HTC Vive HMD with a modified standard controller. Our main contribution in this approach was the witty modification of standard equipment that enabled an easy to use mixed reality setup as well as the tasks designed for comparable results of both setup version.

3.3 Evaluation

In order to evaluate the outcome of our approach an A/B user study has been conducted with n = 56 participants. This was because the main intention of our approach was to compare one same experiment with and without haptics, to identify advantages or disadvantages of their influence. Next to analysing performance values, our study concentrated on a comparison of engagement, immersion and user experience between a MR and a VR setting. In this section the testing environment that was used for this project is going to be explained, followed by details about the used approach, information about the participating users and finally and assessment and evaluation of the gained data and insights.

3.3.1 Testing Environment

As discussed in Chapter 3.1.3 the study approach is separated into two groups of participants, one for the mixed reality setup and the other for the VR one, each in the same virtual environment but a different physical location.

Because the testing process in MR involves throwing of up to 2kg heavy objects up to a distance of roughly 25m, a safe environment was necessary as to prevent damage to man and material. Therefore we decided to set the testing environment up on a sports field on Cal Poly campus (See figure 3.6). The control groups in pure VR did not involve anything but the arm movements during the throwing process and thus did not have any special requirements for the environment; therefore the control group conducted the testing process in a classical lab on campus.

Due to the setup being used indoors in a lab environment as well as outdoors on the sports field, it was necessary for the simulation to run on two devices. We used a Windows PC with an Intel Core i7 4770K processor and a NVidia GeForce GTX 1070 graphics card for testing on the field and a Windows PC with an AMD Ryzen 7 and a NVidia GeForce GTX 1080Ti in the lab. Both setups used the HTC Vive HMD as immersive display with the corresponding modified controller as seen in Fig. **??**.

Additional to the test setup we also required a separate laptop as an interface for study participants to fill in the pre- and post-questionnaires. As this device had no special hardware requirements other than being able to open a webpage in a common bowser we used a MacBook Pro for this.

3.3.2 Procedure

The following part is taken from Lontschar, Deegan, et al. (2020).

In order to get comparable values, each participant was placed at the same position in the stadium and given some time to get accustomed to the environment. The testing was started by supervisor interaction and afterwards run by the participant. The task was to take a virtual object (see Table 3.1) and throw it to a target that spawns in front of the participant on the field. The targets were divided into four sections to

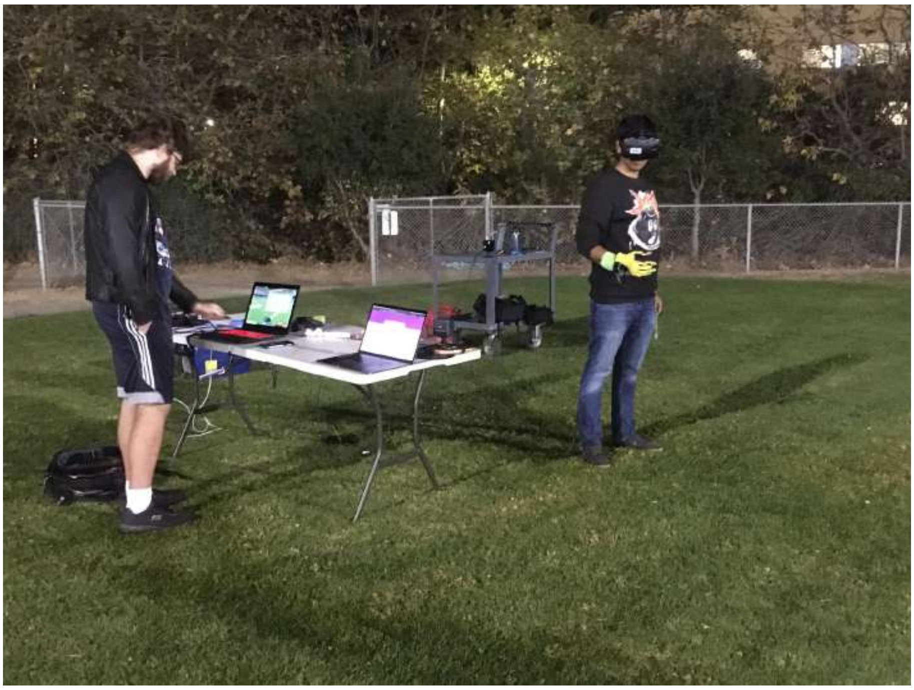


Figure 3.6: Testing setup on the sports field of Cal Poly campus during a test run with a study participant and a supervisor administering the testing process from the laptop.

give the user visual feedback as well as to include gamified gained points calculation to increase motivation. The distance varied randomly for each section between 8ft and 50ft. Each section required 5 throws. Information about the last throw such as strength and angle were displayed on a blackboard on the right side of the test field and participants were encouraged to use this information for help if necessary. After each throw some data (see Section 3.3.2) was saved by the simulation and at the end of each test run, everything was written to a file in JSON format including the participants ID. The weights were chosen to be reasonable within a margin for participants to throw with one hand. For each weight/distance pair, the participants need to intuitively pre-calculate the necessary force on the weight to hit the target. Whether or not real weights add to ones immersion and positive feedback in comparison with a full virtual environment is the given research question.

Type	MR	VR
Baseball	0.19kg	virtual
Weight Disc #1	0.25kg	virtual
Weight Disc #2	0.5kg	virtual
Weight Disc #3	1.5kg	virtual

Table 3.1: Different throwables and their respective weights

Figure 3.7: Left picture shows the empty glove controller that was used during testing. Right picture shows an example how the baseball is held and therefore sending a signal to the simulation.

Controls

To create a more realistic interaction with the simulation, we modified the controller of the HTC Vive. In order to let participants forget that they are actually using controls, we used a common cloth glove and stitched the modified vive controller on it. This glove and the controller have been attached with soft tape to the participants arm in order to prevent it from moving or falling off during the process of a throw movement. We used thin electric cables that were welded inside the controller on the positive and negative contacts of its trigger; these cables were attached to the glove with copper tape to ensure connectivity (see picture 3.7). With this preparation the participants were able to simply tip their index finger and thumb together to send a signal to the simulation. In order to have reasonable haptic feedback for throwing tasks, the testing for MR was conducted on the lower sports complex on Cal Poly campus. This was necessary to prevent accidents or broken glass by throwing weight discs or baseballs. All throwable objects, meaning the baseball and all different types of weight discs, were wrapped with the same conducting copper foil as was the gloves on the controller. Hence, as soon as the user picked up the object it spawned in the simulation at their hand position. In comparison to the MR group, VR participants only had to wear the glove but did not get any weights. They had to interact with pre-spawned virtual objects and just close the connection with their index finger and thumb on the objects position to attach it to their hand. Both version would then move their arms in a manner how they would normally throw and the movement of the controller got tracked and hence the appropriate velocity and direction for the virtual object could be calculated.

Data acquisition

For each throw various data points were saved for later analysis. Those data points included first and foremost the distance between the target and the impact point of the object with the ground, the type of object, sequence number of the throw as well as applied force and release angle of the object.

Questionnaire

Participants were required to fill a pre and post questionnaire respectively before and after experiencing the VLE. The pre questionnaire collected demographics, the post questionnaire assessed immersive attributes after finishing the tasks in the VLE. The post questionnaire was structured in the form of the Game Experience QuestionnaireIJsselsteijn, de Kort, and Poels, 2013. It contained questions for "during" the VLE which included competence, sensory and imaginative immersion, flow, tension or annoyance, challenge as well as positive or negative effects. The questions regarding "after" the experience in form of the Game Immersion QuestionnaireJennett et al., 2008 assess the attributes attention, temporal dissociation, transportation, emotional involvement, challenge and enjoyment.

3.3.3 Participants

We conducted our research for this study with a participants group of size n = 56. These were split into MR and VR group but the split is not reflected in our demographic data. Of the 56 participants, 34 were male, 19 female and 2 identified as other. All participants were university students, most of them from Cal Poly San Luis Obispo, and the average age was 20.59 years old, ranging from 18 to 25. 83.9% had some college credit but no finished degree (See Figure 4.8).

More than half of the participants (58.90%) indicated no or very little previous experience in VR and only one participant though to have expertise in VR usage 3.9.

3.3.4 Assessment

In order to find differences in learning experience between pure VR and MR with haptic feedback, we had our participants engage in two different versions of our research simulation. We tested 40 participants in the MR and 16 in the VR group. The reason for this is the nature of the improvised environment, especially the copper conduction to check a throw in MR, which did not always work properly and a consequential frustration could bias the results. To level out these fluctuations, we put more participants into the MR group.

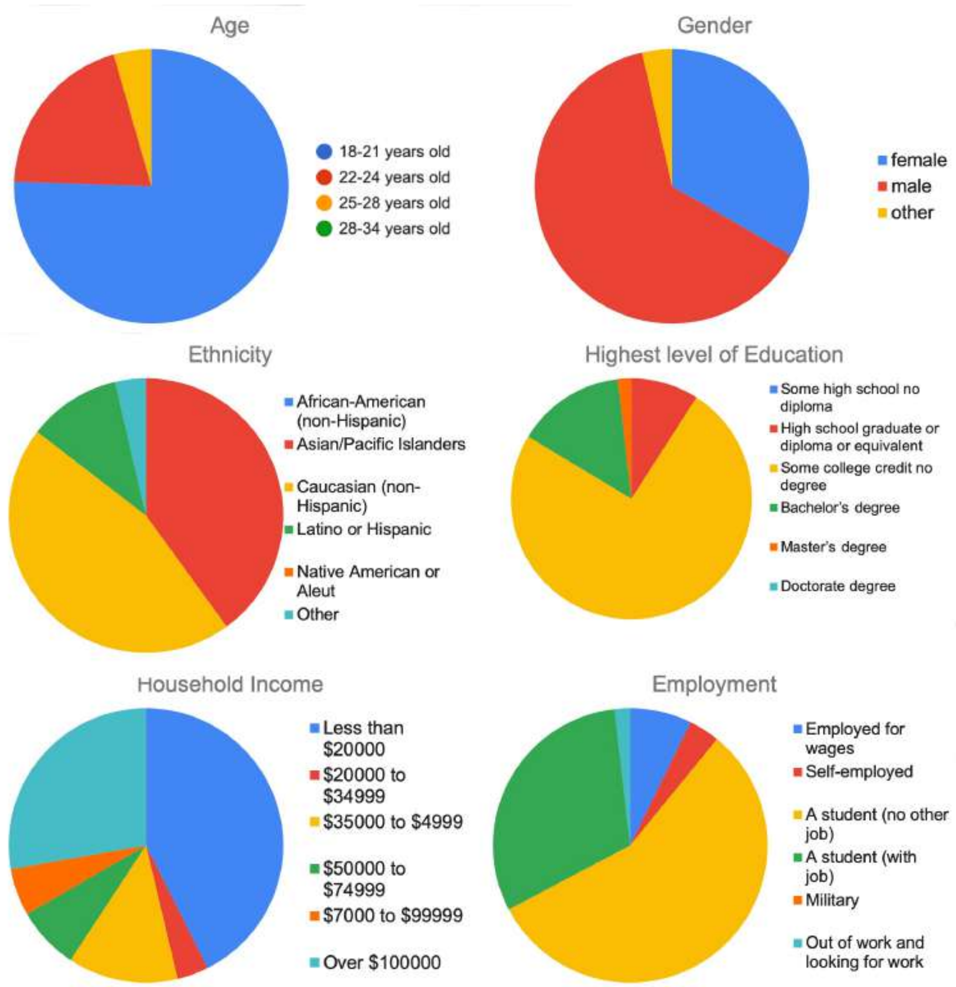


Figure 3.8: Participants demographics. Distribution of the participants age, gender, ethnicity, education, household income and employment.

3.3.5 Findings and Discussion

In this section we will discuss in more detail the gained results from the evaluation and what we can read from them. In order to create these graphs we used a script written in Python. The script read the data provided from both the JSON file of the practical part and the pre- and post-questionnaire answers. As an intermediate step we used a C++ script to extract certain data areas, which were of special interest for our analysis. Areas like all corresponding data for the best third users that achieved the highest learning increase. This data was also read by the Python script, which in turn let us visualize the data in corresponding plots. Some of the most important of these plots will be discussed in more detail in this section.

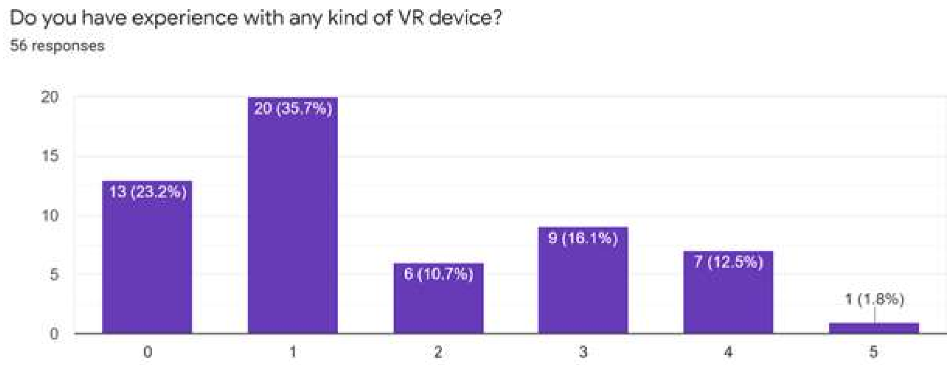


Figure 3.9: VR experience of the tested group: We asked about the level of VR experience on a scale from 0 (not at all) to 5 (a lot).

Throw Data

The acquired data from our participants indicate, that on average, the distance (difference of the impact point to the target center) and improvement assessment (shortening or lengthening the distance over time) for both groups are strikingly similar as can be seen in Fig. 3.10 and the small variances are in regards to the standard deviation statistically irrelevant. However, there is an observable increased improvement outcome for MR participants in certain conditions during the simulation, which is more prominently pronounced when taking a look at the improvement for each single weight object as can be seen in Fig. 3.11.

The distance, as well as improvement for each weight is displayed in this figure and shows a very distinct trend: For lighter weights, the MR participant initially showed a better distance to target outcome ("Baseball #1" and "Weight 0.5 lb"). A similar result was seen when the object's weight was reduced compared to the previous object (from "Weight 2.5lb" to "Baseball #2") in comparison with the VR group. In contrast to that, bigger weights resulted in a greater distance to the target center than for the VR participants, and the improvement was lower as well ("Weight 1lb" and "Weight 2.5lb"). Based on direct verbal feedback of our MR group, we conclude, that the handling of bigger weights is perceived unwieldy. However, the MR group showed a higher learning in comparison to the VR group whenever a larger weight change was instructed.

Further on, we investigated the outcome for the best and worst performances in regard to distance to the target, as well as improvement. Comparing the average distance and the improvement outcome of the upper and lower third of aiming performances in Fig. 3.12, the similarities are still noteworthy, although the improvement for VR participants has a less pronounced standard deviation for best and worst, an effect which is to be found reversed in comparing the best- and worst third improvements as can be seen in Fig. 3.13, but still governed by comparable values. A slight trend

Figure 3.10: Average Distance and Learning of all Participants: (red) for VR and (cyan) for MR participants.

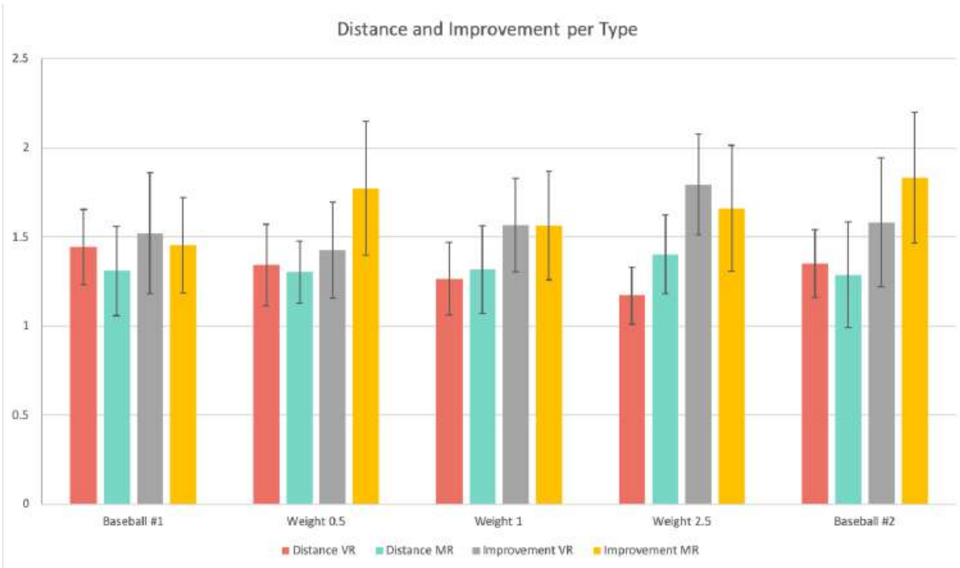


Figure 3.11: Average Distance and Learning per different object/weight type: (red) distance in VR, (cyan) distance for MR, (grey) improvement for VR and (yellow) improvement for MR.

can be observed, showing a trend that the best accurate participants would improve their accuracy more in MR, while the worst accurate participants show a greater improvement in VR. We found that this correlates well with the immersion feedback we received from the Game Experience Questionnaire which we will discuss in the next subsection.

Overall, we could not observe any statistically relevant variance in our data, which

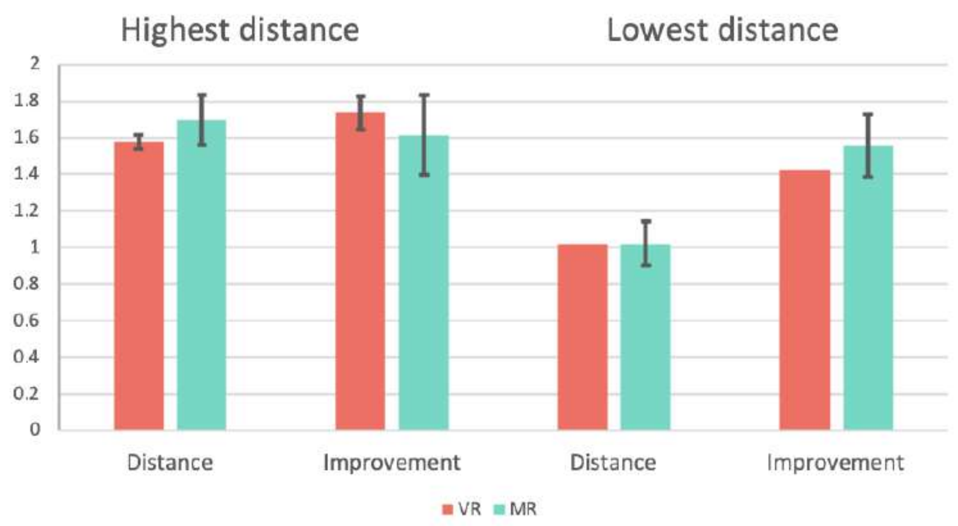


Figure 3.12: Average Distance and Learning for most and least accurate participants: (red) VR and (cyan) for MR.

would underline a notable different performance or improvement result for either group. While there are trends regarding the standard deviation, the results do not indicate any particular improvement of our MR testing group. Note, that we tested a simple mechanical movement, which requires only a basic skillset: throwing objects towards a target. Triggering the let-go point with a simple switch is proven to be effective in games, and works similar in our VR testing environment. Consequently we did not expect better performing MR participants, but the similarity in improvement was unforeseen. A closer investigation in their perceived immersion followed.

Immersion

Conducting the Game Experience Questionnaire to assess the immersion during the VLE experience followed by the Game Immersion Questionnaire do measure the immersion felt after the testing, one can recognise a similar outcome as can be seen in Fig. 3.14.

While there are small variations such as a tendency for MR to feel more involved and also competent during the experience but also claim a slightly higher stress value, we understood that MR participants had to concentrate on a lot more things at the same time to fulfill the given task of hitting the targets. While having a weight in their hand improved their intuition for their interaction it also required additional attention. They also had to focus on holding and releasing the objects in the correct manner, as opposed to the VR group where holding their fingers together was very much resembling the simplicity of pressing a button on a common controller. However, these variations in the given data are small and considering the standard deviation displayed in Fig. 3.14, of minor significance.

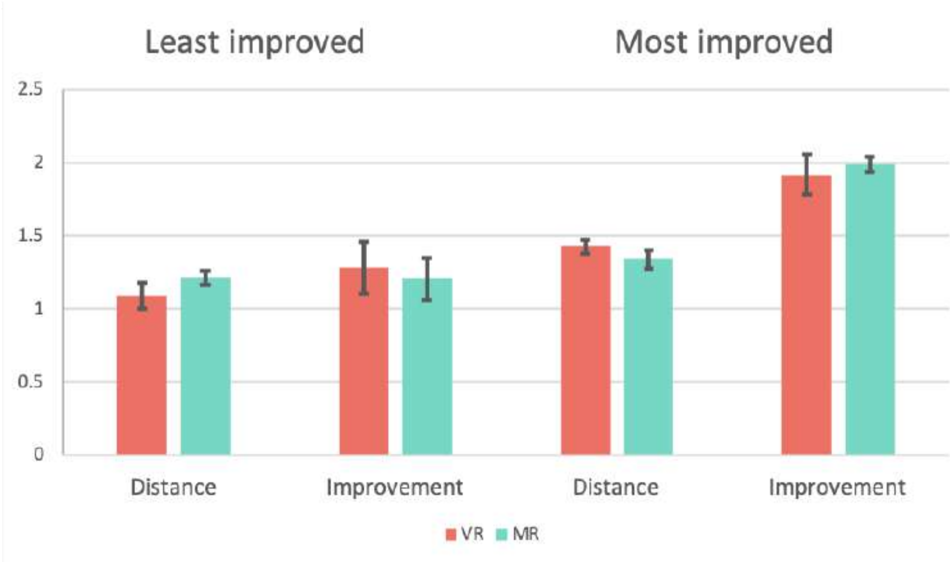


Figure 3.13: Average Distance and Learning for best and worst improving third of our testing group. (red) VR and (cyan) MR participants.

Taking a better look into the best third performances in regards to aiming, the Game Experience Questionnaire delivers notable deviations shown in Fig. 3.15 (a). Here we see the immersion values during the experience are distinctively increased and above the standard deviation for accurate MR participants. It is interesting to note that Fig. 3.18 (a) showing an overall better immersion for MR during the simulation also indicates better attention to fulfill the task at hand, even though the average outcome does not support this. In contrast to this findings, Fig. 3.18 (b) showing similar data points for the immersion perceived after the VLE experience. We interpret this trend as a result of the sense of accomplishment, which could be found in both groups due to their similar performances.

Among the third of participants with the highest measured rate of improvement, those in the MR group reported a higher average immersion for sensory and imaginative immersion as well as flow and transportation than those in the VR group, see Fig. 3.17 (a) and (b). The levels for competence, tension and annoyance, challenge and positive/negative effects, basic attention, temporal dissociation, challenge perceived after the VLE experience, emotional involvement and enjoyment vary only statistically insignificant. However, the strong difference in the standard deviation for enjoyment and especially negative effects is noteworthy and a result of frustration for handling the heavier weights in virtual reality. This trend was present both during and after the simulation as seen in Fig. 3.17 (a) and (b).

Investigating the immersion for the worst third performer in regards to closing the distance to the target, only the basic attention has a significant higher basic attention for the MR group, which is explainable due to the increased required concentration when handling real objects for those with less skills for accuracy. This can be seen in Fig. 3.16. All other immersion indicators show a similar behavior for both groups.

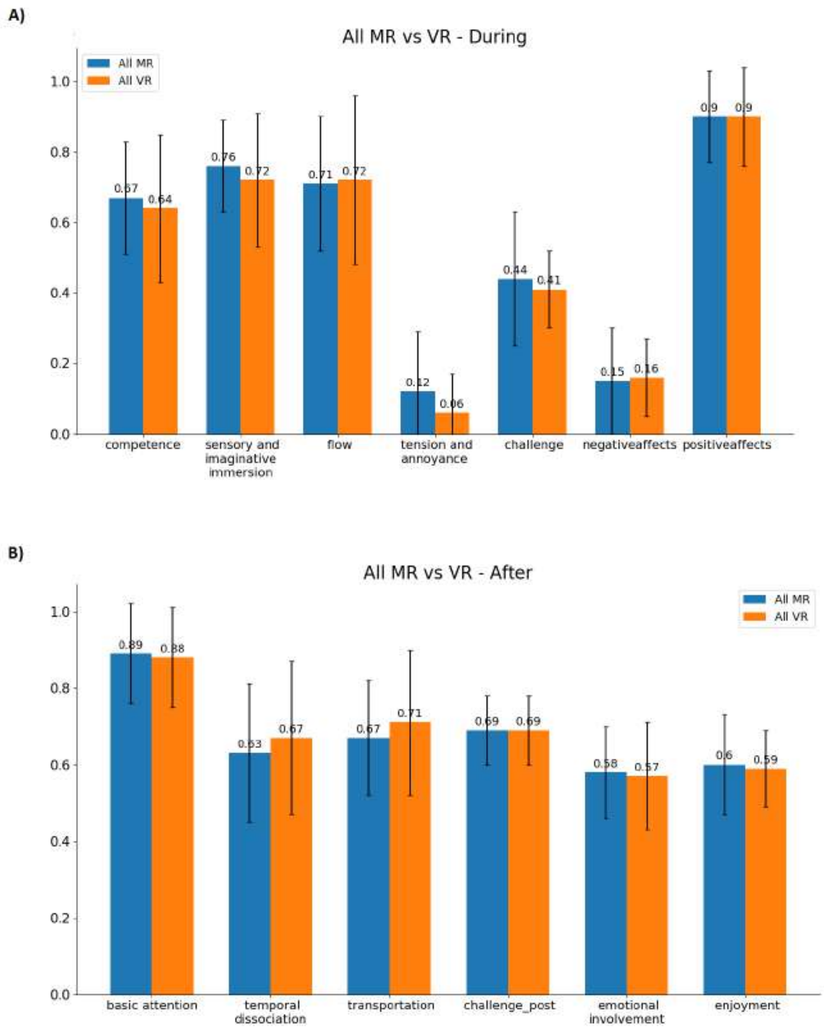


Figure 3.14: Average immersion before and after the VLE experience: (blue) MR and (orange) VR group. Each value is in the range from 0 (not at all) to 1 (absolutely).

Thus, participants whose average distance to the target was in the lower third of all participant reported noticeably higher tension and challenge scores than those in the upper third- especially in MR.

As for the lower third of improvement seen in Fig. 3.17 and 3.18, compared to those in the highest third of learning displayed in Fig. 3.17 (a) and (b), those in the lowest third reported higher sensory immersion and basic attention for the MR group, and higher sensory immersion, flow, challenge, temporal dissociation, transportation, emotional involvement, and enjoyment for the VR group, underlining the principle trend for handling real weights.

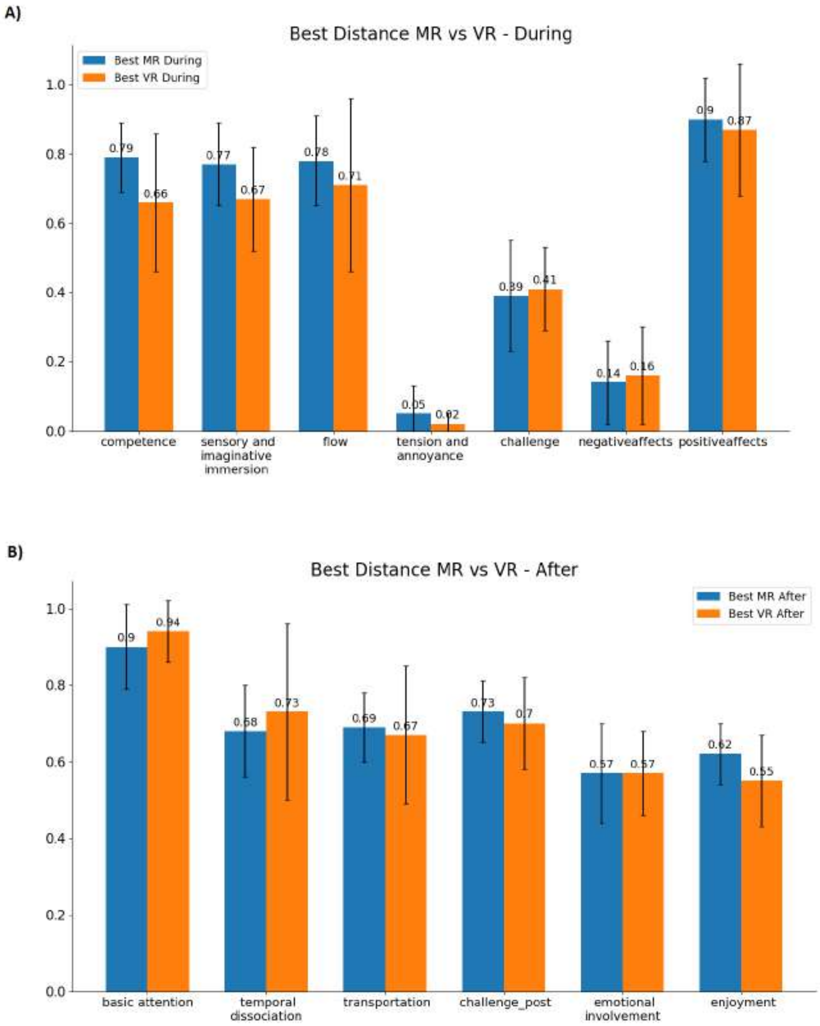


Figure 3.15: Immersion values for the best third aiming performances during and after simulation: (blue) MR and (orange) VR group. Each value is in the range from 0 (not at all) to 1 (absolutely).

Restrictions and Limitations

Due to the makeshift origin of the participants controls we sometimes encountered problems with connectivity between the controller and the object during the test sessions. We anticipated that this issue might negatively affect gained immersion, hence we kept this in mind while analysing the results. Unfortunately, due to an undiscovered bug in earlier versions of the simulation we had to delete some single invalid data points, and their negative consequences on the learning curve of some data sets needed to be excluded from our analysis.

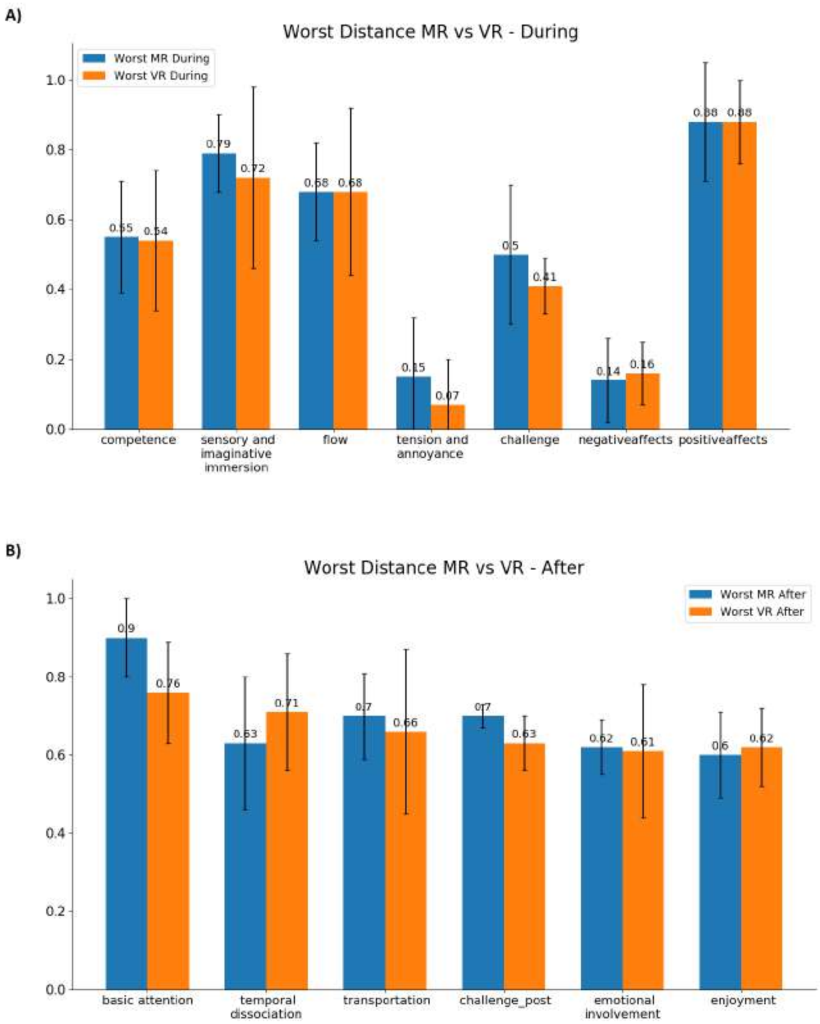


Figure 3.16: Immersion values for the worst third distance during and after simulation: (blue) MR and (orange) VR group. Each value is in the range from 0 (not at all) to 1 (absolutely).

3.3.6 Summary

Over the course of this chapter the user study was explained in detail, starting from the environment established for the testing process, both in MR and VR, over the study procedure and finishing with insights gained from the produced data. Because it was of special importance to our approach, the tasks designed for usage in both environments were explained and how and why they were chosen. Furthermore, the modified controls that were used were discussed in order to make the approach cleared without having used the setup. Especially the way the controllers were modified to serve our desired needs got lit up and how the internal wirings were adapted in order to make an outer interaction with physical real world objects possible. Finally an

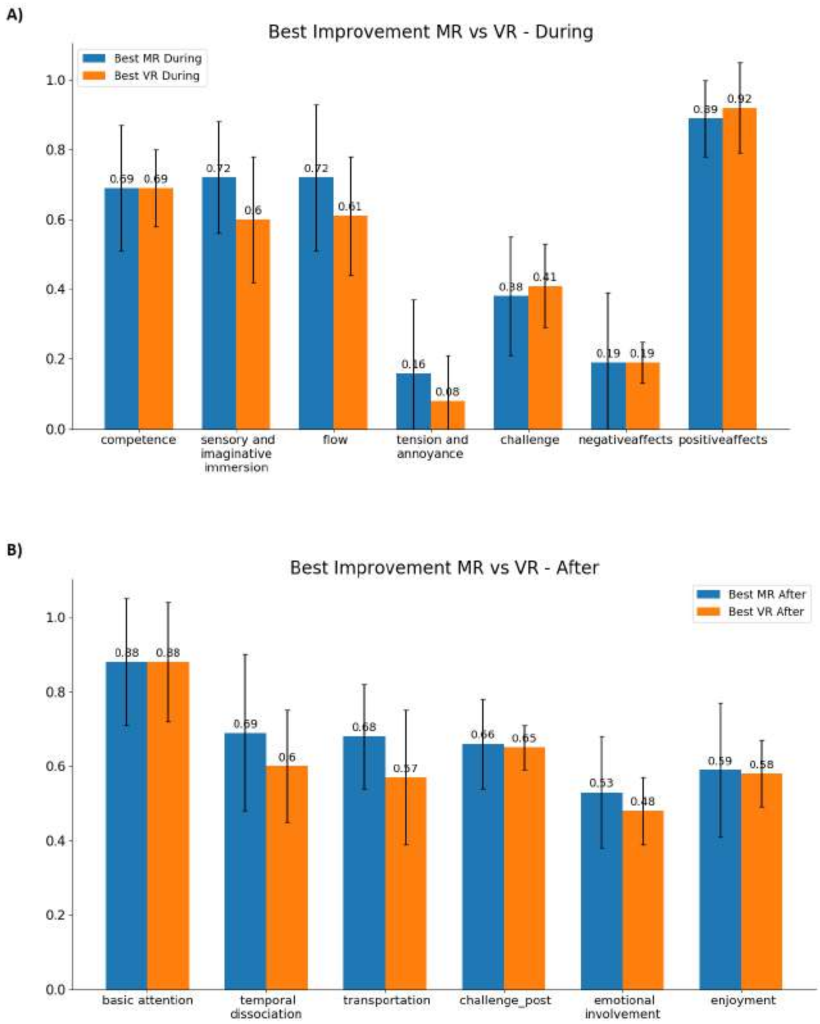
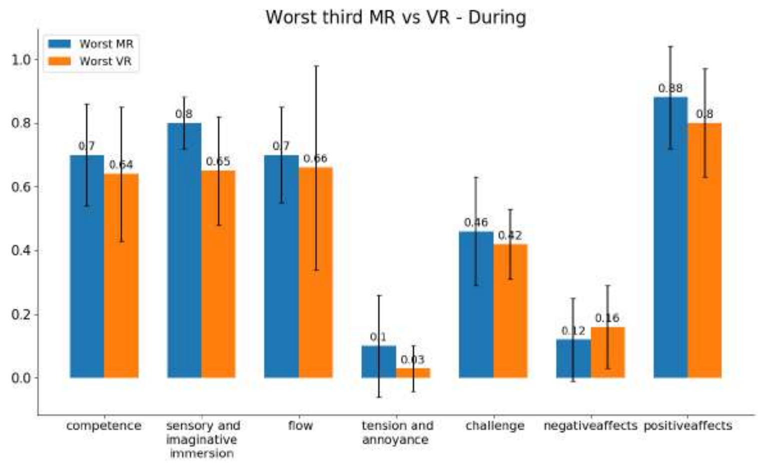


Figure 3.17: Immersion values for participants with the best third improvement outcome during and after simulation: (blue) MR and (orange) VR group. Each value is in the range from 0 (not at all) to 1 (absolutely).

extensive insight into the gained data and the corresponding assessments is given, first focusing on the actual performance values and their development in accordance to the identified learning and gain of better understanding for the environment, followed by a breakdown of the reported immersion values of specific user groups in combination with their respective study results.



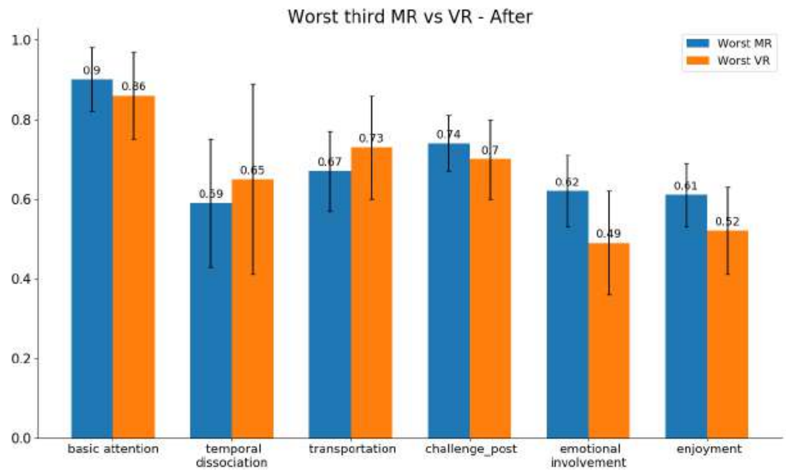


Figure 3.18: Immersion values for the worst third learner during and after simulation: (blue) MR and (orange) VR group. Each value is in the range from 0 (not at all) to 1 (absolutely).

4 Physics Visualization in Virtual Learning Environments

Due to the nature of this work consisting of two separate analysis approaches of effects on Virtual Learning Environments, the following chapter focuses on the second part: Visualization Techniques for Physics phenomena in VRLEs. First the focus will be on system requirements and design decisions for the approach. Then there will be details on the actual development of the project and finally the assessment and evaluation of the gained data and insights. Some parts of this chapter are taken from Lontschar, Pietroszek, Humer, and Eckhardt (2020), as this was the paper produced during the development of this project.

4.1 Concept and Design

In this section insights about this projects basic idea and motivation will be provided. Then the intended target group is going to be explained, follower by a detailed project description, the requirement analysis and finally an overview over the most important tools during the implementation process and the user study. Following up on an idea that appeared in an unrelated discussion, we dug deeper into the matter and its related research. There a general need for an easy to understand explanation of gravitational waves, without any required previous knowledge was identified and thus this muse was further pursued.

4.1.1 Motivation and Goals

In Chapter 2.4 we identified a general tendency that physics theories can be displayed properly and understandably in VR. Furthermore, the visualization of gravitational waves proved to be an even more complicated matter than other abstract theorems and conventional methods like colour coding would apparently not provide desired results, thus alternative methods are required. The need for an immersive and interactive representation of gravitational waves was clear, the idea of GraViz was born. As a first step of evaluating different techniques we decided to concentrate on creating alternative visualization methods for effects of cosmological scale, that is often hard to comprehend for the untrained mind. Furthermore, even though scientifically correct methods are required and results as well as effects need to be in line with latest explorations and insights from astrophysics, the decision was made to include abstractions and concentrate not on high level physics experts but popular science. Additionally this would be one step if many to prevent the spread of falsities and half-knowledge on this important scientific milestone.

4.1.2 Target User Group

Due to the identified popularity of the recent scientific breakthrough of the proof of existence of gravitational waves, everyone interested in the topic can be part of the target user group. Exactly because of the mainstream popularity of this subject, an easily understandable explanation is required. Most people that are not directly researching in this field would not invest the required time to understand the matter in depth and this provides perfect soil for misinformation and false understandings to spread.

In Chapter 2 it was also identified, that many students in engineering and physics experience difficulties with understanding of complex graphs, multidimensional diagrams or formulas. Therefore astrophysics students in introductory courses about gravitation or similar topics could also benefit from the implementation of this project. The nature of VRLEs with interactivity and immersion addresses exactly those needs if implemented properly, thus providing an appropriate and engaging alternative to formulas or static textbook representations.

Based on these mentioned attributes and desired outcomes, the following sections will define the corresponding requirements of such a VRLE in more detail.

4.1.3 Requirement Analysis

In this section we discuss a fundamentally important aspect of software development projects. Defining the requirements of a project before the implementation provides the possibility to consider the needs of all users from the application in terms of system operation as well as system behaviour (Chen et al., 2013). Thus this section is split into functional and non-functional requirements, each concentrating on the respective aspect.

Functional Requirements

1. Environment Specific
    a) The experiment has to be usable in VR and on a Computer
    b) It should represent physics phenomena caused by gravitational waves correctly
    c) The environment has to not be overloaded with visual information
    d) There should be a representation of space-time to represent the effect in empty space.
    e) A representation of e.g. our universes planets should give the user some sort of relation anchor

f) The source of the gravitational waves has to be made visible
g) Scales of represented objects in the environment should be as close to reality as feasibly possible
h) The user has to have some sort of textual or dedicated visual information, additional to the represented objects.

2. Task Specific
   a) The user has to be led through the experiment without further necessary instructions
   b) It has to be clear for the user what to do at any time during the experiment.
   c) There has to be a possibility for the user to move in all dimensions
   d) The user should be guided to find answers to the most important facts about gravitational waves in the simulation
   e) The waves effects should be adjustable by the users
   f) There has to be a possibility to pause the simulation in order to inspect anything closer if necessary

Non-Functional Requirements

As opposed to functional prerequisites, non-functional requirements are concerning system behaviour that is not directly connected to available functions. They are generally including software requirements such as usability, reliability, safety and availability. In the following list the required traits are defined as such:

1. Usability
   a) The simulations should be intuitive to use
   b) All possibilities for exploration should be visible or easily reachable for the user
   c) The behaviour of the simulation should be realistic and corresponding to theoretical background
   d) There should be some guidance system to lead the user through the simulation
2. Reliability
   a) The user has to be able to use the simulation smoothly without lag or stuttering
   b) Fallback mechanisms must ensure recovery from any potential problem
   c) There should be no interruptions, unintended shutdowns or other errors
   d) It has to be possible to run the simulation indefinitely
3. Performance and Responsiveness
   a) The experiment should consistently run at high (¿= 30) frames per second
   b) There should be no lags or interruptions that could cause user irritations, or motion sickness during the exploration

c) No user interaction should cause any behaviour that would overload the simulation

4.1.4 Design

Design Basis

Due to the identified popularity of the discovery of gravitational waves, both in professional as well as in popular science, an easily understandable representation and explanation of them is deemed necessary. VR has proved to provide appropriate possibilities for engaging, immersive alternatives towards two-dimensional approaches of complicated theorems and graphs. Thus the goal is to utilize those possibilities in line with our identified requirements to create a VRLE that can be used to provide fundamental understanding as introductory starting point in the research area of gravitational waves and their effects, or solely to provide better basic understanding for the amateur. Next to the required functionality of our approach, a way to measure actual effectiveness and impact of the planned implementation is necessary. Thus, a questionnaire has to be designed to compare knowledge of the participant before and after experiencing the VLE, hence showing any developed insights in a quantifiable manner.

Conceptual Approach Design

Based on our initial idea and the identified requirements for our analysis as well as for potential users a conceptual design was devised, as can be seen in Figure 4.1. The core elements in this design are the visualisation of gravitational waves effects and their calculations in the background, along with a well thought though user interface to allow intuitive exploratory learning. The environment should represent the view of a free moving entity with a wide ranging view of the universe that the user controls. Furthermore the user should have control over visible cosmological in order to analyse difference in their interactive behaviour according to their positions on a scale that would otherwise be very hard to understand. For this an appropriate user interface and corresponding controls need to be designed.

As the effects gravitational waves are of such a tremendous proportions, that it would be incomprehensible and essentially invisible in a fully realistic simulation, there is also some scaling required in order to make the visual effects visible to the user in an appropriate manner while still being of reasonable relation. Finally, as the main intention of this project is the measuring of gained knowledge and understanding, appropriate tasks have to be devised for the users in the simulations in order to lead them to finding the required insights.

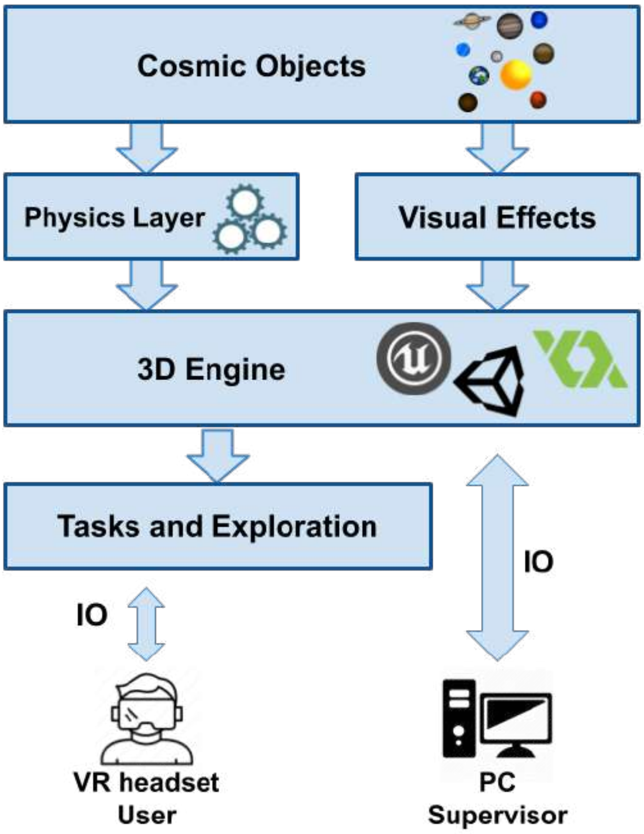


Figure 4.1: Conceptual Design

Visualization and Effects

Representing the core mechanic of this VRLE, the visualization of gravitational waves and their effects is the first and most important aspect to plan for the further development process. In order to create appropriate visual representations, even if they will be scaled for better visibility, correct calculations need to be made by the system, referring to the actual theoretical background of astrophysics research. These effects need to be projected on the whole environment at all times, as the effects are omnipresent in the affected universe. Due to the fact that the universe is mostly empty space, some visual effect to represent space time, thus every point of space, is needed. Because these calculations can sum up to be very expensive for the CPU, as each single element in the simulation needs to be calculated separately, some optimisations might be required to enable smooth behaviour while still being realistic.

User Interface

In order to get a better understanding of what is happening in the simulation, next to the visual representations in the environment the user also needs an explicit user interface that shows necessary information. This either has to be realized in the style of a non interfering head-up display or directly at the users controllers position. Mainly the displayed information should contain current attributes of the gravitational waves effect and some further insight into what is currently happening around the user.

Controls

In order to provide greater interactivity in the simulation and also create the possibility to adjust the causal attributes of gravitational waves, some expanded set of controls is required. The challenge here is to unite several required functionalities on the restricted amount of buttons available on a standard HTC Vive controller. It's necessary to allow the users to move in all directions of three dimensional space or at least in the x-y plane with an appropriate scaling, in order to reach all important areas without having to move around physically. Furthermore, the users will have to have access to at least two other attribute scales, requiring each a positive and negative input, resulting in at least eight more separate input methods that are necessary. Finally the user has to be able to pause the simulation any time they find the need to analyse something in more detail.

Tasks

While the visualisation displayed inside the VRLE combined with appropriately designed questions in a corresponding questionnaire provide the necessary base for this research approach, the visual information could proof to be overwhelming or confusing without any further guidance to the user. Therefore we want to design a set of tasks that can be displayed in the HMD in order to explain the user what are the possibilities to explore in the environment and how to reach them. Furthermore the users should get a short introduction into the system controls ahead of the VR experience, but as a reminder the corresponding controls to reach each explained task should be repeated in the form of certain tasks and their description. Following the tasks, each user should be able to fully understand the effects of gravitational waves. These tasks should be controllable from the supervisor on the PC and it also has to be possible to go back and forth between them, in order to let a user repeat certain tasks if they claim the need for further insights.

4.1.5 Tools and Frameworks

In the following paragraphs some of the most important tools, frameworks or techniques used in this project are being explained and reasoning is given why they were used over potential alternatives.

Python In this project we also used Python and C++ for their variety of functionalities for data analysis and for know-how of previous projects, like described in the corresponding part of Chapter 3.

C++ C++ was used as main programming language for this project, because various libraries in this language let us access necessary functions for the further implementation plan. While the language itself already provides a mighty tool in this manner, some the C++s frameworks, which are described in the following paragraphs, provided the most important functionality that lead to the choice of this programming language over any potential alternative. Among others the most important operations provided by C++ are low level memory and even direct GPU access, thus making it more efficient for all necessary calculations. Additionally to superior processing capabilities there are also all necessary frameworks available to port our approach into a VRLE.

OpenGL Due to the complexity of various rendering approaches and the rendering pipeline, we decided to base the gravitational waves project on OpenGL [1] (Woo, Neider, Davis, & Shreiner, 1999). The framework provides many built in functions to decrease the effort for creating a such pipeline and thus let us create an effective environment for our simulation. Generally it is a popular choice for any project involving high performance graphics calculations. We were also able to expand several built-in methods of the framework to fulfil our requirements to the simulation, tailoring the functionality for the needs of this approach.

Shaders As a core functionality of OpenGL, Shaders [2] need to be mentioned here. While there is no other possibility to choose from and therefore no alternatives towards the usage of Shaders, they represent almost a whole programming language on their own. While GLSL, the language shaders are written in, resembles C, it is generally tailored for matrix manipulation and high performance graphics calculations. An OpenGL program normally uses a variety of different shaders, each a separate small class tailored for some specific graphics functionality. Those shader programs work on the GPU and require some sort of input from the CPU via a specific variable mapping. Typically such program contains at least one vertex and one fragment shader, where the first manipulates and calculates pixel positions and sends them to the second, that then generates the final output color for the end image. Another special kind of shaders is the compute shader, which takes input from the CPU and instead of calculating pixel positions and colors calculates arbitrary methods and sends the result back to the CPU. This kind of shader is especially important as it enables the outsourcing of complex parallel computations from the CPU to the GPU, thus avoiding overload and increasing performance during runtime.

[1] https://www.opengl.org/

[2] https://learnopengl.com/Getting-started/Shaders

OpenVR For this project we needed to directly read e.g. position and rotation values from the HMD and therefore we decided to use a lower level interface for most common HMDs with OpenVR [3]. OpenVR provided all necessary values for our calclulations and only required small scale adaptions in the processing chain, thus presenting a convenient interface for our needs.

Head mounted displays All our experiments with user study participants were conducted with the head mounted display HTC Vive Pro Eye. This HMD were chosen due to their comparably high performance and wearing comfort over similarly price competitor model. Furthermore the high resolution provided by this headset was found sufficient while this was not the case with some other ones being tested. The high resolution and performant frame rate was a very important part in our decision because it influenced the result of our visualization process a lot, effectively rendering our approach useless if the display would not be able to show the appropriate images in good enough quality.

First testing approaches in this project were completed with the Oculus Rift CV2 HMD but it's inferior resolution compared to the more advanced HMDs lead to a hardware change early in the development process. Additionally it was not nearly as comfortable to wear than the HTC headset.

Multisample Anti-Aliasing (MSAA) As HMDs frequently require higher image resolutions than conventional screens, inferior environment quality inside the HMD view also became an issue at one point during the development phase. While there are several possible approaches towards this problem, like smoothing the resolution artificially, anti-aliasing is a very popular one. Because quick and simple anti-aliasing approaches did not provide an image of enough quality, a further step towards MSAA was found necessary to provide sufficiently smoother images inside the HMD.

Processors and Graphics Cards In the beginning we used the same setup for this project as we did in the haptics project of Chapter 3. This proved to be sufficient only for the first few implementation tries. Later there were complications at some point in the development process with the graphics card running into its limits during heavy calculations. Therefore we decided to upgrade it to a NVidia GeForce Titan V to ensure a high frame rate and a smooth experience during the simulation.

4.1.6 Summary

In this chapter the design process of this project was described. Starting with projects first idea and the corresponding motivation to pursue it further, then a detailed explanation of our identified requirements to the implementation and the desired target group that would be mainly intended to use the produced outcome. Lastly

[3] https://github.com/ValveSoftware/openvr

a detailed explanation in the conceptual design plan and the specific parts of the program that would make an appropriate application fulfilling our identified needs. Additionally the most important tools and frameworks used during the development approach were explained in the last part of this chapter, with some insights why OpenGL was our preferred graphics API and how some problems with resulting output images were approached with anti aliasing techniques.

4.2 Development

In this section more details about the practical part of this project are explained. Starting with an overview of the used system architecture, followed by some necessary theoretical background that was implemented and closed up with a general explanation of the resulted VRLE

Some parts of this section are taken directly or in a slightly adapted version from Lontschar, Pietroszek, et al. (2020), because this thesis was based on the project over the course of which this paper has been produced.

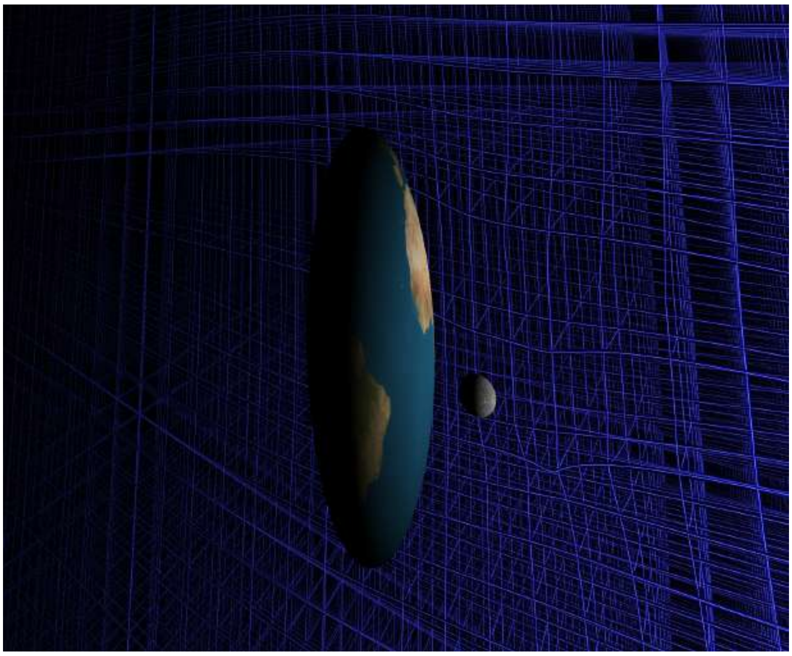


Figure 4.2: Representation of earth with orbiting moon in the space time grid. Everything under the effect of gravitational waves at one point in time.

4.2.1 System Architecture

The core functionality of this project is the visualization of gravitational waves and the representation of space time that is being distorted by their effect. This is all handled via a main function that initiates the whole program with corresponding states and positions and loading of necessary files. Afterwards a continuous loop is started that handles all I/O procedures for each frame until the window is closed, meaning corresponding updates of user as well as object positions according to interaction as well as every single pixel being calculated respective to the current influence of the gravitational waves at this moment. While shaders on the GPU are mainly responsible for the correct visual display of all elements inside the simulation, one specific sort, the compute shader, is used to calculate certain values that are being sent back to the CPU for further processing. This explanation is summarised visually in Figure 4.3.

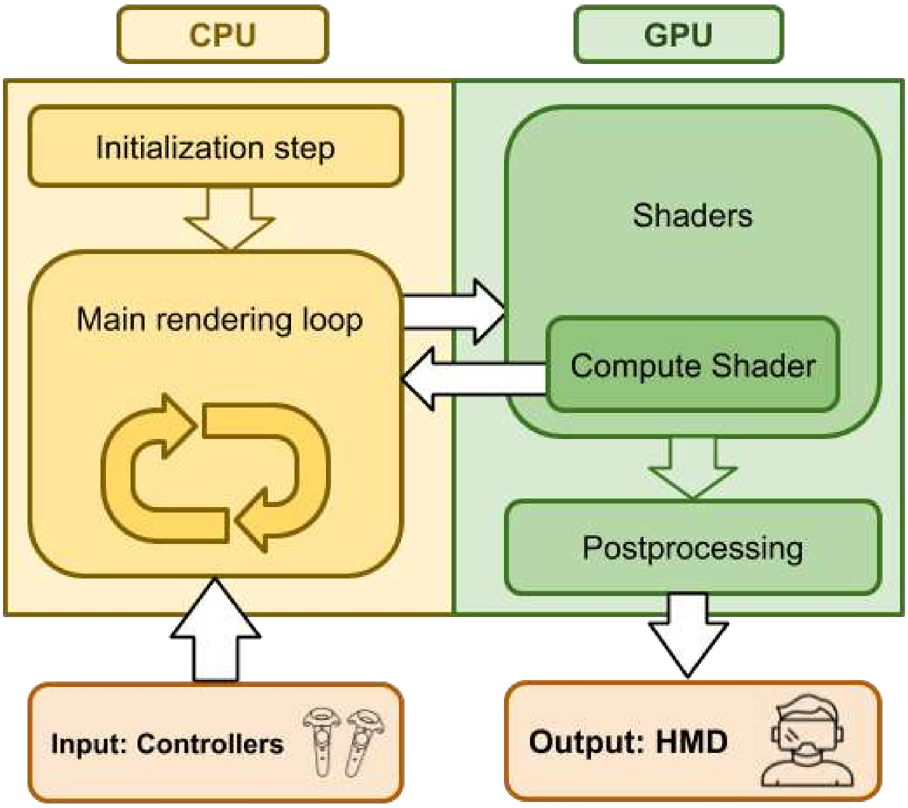


Figure 4.3: System Architecture Diagram

4.2.2 Theoretical Background

To calculate the gravitational wave effect of the binary system on space, we start from the flat space field equation (constant in time)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{4.1}$$

with additional small deviations h from that flat space

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \tag{4.2}$$

with the wave equation

$$[\partial^2 h]_{\mu\nu} = 0 \tag{4.3}$$

Solutions to Einstein's equations show that a gravitational wave metric oscillates sinusoidal:

$$h_{\mu\nu}(t, z) = h_{\mu\nu}{}^0 sin(k(t - z)) \tag{4.4}$$

Given a moving gravitational wave along the z-axis, planes in xy experience different values for different times t, which make the wave transferal, as the metric shows:

$$
\begin{aligned}
g_{xx} &= 1 + h_{xx} \\
g_{yy} &= 1 - h_{xx}
\end{aligned}
\tag{4.5}
$$

We pre-calculated the wave distribution for one period of the binary stars and stored this in an array (wave-array) on the GPU. Since the torque stays constant, meaning frequency and distance are inversely proportional, changing the torque would result in a change of amplitude. Different frequencies can also be handled by scaling the wave-array. As long as the masses of the binary star system stay constant, this pre-calculated wave-array passes within reason correct values for a qualitative meaningful observation.

4.2.3 General Development

The gravitational force is described as a vector field consisting of a weighted vectors for every point in space. Early testing showed, that the presentation of a regular vector grid in VR is overly complex and hard to get immersed into. Other attempts with color coding the strength of the gravitational force in addition to the directional vector showed similar weak results. To illustrate the gravitational waves, we rather decided to use a density grid: regular points in space, which are connected in x, y and z- direction and are warped due to gravitational forces.

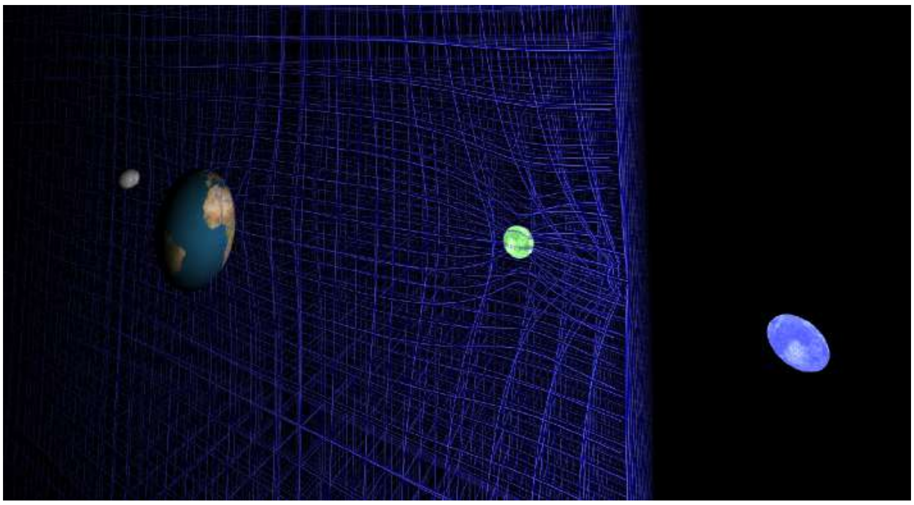


Figure 4.4: VLE scene near binary stars with a heavily distorted density grid because of the stars masses.

To further improve the understanding we decided to add representations of the earth with an orbiting moon to show familiar objects the participants can relate to, as they are as well as the density field exposed to our generated gravitational waves. In the VLE the participants can also observe a two star binary system which represents the source of gravitational waves. Using a real scale environment, it becomes apparent that the distances of the solar objects are too great to be visible in one scene, therefore we decided to use an observable, artificial scale. This allows us to show all objects, such as planet Earth, the moon and the source of the gravitational waves, the binary system, in one observable scene. This way, participants are able to derive correct conclusions about the nature, origin and impact of gravitational waves. All stellar objects also display their gravitational effects in the density grid.

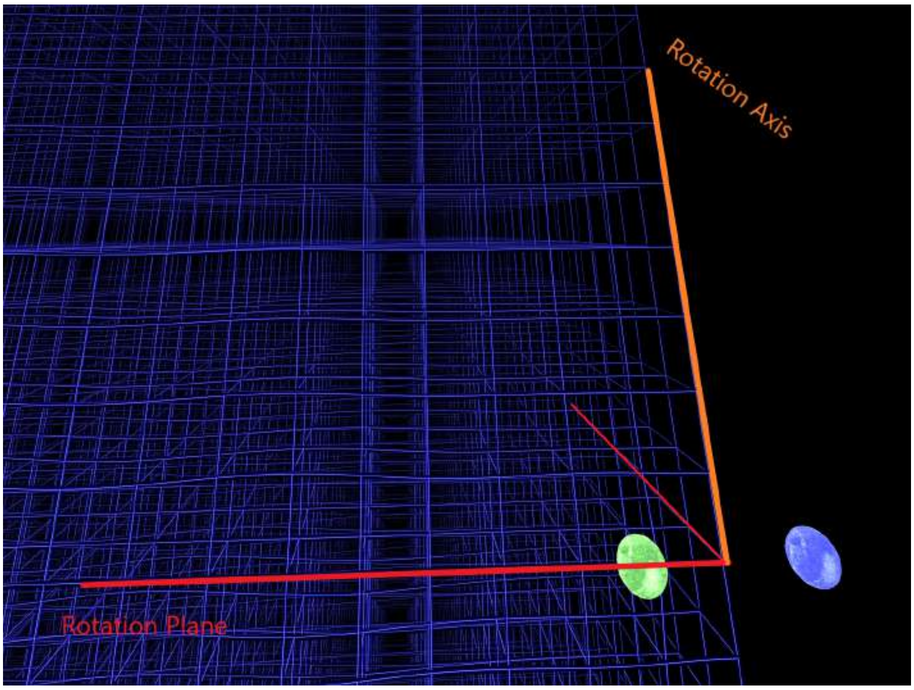


Figure 4.5: The image used to indicate possible answers for question #5.

The VLE environment consists of the planet Earth, the orbiting moon, and the binary star system which rotates around the y-axis and oscillates in the xz plane. A density grid is applied to one quarter of the plane, crossing through it in y-direction. This setup lets the VLE participant observe the Earth extending half way out of the grid, as well as the binary system crossing the grid for one quarter. This quartered representation is necessary in order not to overload the visual representation and obstruct the view on the objects. The participants are able to freely move around the x-y plane with the touch pad of a VR controller and can per request also change the position up and down on the y axis. Moreover and most importantly, the controller can be used to measure the current wave-effect-magnitude on every point in space. This setup lets the participant experience the uneven wave distribution around the wave-source, which focuses its maximum magnitude on the xz-plane. Additional to the gravitational waves traveling through the density grid, each stellar object in the scene displays their respective gravity as well, in order to make the distinction between gravity and gravitational waves unambiguous.

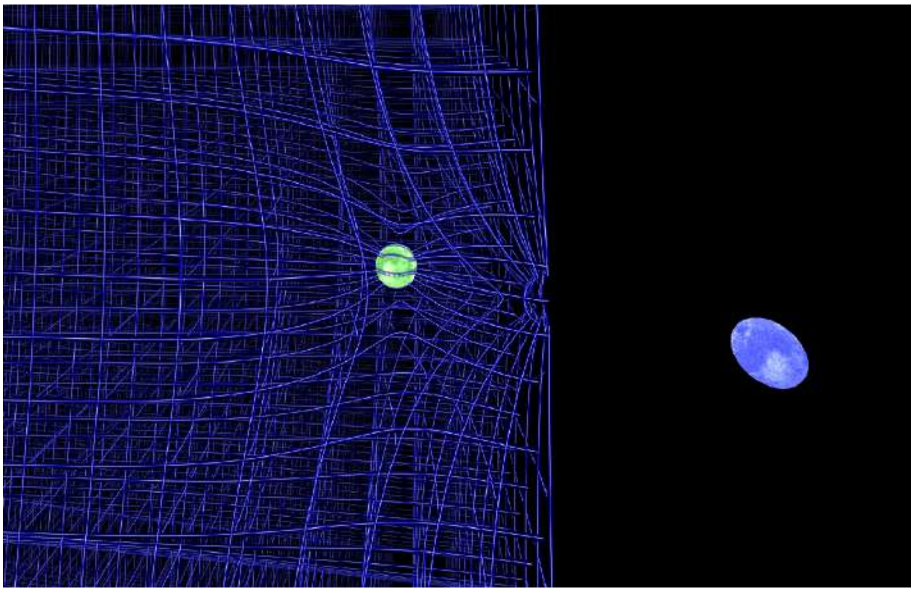


Figure 4.6: The binary stars as source of gravitational waves in the VLE.

The density grid consists of a three dimensional line grid rendered in OpenGL using vertex, geometry and fragment shaders to create a billboard like laser representation of each grid line. In order to create a decent and smooth behaviour of the density grid in regards of gravity and also gravitational waves representation, the grid was subdivided in 10 sections between each line intersection, which in turn is being separately distorted by gravity and gravitational waves respectively. In order to let each separate grid point be influenced by every object and also the gravitational waves effect, we created a distortion function inside the vertex shader that calculates a distance to each stellar object and adds a displacement to the initial position depending on the squared distance and mass factor of each object. For a more realistic representation of the gravity behaviour of earth, moon and the binary stars we also included a maximum displacement function to make the grid stop on the surface of each body and wrap around it. For an even more in depth impression of the influence of gravitational waves we also decided to let the model of earth be deformed according to the current magnitude of the waves effect at earths position. In order to give the participant the ability to measure the gravitational waves magnitude numerically at each point in the represented space time grid, additionally to the visual impression, we utilized compute shader. This shader calculated the same displacement that gets added for each grid element but for the current position of the controller and writes this value on a shared buffer array, which gets in turn read by the GPU. From there it is again sent to the GPU into another billboard render to display it visually slightly above the controller. Moreover we added a gauge representation that would move an indicator according to the measured value in order to provide dedicated UI information accessible for the user at any time.

4.2.4 Summary

In this chapter an explanation about the taken approach during the development of this project have been given. Starting with a broad overview and an explanation of the used system architecture, followed by an insight into some necessarily implemented theoretical astrophysics background and finishing with a general explanation about the implemented VRLE and why some of the elements have been created the way they are.

4.3 Evaluation

The evaluation process of this project follows a multi step approach with a pre-questionnaire, the VRLE experience and a corresponding post-questionnaire, carried out by n = 35 study participants. While initially there was a plan for an A/B testing approach with a control group that was supposed to learn about gravitational waves in conventional manners, the gained results from the core group were found to be sufficient, thus this step was abandoned. The multi-step approach was necessary because a comparison between the users knowledge before and after the VRLE needed to be done. In the following chapters more details about the design of this user study are going to be explained, followed by information about the participants, the test setting and finally insights about the gained data and the corresponding conclusions.

4.3.1 Design, Procedure and Goals

To measure a gain in understanding, we let the group of participants complete a pre-questionnaire and post-questionnaire (see Section 3.3.2), respectively before and after the VRLE experience. During the simulation the participants were guided by two main tasks:

1. Move around and measure different areas for their wave-amplitude around the binary star system to illustrate the irradiation distribution. Try to find the area that is most affected by the waves effect.

2. Change the distance and period-time of the binary star system and observe the behaviour of gravitational wave-magnitude and distribution in succession.

The goal of these tasks inside the simulation was to further illustrate the linear dependency of wave-amplitude and torque and overall fortify the general understanding of correlations between gravitational waves source and effect. Furthermore, they were laid out to lead the participants to find the answers to our research questions that are introduced as seen in and especially understand why the answers are right.

In order to assess any change in understanding of gravitational waves from the participants, we required everyone to complete a pre and post survey before and after the VLE experience. To evaluate previous and gained knowledge we designed five questions as follows:

1) What type of waves are gravitational waves?
2) How does the magnitude of the gravitational waves effect change if the radius between the rotating stars changes?
3) What happens to a distant planet if the two stars collide, merge and would be on one place?
4) How does the magnitude of the gravitational wave effect change if the rotation speed of the rotating stars changes?
5) Which area in space time is most affected by the gravitational waves effect?

Each participant was asked to answer these question to the best of their knowledge in each of the questionnaires and were also allowed to re-visit the VRLE for further confirmation if they were still in doubt afterwards.

4.3.2 Study Setting

As this study did not involve much movement in the physical world and mostly everything was done inside a VRLE, it was conducted in a lab environment on campus.

Due to the extended GPU shader work in graphics calculation for the VR representations, we used OpenGL for the graphics API in combination with OpenVR as VR library. Our testing took place on a Windows PC with an AMD Ryzen 7, an NVidia GTX Titan V graphic card and HTC Vive Pro Eye HMD. In Figure 4.7 a user study participant during the process of exploration inside the VRLE is shown.

Figure 4.7: Study participant during VLE experience. In game view seen on screen on the left.

4.3.3 Participants

Next to knowledge gain and immersion feedback also some demographics information was gathered about the user study participants, as can be seen in Figure 4.8. The biggest part of our study participants were students with or without a job and in the age range of 18 to 24 years old. 18 participants indicated to be male, 15 to be female and 2 did not want to classify themselves in the binary gender system. The most commonly represented ethnic groups were of Caucasian and Asian ancestry and more than 75% of the participants did not yet finish any college degree.

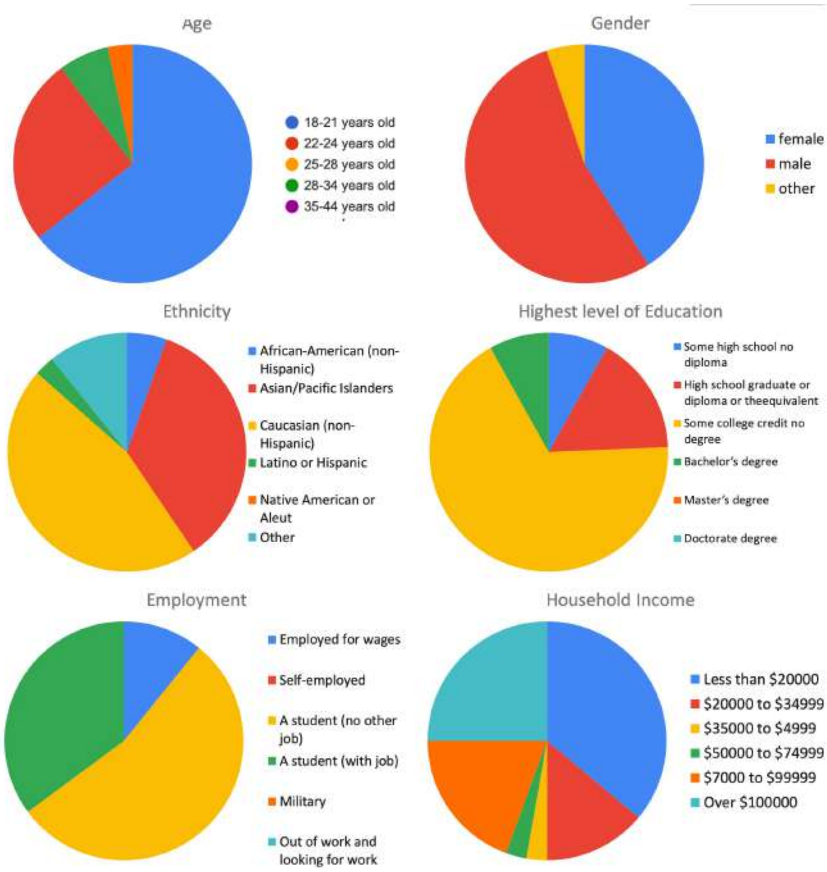


Figure 4.8: Group demographics. The distribution of the participants age, level of education, employment status, ethnicity, gender and annual household income.

4.3.4 Assessment, Findings and Discussion

Research question response evaluation

The acquired data showed a striking increase in understanding of our proposed research questions. As seen in Fig. 4.9 already the average amount of each separate question for all participants shows an eminent gain of positive responses after the exploration of our simulation scene. The right column displays the average for all questions and supports the first insight. We calculated a value of 27.56% correctly chosen answers before the VLE and 81.08% afterwards, which sums up to an increase of more than 50%, an even better result than we initially expected in an optimal

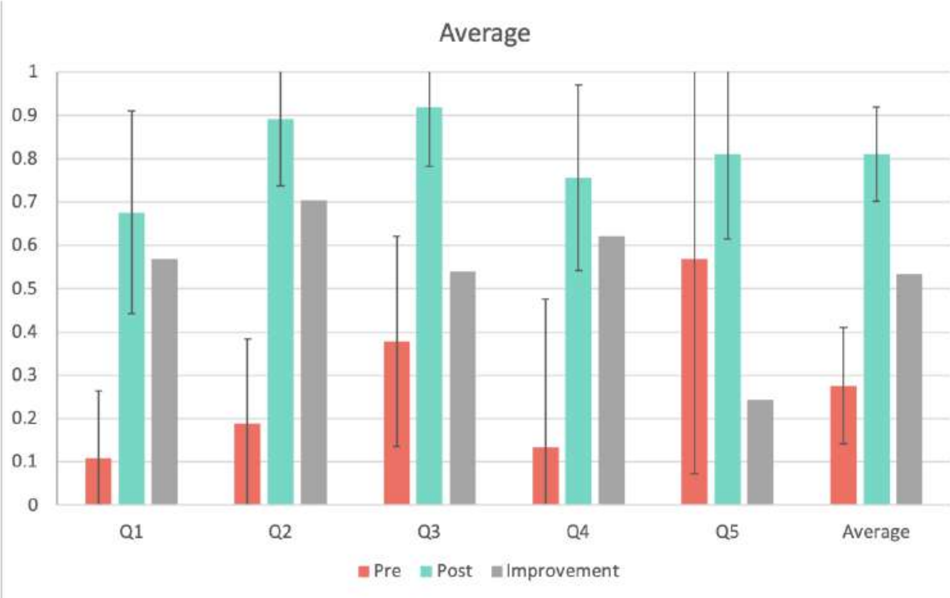


Figure 4.9: Result score for each question and all participants: (orange) pre- and (cyan) post-questionnaire. (grey) improvement.

outcome. Especially question #2 "How does the magnitude of the gravitational waves effect change if the radius between the rotating stars changes?" seems to be the least intuitive for most participants before seeing the simulation and therefore shows the highest percentage gain. This assumption also got confirmed by verbal feedback of multiple participants that stated that their intuition had told them the exact opposite of what happened in the simulation regarding this attribute of the rotating stars. It is also worth mentioning that for many participants the two different type of waves were not entirely clear, even with the displayed visual representation, which most likely lead to some slight skew in the collected results of question #1. All groups of best or worst participants in the following section concern the upper or lower third respectively of the overall data set in regards to the currently discussed attribute.

Fig. 4.13 (a) illustrates a striking difference in the ratio of correct to wrong answers, especially for the subgroup of participants that on average improved themselves the most. This leads to the insight that especially people who have barely any or a wrong understanding of the research topic can benefit extensively from our representation. This is also confirmed in the Fig. 4.13 (b) as it shows that the part of our group who scored the lowest in the pre-survey also indicated a very high improvement in their respective post questionnaire answers. Four out of five questions showed improved outcomes even for participants with already comparably good prior understanding as seen in Fig. 4.13 (a). Only one of the questions showed a slight decrease in correct answers, but as question five (#5) shows the only negative development (also seen in Fig. 4.10 (b)), we concluded that the missing "I don't know" choice for this answer increased the random noise and therefore diminished the overall outcome. As the group with best pre-questionnaire score results and least improvement are most probably

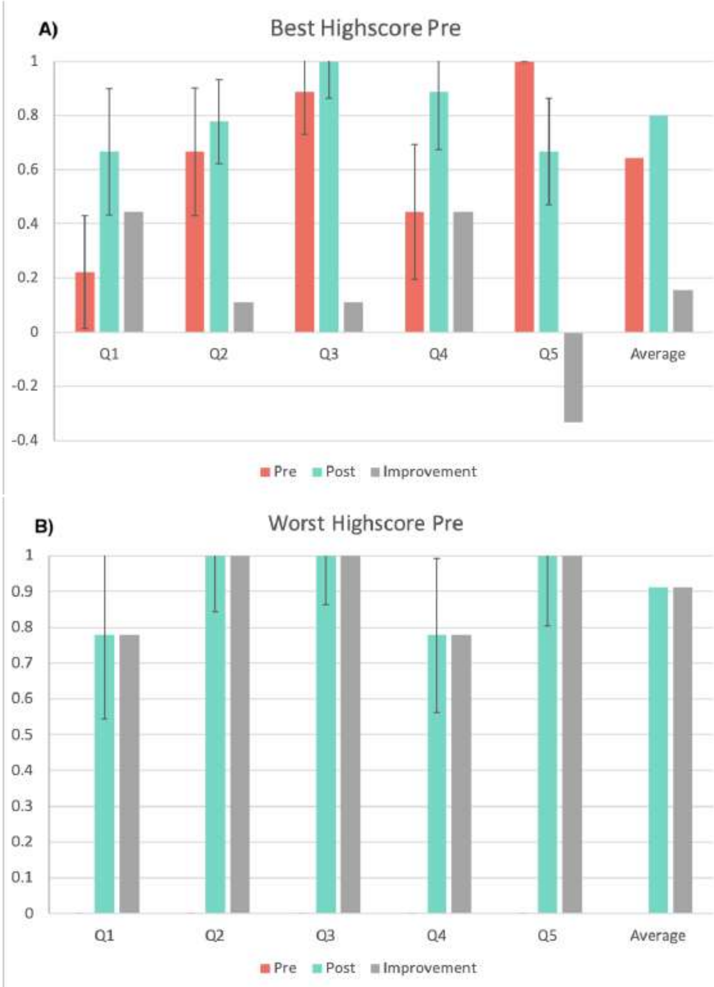


Figure 4.10: Result scores for participants that showed the highest and lowest score before the VLE: (orange) pre- and (cyan) post-questionnaire. (grey) improvement.

the same participants for the biggest part, we can see a very similar pattern in both mentioned figures. The results shown in Fig. 4.10 clearly identify a confirmation for the previously taken assumption in Fig. 4.13, as it displays the results for the group of participants that chose the least correct answers prior to the VLE experience with a very similar pattern. What is especially notable here: even participants, which apparently did not have a fitting impression of the gravitational waves effect prior, could achieve an even slightly better score than average post experience score.

It is also worth noting that even the group of participants with the lowest average of correctly chosen answers after experiencing the VLE still show an extraordinary improvement of 30%.

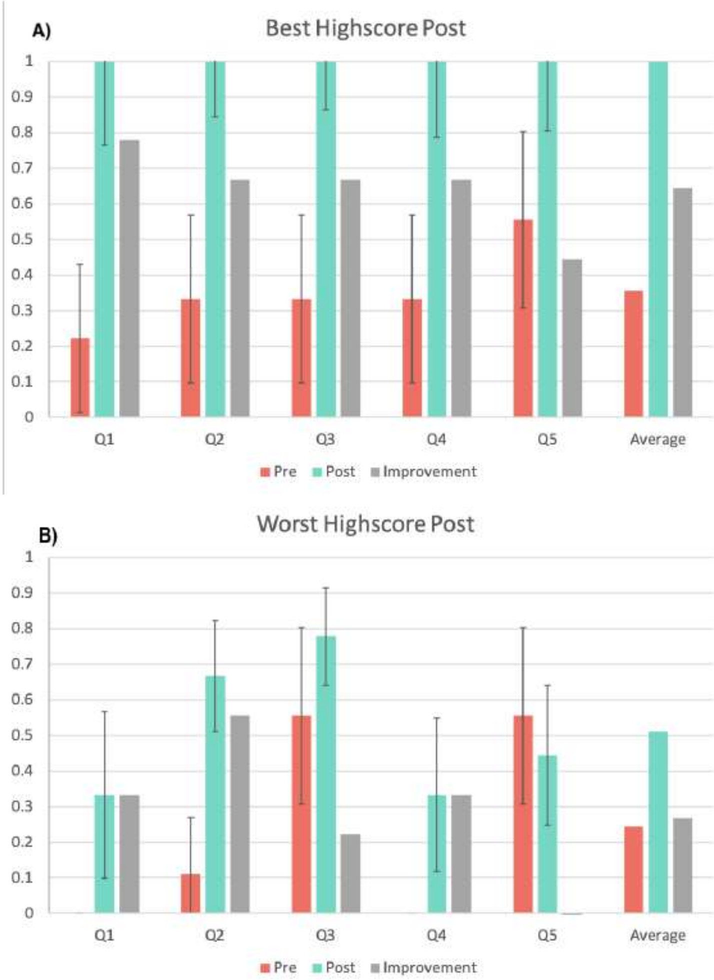


Figure 4.11: Result scores for participants that showed the highest and lowest score after the VLE: (orange) pre- and (cyan) post-questionnaire. (grey) improvement.

Immersion values evaluation

Conducting the Game Experience Questionnaire (GEQ), we assessed the immersion during the VLE experience followed by the Game Immersion Questionnaire(GIQ) measuring the immersion felt after the testing. Fig. 4.12 (a) shows that even some of the participants seemed to feel not overly competent in finishing the given tasks of finding answers to the respective research questions, on average they were still positively affected and stated a high sensory and imaginative immersion. Part (b) in the same figure suggests that participants were overall still trying their best to achieve the necessary knowledge to find the correct answers and enjoyed the simulation, even though they felt challenged by it. It's notable that on average the participants were stating to feel less challenged during the experience than afterwards, which is probably caused by the difficulty of answering the research questions and remembering the

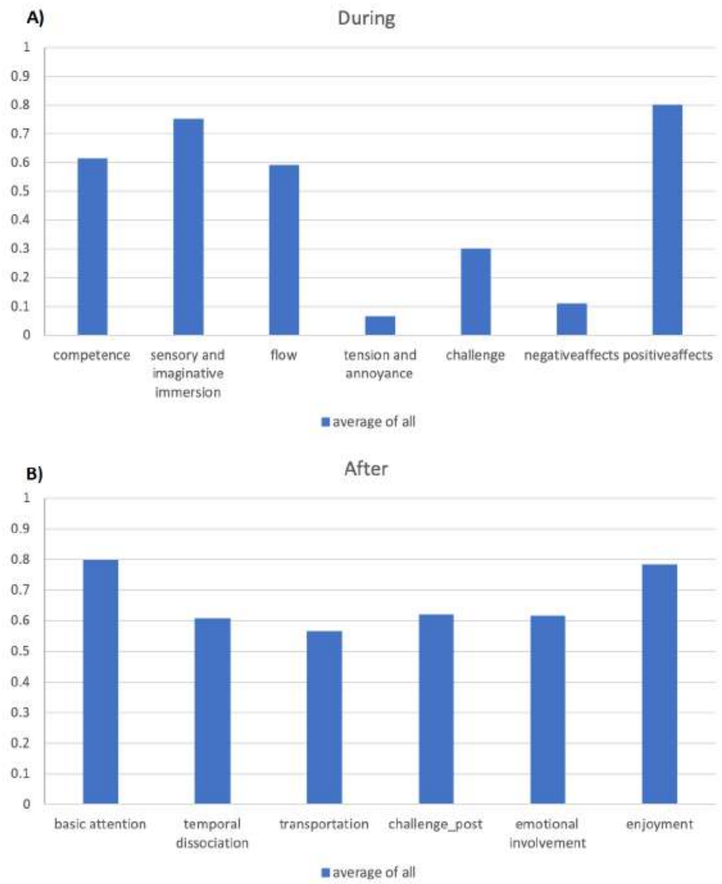


Figure 4.12: Immersion level for all participants during and after the VLE. Each value is in the range from 0 (not at all) to 1 (absolutely).

gained impressions of the VLE. According to verbal feedback many participants were also slightly overwhelmed by processing the gained information during and after the VLE experience.

Comparing the immersive responses of best and worst scoring participants of the pre-questionnaire as can be seen in Fig. 4.14, even seemingly big differences in previous knowledge and understanding does not influence the immersive impressions of the participants in a significant manner. What is remarkable is to compare the stated challenged feeling for both groups during and after the VLE experience is approximately the same. This suggests that participants with a high pre-questionnaire score felt equally challenged with the simulation, even though they already brought some comparably good understanding of the subject. We assume this is because most participants were not aware of their correct perception, as they were only told the correct results after finishing the post questionnaire.

We identified a noteworthy tendency about participants who achieved the worst score post VLE to state overall higher immersive involvement than their best scoring counterpart, as can be seen in In Fig. 4.15. Moreover, the stated feeling of higher

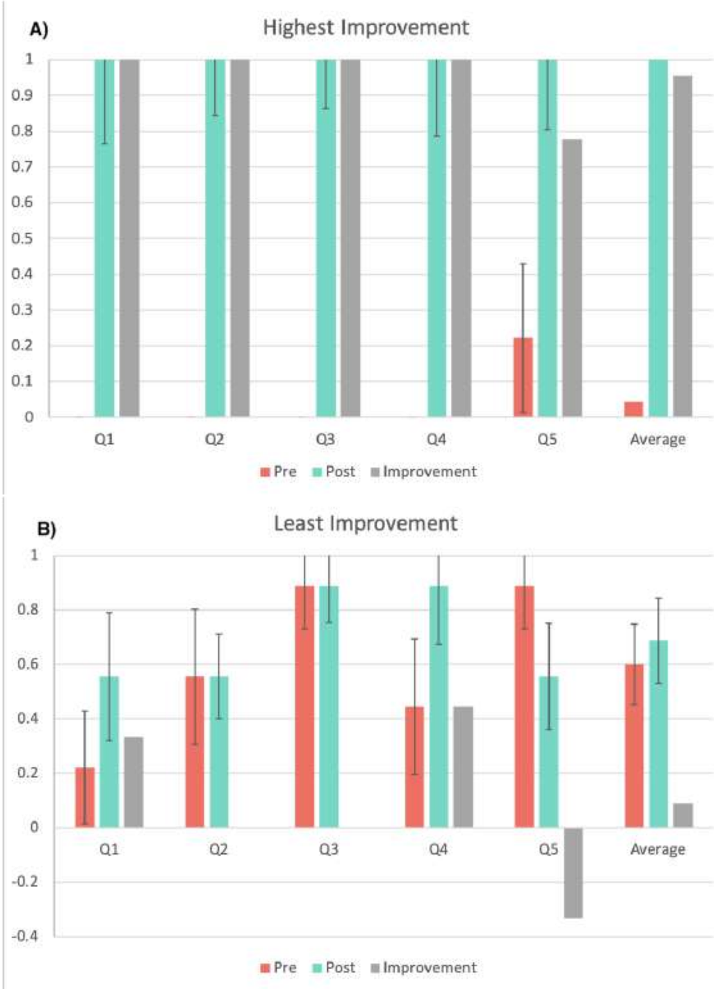


Figure 4.13: Result scores for participants that improved the most and least after the VLE: (orange) pre- and (cyan) post-questionnaire. (grey) improvement.

competence and given attention to fulfilling the tasks is remarkable, as the outcome of the research question evaluation would suggest the opposite. Observation of the participants during the VRLE and verbal feedback indicated that some participants got distracted of the actual task at hand and therefore from interpreting the scenery and its information by the strongly moving and colorful scenery. This could be the cause for the overall lower score of the participants that still stated a higher than average enjoyment, emotional involvement as well as attention afterwards.

4.3.5 Summary

In this chapter insights about the evaluation process were given. First the approach taken for the user study, its design as well as the taken procedure are explained, followed by an insight into the study setting and the participating users. Finally the chapter is introducing the gained data and what exactly the data tells, firstly concen-

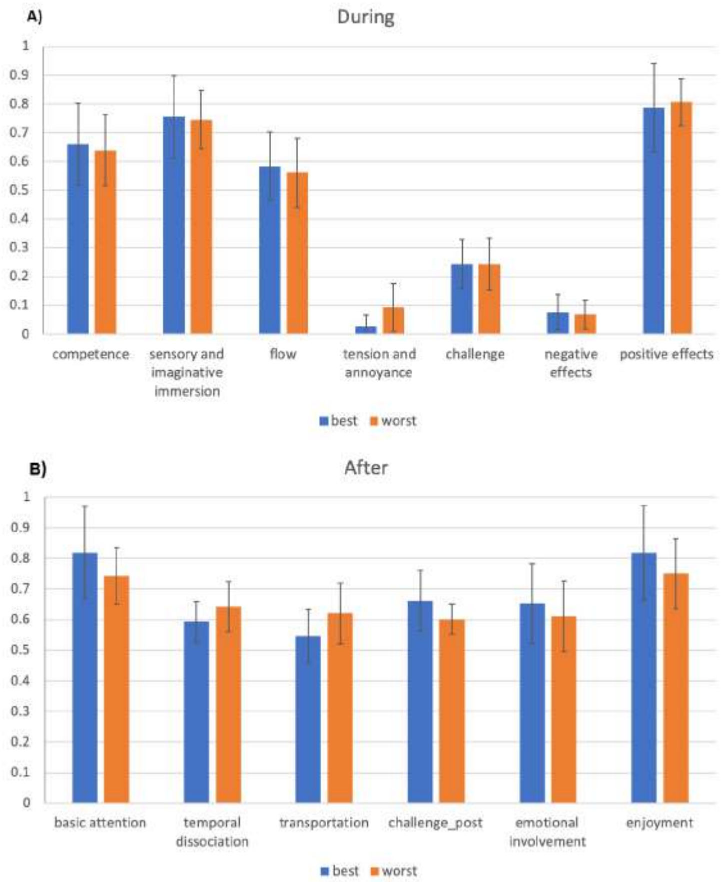


Figure 4.14: Immersion level for participants that showed the highest and lowest score before the VLE. Each value is in the range from 0 (not at all) to 1 (absolutely): (blue) best- and (orange) worst third scored participants.

trating on the research questions responses and thus the actual gained knowledge of the users, and secondly analysing the reported immersion values and putting them into relation to performance in previously mentioned question responses.

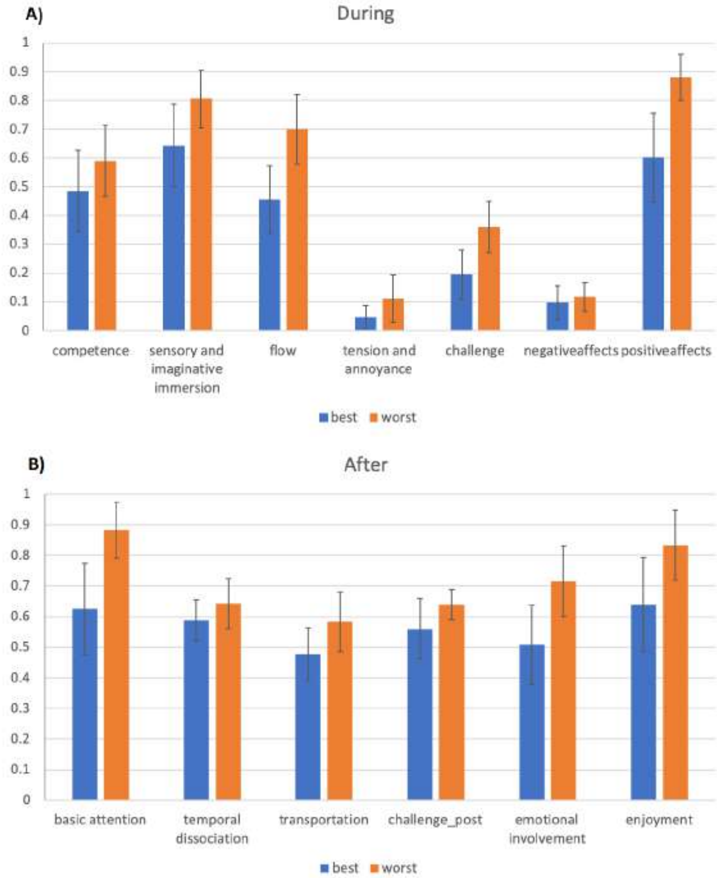


Figure 4.15: Immersion level for participants that showed the highest and lowest improvement after the VLE. Each value is in the range from 0 (not at all) to 1 (absolutely): (blue) best- and (orange) worst third improvement outcome of all participants.

5 Conclusion and Future Work

In this chapter all insights and conclusions gained over the course of each project are summarized and future perspectives for more advanced approaches towards haptics in virtual reality learning as well as newer approaches and techniques in physics visualization are given.

5.1 Conclusion

5.1.1 Haptic Feedback in VRLEs

Overall, our experiment found that neither learning in a mixed reality environment compared to learning in pure virtual reality was strictly better than the other under the restrictions of our experiment, by investigating a simple mechanical task. We were able to see improvement in some areas, such as with less heavy weights, but the unwieldy nature of the heavier weights, combined with the unfamiliarity of throwing such an object, caused too much interference in mixed reality to properly measure learning- an issue that was not present in pure virtual reality. However, a general trend for higher immersive values was observed for the MR group, which is explainable for handling real objects. Future experiments may want to use objects that participants are more used to throwing. At present, our findings show that in comparison, haptic feedback for simple tasks such as throwing weights, does not provide enough advantages to justify the extra cost and complications of setting it up, but perhaps in the future with better technology we can improve results.

5.1.2 Physics Visualization in VRLEs

We developed a virtual learning environment to convey the subject of gravitational waves. Identifying three areas of study: wave source, spatial irradiation distribution and wave type, we conducted a pre- and post VLE experience questionnaire as well as measuring the perceived immersion. We achieved striking results in transmitting the subject matter as the results of our analysis on understanding of popular science level gravitational waves conclude. We have successfully shown, that our immersive and interactive representation of this highly complex physics topic can be used to enhance the understanding of gravitational waves at least as a foundation for further research or as a basic understanding. Furthermore the feedback gained during the study process and in regards of immersion and feeling of interactivity was highly positive and even induced interest in the topic where people stated a basic disinterest before the VRLE experience.

5.2 Future Work

5.2.1 Haptic Feedback in VRLEs

One of our main concerns regarding the outcome of our analysed data was the already anticipated skew because of issues in usability of the available tools. Even though we could identify tendencies for some parts of our tested application, like the better immersive feeling in MR when changing weights of thrown objects and corresponding score developments, we intend to continue the research on this topic with more sophisticated controls and more exactly formulated tasks. Those could include a number of techniques or specific movements involved in surgery or fitting games without the common help of artificially adjusted placement to overcome inaccuracies of any means of controls. Thus said the main point to concentrate on would be more advanced haptic tools that have been developed specifically for this kind of usage instead of makeshift tools like in the approach taken in this project.

5.2.2 Physics Visualization in VRLEs

While no direct expansion on this projects codebase is planned for the upcoming future, follow up approaches on the topic will encompass further expansion into more detailed gravitational waves insights via real events like the collision of a binary black hole system that was measured in 2016. Not only will this create the possibility to device a simulation that is following exact data that is available from events that really happened, but with an approach taken from a very small code base it would enable us to thrive into different simulation techniques and leave more room for new ideas instead of having to adapt old implementations.

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