Lontschar Stefan Franz, Bsc

Visualization Techniques and Haptic Feedback in Virtual Reality Learning Environments

Master's Thesis

to achieve the university degree of
Master of Science
Master's degree programme: Software Engineering and Management

submitted to

Graz University of Technology

Supervisor

Assoc.Prof. Dipl.-Ing. Dr.techn. Christian Gütl

Institute of Interactive Systems and Data Science
Head: Univ.-Prof. Dipl.-Inf. Dr. Stefanie Lindstaedt

Co-supervisor

Assistant.Prof. Ph.D. Christian Eckhardt
California Polytechnic State University

Graz, November 2020

Lontschar Stefan Franz, Bsc

Visualisierungstechniken und Haptisches Feedback in Virtual Reality Lernumgebungen

Masterarbeit
zur Erlangung des akademischen Grades
Diplom-Ingenieur
Masterstudium: Softwareentwicklung-Wirtschaft

eingereicht an der

Technischen Universität Graz

Betreuer
Assoc.Prof. Dipl.-Ing. Dr.techn. Christian Gütl

Institute of Interactive Systems and Data Science
Head: Univ.-Prof. Dipl.-Inf. Dr. Stefanie Lindstaedt

Co-Betreuer
Assistant.Prof. Ph.D. Christian Eckhardt
California Polytechnic State University

Graz, November 2020

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master's thesis.

_____

Date

_____

Signature

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt, und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche kenntlich gemacht habe. Das in TUGRAZonline hochgeladene Textdokument ist mit der vorliegenden Masterarbeit identisch.

_____

Datum

_____

Unterschrift

Abstract

Virtual Reality Learning Environments (VRLEs) have proven to prevail in certain applications over conventional learning methods by drastically improving immersion, interactivity and especially interactive visualization. While being already adopted in various mainly educational institutions, Virtual Learning Environments (VLEs) still remain a topic of an open debate whether its influence is exclusively positive. Till this day on there is active research happening trying to shed more light on this question.

Among all the aspects that require such an investigation, two of them were selected and looked into in this thesis, becoming objectives of two separate projects. The adopted approaches concentrate on the effect of visualization techniques chosen for complex theories and formulas in an immersive, interactive way and the other other one on the influence of haptic feedback on intuitive learning and performance improvements. The positive effect of haptic feedback in such applications as medical simulations appears to be doubtless; however, in other implementations this influence may appear not beneficial enough for the potentially expensive hardware or cumbersome implementation. The second objective was to further inspect the qualities of dynamic visual representations of complex formulae, which have already often shown higher long term results in understanding and memorization. Both studies together involved close to 100 study participants.

The first VRLE involving haptic feedback in virtual reality has shown certain trends that are supporting the initial assumption of the importance of an additional haptics channel. The system included conventional virtual reality controllers with custom modifications - a simple but effective method of introducing haptic feedback elements. Under the restrictions and limitations of the setup a general statement of the effectiveness of mixed reality systems could not be derived, but certain important insights were obtained nevertheless. Furthermore, notable influence of the quality of such a low-budget setup on the haptics implementation could be identified - therefore, future work on the matter is required to make use of a more reliable hardware implementation. The second project examines a visualization technique for gravitational waves and their effects, a recent discovery in astrophysics. An immersive and interactive VRLE experience was implemented where participants could explore the influence of gravitational waves freely with an understandable visual channel and several interaction methods. The user study conducted within this project has shown a striking improvement in understanding among the testing respondents. Additionally, strong indications of high engagement and positive influence of the application could be identified within an immersion analysis via the Game Experience Questionnaire in both studies.

Kurzfassung

Virtual Reality Learning Environments (VRLEs) haben sich in bestimmten Anwendungen gegenüber herkömmlichen Lernmethoden durchgesetzt, indem sie das Eintauchen, die Interaktivität und insbesondere die interaktive Visualisierung drastisch verbessert haben. Virtual Learning Environments (VLEs) als deren Vorgänger wurden zwar bereits in verschiedenen Bildungseinrichtungen eingeführt, sind jedoch weiterhin Gegenstand einer offenen Debatte darüber, ob ihr Einfluss überwiegend positiv ist und damit Mehraufwand rechtfertigt.

Zwei solcher Anwendungesbereichen, die eine genauere Untersuchung erfordern, wurden ausgewählt und in dieser Arbeit im Zuge von eigenen Projekten, welche zusammen annähernd 100 Studienteilnehmer involvierten, näher betrachtet. Die gewählten Ansätze konzentrieren sich einerseits auf die Wirkung von Visualisierungstechniken für komplexe Theorien und Formeln und andererseits auf den Einfluss von haptischem Feedback auf intuitives Lernen und Leistungsverbesserungen. Der positive Effekt von haptischem Feedback bei Anwendungen wie medizinischen Simulationen ist unangezweifelt, in anderen Implementierungen scheint dieser Einfluss jedoch für die möglicherweise teure Hardware oder die umständliche Implementierung nicht vorteilhaft genug zu sein. Das Ziel des zweiten Projektes bestand darin, die Eigenschaften dynamischer, visueller Darstellungen weiter zu untersuchen, welche bereits häufig verbesserte Langzeitergebnisse gezeigt haben.

Das erste VRLE mit haptischem Feedback in Virtual Reality hat bestimmte Trends aufgezeigt, welche die anfängliche Annahme der Bedeutung eines zusätzlichen Haptikkanals stützen. Das System umfasste herkömmliche Virtual-Reality-Controller mit benutzerdefinierten Modifikationen - eine einfache, aber effektive Methode zur Einführung haptischer Feedback-Elemente. Unter den Einschränkungen der durchgeführten Studie konnten zwar keine allgemeine Aussage über die Wirksamkeit von Mixed-Reality-Systemen abgeleitet, allerdings andere bestimmte wichtige Erkenntnisse gewonnen werden. Einflüsse von teilweise unzuverlässigen Signalen der selbstkreirten Lösung haben sich allerdings negativ ausgewirkt, weshalb weitere Entwicklungen im Hardwarebereich dieser Anwendung erforderlich sind. Das zweite Projekt untersucht Visualisierungstechniken zu Gravitationswellen und deren Auswirkungen. Es wurde eine immersive und interaktive VRLE implementiert, bei der die Teilnehmer den Einfluss von Gravitationswellen mit einem verständlichen visuellen Kanal und verschiedenen Interaktionsmethoden frei untersuchen konnten. Die im Rahmen dieses Projekts durchgeführte Studie hat eine bemerkenswerte Verbesserung des Verständnisses unter den Testbefragten gezeigt. In beiden Studien konnte über eine Immersionsanalyse ein hohes Engagement und positive Einflüsse der Anwendung identifiziert werden.

Acknowledgments

Contents

Contents

1. Introduction

In this chapter the motivation for this thesis and the separate projects, 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 is 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. Reflections of this can also be seen in developments of the number of graduates in these areas. This number urgently need to be increased, be that via raising of either the motivation of the students, their general interest in the topics or providing better explanations and increased insight into the long term values. These among many other possibilities need researched further and the most promising ones need to be pursued (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. They provide countless possibilities to engage learners more actively into properly provided teaching material, especially abstract or complicated theories and phenomena have shown great benefit of such. VLEs 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 has already shown promising results on 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 of this work will for the biggest part be on the learners point of view. Specifically visual information overload with visualization techniques used for complex theorems and haptic feedback channels as ways to improve intuitive understanding and learning have been identified as topics that urgently require new insights.

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 continuously require further development and new approaches.

1.2. Contribution

This work contributes to two separate specialized research topics in VRLEs with two independent projects.

First, an extensive study with 55 participants has been conducted in order to research general effects of haptic feedback 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. The novelty of the approach chosen for this topic is the methodology to provide true to the real world haptic feedback in an affordable and easy manner. While the desired generalized answer of haptics influence could not be found, more specialized settings indicated definitive advantages of haptics channels and the devised controls pose an accessible method therefore.

The second project encompasses an analysis of alternative visualization methods for gravitational waves representations in an interactive VRLE, providing better intuitive understanding compared to previous approaches taken. A density grid representation of space time that is morphed in correspondence to projected gravitational waves at every moment is the devised technique that was developed for this. The corresponding analysis was also done with a connected user study in which 35 participants confirmed initial assumptions about the positive influence of the developed approach, showing strikingly improved results.

1.3. Structure of the Work

This thesis is separated into two different concerns, haptic feedback and visualization techniques in VRLEs. Therefore, the core chapters for each project are represented twice, once for each concern.

In Chapter 2 a general informative background and corresponding related approaches to both concerns is given. It provides the reader with examples about what past and current research has been concerned with in the respective areas. First, an overview insight into education and STEM and the important developments is presented, followed by related ideas about virtual learning environments. Then background about applications with haptic feedback in different variations and their impact in specific research areas is given. Finally important observations about graphics implementations for physics visualizations are pointed out. All areas provide the reader with ideas about the underlying reasons for various design and approach decisions taken in the later chapters of this work.

Now the thesis' core concern is split into Chapter 3 and Chapter 4, each concerning one separate topic that was mentioned before and both in a similar structure with

design, development and evaluation as their subchapters.

In Subchapter 3.1 and 4.1 the devised designs coming from the basic ideas and corresponding research are explained. After the motivation for each project is highlighted, the requirements for them, both functional and non-functional are described. Then, the resulting design is illustrated with an according conceptual design diagram. At the end the used tools to achieve these designs and the requirements are highlighted.

Subchapter 3.2 and 4.2 give insights into the technical details about the implementation of each project. The system architecture, general development process and core elements that were developed are described here. Both subchapters also point out the respective user interaction possibilities as important parts.

In Subchapter 3.3 and 4.3 the creation of desired research data and its evaluation is elucidated, providing information about the taken study approaches and clues found in the analysed data. Coherences between chosen design decisions and resulting outcome and patterns of the created data are pointed out and the tools used to achieve such insights are explained.

Chapter 5 closes both main chapters up with a recap about gained experience in the process of researching, developing and evaluating the projects. Some decisions made over the course of the creation of each part are put into contrast to the resulting outcome and conclusions about how they affected some progress are presented.

Finally, in Chapter 6 conclusions about the overall approach and each projects results are given along with an outlook about potential improvements to be implemented future approaches.

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 described 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. This will be followed by advancements in the area with the help of virtual learning environments and virtual reality as a learning aid. 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, as those specialized topics provide important insights into related work for both developed projects.

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 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 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 USA 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 from 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 STEM 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 interdisciplinary knowledge.

While it can be seen 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 observation 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 in the end even 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 can be confirmed in more recent works (Castro, 2019; Sahni, 2019).

While there have been several successful attempts, there still remains a lot to be discovered 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 groups 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 observations 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 their needs and enabling additional interfaces for the measurement of self-explanation of a student, they identified improved results of the students exploration and also of its evolution in regard to ACEs coaching, which supported their hypothesis of its importance.

2.1.3. Increasing Interest and Engagement 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
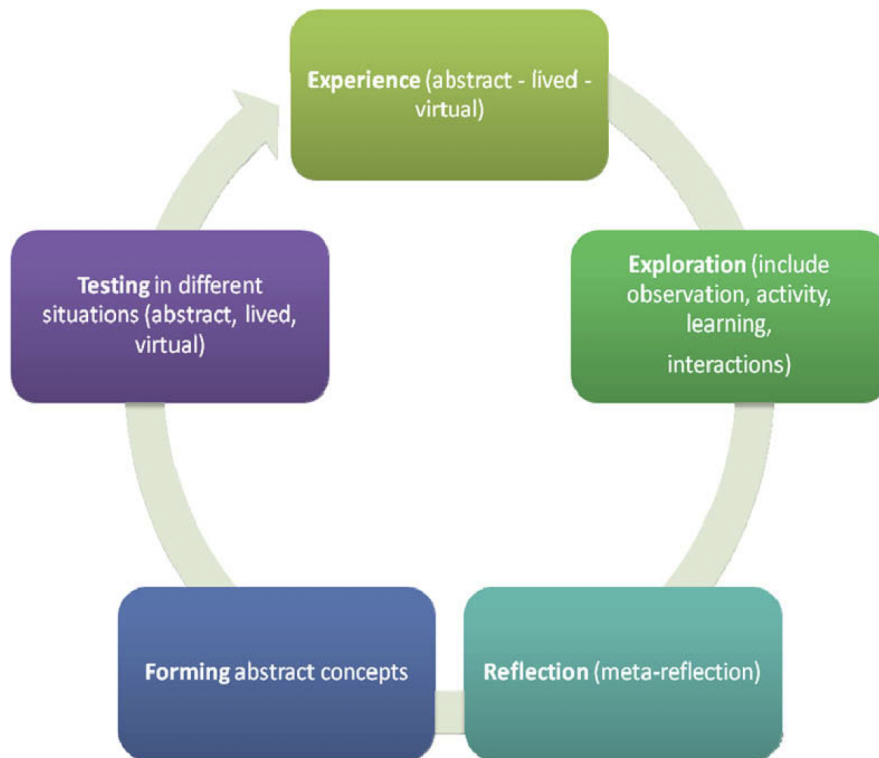
Figure 2.1.: Exploratory Learning Model, (taken from de Freitas and Neumann (2009))

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

Kiryakova, Angelova, and Yordanova (2014) built up on Kapp's 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. These were identified to be helpful to understand the underlying factors for positive impacts of game mechanics inclusion (see 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 more solid and steadier results.
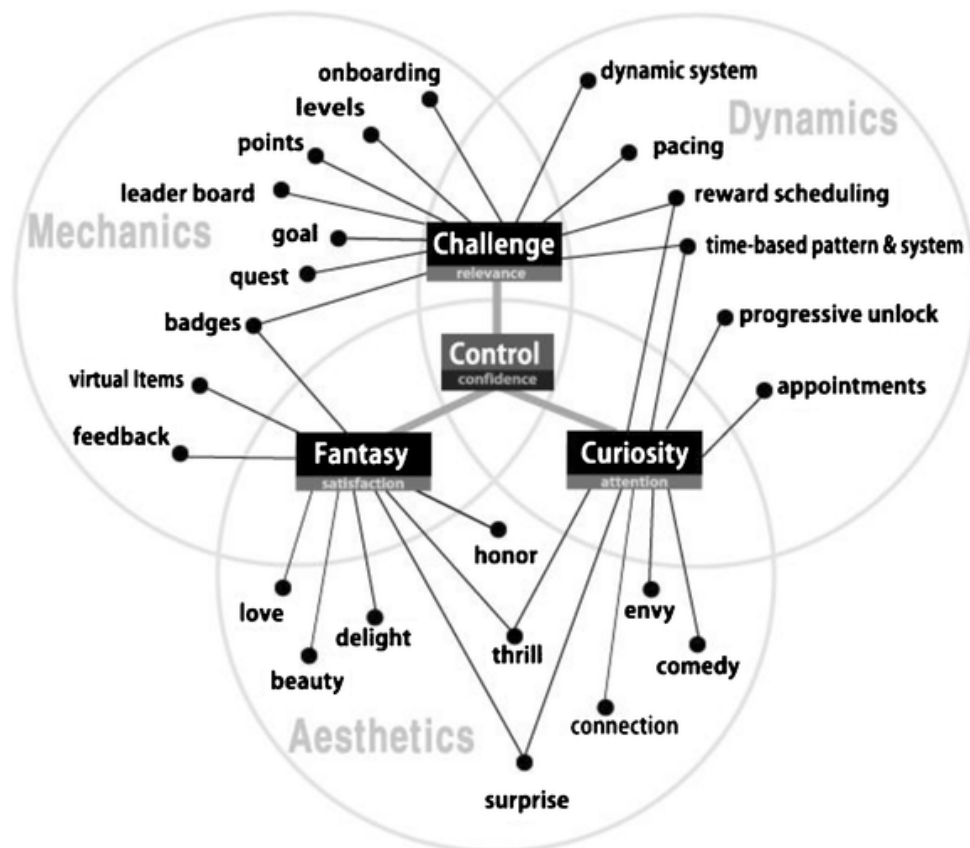
Figure 2.2.: Fundamentals for Dynamic Model for Gamification (taken from J. T. Kim and Lee (2015))

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

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 the focus will be 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 sections in this chapter are focusing on some more specialized applications of VLEs, especially some that led to decisions being made in the practical part of this work.

2.2.2. Learning in Virtual Reality

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 effectively the same information in a video of the renderings. While theoretically the available information was the same, they could identify a greatly increased 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 of the main identified advantages of VLEs, namely enhancing, motivating and stimulating the learners understanding, they even identified strong indications of VLEs in combination with VR or Mixed Reality (MR) or Augmented Reality (AR) 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 exploded 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 any kind of immersive interface is necessary. Here most commonly a Virtual Realtiy Headset or Head Mounted Display (HMD) comes into play. These devices contain as their core functionality a stereo screen, one for each eye, that allows 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 by changing the image shown on the screens. 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 HMD manufacturers, provided several high end devices for the end customer already, mediocre and appropriate 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. Albeit 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 results almost as good 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 if the corresponding applications are fitting these restrictions. 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.

Although it does not help with the accessibility issue, Cave Automatic Virtual Environments (CAVE) Cross Reality (XR) 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, & 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.

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. Haptic Feedbacks Influence

In various simulation systems, haptic feedback has become an integral component. For example, in systems designed for gaining and upgrading surgical skills (van der Meijden & Schijven, 2009; Våpenstad, Hofstad, Langø, Mårvik, & Chmarra, 2013b), 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). Contrary to those supporting claims,

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, XVR, MR or AR	*Cross, Mixed or Augmented Reality* Combining the real and the virtual world With haptics, visual or other augmentations	Abdoli Sejzi (2015), Azuma (1997), Kondo (2006)
VHMR	Visuo-haptic mixed reality Specialized MR domain that merges visual and tactile perceptions in a collocated approach	Cosco, Garre, Bruno, Muzzupappa, and Otaduy (2012), Frid, Bresin, Pysander, and Moll (2017)
VRLE	*Virtual Reality Learning Environment* Combination of VLE and VR	Thorsteinsson and Shavinina (2013)
HMD	Head Mounted Display[a][b]	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	Any combination of force, tactile, vibrotactile or proprioceptive Feedback	Cichocki et al. (2007) Bark et al. (2015)

Table 2.1.: Commonly used Terms and Abbreviations and their definition

[a]https://www.vive.com/
[b]https://www.oculus.com/

other approaches found no significant learning benefit from haptic feedback or even indicated a negative influence if the implementation is not done properly (Våpenstad, Hofstad, Langø, Mårvik, & Chmarra, 2013a). While this might be correlating with more advanced controls and implementations, there are still uncertainties left to be clarified.

2.3.3. Implementations in Virtual Reality

One aspect of haptic feedback in VR that comes up inevitably is a common issue with appropriate 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 [1] 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.
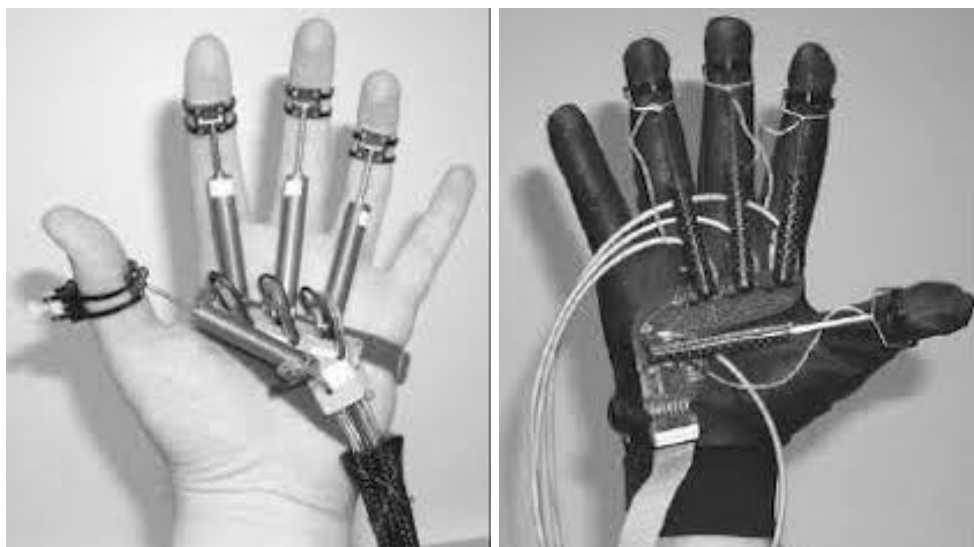
Figure 2.3.: Rutgers Master II and Rutgers Master II-ND. ©Rutgers University (retrieved from Bouzit, Burdea, Popescu, and Boian (2002))

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

---

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

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. After many confirming research findings the assumption of actual vibrotactile haptic feedback with any sort of appropriate controls yielding superior results to any visual or otherwise simulated sort comes easy. 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, which they implemented in two separate version as seen in Figure 2.4. This implies at least a tendency for MR setups to provide stronger positive effects than purely simulated haptics in just VR.

Figure 2.4.: Custom glove with vibrotactile stimulations on the left and Sense Glove DK1 on the right, used for comparison of different haptic feedback stimulations in Kreimeier et al. (2019)

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.

Especially in mixed reality applications utilizing haptic feedback with real world objects a potentially severe problem for intuitiveness remains, misalignment issues of virtual and real world objects. Especially in applications involving high accuracy tasks using virtual tools this can heavily disturb immersion and thus create a big distracting factor, negatively influencing learning and memorization. Cosco, Garre, Bruno, Muzzupappa, and Otaduy (2012) created a proof of concept implementation with a four step solution (see Figure 2.5) for this problem using see through display technology in a visuo-haptic mixed reality environment. Even though such correction approach is not within the focus of this thesis, the importance and impact of those potential issues and the proposed solution shown in this work make it a worthy mention.

Figure 2.5.: Pipeline of visiohaptic implementation in Cosco, Garre, Bruno, Muzzupappa, and Otaduy (2012). From left to right: (a) Real world scene; (b) Virtual view after image-based removal of hand and tool; (c) Composition of virtual object; (d) Final view, free of tool-hand misalignments.

Specialized Application Domains

Various application domains came to see and embrace the benefits of haptic feedback enhanced virtual learning environments in different schooling or training processes.

Lahav and Mioduser (2008) showed the usefulness of haptic feedback in VR implementation for the blind population, opening possibilities for visually impaired people to utilize advancements in VR simulations. In their approach it was possible for the participants to recreate a map of the virtual environment much like they would in real life, only lead by an exploratory and an orientation task, gaining feedback via a force-feedback-joystick.

Han and Black (2011) showed, that haptic feedback improved understanding of abstract physics concepts in elementary school pupils. Their ability to recreate experiment settings and recall learning contents improved significantly with the addition of force and kinesthetic feedback, with the latter being less effective. The setting of their experiment included more than 200 pupils and compared a teaching environment for energy transmission in a mechanical system with multiple gears with and without added haptic feedback channels. While not being overall conclusive and with some further analysis required, they showed confidence that an application with haptics in such a setting is beneficial.

Additionally, NASA[2] published approaches where they could indicate the usefulness of haptics. In Bowen Loftin (1994) the benefits of such simulations for both astronauts and ground based personnel is discussed and the results for training Hubble Space Telescope Repair and Maintenance Mission flight teams are shown. In more recent publications they show how they use consumer hardware to create realistic haptic feedback to improve their engineering workflow. Specifically in Delgado and Noyes (2017) they show a simulation of the ISS where users get the chance to experience virtual as well as tracked physical objects using their Active Response Gravity Offload System.

These and many other works provide countless examples on how haptics are a compelling aspect of VR simulations and while all of these domains seem promising, in the following part the focus will be on an especially important domain, medical simulations. The possibilities for 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 and corresponding controls enabling which are continuously being developed.

Khaled et al. (2004) 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, and 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 in corresponding study approaches.

Van der Meijden and Schijven (2009) also state the intuitive advantage of force feedback, but analysed the actual outcome of adding haptic interfaces to virtual simulations. While VR on its own is essential and medical VR training 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

---

[2]https://www.nasa.gov/

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.

Haptic feedback with throw movement learning

Figure 2.6.: Basketball Free-Throw simulation in first person perspective. (retrieved from A. Covaci, Olivier, and Multon (2015))

With such highly specialized applications and corresponding domains it becomes clear, that haptic feedback has to have some kind of major influence on learning behaviour of participants in such studies. What seems to be lacking is a general numeric value of haptics, showing it's influence in one and the same application with and without it. A trend has been discovered where implementations involving throw movements were popular in determining effective influence of haptics, compared to non-haptic counterparts, for example in ball game trainings. Frid, Bresin, Pysander, and Moll (2017) analysed a setting in this direction of thought. During a task involving virtual ball throwing movements they paid close attention to gaze trajectories and behavioural patterns, trying to find influencing factors of haptic and auditory feedback in corresponding setups. A big lacking point in their approach was a rather small number of participants and a lack of consistent data across those. Similar to this

approach, Frid, Moll, Bresin, and Sallnäs Pysander (2019) also analysed a virtual throwing task and how participants behaviour is influenced by haptic and or auditory feedback. They as well could point out an increase of intuitiveness and even stated a claim of improved performance in an appropriately chosen setup that is enhanced with such feedback functionalities. Haptic force feedback in their implementation was achieved with the SensAble™PHANToM® desktop device. Especially interesting was the overall consensus that any combination of auditory and haptic feedback reduced error rates and increased intuitiveness in their setting by a significant amount.

The methodology in the work of Alexandra 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 setting. 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 and they even further reinforced this claim in a later approach in a similar setting (A. Covaci, Olivier, & Multon, 2015). In their follow-up paper their implementation included a detailed analysis of the throw trajectory of each thrown basketball which got compared to a dataset previously created with the help of a professional player. Their CAVE setup involved real world basketballs that were recognised by the virtual environment and tracked accordingly (see Figure 2.6). Additionally to visual and real haptic feedback they also analysed behaviour of audio While confirming the general positive influence of haptic feedback in learning behaviour and the supported development of participants, some outcomes are claimed to be still inconclusive and requiring further analysis. Overall they again pointed out the urgently important aspect of appropriate representations that need to be implemented for such simulation to achieve desired positive results.

Table 2.2.: Haptic Feedback implementations review

Implementation Technique and Details	Conclusion	Reference
Resistance guidance, friction. Guidance on robotic steering wheel with friction resistance	Haptic feedback in form of friction guidance improves immediate performance but does not increase long lasting learning	Crespo and Reinkensmeyer (2008)
Friction resistance. Handles with haptic resistance	Rejected by 90% participating experts due to insufficient implementation accuracy. Highly realistic feeling required for positive effects.	Våpenstad et al. (2013a)
Ultrasonic elastography. Dynamic haptic sensor actuator system.	Haptic feedback was found to be indispensable in medical VR simulations concerning tissue operations and a claim was made that also other domains could benefit of the developed haptic system.	Khaled et al. (2004)

Vibrotactile compared to visual feedback. Vibrotactile actuators similar to speakers	Comparison of various feedback channels in Brain Computer Interface applications showed tactile feedback to be indispensable for learning and performance improvements, especially with distracting factors or a visually overloaded channel	Cichocki et al. (2007)
Force and kinesthetic feedback. Force feedback joystick compared to visual kinetic simulation	While both approaches showed improvements in short term understanding, only force feedback provided a sufficient cognitive grounding for improved future learning	Han and Black (2011)
Various force components. Mechanical link mechanism attached to fingertips	Added force components improved the perceived handling of virtual objects and accuracy thereof compared to non-haptic test group	Yoshikawa and Ueda (1996)
Force and kinesthetic feedback. Gear mechanism with adequate force feedback and simulated equivalent kinesthetic simulation	Both force and kinesthetic feedback were found to improve understanding and memoization of physics concepts, which was confirmed in corresponding recall, inference and transfer tests with n=175 evaluated participants.	Han and Black (2011)
Visuo-haptic feedback. AR setup with real and virtual tools	Comparing task completion time and recall results of an MR task involving virtual and real world tools a highly negative impact of object misalignment to those values could be shown. Thus, a computational algorithm has been developed to counteract such. Therefore MR implementations which require accuracy need to be aligned with the real world as good as possible.	Cosco et al. (2012)
Visual, audio and force feedback. Simulated and actual haptic variant, both with friction sounds.	In this multi-step research approach inside a CAVE setup involving free-throwing of a virtual ball, a combination of visual, audio or force feedback was compared. A combination of all feedback channels resulted in the best overall learning outcome but potential issues with Incongruities between sensory inputs have been highlighted.	Frid et al. (2017), Frid et al. (2019)

Force feedback. Real world basketball.	Using a real world basketball, that is tracked with a motion capture device in a CAVE setting, an analysis of corresponding throw trajectory and gaze behaviour indicated drastic improvements in consecutive throws when haptic feedback with a real basketball was involved. Pure visual testing groups showed the weakest results, followed by visually guided group and haptic plus visual guidance as the best group.	A. Covaci et al. (2015)

These and similar approaches provided some of the main motivating ideas to build upon for some implementation designs chosen over the further course of this thesis.

2.4. Physics Applications 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 are 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 those game mechanics could help filling in gaps 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. Gravitational Waves

This section was taken in slightly adapted form from Lontschar, Pietroszek, Humer, and Eckhardt (2020), as it is one of the two papers this thesis is based on.

With latest developments in physics in general and the applications and research in VLEs thereof, gravitational waves appear often in corresponding research. They are a most recent breakthrough discovery in astrophysics and therefore, next to personal interest, their background and current literature status became especially interesting. They were 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 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), this would result in a periodical difference in gravity (Allen, Andersson, Kokkotas, & Schutz, 1998). Since gravity expands with the speed of light,
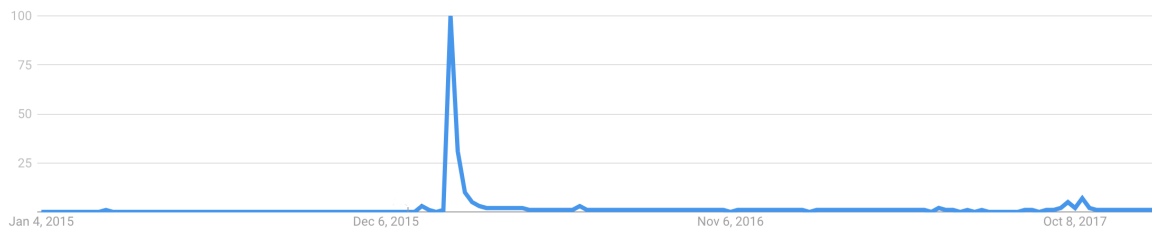
this periodical force shift propagates as waves. Moreover, cosmological catastrophic events such as supernovae but also great moving masses can produce observable gravitational waves(Yakunin et al., 2010). One commonly described source are binary star systems, as was observed by LIGO, due to their orbit towards each other and the oscillating change of position relative to an outside observer in the orbit-plane.

2.4.3. Gravitational Waves Visualizations

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. According to Google Trends (see Figure 2.7), a tremendous increase in public interest in the matter of gravitational waves after their detection by LIGO can be identified. Tightly related to this general interest, a demand for further explanation is apparent if one is looking at related queries on the topic. Looking at part c) of this figure it also becomes clear, that scientific interest on the topic has almost doubled since their detection. Even though the public surge of interest was apparently short lived, the impact was big enough to have a lasting effect on a notable amount of the population and intuitive explanation methods became actively searched and developed. Also more recent works confirm this and also talk about the public interest and some connected hyperbole about the "Discovery of the century", while actual understandably explanation might be missing (Faktorovich, 2019) . Common approaches for such explanations are static images on the lower end and visualized 3D simulations on the higher one. Since in both cases depth impression is absent, the illustration is often reduced to a two dimensional representation in order to not overload the visuals, neglecting potentially vital information for grounded understanding. Furthermore, the absence of interactivity is evident. VR makes it possible to immerse the learner into a VRLE that is enhancing, motivating and stimulating learners' understanding of certain events (Abdoli Sejzi, 2015; Callaghan et al., 2008; Kondo, 2006; Pan, Cheok, Yang, Zhu, & Shi, 2006). Moreover, interactive VLE's have shown the ability to transmit physical phenomena surpassing traditional learning methods, as was also mentioned in previous chapters (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 Virtual Interaction with Gravitational Waves to Observe Relativity (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 at 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, for example with 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. Background and Related Work

a) Google Trends for the term "gravitational waves" between 2015 and 2017.
Retrieved from https://trends.google.com/trends/explore?date=2015-01-01%202017-12-31&q=gravitational%20waves

b) Google Trends related queries for the term "gravitational waves"

c) Frequency occurance of the term "gravitational waves" in Googles english book corpora from 1900 until 2019.
Retrieved from https://books.google.com/ngrams/graph?content=gravitational+waves&year_start=1900&year_end=2019&corpus=26&smoothing=0

Figure 2.7.: Google search trends related queries and string occurrence in books for the term "gravitational waves."

2.4.4. Visualization Techniques

Due to the often complicated calculations that are necessary in order to determine correct 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[3], Apples Metal[4] or Microsofts DirectX[5], in the further part of this work the focus is going to be on OpenGL[6], 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 graphic programming might require (Carr, 1997). While talking about *how* to implement appropriate visualizations, one also has to think about *why* proper visualizations are required. A fundamental motivation towards the *why* is a quote of a very important physicist that devised many underlying theories for the area of astrophysics : *"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 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 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

---

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

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

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

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

job, Jimenez et al., 2011 analysed upcoming alternatives and promising new approaches that appeared based on morphological anti-aliasing (MLAA). 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 at 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.

VLEs are providing popular alternatives to the sometimes lacking traditional learning approaches and especially in an even more focused approach with VRLEs are showing 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 of them might lead to be beneficial for the encompassing topic of VRLEs and learning performance of such.

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. Applications involving throwing movements and ball game learning have been identified to benefit haptic feedback in the form of physical objects combined with virtual environments in MR settings. Thus this came to be of special interest for more detailed analysis and from there the basic idea for a further study approach evolved.

Representing a prime example of complicated theorems and formulas, developers of applications to teach various topics of physics already looked into virtual represen-

tations thereof 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 especially 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 concerning these identified specific interest domains is going to be discussed. The chapter is split into 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. Afterwards the second project is described in the same structure.

3. Haptic Feedback in Virtual Learning Environments

This thesis is split into two separate projects concerning different aspects. The following chapter will focus on the first of them: Haptic Feedback and it's influence in Virtual Reality Learning Environments(VRLEs) with details about the approach and implementation. First the focus will be on system requirements and design decisions taken for the approach. Then, details on the actual development of the project will be given and finally the assessment and evaluation of the gained data and insights are described.

Some parts in the following sections were taken from the paper "Analysis of Haptic Feedback and its Influences in Virtual Reality Learning Environments" by Lontschar, Deegan, Humer, Pietroszek, and Eckhardt (2020) and lightly adapted later. The publication was based initially on the project described in this chapter. The adopted parts are indicated separately and contain fragments of the original documentation and implementation of the application described over the course of Chapter 3.

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 the identified requirements to it. The main idea for this project, that came out of corresponding literature research (see Section 2.3.2), was to find an appropriate setting, which allowed a certain mechanical task to be carried out in two equivalent ways, with and without haptic feedback, to get a meaningful comparison of haptics effects on learning behaviour and performance. These two ways will over the further course of this chapter be referred to as Virtual Reality(VR) and Mixed Reality(MR) part respectively. This basic idea also represents the main research question analysed over the course of this first project in this thesis. Furthermore, analysis approaches concerning throw movements in MR setups involving real world objects appeared to be fitting for the desired outcome (see Section 2.3.3).

3.1.1. Motivation and Goals

In Section 2.3 an uncertainty about the positive, negative or any effect at all of an added haptic feedback channel in Virtual Reality Learning Environments(VRLEs)

was identified. Considering on the one hand the fact that the intuitive idea about it is very appealing and, on the other hand, some contradicting opinions about it, this issue appeared to require a more detailed analysis. Various approaches on this topic have been tested already in related works, some of them conducted using very sophisticated hardware assistance and very detailed reference data sets. However, a more affordable and simplified approach that is not influenced by small scale data variance and concentrated a more generalized effect of haptics seems to lack attention and research. Thus the idea came up to concentrate on finding an application that focuses less on very precise movements on a small scale, like they were found in Section 2.3.3, 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, that feels natural to them, influences their behaviour and especially their development and progression inside a MR environment. Afterwards, this data has to be compared with a test group that used a pure virtual interface in VR. The detailed requirements for this setup are going to be specified in the following sections.

3.1.2. Target User Group

Due to the main reason for this project's implementation being a specifically generalized analysis of haptic feedback's influence in VLEs, no particular target group definition is necessary. While the user study is being performed on the grounds of a university campus, mainly students are going to participate in a corresponding user study. However, the application domain is not restricted to any specific demographics group and thus anyone should be able to use it and is free to do so.

3.1.3. Requirement Analysis

In this section a fundamentally important aspect of software development projects is discussed. 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, one also has 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. General Requirements

    a) The VLE 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 has to be displayed to the user

2. Environment 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 transportable
    c) No obstacles have to be 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 and immediate orientation

3. Task Specific

    a) The task needs to be repetitive in such a way as 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 interactable 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 interactable equivalently in VR and MR
    f) The user needs 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 any bug should occur

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

3.1.4. Design

Some parts of this Section are taken in slightly adapted form from Lontschar, Deegan, et al. (2020).

Design Basis   As the need for an appropriate task and virtual environment for study participants during the analysis on haptic feedback effects was identified, a previous project that concerned a similar matter came up as a starting point. This project involved a learning environment for understanding Newtonian mechanics in different planetary environment, specifically in terms of projectile motion caused by a throw movement in a pure VR VLE. With this approach an improvement in intuitive understanding of scale and order of Newtonian Mechanics in different conditions like gravity and air density could be shown (Brown et al., 2019). While this implementation was not concerning any sort of haptics, the principle of analysis serves as a good starting point for the design of a follow-up project, especially because all source code and information from the original developers was available. Furthermore, their testing approach already provided a good idea on how to setup a project for the identified requirements to design tasks in an environment that create intuitive understanding for physical object movements and throw trajectories corresponding to weights and form.

   Based on these insights a first conceptual architecture was designed as seen in Figure 3.1.

Approach Design   Based on the idea of the previously mentioned project and to further expand on the question whether haptic feedback contributes to the learning
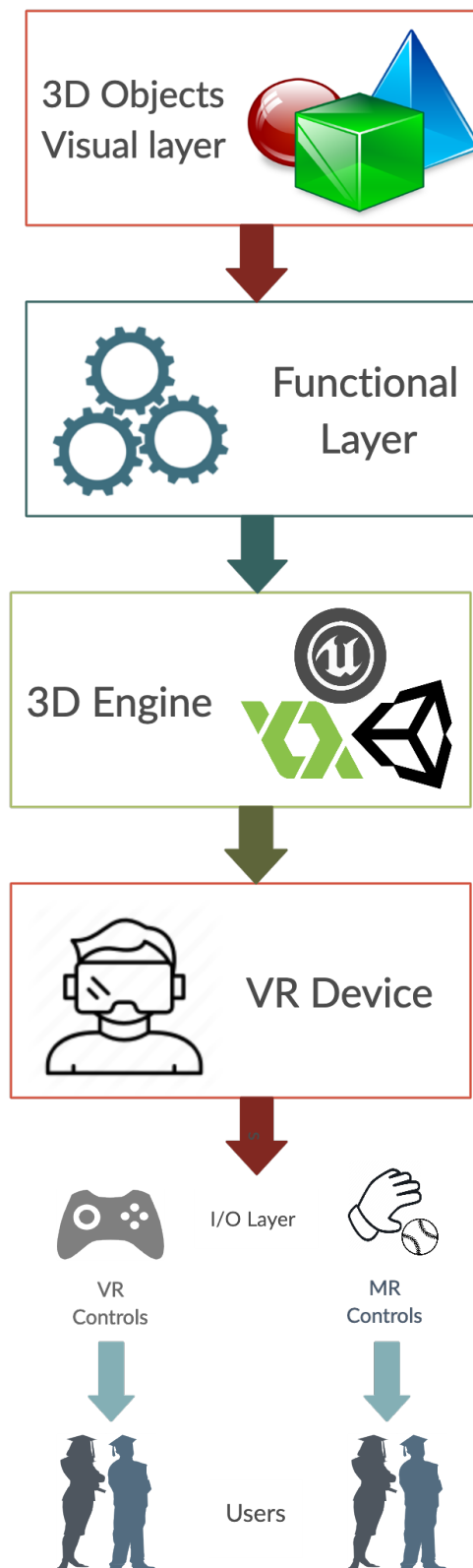
Figure 3.1.: Conceptual Design

outcome and performance in VLEs, as well as to assess the immersion in comparison with plain virtual feedback, a VR test environment which encompasses a simple mechanical task to throw objects towards a target was devised. 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.

The basic premise was to identify a simple task which can be employed into a VLE. There haptics should be introduced for one group of participants and while a control group would be doing an identical test process but in pure VR, without changing any other simulation components. For that, a throw-and-hit assignment for VLE participants was conceptualized, where utilization of haptics is intruded 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 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 VR group, on the other hand, should have virtual weights only. Ensuring appropriate insights regarding the users experience and the corresponding operation inside the VLE also a questionnaire before and after the practical participation is required, which can then be evaluated together with the corresponding data created in during the VRLE experience..

Implementation Design Having decided on the general approach and activity, the focus will now be on the design of the overall setup. In contrast to the previous project (as mentioned in Section 3.1.4), this follow-up approach is supposed to be connected to 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. This is supposed to help users in the VRLE to get a more realistic feeling about the simulation and reduce distraction from any behaviours that would not correlate with anything known from nature and actual physics.

The need for these objects to provide certain functionalities, in order to be properly interactable for the user and also to be recognised appropriately by some management and control system in the described environment, was identified. 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. No supervisor intervention should be required during the test process in order to reduce potential error cases, thus the need for a robust software system and the ability to recover from any potential problems. Due to the nature of software and the frequent inability of covering every single possible case, the need for an emergency reset functionality is also given.

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. All previously mentioned objects

need to be included in a such scene. There all created assets are combined, displaying interactable objects with scripts that provide necessary functionality and invisible, non-interactable objects that care for all management required in the background. Furthermore, given packages from the game engines store allow easy access to VR frameworks and thus makes interaction with the scene from a HTC Vive HMD possible without the need for sensory development. Adaptions to those packages need to be made in order to create desired behaviour and realism for all virtual objects correlating to their real world counterparts.

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.

3.1.5. Tools and Frameworks

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

Head mounted displays   All experiments with user study participants were conducted with the head mounted display HTC Vive. This HMD was chosen due to it's comparably high performance and wearing comfort over similarly priced 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 the project was driven by Nvidia graphics cards and Intel or AMD processors. The PC used in the lab environment included a GTX 1080Ti graphics card and an AMD Ryzen 7 CPU. Because one part of the project was carried out on the outside, also a Laptop was required to be used there in order to run the created software. This laptop 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, the decision came quick to combine functionality and visual representations in this project in Unity (Haas, 2014; Technologies, 2019). Existing expertise and experience as well as given functionality of 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 information and send the appropriate image output to these screens with the developed software, SteamVR [2] and the SteamVR package in Unity was used. In Unity's environment the SteamVR package provided all data handling from and to the developed 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.

Game Immersion and Game Experience Questionnaire In order to evaluate behavioural data of the user study participants and the effects of the created VRLE on them, a framework of questions and a corresponding interpretation was required. Because of previous experience and plentiful positive peer reviewed feedback the Game Immersion Questionnaire (GIQ) and Game Experience Questionnaire (GEQ) were used (IJsselsteijn, de Kort, & Poels, 2013; Jennett et al., 2008). The GIQ provides established questions to quantify users feeling of immersion in game like environments while the GEQ concentrates on corresponding effects lasting until after finishing the VRLE experience. Both questionnaires provide meaningful insight into the users sense of well being while and after performing tasks in the VR environment and makes it possible to put this data into relation with other measured aspects to find correlations and influences. While both questionnaires are well established and have been referenced often, newer approaches have appeared over the years. The tendency goes towards alternative and supposedly better ways of measuring immersion but the decision was made to use those questionnaires as the team had previous good experience and also time constraints prevented experiments with unknown frameworks in this area.

---

[1]https://www.gamedesigning.org/career/video-game-engines/
[2]https://store.steampowered.com/steamvr

Python   Because each separate study led to many data sets being produced, it was not feasible to analyse the data by hand. To support the process of data analysis and create smaller data sets and graphs for further evaluation, Python 3[3] was used, because the developers were familiar with the language and it provides a large built in choice of functionality that could be used, as well as many frameworks supporting further functionality. Additionally, some data sets required an additional preprocessing step which was done with C++ version 11[4], as here some functionalities that were already used in previous projects could be utilized.

Python Libraries   To support reading data from raw CSV files in an appropriate format, python CSV library as well as Pandas[5] were used, because of their straightforward approach and easy access of the read data (McKinney et al., 2010; Shafranovich, 2005; Van Rossum, 2020). For various calculations with the gained data and to further process it, Numpy[6] and SciPy[7] became the first choice, as they provided all necessary functions in the shortest and least complicated way of turning raw data into a format that showed actually interesting aspects of it (Oliphant, 2006; Virtanen et al., 2020). Finally, in order to create meaningful visual representations MatPlotLib[8] was used , as the standard configuration of it's created plots was already very similar to what was planned to be created and thus saved time and effort in the visualization part of the evaluation process (Hunter, 2007).

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.

In order to create a sustainable way of mounting the modified controller of the HTC Vive on each users hand, a conventional fabric glove was used, as this could be easily removed and attached. The controller was stitched on to the glove and in order to fixate its position and to keep it held in place even during rapid movement additional medical bandage tape was used. The fixation on the participants arm with bandage tape is required as additional safety measure. Otherwise throwing movements would potentially also detach the controller setup and cause potential damage to people or material.

A power supply was necessary for the outdoor setup. For this a conventional gasoline driven, portable, electrical generator unit was used. 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 the case of this setup.

---

[3]https://www.python.org
[4]https://en.cppreference.com/w/cpp/11
[5]https://pandas.pydata.org/
[6]https://numpy.org/
[7]https://www.scipy.org/
[8]https://matplotlib.org/

For the outside setup camping tables were used for placement of VR sensors, laptops and generator. A moving table on rolls was used for transportation of all equipment between the laboratory and the outdoors setting.

3.2. Development

In this subchapter an in-depth look into the developed components of the final application and its important aspects is given. Firstly, an overview of the implemented virtual environment is given, including an explanation of the system architecture. Secondly, more details on the user interface for test users and supervisors will be discussed, including an explanation of how the MR interface of the user was realized. This includes a detailed view on the implemented throwing mechanics and how they are recognized and evaluated by the system. Finally, an insight into the high-score functionality, the points gained for each throw and their calculation, as part of the gamification element is provided, as has been discussed in Section 2.1.3.

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. Implementation

To gain a measurable outcome a Virtual Learning Environment(VLE) resembling a soccer stadium was created (see Figure 3.2). "Learning" over the further course of this chapter relates to the improvement of accuracy and so the gain of intuitive experience of a 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. For insights on how the feeling of immersion is being influenced by haptic feedback, each participant had to complete a survey before and after the VLE experience (see Section 3.3.2) (Lontschar, Deegan, et al., 2020).

The approach implemented in this project includes an automatic sequence of a repetitive task of throwing certain different objects into targets that appear at randomized positions at given distances in front of the users. The whole system works fully automatic with each important aspect being handled by its respective class in the program. Every movement of the user is being tracked via the HTC Vive controller that is being in turn being tracked by infrared lighthouses and positions as well as interactions are evaluated accordingly by the software system.

3.2.2. System Architecture

Based on the initial design and after analysing requirements and deciding on implementation details, a conceptual architecture representing the experiment workflow was created (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 the MR variant. In order to create a non-blocking workflow, the practical and questionnaire part were split and handled via two separate devices, enabling parallel runs for two users, one doing following tasks in the simulation and the other filling pre- or post- questionnaire. For the practical side, the whole virtual environment is created with Unity3D and all interactions, VR as well as data management is done with corresponding packages. Some of those packages are imported from the Unity Store (VR I/O management, Unity physics) and all custom functionalities self-written in the further development process. To ensure proper data flow and preservation of all important information, an observer class is created, which listens to trigger events in the scene in order to evaluate current object and user controller positions. This data is being saved on grab and release of virtual objects as well as impact of the object on the ground. Certain information is sent from the observer to the spawner classes. These, depending on the current stage of the simulation, in turn spawn corresponding objects and make the test run fully automatic. Interaction from side of a supervisor is only necessary to start the test run or if a non-recoverable error should occur.

Each object, throwables and targets, has their own functionality and is managed by throwable- and target-spawner classes respectively. The GUI in traditional manner is done with the help of a billboard class, which is 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 main interaction mechanic for the user, which was a grab event that was technically translated into a trigger press. This is also the part where MR comes into play in the corresponding variant. More more details on that can be found in Section 3.2.4.

Everything recorded in the VLE via the observer class is then being exported in CVS format. After all participants in both variations of the simulations are done conducting the user study, the gained data is being analysed in an external setup using Python

and C++ for data processing and analysis. A detailed description about the evaluation of said data is described in Chapter 3.3.
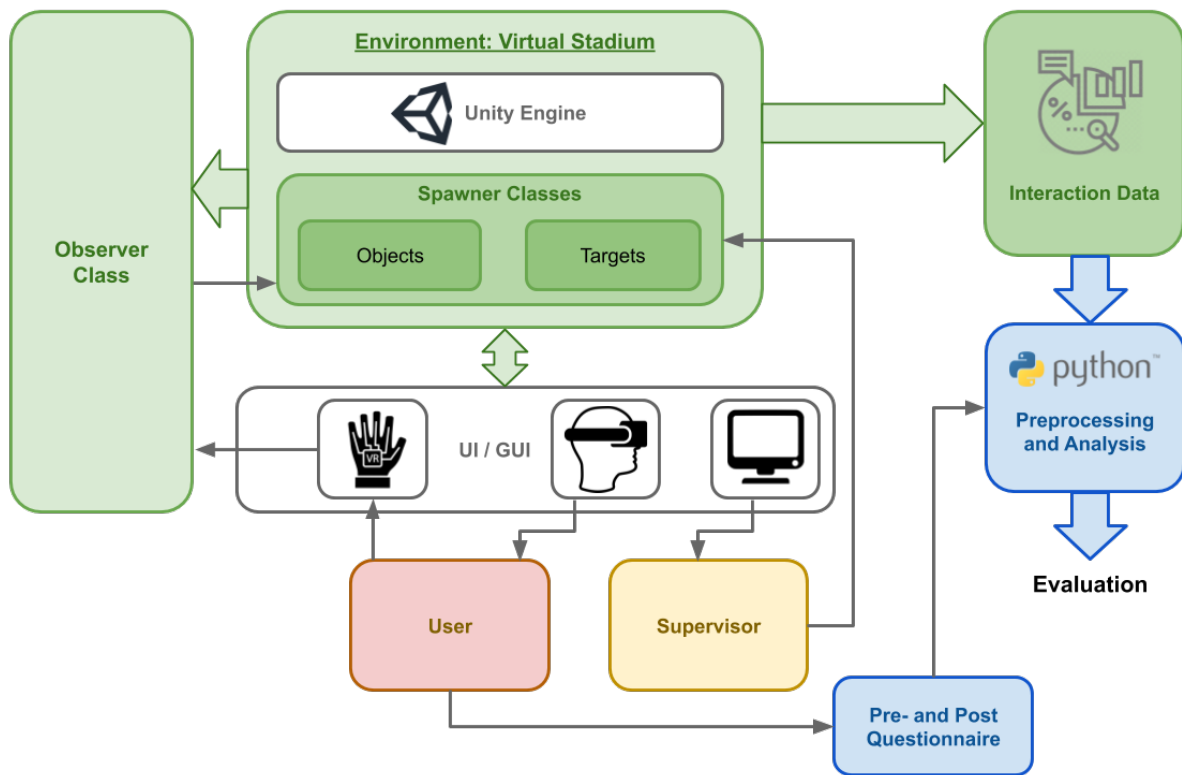

Figure 3.3.: System Architecture

The following sub-sections each give more details for the important aspects of this project.

3.2.3. Core Software Elements

While the novel part of this project was the implementation of the MR interface for the devised throwing task and the corresponding evaluation of those, several software components and classes were required in order to ensure appropriate behaviour of the system and provide a stable and user friendly environment, that also behaves realistically enough to ensure intuitive learning.

Observer   As there are several aspects and inputs of the virtual environment that need to work together, linking them all separately would result in chaotic and error prone patterns. Thus, an observer class was created to manage everything happening in the VLE and notify all other class instances about everything they need to know, while paying close attention to every action that happens in the scene, coming together in one central place. Next to ensuring the appropriate sequence of actions happening

in the VLE, the observer class is also responsible for recording everything necessary during the throws. In the end all recorded data is written to a file with the test users id for further processing in the preprocessing and evaluation stage.

Some of the most important functionalities of the observer are:

- Listen to grab events and prepare data saving if a throwable object collides with the floor afterwards.
- Notify the blackboard about current throws happening.
- Give information to the spawner classes if a valid throw is recorded.
- Save a ground truth counter of throws to ensure the same behaviour in each test run.
- Write throw data to an internal storage on each throw.
- Write stored data to a file on finished test run.

Vive Grab and Throw handler   In order to implement the throwing mechanics, two software classes were created to handle all interactions between the controller and the virtual throwable objects. Their core functionality is firstly a method that "grabs" virtual objects and holds them at the controllers position via a fixed joined attribute. Some modifications in position and angle were necessary in order to get very close to the actual real world object. Secondly, on release of the virtual and real world objects, unity physics was not behaving appropriately initially and trajectories of the virtual objects were not at all in line with real ones. To compensate this, the throw handler class manipulates the virtual objects release angle an velocity in correspondence to the previous controller positions plus the object offset. In order to smooth this value and remove eventual frame rate drops or any stuttering, an average of the past 10 position values was taken, where one position was saved every 0.1 seconds. More details on the throwing and how the virtual interacted with the real world will be seen in the next chapter.

Spawners   Because the chosen task for the test users includes repeatable behaviour, an implementation of some kind of spawning management for both throwable objects (see Figure 3.4) and targets to hit was required. 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 the previously designed test procedure. Thus, spawning targets at slightly increasing distances for each throw. Additionally a throwable object is spawned upon throw initiation, in this case a grab movement of the arm with the controller glove (See Figure 3.6). 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 object spawner 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 until supervisor interaction.

The spawn position for all throwable objects is set to be exactly at the users controllers position with a specific offset function that moves the virtual object onto an appropriate position corresponding to the real world object. While this function involved a straightforward naive approach it was reported sufficient by test users feedback and no irritation resulting from position offset could be identified. This was positively surprising at first, because some insights from Chapter 2.3 indicated potential problems with insufficiently accurate MR implementations and deviations to expected values, but as early testing showed positive feedback, the initial approach was kept as is. It was found that the high level of abstraction was sufficient as the user had only virtual visual and real world haptic input channels, thus not creating too many discrepancies, even though they would not be aligned absolutely correct.
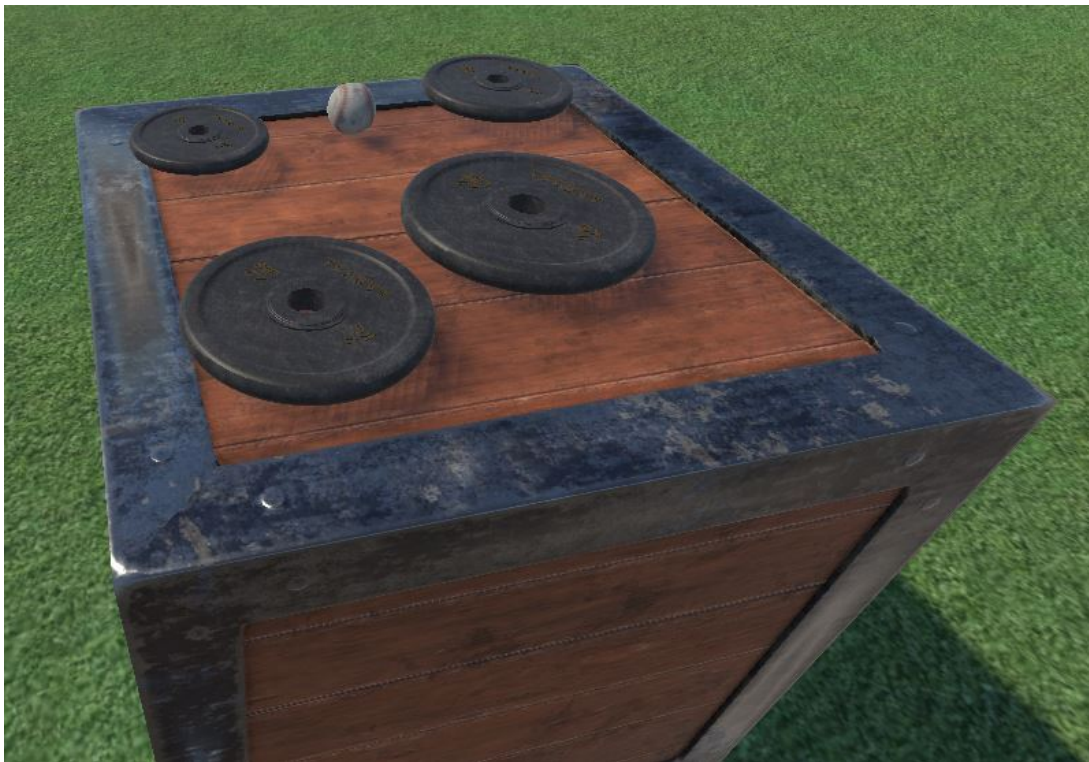

Figure 3.4.: All available throwable objects. Normally they are only visible on task engagement.

3.2.4. User Interface and Controls

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

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 lies 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. GUI in the conventional sense in this project is represented as 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 3.2.5 for further information on how this information is calculated.

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

UI User Interface represents every possible way how information can flow bidirectional 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 3.6), which includes one trigger control mechanism and the movement itself.

Throwing mechanics

The design of this controller allows the system to work equivalently with or without objects in the real world. There are copper conductors on thumb and index finger which serve as triggers and send a signal on being pressed together. This movement allows the initiation of a grab event in the simulation that is registered by the environment.

45

The grab works either via a direct connection of the copper conductors on thumb and index finger, or via an object that is wrapped in copper foil, thus acting as a electrical bridge. The objects behaviour in the game is designed to be like a real object to make the feeling upon release as natural as possible. In order to achieve this, the virtual object is fixed onto a position as close as possible to where it would be in the real world. This position is calculated via a corresponding script and results in a placement relative to the users hand position. For each frame, position and velocity of the controller and object are recorded and upon release a corresponding release velocity and direction is calculated, thus enabling a natural behaviour with the help of built in unity physics.

To create a more realistic interaction with the simulation, a modified controller of the HTC Vive was used. In order to let participants forget that they are actually using controls, a common cloth glove was used and the modified Vive controller was stitched onto it. This glove and the controller have been attached with soft medical tape to the participants arm in order to prevent it from moving or falling off during the process of a throw movement. Thin electric cables were welded inside the controller on the positive and negative contacts point of its trigger; these cables were attached to the glove with copper tape to ensure connectivity (see Figure 3.6). With this preparation the participants were able to simply tip their index finger and thumb together to send a signal to the simulation, as it was done in the VR part of the testing group. 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, more pinching the objects than grabbing them because of the missing haptic feedback. In both versions the users 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. The feeling of weight and inertia that the MR group received is planned to induce more natural behaviour into the movement and thus expected to result in more rapid improvement of accuracy over the course of the testing process (Lontschar, Deegan, et al., 2020).

3.2.5. 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.

Figure 3.6.: On the left is the empty glove controller that was used during testing. On the right is an example how the baseball is held and sending a signal to the simulation.

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 is a sum of points to represent the set and also an overall sum at the end. The sum of points is used to have a of high score system to spark that further encourages users to try to achieve high scores in each throw.

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

3.3. Evaluation

In this subchapter the process of how insights are being generated using the developed application from the previous subchapters are explained. Therefore, first the design of the user study approach is being described. Afterwards a description for the study setting is given and explanations for why certain decisions have been made and involved tools have been used is given. Next, a short insight into the participating users demographics is given and in the final section the actual values being produced

by the whole study approach are being analysed. The subchapter is closing up with a summary, where most important insights gained with the evaluated data are recapped and key points to take away are pointed out.

In Section 2.3 no common consensus could be identified that would satisfy the answer if an additional haptic feedback input channel provides positive influences for every VRLE. This also represents the main analysis idea of this project, to identify advantages or disadvantages or any influence at all coming from the additionally provided input channel of haptic feedback. While research of related works has shown that haptics is essential for certain applications, a general statement is still missing in order to justify a usually more complicated MR setup. Next to the analysis of overall influence, it is also desired to find the settings and situations in the approach that benefit the most from haptic feedback. Additionally, the difference in immersive engagement between both group is being evaluated. Thus, the research questions this projects is concerned with, that evaluate the influences of haptics provided with an easy to setup and cheap solution, are as follows:

- Identify general advantages or disadvantages coming from an additionally provided input channel of haptic feedback.
- Find specific situations in the VRLE, where a haptic input channel provides a positive influence over the non-haptic simulation.
- Evaluate any differences in engagement, specifically for situations where distinctive advantages can be identified.

3.3.1. Study Design

As introduced in Subchapter 3.1.4 the study approach is separated into two parts involving two groups of participants, one for a mixed reality setup and the other for a pure virtual one, each in the same VRLE but a different physical location. In this section the shared study design is presented and differences between the two settings are described. In order to evaluate the outcome of this approach an A/B user study has been conducted with n = 56 participants split into a VR and a MR group, representing the two sides of an A/B comparison study. This was because the main intention of the chosen approach was to compare the same experiment with and without haptics. Next to analysing performance values and in that manner learning, the study concentrated also on the assessment of engagement, immersion and user experience between a MR and a VR setting, thus evaluating not only learning progress but also factors of usability and users well being.

While the performance data that is used to identify learning behaviour is being produced purely by using the simulation and following the devised tasks, the immersion evaluation is done with the help of a post-questionnaire after the VRLE experience, that is designed specifically for this purpose. Additionally, the pre-questionnaire evaluates users demographics and information about VR experience. Therefore, both questionnaires represent an essential part for the evaluation of the taken approach.

3.3.2. Setting and Instruments

Because the testing process in MR involves throwing of some heavy objects of up to 2.5lb (see Table 3.1) to a distance of up to roughly 25m, a safe environment was necessary to prevent potential damage to man and material. To ensure this, the decision was taken to set the testing environment up on a sports field on Cal Poly campus (See figure 3.7), where a lot of free space is available in all directions. The control groups in pure VR did not involve anything special in the real world but necessary space for required 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 typical lab environment on campus, where sufficient space was easily available after minor rearrangements.

Type	MR	VR
Baseball	0.32lb	virtual
Weight Disc #1	0.5lb	virtual
Weight Disc #2	1.0lb	virtual
Weight Disc #3	2.5lb	virtual

Table 3.1.: Different throwables and their respective weights

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. A Windows laptop with an Intel Core i7 4770K processor and a NVidia GeForce GTX 1070 graphics card was used for testing on the field and a Windows PC with an AMD Ryzen 7 and a NVidia GeForce GTX 1080Ti was used in the lab environment. Both setups used the HTC Vive HMD as immersive display with the corresponding controller that has been modified for this studies purpose as seen in Figure 3.6. The HMD includes two infrared base stations that record and translate the HMDs and the controllers position into the virtual world.

Additional to the test setup also a separate laptop was required 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 web browser, a MacBook Pro early 2018 was used for this purpose, as it was available from the developers involved in the project.

Questionnaire

Participants were required to fill a pre and post questionnaire respectively before and after experiencing the VLE. The pre questionnaire collected the participants demographics information, while the post questionnaire assessed immersive attributes after finishing the tasks in the VLE. The post questionnaire was structured in the form of the GEQ (IJsselsteijn et al., 2013). It contained questions for "during" the VLE which included competence, sensory and imaginative immersion, flow, tension or annoyance,

Figure 3.7.: 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.

perceived challenge as well as positive or negative effects. The questions regarding "after" the experience in form of the GIQ assess the attributes attention, temporal dissociation, transportation, emotional involvement, challenge and enjoyment. All questions were to be answered in the form of a Likert-Scale, measuring each value from 1 to 5 (Jennett et al., 2008).

In order to include all those values into the evaluation process, corresponding Google Forms[9] were created, split into a pre and post VLE part and linked via a unique identifier for each participant.

3.3.3. Procedure

Parts of this and the following two subsections are taken from or based on the respective sections of Lontschar, Deegan, et al. (2020).

Using designs and tools determined in previous sections the actual user study testing was then conducted with participants that signed up for 15 minute time slots in a prepared Doodle[10] form. This time frame was the first estimation after internal testing of the system and questionnaires.

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

---

[9]https://www.google.com/forms/about/
[10]https://doodle.com/free-online-appointment-scheduling

testing was started by supervisor interaction and afterwards run automatically by the participant just following the in game mechanics. The task was to take a virtual object (see Table 3.1) and throw it into a target that spawns in front of the participant on the field. The targets were divided into four sections to give the user visual feedback as well as to include gamified gained points calculation to increase motivation The targets distance to the user increased for each throw, starting at 2.5m for the first and 20m for the last throw for each thrown object. After finishing five throws with one object, the task advanced to the next object in pre defined order, increasing the objects weight. An order starting from a baseball, then a weight disc, followed by consecutively heavier discs and finishing with a control run with the baseball again. Overall each user was throwing 25 times, 5 times with each object. The switch between different objects and weights was suspected to introduce more distinct differences between MR and VR group and thus should help to define influences. Information about the last throw such as strength and angle were displayed on the information 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 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 for later combination of questionnaire and throw data. 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. The main difference in the study process between MR and VR group was the required assistance of a supervisor for the MR group. Because the tasks were all involving an actual throw of a real world object, a supervisor had to fetch the object and bring it back to the study participant for the next throw. This process was automated in the VR group, as no real world objects other than the controller were required (Lontschar, Deegan, et al., 2020)).

During the study process the initially assumed time of 15 minutes proofed to be fairly accurate. Mostly all participants in MR finishing in roughly 12 to 17 minutes. Participants in the VR group were on average finishing the overall process within 10 to 13 minutes. The reason for the VR group to use less time is the missing interaction with the real world, thus less necessary aiding of the supervisors and so a faster overall process. The questionnaires required approximately 5 minutes from each user to be completed and the rest of the time was used for the practical task and some preparation thereof.

3.3.4. Study Participants

The research for this study was conducted with a participants group of size n = 55. These were split into MR and VR group to 40 and 16 respectively. This unequal split happened because the MR data was slightly more inconsistent and required more confirmation data sets. It is also not reflected in the demographic data. Of all the participants, 34 were male, 19 female and 2 identified as neither. 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 3.8).
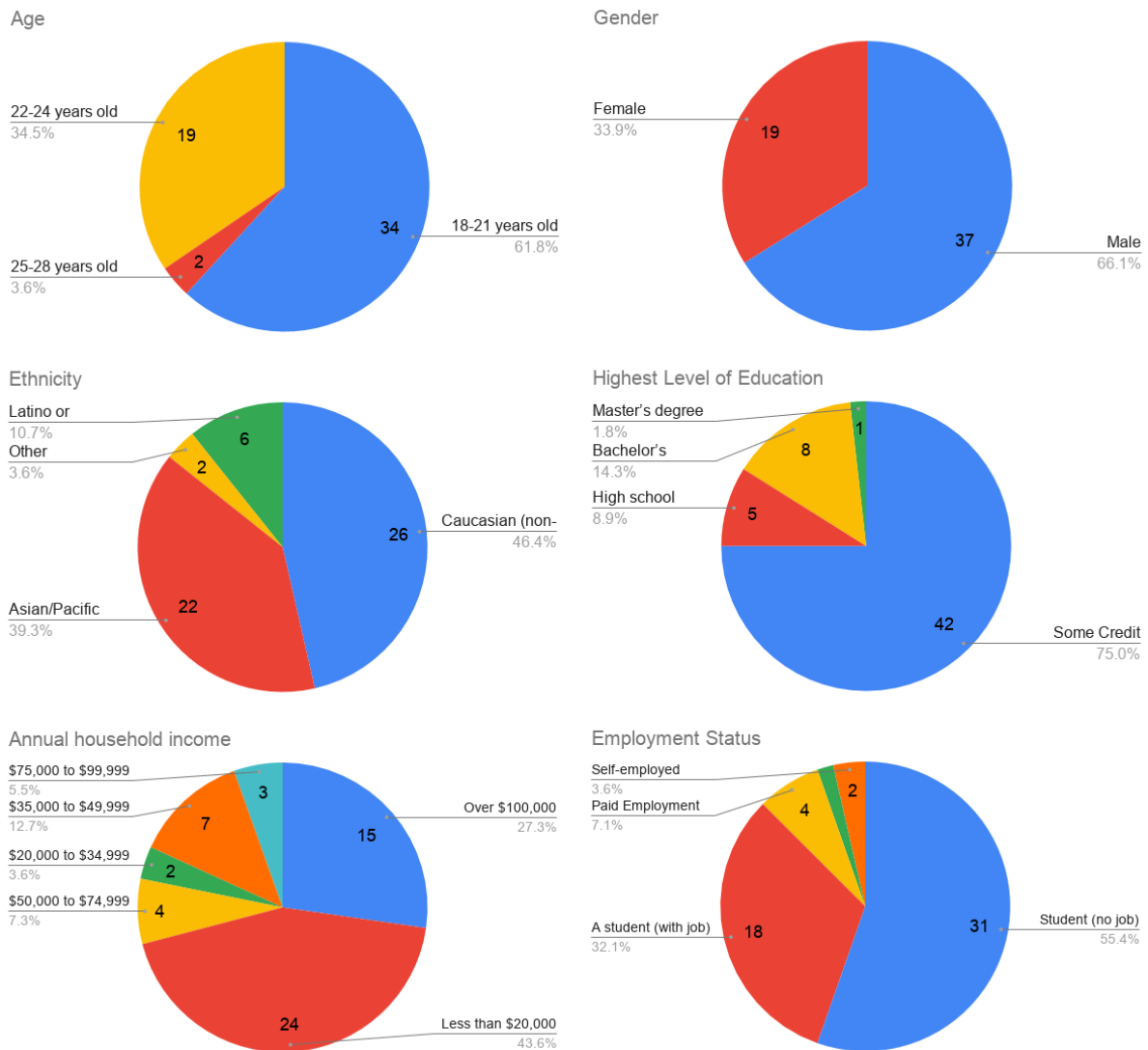

Figure 3.8.: Participants demographics. Distribution of the participants age, gender, ethnicity, education, household income and employment.

More than half of the participants (58.90%) indicated no or very little previous experience in VR and only one participant thought to have expertise in VR usage, as seen in Figure 3.9. While this was not predicted and the assumption was that the participants would mostly have a least mediocre experience, verbal and data feedback indicated that there was no issue with the lack of previous expertise in VR. This was most probably thanks to very easy and intuitive controls in both groups.

Do you have experience with any kind of VR device?
56 responses
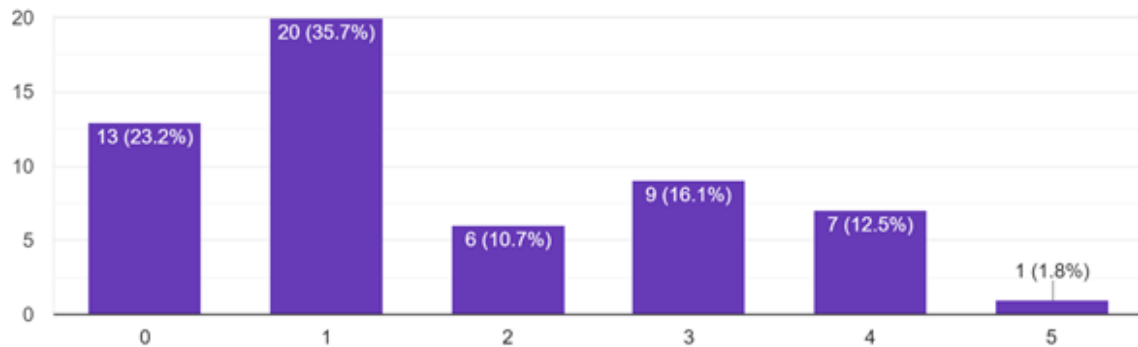
Figure 3.9.: VR experience of the tested group: Participants were asked how they judge their level of VR experience on a scale from 0 (not at all) to 5 (a lot).

3.3.5. Results

In this section the gained results from the evaluation and what one can derive from them will be discussed in more detail. In order to create these graphs, a script written in Python was used to run through all the raw data. The script read the data provided from both the JSON file of the practical part and the CSV files from pre- and post-questionnaire answers, providing insights in certain interesting data aspects in a more understandable graph form. As an intermediate step a C++ script was used to extract certain data areas, which were of special interest for the analysis. Areas like all corresponding data for the best third or worst third of users that achieved the highest or lowest learning increase respectively. This data was also read by the Python script, which in turn visualizes the data in corresponding plots. Some of the most insightful ones of these plots will be discussed in more detail in this section. Both the performance and learning values and the corresponding immersion feedback from the questionnaire give different insights, therefore each of these two aspects is discussed in the respective subsection. . In order to find differences in learning experience between pure VR and MR with haptic feedback, the study participants were engaged in two different versions of the developed research simulation. 40 participants were tested in the MR and 16 in the VR group. The reason for this split was the nature of the improvised controller. Especially the copper conduction between controller and objects that triggered a throw in the VRLE was affected by external factors like moisture, thus potentially inducing irritating attributes. Therefore, a higher number of datasets for the MR group, compared to the VR group, was required, as the latter were not influenced by any real world factors (Lontschar, Deegan, et al., 2020).

The following paragraphs regarding throw data and immersion, as well as the corresponding graphs, are taken from Lontschar, Deegan, et al. (2020).

Throw Data

The acquired data from the participants indicates that, on average, the distance (difference of the impact point to the target centre) and improvement assessment (shortening or lengthening the distance over consecutive throws) for both groups are a lot more similar than initially expected, as can be seen in Figure 3.10. The small variances are in regards to the standard deviation statistically irrelevant.
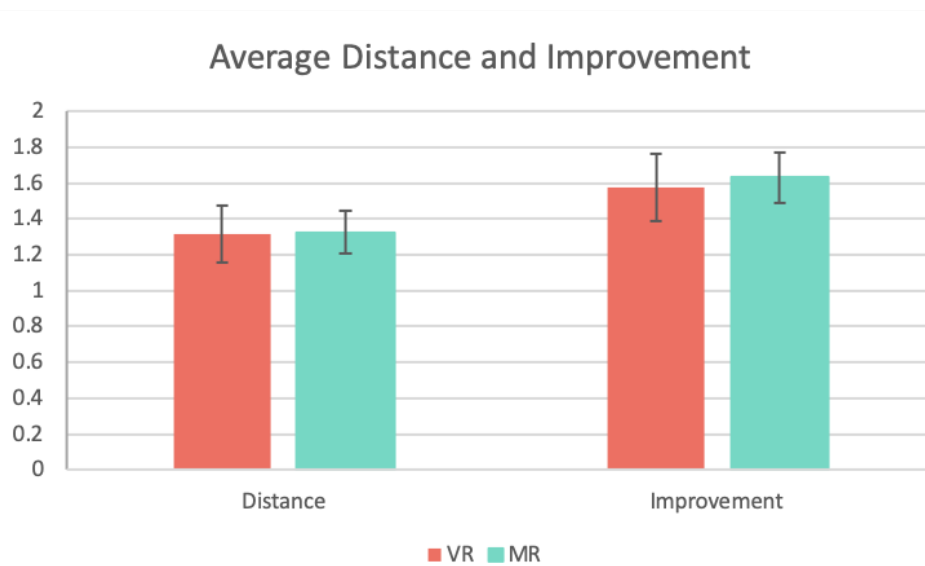
Figure 3.10.: Average Distance and Learning of all Participants: red for VR and cyan for MR participants.

However, there is an increased improvement outcome observable 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 Figure 3.11. The distance, as well as the average improvement over five throws for each weight is displayed in this figure and shows some very distinct trends. For lighter weighted objects, the MR participant initially showed a better distance to target outcome ("Baseball #1" and "Weight 0.5lb"). 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 and heavier weights resulted in a greater distance to the target centre than for the VR participants, and the improvement was lower as well ("Weight 1lb" and "Weight 2.5lb"). Based on direct verbal feedback of the MR group, as well as confirmation in the performance data, a conclusion comes up that the handling of bigger weights is perceived unwieldy. However, the MR group still showed a higher learning in comparison to the VR group

whenever a larger weight change was instructed, especially a big difference in weight is apparently taken more into consideration for the throws in MR than in pure VR.
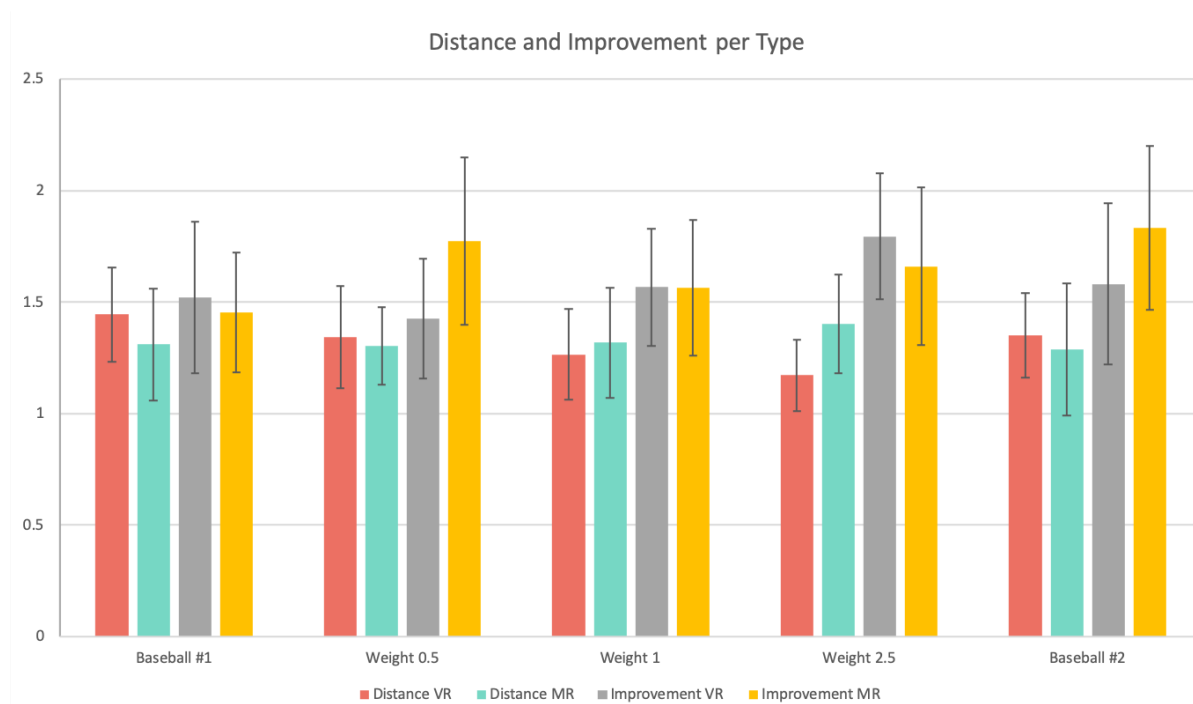

Figure 3.11.: Average Distance and Learning per different object/weight type: distance(red) in VR, distance for MR(cyan), improvement for VR(grey) and improvement for MR(yellow).

Looking closer into specific aspects of the data, more insights can be gained. The outcome for the best and worst performances in regard to distance to the target, as well as its improvement gives some more worthy insights than the overall average. Comparing the distance and the improvement outcome of the upper and lower third of aiming performances in Figure 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 seen in Figure 3.13, but still governed by comparable values. A slight trend can be observed, showing a tendency that the best accurate participants would improve their accuracy more in MR, while the worst accurate participants show a greater improvement in VR. It is apparent that this correlates well with the immersion feedback that was received from the GEQ, which will be discussed in the next subsection.

Overall, a statistically relevant variance in the produced data, which would underline a notably different performance or improvement result for either group over the whole study process, could not be observed. While there are trends regarding the standard deviation, the results do not indicate any particular improvement for the MR testing group, which does not confirm the initial assumption. Even though on overall data not
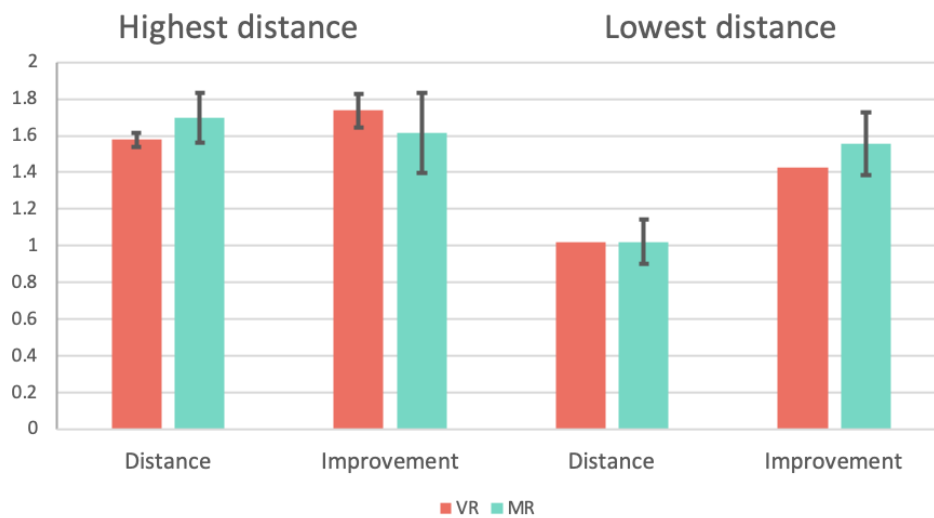
Figure 3.12.: Average Distance and Learning for most and least accurate partici-
pants: VR(red) and for MR(cyan).

many striking aspects can be identified, certain different properties came to indicate
their importance, like the changing of the interactable objects weight and form.

Immersion

Conducting the GEQ to assess the immersion during the VLE experience followed
by the GIQ to measure the immersion perceived after the VRLE, important insights
into the participating users perceived feeling induced through the VRLE can be found.
Analysing these values in Figure 3.14, one can recognise a similarly outcome for both
groups on overall average, as it was also found for the learning values in the previous
section.

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, it is
understood that MR participants had to concentrate on more things at the same time
to fulfil the given task of hitting the targets. The added haptics information channel
was only thought to add intuitive feeling as a positive aspect, but here also a negative
impact is indicated. While having a weight in their hand improved their intuition for
the interaction, it also required additional attention and concentration. The participants
also had to focus on holding and releasing the objects in the correct manner to ensure
connectivity. While this supposedly is very similar to the intuitive interaction with
such objects it still added a certain amount of uncertainty to the interaction, because
it was not absolutely aligned with the virtual world, which is an important aspect
as was found in Section 2.3.3. On the opposite the VR group was only pressing their
fingers together, which very much resembles the simplicity of pressing a button on a
common controller, thus leaving more attention free for concentration on the task itself.
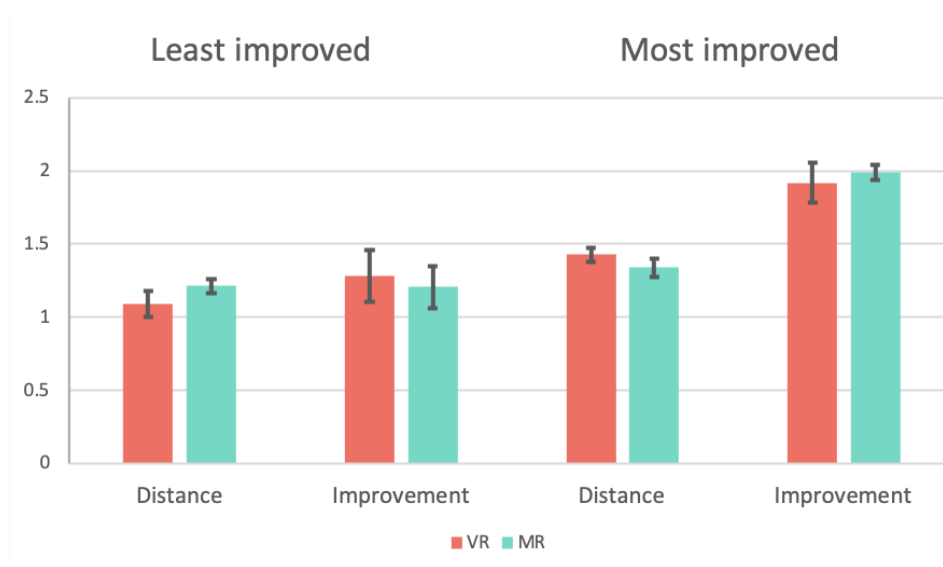
Figure 3.13.: Average Distance and Learning for best and worst improving third of the testing group: VR(red) and MR(cyan) participants.

However, these variations in the given data are small and considering the standard deviation displayed in Figure. 3.14, of minor significance.

Taking a deeper look into the best third performances in regards to aiming, the GEQ delivers notable deviations as shown in Figure 3.15 (a). Here the immersion values during the experience are distinctively increased and above the standard deviation for accurate MR participants compared to the VR group. It is interesting to note that Figure 3.18 (a), while showing an overall better immersion for MR during the simulation, also indicates better attention to fulfill the task at hand, even though the outcome of performance values does not support this. In contrast to these findings, Figure 3.18 (b) showing similar data points for the immersion perceived after the VLRE experience. This trend can be interpreted as a result of the sense of accomplishment, which could be found in both groups due to their similar performances that they perceived mainly via the direct feedback in form of the gamification element of the added high score system.

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 Figure 3.17 (a) and (b). The levels for competence, tension and annoyance, challenge during and positive/negative effects, basic attention, temporal dissociation, challenge perceived after the VLE experience, emotional involvement and enjoyment vary only statistically insignificantly. However, the strong difference in the standard deviation for enjoyment and especially negative effects is noteworthy and probably a result of the handling with heavier weights in virtual reality that might have been confusing counter intuitive for some users. This trend was present both during and after the simulation as seen in Figure 3.17 (a) and (b).
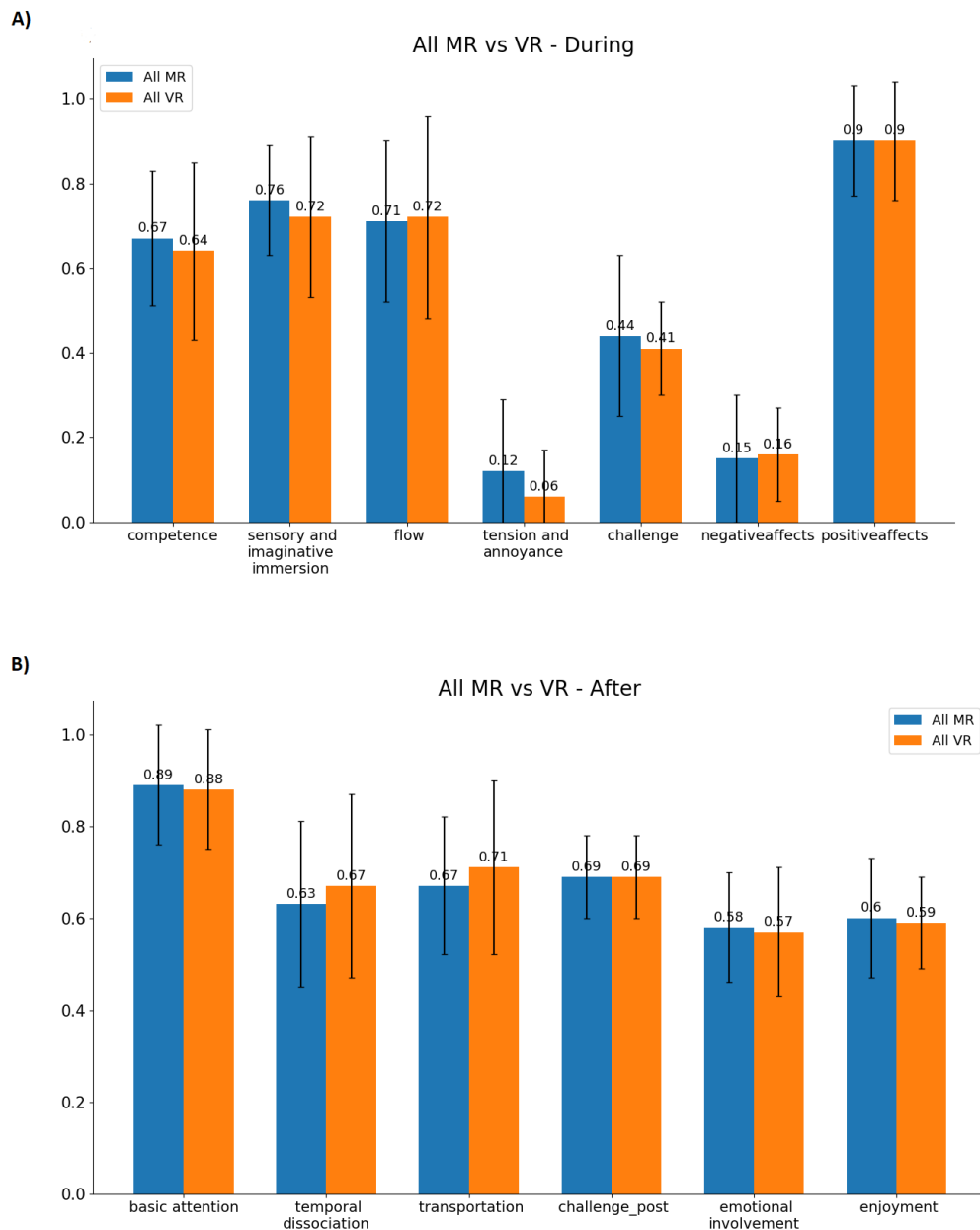
Figure 3.14.: Average immersion before and after the VLE experience: MR (blue) and VR (orange) group. Each value is in the range from 0 (not at all) to 1 (absolutely).

Investigating the immersion for the worst third performer in regards to closing the distance to the target, only the basic attention seems to be significantly higher 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 Figure 3.16. All other immersion indicators show a similar behaviour for both groups.
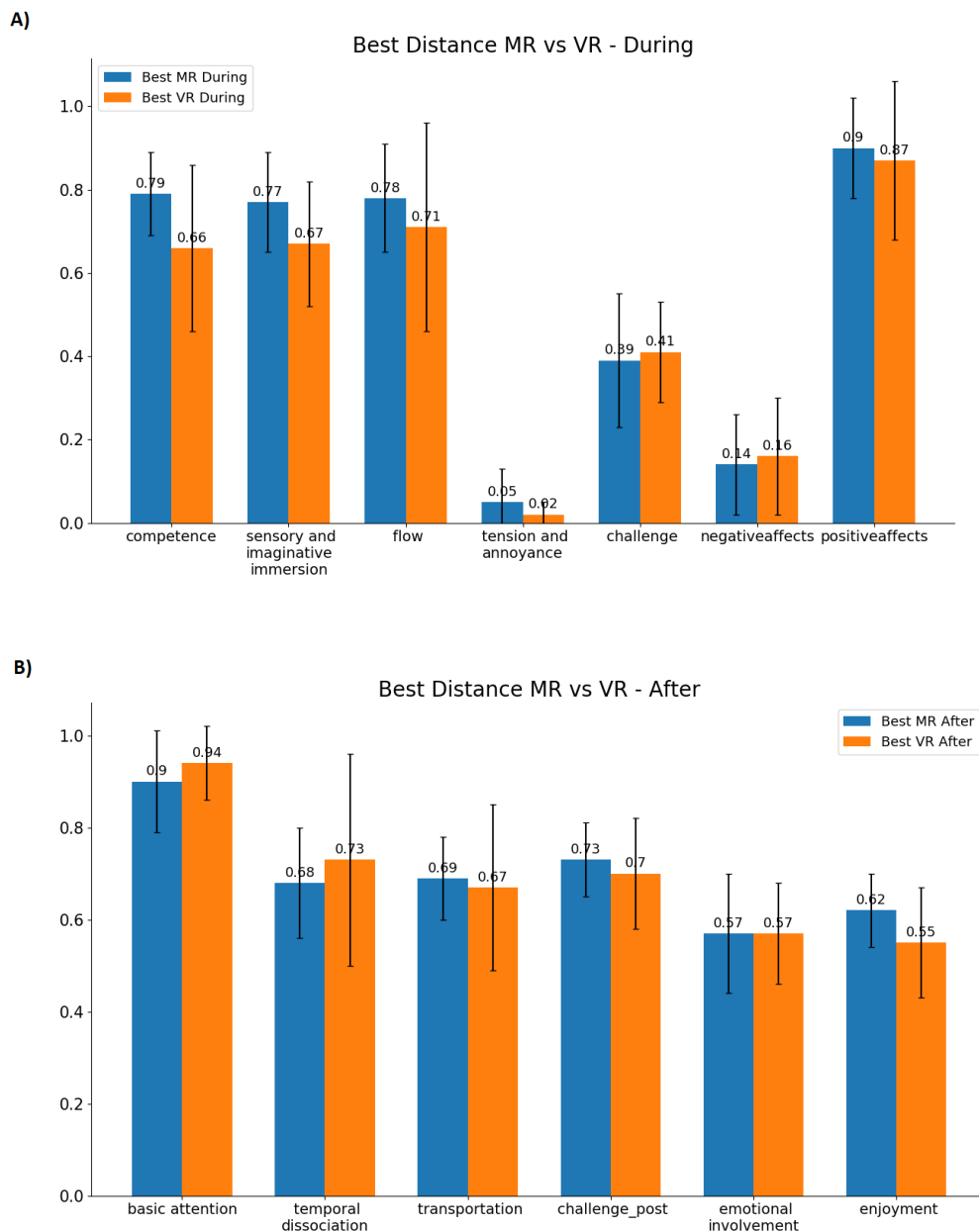
Figure 3.15.: Immersion values for the best third aiming performances during and after simulation: MR (blue) and VR (orange) group. Each value is in the range from 0 (not at all) to 1 (absolutely).

Also 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, which is probably connected to increased stress.

As for the lower third of improvement seen in Figure 3.17 and 3.18, compared to those in the highest third of learning displayed in Figure 3.17 (a) and (b), those in the
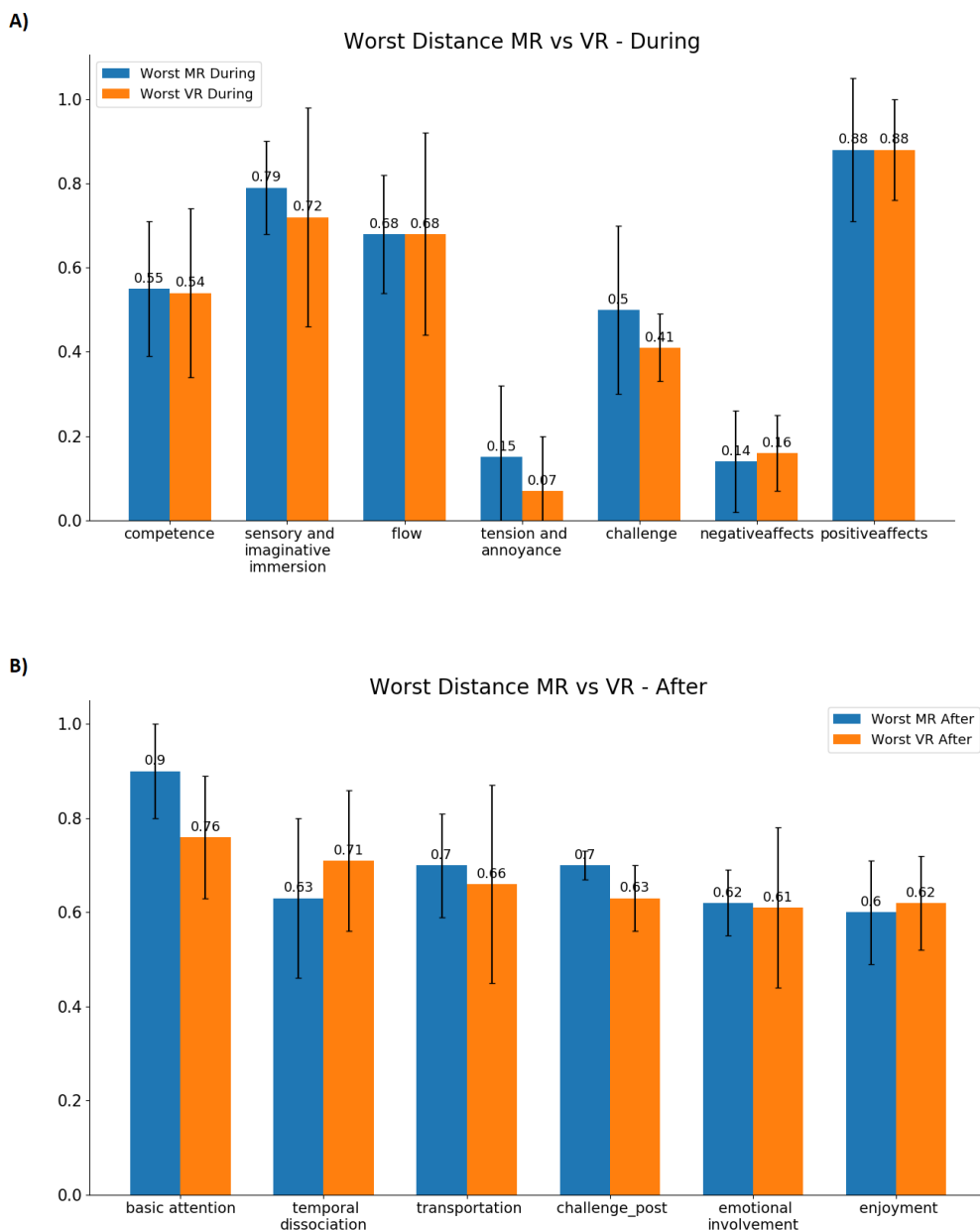
A)

B)

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

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.

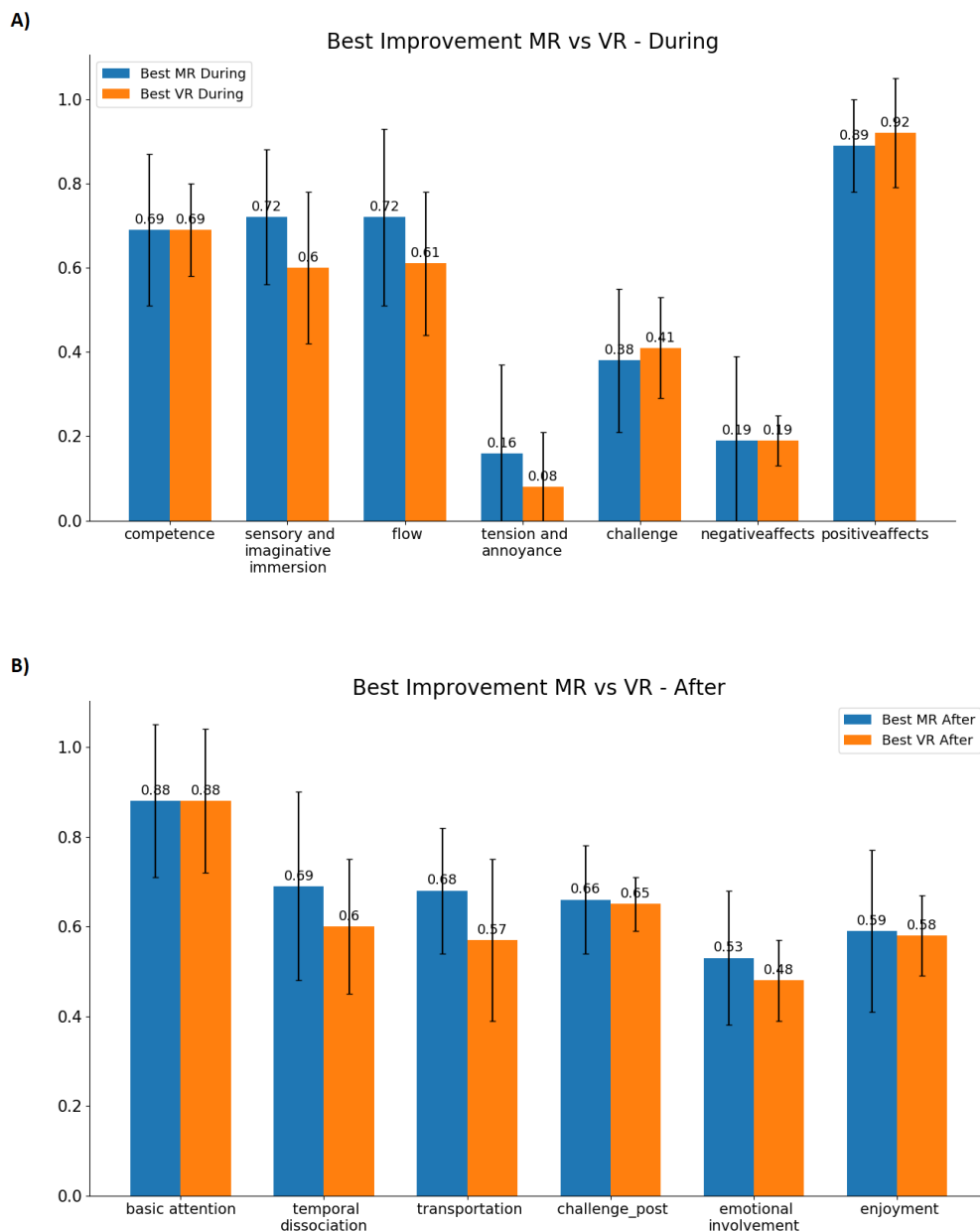Additionally to the gained numeric insights of the questionnaires, verbal feedback

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

of both groups indicated a fun approach and thus good usability. The MR group was especially excited about the style of the application of throwing objects around in VR and having corresponding haptic input perception. This also leads to the assumption of a potentially very engaging setting for similar approaches.
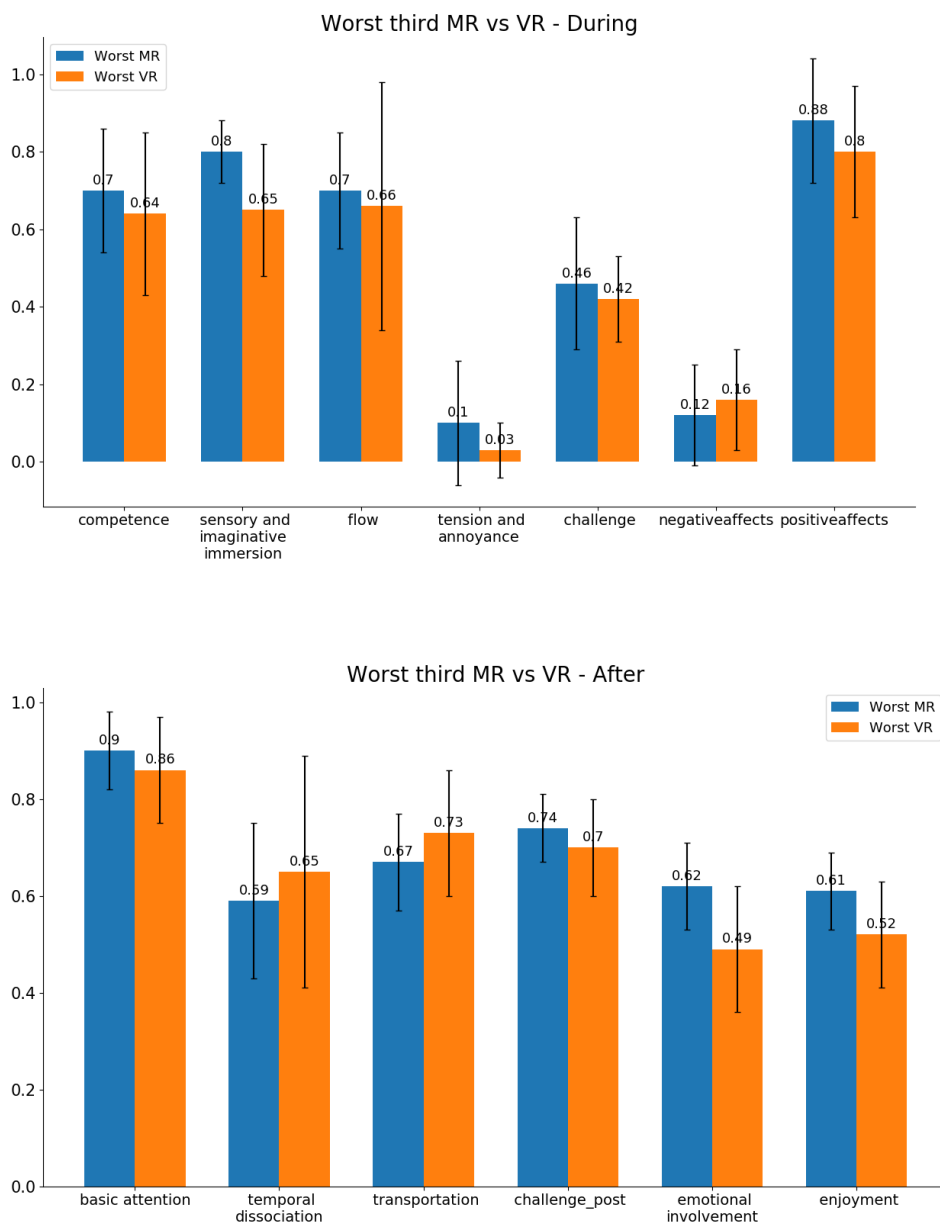
Figure 3.18.: Immersion values for the worst third learner during and after simulation: MR (blue) and VR (orange) group. Each value is in the range from 0 (not at all) to 1 (absolutely).

Restrictions and Limitations

Due to the makeshift origin of the customised controller, problems with connectivity between the controller and the object were sometimes encountered during the test sessions. It is anticipated that this issue might negatively affect gained immersion, hence

this was kept in mind while analysing the results. Only one test run had to be aborted before being finished, because moisture from dew in the evening was interfering too much with the controls connectivity and the simulation was not working reasonably any more. The last set of throws had to be omitted from this participants data. Unfortunately, due to an undiscovered bug in earlier versions of the simulation, some single invalid data points were produced that created heavy outliers in performance data. These data sets had to be partly omitted from the analysis, but luckily only the data of the five first participants were affected and the bug could be fixed for later versions. Finally, the inconvenient fact that HTC Vives lighthouse trackers are using infrared sensory mechanics lead to the testing process being restricted to only a few hours during dawn of each day. This was not taken into consideration for the first trial of the testing the prototype with study participants, therefore everyone participating in the initial run could not generate any useful data because the tracking of the HMD did not work at all in bright sunlight.

Discussion

Overall, a statistically relevant variance in the produced data, which would underline a notably different performance or improvement result for either group over the whole study process could not be observed. While there are trends regarding the standard deviation being smaller for MR and therefore more similar data seems to be generated for all participants, the average results do not indicate any particular improvement for the MR testing group. However, when analysing specific aspects of the data one can indicate improvements for haptics when changing weights and when handling intuitively known forms like a ball. Drastic changes in weight and therefore physical behaviour is also perceived better in a MR setting, most probably because intuitively expected behaviour is in line with the visual channel and supported by the haptic feeling. Whereas for the VR group the physics behaviour is accurate but not initially expected, as every objects feels the same without its real world weight. Overall the findings in immersive and engagement analysis, also taking into consideration verbal feedback during the simulation, suggest only positive influence of real world object interaction in a VRLE. While an assumption was made that this is connected with the novelty for many users of having a more realistic interaction method, this tendency seems to be true for all study participants and many of them indicated very little previous VR experience. These insights seem to be similar to what comparable and more detailed approaches found (A. Covaci et al., 2015).

Notably the tasks involved in this analysis are simple movements and interactions which do not require an advanced skill set like in some comparable related research works. Thus, the assumption that haptics would introduce higher performance improvements than in the VR group was taken, which did not get confirmed in this study as a general statement. Most probably fine tuning for the used controllers and all time assurance of connectivity would improve the expected outcome of registered data. With improved haptic information for the user the results should be more comparable

to Frid et al. (2019), which was expected. Also changes in the visual feedback channel in accordance to the real world objects would improve intuitive perception as even minor deviances apparently induce distraction. Similar insights found in related work in Section 2.3.3 also indicated such interferences and even though they point it out for see through devices, in this project it could also be seen that it influences this VR only view simulation as well (Cosco et al., 2012). Thus, these provide only some of the possibilities for future work that will be discussed in the last chapter of this thesis.

Next to the general statement that could not be confirmed, some situations during the VRLE experiment runs with study participants could be identified that profit from the haptic feedback channel compared to the VR only group. These insights suggest that it is indeed worth the additional effort for many basic implementations, especially where familiar or smaller objects are manipulated in VR.

While providing a more accessible and cheaper solution to add haptics information to teaching processes involving real world objects the developed application process did not completely remove issues with corresponding hardware. Still, the gained insights provide important information and the controller implementation a proper foundation for further work on accessible haptics applications to analyse more effects and influences.

3.4. Summary

In this chapter the three core aspects, design, development and evaluation, of the first project described in this thesis, haptic feedbacks influence in virtual reality, were explained in the respective subchapters.

Subchapter 3.1.4 explained the intended design and concept for this project, followed by its identified requirements and the used tools to achieve the desired outcome in the further development. 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 a task 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. Additionally, game elements were to be added in the environment in order to increase participants engagement and focus on the tasks at hand. The resulting design in compliance with the indicated requirements provided the baseline for such VRLE that could provide the desired results. An established questionnaire framework, the GEQ, was chosen to evaluate corresponding VR attributes of test participants during the process. In the next subchapter the actual implementation will be discussed in detail.

The development process of this projects was described in Subchapter 3.2. 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 made in the design process were leading towards a 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 the specially designed user interface and its controls, devised to enable this hybrid system, the implemented spawner system used to create a half automated testing process and finally the high score system, 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. The 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. While the implementation of this mixed reality glove was found to be still too unreliable at times, it could be improved with more expertise in mechanical engineering while still being absolutely low priced compared to some industry level solutions.

In Subchapter 3.3 the study approach of this project 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 the approach, the tasks designed for usage in both environments were explained and how and why they were chosen. Especially the way the controllers were modified to serve the desired needs got mentioned again because it represents a core aspect of this studies approach. Finally, an extensive insight into the gained data and the corresponding assessments is given, first focusing on the 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. The gained information from the evaluation gave clues that haptic feedback is most likely not strictly improving every VRLE, even if concerning object movements, but certain situations could be identified that profit for sure from the additional input channel for the user.

4. Physics Visualization in Virtual Learning Environments

As mentioned before the core concerns of this thesis are split into two different analysis approaches regarding effects on Virtual Reality Learning Environments. This chapter focuses on the second part: Visualization Techniques for Physics phenomena in VRLEs. All detailed aspects of the approach will be discussed in their respective subchapters. First the system requirements and design decisions for the further development will be discussed. Then there will be details on the actual implementation of the project and finally focus will lie on the assessment and evaluation of the gained data and the resulting insights.

Some parts of this chapter are taken from the paper "An Immersive and Interactive Visualization of Gravitational Waves" by Lontschar, Pietroszek, et al. (2020), as this scientific publication is based on the project described in this chapter. These parts are indicated separately and contain sections of the original documentation and implementation.

4.1. Concept and Design

In this subchapter insights about this projects basic idea and motivation will be provided. Then the intended target group is going to be explained, followed by a detailed project description, the requirement analysis and finally an overview over the most important tools used during the implementation process and for the user study. The basic idea appeared from an unrelated discussion about the matter due to general interest. While following up on an idea and some deeper look into the matter and its related research a potentially important project started to develop. A general need for an easily understandable explanation of gravitational waves, without any required previous knowledge was identified and thus this initial inspiration was further pursued.

4.1.1. Motivation and Goals

In Section 2.4 a tendency for physics theories being displayed properly and understandably in VR has been identified, indicating many times better long term understanding than with using comparable material on paper or two dimensional screens. Furthermore, the visualization of gravitational waves proved to be an even more complicated

matter than many 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 an intuitive and intractable visualization of gravitational waves came up, GraViz was born. As a first step of evaluating different techniques the focus came to creating alternative visualization methods for effects of cosmological scale that are 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 in terms of distance and size scaling, concentrating not on high level physics experts but popular science. Such trends could also be identified in corresponding research and Google Trends analysis, confirming initial assumptions about the importance of this viewpoint. Additionally, this would be one step of many to prevent the spread of falsities and half-knowledge on this and other important scientific milestones.

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 of science would not invest the required time to understand the matter in depth and this provides perfect soil for misinformation and false understandings to spread, just because it is or was a popular topic to talk about.

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. VRLEs with their natural attributes interactivity and immersion address exactly those needs, if implemented properly. Thus, they provide an appropriate and engaging alternative to formulas or static textbook representations. Not only show VRLEs the potential to be an improvement over traditional learning methods in this topic but also show strikingly better results compared to even sophisticated 3D simulations in corresponding research approaches.

Based on these identified attributes and the 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 a fundamentally important aspect of project development is discussed. Defining the requirements of a project before the implementation provides the possibility to consider the needs of all intended users from the application in terms of

system operation as well as system behaviour (Chen et al., 2013). Also requirements for the later analysis can be kept in mind in the design process. 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 the physics phenomena caused by gravitational waves correctly according to theoretical background
   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 seemingly empty space.
   e) A representation of e.g. our solar systems planets should give the user some sort of familiar 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) After an introduction, the user should 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 binary star systems attributes 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 according to the 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, only to be stopped if desired

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 irritations or motion sickness for the user 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. Virtual reality proved to provide appropriate possibilities for engaging, immersive alternatives towards two-dimensional approaches of complicated theorems and graphs. Therefore, the goal of this project is to utilize those possibilities in line with the previously 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. Additionally, it should be able to be used to provide better basic understanding for an amateur. Next to the required functionality of the 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 the initial idea and the identified requirements for the VRLE experience, its evaluation 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 visualization of gravitational waves effects and their calculations in the background, along with a well thought through 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 at least partly control over visible cosmological elements in order to analyse differences 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 of gravitational waves are of such 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 observable to the user in an appropriate manner, while still being of reasonable relations. This also counts for the respective size of visible planets, moons and stars, because a fully accurate scale in this sense would make it impossible to fit all objects together in one observable scene. 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.
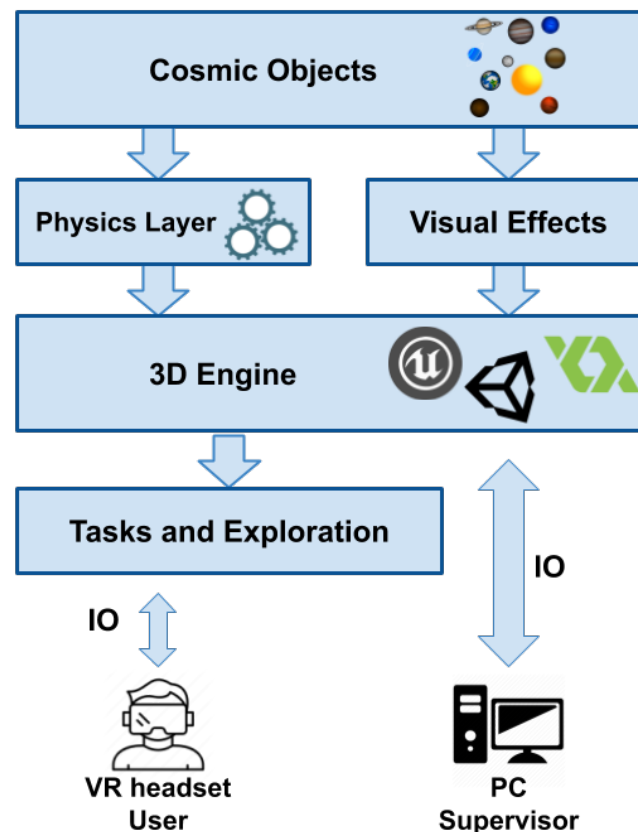

Figure 4.1.: Conceptual Design

Visualization and Effects

Representing the core element 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 and usability, 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, and with that every point of space, is needed, instead of the actual nothingness. 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

Aiming 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 at the controllers position.

Controls

To provide greater interactivity in the simulation and also to 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, without relying on error prone self-programmed movement controls. It is 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. Therefore, at least nine control elements need to be appropriately mapped on to six available buttons to make intuitive controls with only a short introduction possible.

Tasks

While the visualization 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, a set of tasks need to be designed that can be displayed in the HMD in order to explain the user what the possibilities to explore in the environment are and how to reach them. The display style of these informative texts should be in a non interfering heads-up display manner. Furthermore, the users should get a short verbal 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 respective 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 and techniques used in this project are being explained and reasoning is given why they were used over potential alternatives.

C++ C++ was used as main programming language for this project, because various libraries in this language give access to 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 potential alternatives. 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 the developed approach into a VRLE and thus, making it trivial to display the experience in a HMD.

OpenGL Due to the complexity of various rendering approaches and the rendering pipeline, it was decided to base this project on the OpenGL[1] framework (Woo, Neider, Davis, & Shreiner, 1999). This framework provides many built in functions to decrease the effort for creating a such pipeline and thus makes it possible to create an effective environment for the planned simulation. Generally, it is a popular choice for any project involving high performance graphics calculations as it was also confirmed in the corresponding research in Section 2.4. Not only does it provide a very good and wide ranging set of tools already prepared, it is also possible to expand several

---

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

built-in methods of the framework to fulfil some of the identified requirements to the simulation. Thus, tailoring the functionalities for the needs of this approach proved to be feasible.

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 in OpenGL, they represent almost a whole programming language on their own. While GLSL[3], the language shaders are written in, resembles C, it is generally specialized for the necessary functionalities of the graphics pipeline like 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, which then generates the final output colour 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 colours 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.

OpenVR For this project it is necessary to directly read e.g. position and rotation values from the HMD and therefore a lower level interface was chosen to make this part easier. The popular choice for this that can be used for most common HMDs is OpenVR[4]. OpenVR provided all necessary values for the required calculations and only small scale adaptions in the processing chain were necessary, thus presenting a convenient interface for this projects needs.

Head mounted displays In order to display this experiment as a proper VRLE the head mounted display HTC Vive Pro Eye[5] was used. This HMD was chosen due to its comparably high performance and wearing comfort over similarly priced competitor models. While being slightly more expensive than comparable models from other manufacturers, the resolution and especially wearing comfort were indicating this to be the superior choice. The high resolution provided by this headset was found to be sufficient for an appropriate display of the rendered visualizations, while this was not the case with some other HMDs being tested like the Oculus Rift DK1. Also the performant frame rate was a very important part towards the decision because it influenced the result of the visualization process a lot, effectively rendering the

---

[2] https://learnopengl.com/Getting-started/Shaders
[3] https://www.khronos.org/opengl/wiki/Core_Language_(GLSL)t
[4] https://github.com/ValveSoftware/openvr
[5] https://www.vive.com/eu/product/vive-pro-eye/overview/

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 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. In Section 2.4.4 modern research approaches were found that would provide possible superior alternatives to MSAA, but these required a potentially much longer setup process than using MSAA, while MSAA already provided sufficient results.

Processors and Graphics Cards   In the early stages of development the same setup was used for this project as it was used for the haptics project of Chapter 3. This proved to be sufficient only for the first few implementation trials. Later there were complications at some point turning up with the graphics card running into its limits during heavy calculations. Therefore, an upgrade to a NVidia GeForce Titan V was made to ensure a high frame rate and a smooth experience during the simulation, because the hardware was available on site.

Python   This project 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.

Game Immersion and Game Experience Questionnaire   For the evaluation of the users feeling of immersion during and experience right after participating in the VRLE the same questionnaires as described in Section 3.1.5 were used.

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 used for the implementation to be scientifically accurate. Next a general explanation of the resulted VRLE and its elements and closed up with a summary recapturing the most important insights.

Some parts of this section are taken directly or in an adapted version from Lontschar, Pietroszek, et al. (2020), because this part of the thesis and the corresponding project are based on this paper, which has been produced over the course of its development process.
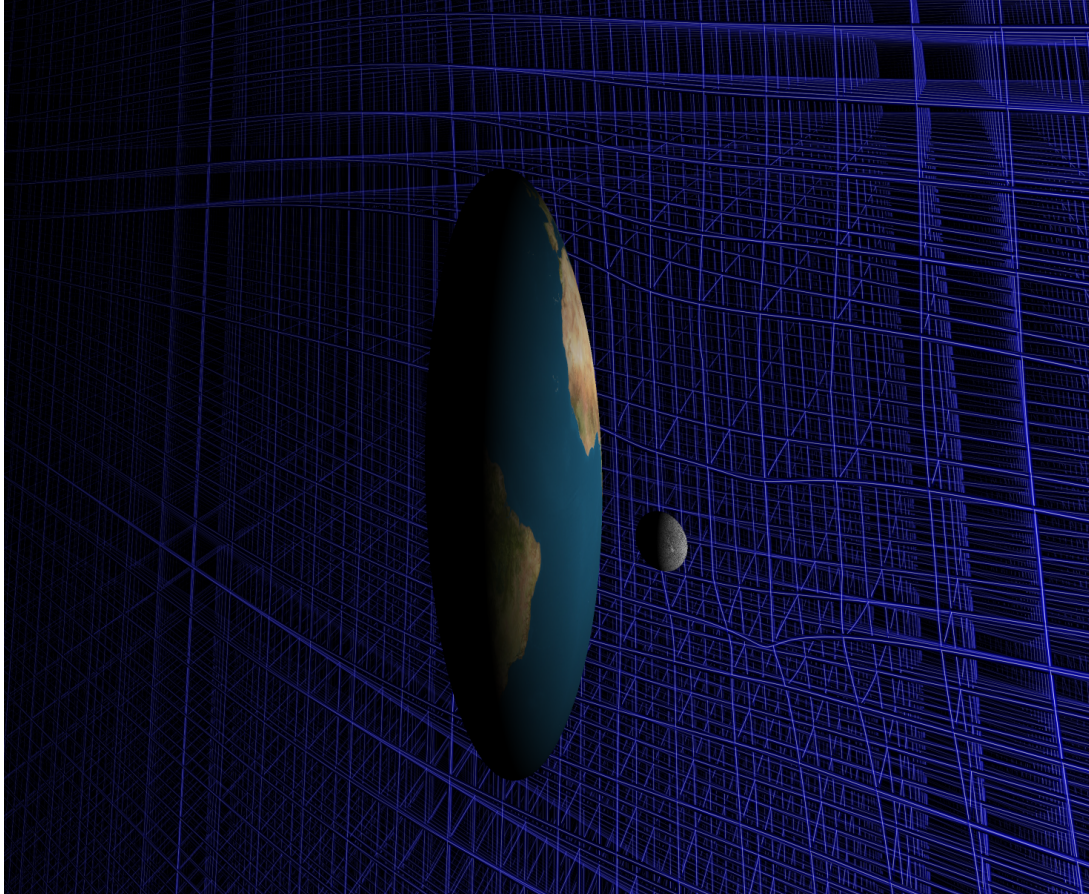

Figure 4.2.: Representation of earth with orbiting moon in the space time grid. Everything under the effect of gravitational waves at one point in time.

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. This means that updates of user and object positions according to interaction need to be done at every frame as well as every single pixel of the grid and all objects need to be calculated respective to the current influence of the gravitational waves at this time and position. 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.
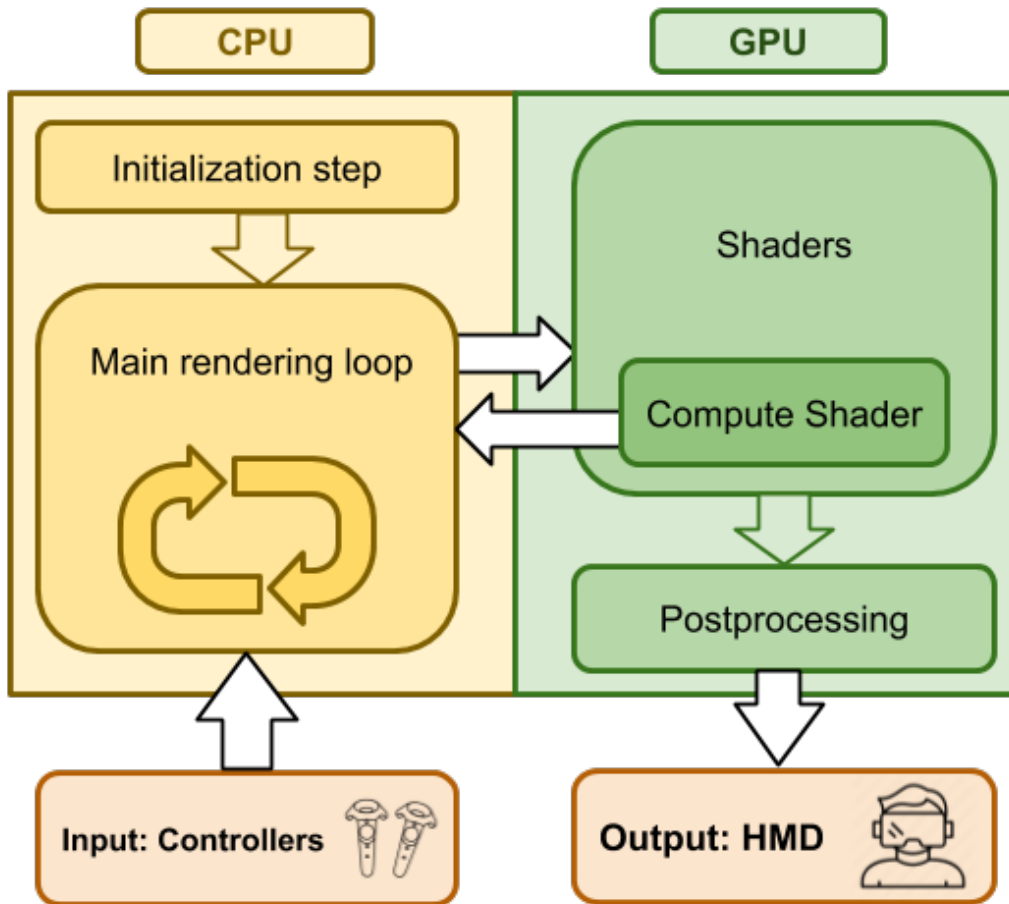

Figure 4.3.: System Architecture Diagram

4.2.2. Theoretical Background

This section is taken in slightly adapted form from Lontschar, Pietroszek, et al. (2020).

While the main concern of this project is not about dedicated astrophysics theory, a certain amount of theoretical background is still required for the creation of an appropriately accurate representation. The necessary formulas and their usage are described in this section.

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

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

is taken as a starting point with additional small deviations h from that flat space

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

and 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 x-y experience different values for different times t, which makes the longitudinally expanding wave also transverse, as the metric shows:

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

The wave distribution for one period of the binary stars was pre-calculated according to those formulas and stored 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, thus it can be easily used in an infinitely looping manner as a base factor. Different frequencies can also be handled by scaling the wave-arrays dimensions. As long as the masses of the binary star system stay constant, this pre-calculated wave-array passes within reason correct values for a qualitatively meaningful observation.

4.2.3. Implementation

This section is taken in slightly adapted form from Lontschar, Pietroszek, et al. (2020).
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. This has also been confirmed by related works that came up in corresponding research. Other attempts with colour coding the strength of the gravitational force in addition to the directional vector showed similarly weak results. To illustrate the gravitational waves, the decision was made to instead use a density grid: regular points in space, which are connected in x, y and z- direction and are warped corresponding to gravitational forces at each point at all time. The density grid consists of a three dimensional line grid rendered in OpenGL using vertex, geometry and fragment shaders (see Section 4.2.5) to create a billboard-like laser representation of each grid line that is always displayed in the direction of the users viewport. 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 sub-sections between each line intersection, where each section in turn is being separately distorted by gravity and gravitational waves respectively. To

let each separate grid point be influenced by every object and also the gravitational waves effect, a distortion function inside the vertex shader which 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 has been created. For a more realistic representation of the gravity behaviour of earth, moon and the binary stars also a maximum displacement function has been included, in order to make the grid stop on the surface of each body and wrap around it, resulting in a more realistic and understandable appearance instead of grid lines clipping through otherwise solid visual objects. For an even more in-depth impression of the influence of gravitational waves, the model of earth gets deformed according to the current magnitude of the waves effect at earths position. This deformation is handled in the same principle as the grid displacement, just projected onto the object rendering function of the earth. The displacement method used for gravitation calculation of the earth be seen in Listing 4.1.

Listing 4.1: Pixel displacement function for gravity

```
// incoming variables
uniform vec3 SpherePos;
....
uniform float scale;
...

vec4 getAttractedPosition(vec4 attracted_pos) {
    vec4 pos = attracted_pos;
    vec3 dir = SpherePos − pos.xyz;
    float d = length(dir);
    float max_d = d − scale;
    if (max_d < 0) return pos;

    float a = 0.0001;
    float force = (a) / pow(d,2);
    force = pow(force, 5.5/10.);
    if (force > max_d) force = max_d;

    vec3 norm_dir = normalize(dir);
    // clamp function for more defined approach test
    // pos.xyz = clamp(pos.xyz + norm_dir * force, pos.xyz, (SpherePos − norm_dir * scale));

    pos.xyz = pos.xyz + norm_dir * force;

    return pos;
}
```

To further improve the understanding, representations of the earth with an orbiting moon were added to show familiar objects that the participants can relate to in a certain manner. They are as well as the density field exposed to the generated gravitational waves, thus increasing the gained visual impressions for users. 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 an artificial scaling function towards all objects was implemented in order to bring them all together in a visible manner into the same scene. This makes it possible to show all objects, such as planet Earth, the moon and the source of the gravitational
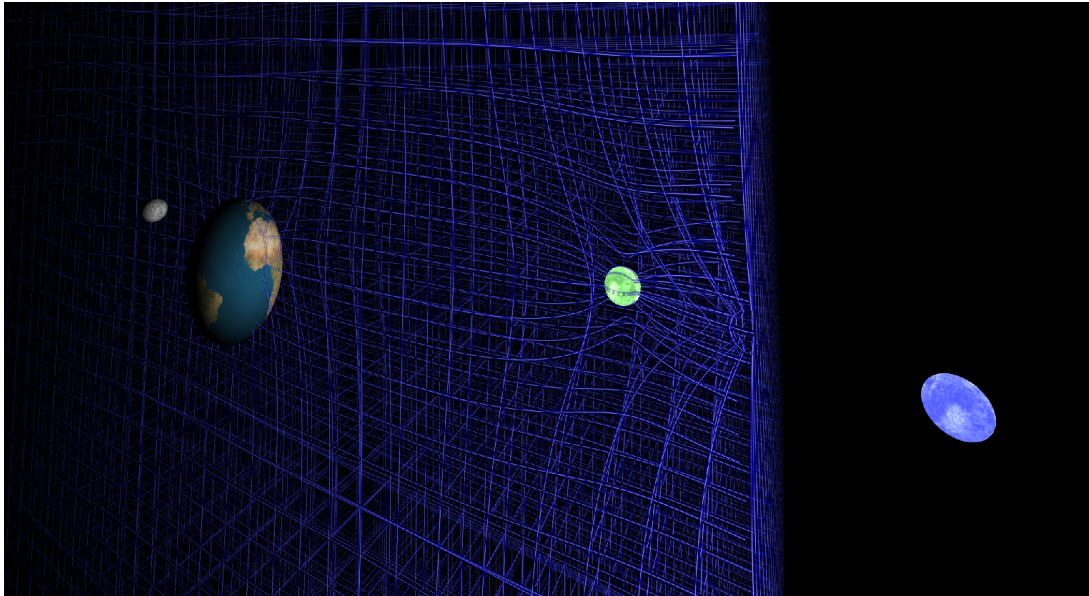
Figure 4.4.: VLE scene near binary stars with a heavily distorted density grid because of the stars masses.

waves, the binary system, in one observable scene as opposed to them being tiny dots if a completely accurate scaling was chosen. This way, participants are able to derive correct conclusions about the nature, origin and impact of gravitational waves. All stellar objects also have their own gravitational effects represented in the density grid. An overview of the scene with all elements on display can be seen in Figure 4.4.

4.2.4. Initial View and Controls

This section is based on the corresponding parts of Lontschar, Pietroszek, et al. (2020).

The entry point of 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. The density grid is applied to one quarter of the plane, crossing through it in y-direction. This setup lets the VLE participants observe the Earth extending half way out of the grid, as well as the binary system crossing the grid for one quarter in their initial view, thus giving an overall impression from the very start. 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 a good part of the area in the direction of the Z axis in reach. To avoid overly complicated control mechanisms and due to restricted amount of buttons on the used HTC Vive controller, movement on the Z axis was possible only per request and with assistance of a supervisor. Because mostly everything interesting is reachable from the initial point on the Y axis, vertical movement was seen as an edge case. Furthermore, the user was given the possibility to adapt the attributes of rotational velocity and length of radius of the binary star systems

orbit with their controller, which was required for a gain of interactive understanding of the corresponding influences. Moreover and most importantly, the controller can be used to measure the current wave-effect-magnitude on every point in space in the form of a visual representation of a measuring gauge. 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 travelling 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.
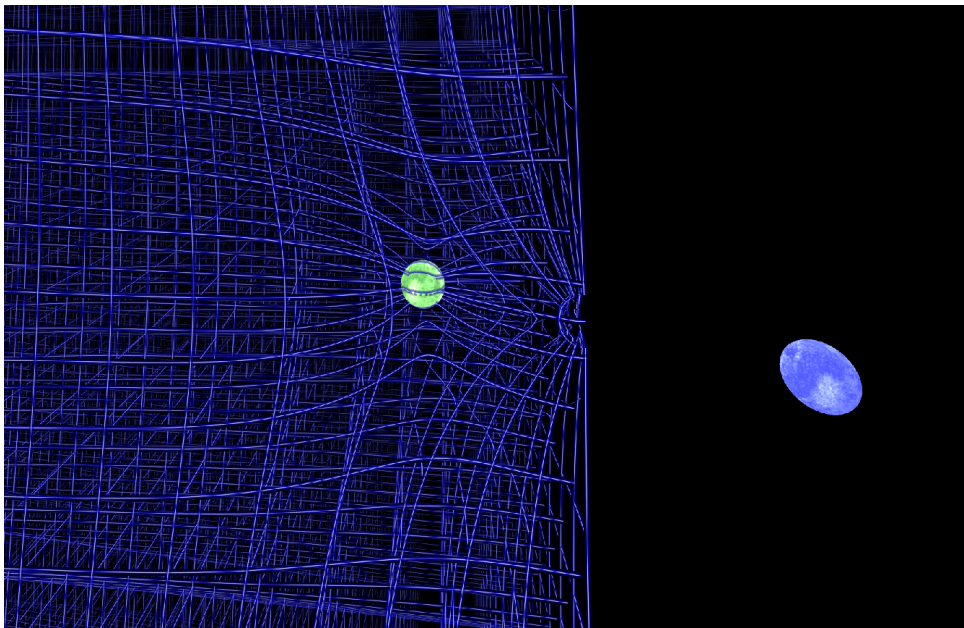
Figure 4.5.: The binary stars as source of gravitational waves in the VLE.

4.2.5. Shaders

Every visual representation in the VRLE was rendered using OpenGL shaders in a three dimensional sky box. While functionality and interaction is handled completely with C++ code on the CPU, after positions of objects in the scene are determined, they are sent to the GPU and handled in the form of shaders. Shaders are small programs on their own written in a C++ - like language, GLSL, and use dedicated input and output variables to communicate with the CPU and with each other. They also always work in a defined order (see Figure 4.6).

The CPU sends positions, as well as object form and texture information to the Vertex shader on the GPU. There, any necessary calculations for the position are made. In this approach for example the deformation of the density grid is being handled in this first shader step (see example in Listing 4.2). Positions for all objects emitting gravitational forces, the current grid-sub-section position as well as the

Listing 4.2: GLSL Vertex Shader example used for the density grid

```glsl
#version 330 core
layout(location = 0) in vec3 vertPos;

uniform vec3 SpherePos;
...
uniform mat4 P;
...
out vec3 vertex_pos;
out vec3 scolor;
uniform sampler2D tex2;
uniform vec2 bi_star_facts;
...

void main()
{
vec4 attractedPosition = M * vec4(vertPos, 1);

vec4 tpos = Ry * M * vec4(vertPos, 1.0);
vertex_pos = (M * vec4(vertPos, 1.0)).xyz;
camvertex_pos = vec3(V * attractedPosition);
gl_Position = P * V * attractedPosition;

// Calculate gravitational waves effects discplacement
tpos/= 5 * bi_star_facts.x;
tpos.xz += vec2(1,1);

vec4 spiralcolor = texture(tex2, tpos.xz * 0.5);

float amplitudefact = bi_star_facts.x*bi_star_facts.y;
float gw_force = spiralcolor.r*amplitudefact;

vec3 normVertPos = normalize(vertPos);
float f = dot(normalize(vec2(length(normVertPos.xz), normVertPos.y)), vec2(1,0));
float y = sign(vertPos.y);
attractedPosition.y += y*(0.02 * f * gw_force);
...
// Add normal gravity effect to displacement
attractedPosition = getAttractedPosition(attractedPosition);
...
if (attractedPosition.z > 0) attractedPosition.z = 0;
if (attractedPosition.x > 0) attractedPosition.x = 0;

gl_Position = P * V * attractedPosition;
scolor = spiralcolor.rgb;

}
```
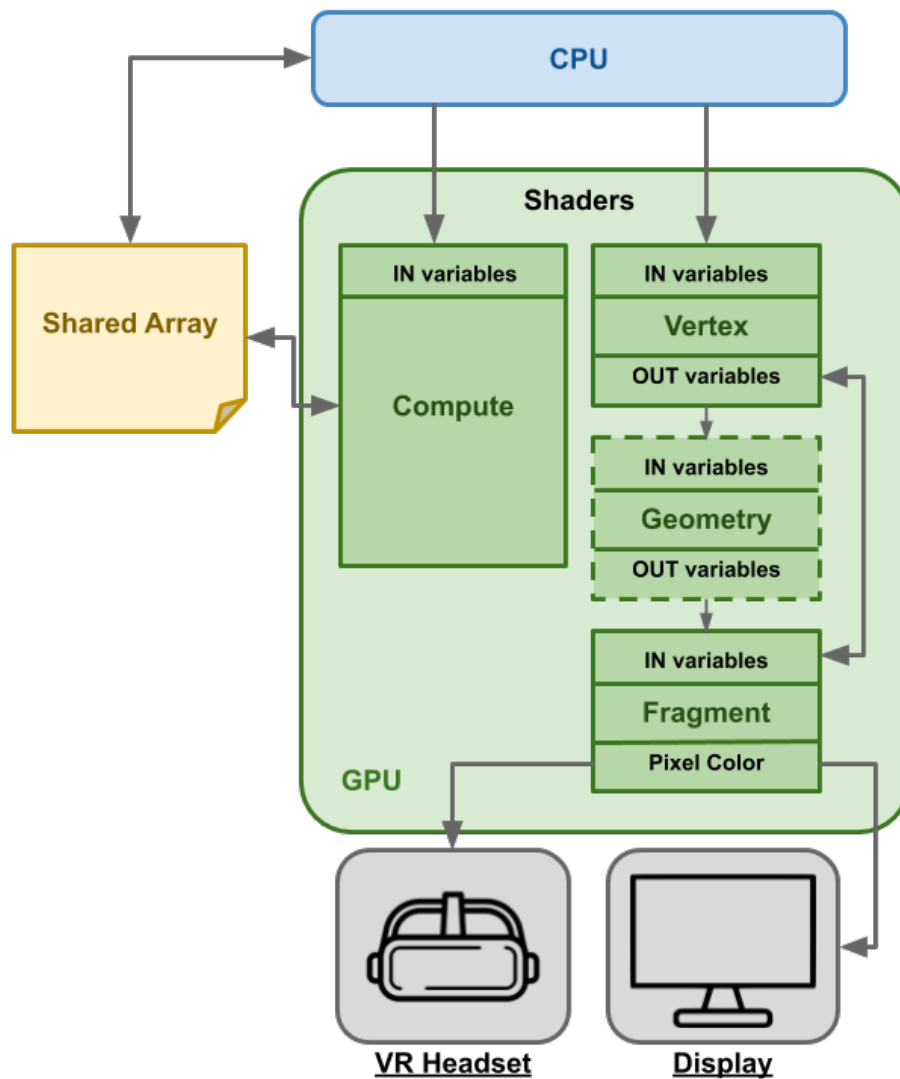
Figure 4.6.: Shader interaction Diagram. Vertex, optional Geometry and Fragment
as well as Compute shader

corresponding texture address and gravitational waves attributes are handed to the
shader in pre-defined variables on the CPU. Additionally, View, Model and Rotation
matrices are handed to the shader. While the vertex shader is normally responsible for
the calculation of appropriate positions that are later used to render corresponding
textures, in this application the it also reads the pre-calculated gravitational waves
data from a texture. After these position calculations the shader writes everything to
pre-defined *out* variables, which in turn are read by the next step in the shader chain. In
this case the position influenced by gravitational waves. Moreover, the colour argument
needs to be passed through for later steps, as the CPU can only send information to
the first shader.

All output variables from the vertex shader need to be read by the following step in

the shader chain. While it is not an obligatory step, this application used geometry shader as second part in the chain for the grid rendering (see Listing 4.3). Geometry shaders can alter the appearance of single input points from the vertex shader in various ways. Here it was used to create a rectangle for each grid-sub-section point. Therefore, creating four output coordinates from each one input position. Combined with some matrix calculations with the camera position this results in a texture that always looks into the direction of the user. In this case some restraints were added in order to not make the grid break apart, thus creating a partial billboard, where a connected line would always show towards the camera. This made it possible to create the impression of an actual round grid line, while the texture is in reality only displayed on a rotated rectangle. Some calculations are made to determine all four edge points of the rectangle and are emitted separately, ending with the *EndPrimiteve();* command, which sends these on to the next shader. The amount of output vertices has to match the form and number defined in the beginning of the shader file. The colour is just passed on, like in the vertex shader, but needs to be done here for each resulting coordinate. The texture mapping is important, as the triangle_strip argument defines the connection of emitted vertices, and with that their resulting position. Therefore, the texture coordinates are hooked to each edge, so the shader framework can handle the appropriate rendering.

The last step of a normal shader chain is always a fragment shader. Receiving finished positions and corresponding texture coordinates, this shader finally calculates the colour value for each pixel on the output image. In the simplest version, this shader only reads a texture that needs to be rendered on the corresponding coordinate, resulting in a one-line function. In this application also a certain fade-out effect was required to prevent visual overloading of a grid at full opaqueness (see Listing 4.4). Therefore, a simple exponential function was created that would set every rendered coordinate less opaque the further away it is from the camera, creating semi-transparent grid that makes it easy to orient inside.

Next to the normal Vertex, Geometry and Fragment shader also a Compute shader was used in the development. While in principle it works in the same manner and takes pre-defined input variables for calculation from the CPU, it can work on its own without other shaders and it does not have defined *out* variables. Instead it has access to an array that is shared with the CPU which it can read and write values to. Using these attributes it calculates the gravitational waves effect on the controllers position using matrix calculations in the same manner as the Vertex shaders of the other render chains. This calculated value is then written to the shared array, which in turn can be read by the CPU, thus making backward communication from GPU to CPU possible. The value is used for measuring gravitational waves in the study process and explained further in the next section.

Listing 4.3: GLSL Geometry Shader example used for the density grid

```
#version 330 core
layout (lines) in;
layout (triangle_strip, max_vertices = 4) out;

in vec3 vertex_pos[];
...
out vec3 camvertex_pos_g;
...

void main() {
    vec2 vert_pos_one = vertex_pos[0].xy;
    vec2 vert_pos_two = vertex_pos[1].xy;

    vec3 camvert_pos_one = camvertex_pos[0];
    vec3 camvert_pos_two = camvertex_pos[1];
    float width = 0.002f;

    // bottom left
    gl_Position = gl_in[0].gl_Position + vec4(0.0, -width, 0.0, 0.0);
    camvertex_pos_g = camvert_pos_one;
    texcoord = vec2(0,1);
    fcolor = scolor[0];
    EmitVertex();

    // bottom right
    gl_Position = gl_in[1].gl_Position + vec4( 0.0, -width, 0.0, 0.0);
    camvertex_pos_g = camvert_pos_two;
    texcoord = vec2(1,1);
    fcolor = scolor[0];
    EmitVertex();

    // top left
    ...
    // top right
    ...

    EndPrimitive();
}
```

4.2.6. User Interface and Interaction

As mentioned in the earlier part of this subchapter, the user has the possibility to measure gravitational waves effects exactly where the controller is held. This is possible due to a virtual gauge representation that is rendered slightly above the current controller position. The gauge is a simple texture rendered with shaders in the same principle as explained in the previous section (see Figure 4.7). The special part of this visualization is that it moves an indicator according to the measured value in order to provide dedicated UI information accessible for the user at any time, thus giving the impression of an analogue gauge.

The used functionalities combine compute shader with a normal shader chain. The CPU sends the controller position in addition to all other rendered objects into a compute shader program. There calculations are made, as described in the previous section, and the result is written on to the shared array. The CPU reads the result and sends it into the gauge render chain, where in turn it is used to rotate the

Listing 4.4: GLSL Fragment Shader example used for the density grid

```
#version 330 core
out vec4 color;
in vec3 vertex_normal;
...
uniform sampler2D tex;

void main()
{
    float f=0.25;

    float depth = 1. + camvertex_pos_g.z*f;
    if(depth<0)depth=0;

    depth = pow(depth,7);
    vec4 color4= texture(tex, texcoord);
    if(color4.a < .1) discard;
    color4.a *= depth*2;
    color = color4;
    color.a = color.b*depth*2;
}
```

indicator accordingly. Therefore, it gives 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 in the grid and on the other objects.

4.2.7. Virtual Reality Display

Everything in the application is being rendered via a dedicated VR render class that utilizes OpenVR. This class includes an interface to read the VR headsets and controllers positions, which is used by the main application for corresponding calculations. While part of the functionality is taken as is from the framework, adaptions to read controllers positions properly have been made. The class takes the main application as an input reference which is used for the output image rendering, which is sent to the headset in the form of a left and right channel. The right channel is additionally sent to the main screen, which creates the possibility to supervise what the users are seeing in the VR environment, for additional guidance during the study part. Another adaption that had to be made was a wrapper class for the main function. This was because the main function was devised for rendering on a Full-HD screen in the lab, while the used HMD used a much greater resolution of 2880 x 1600 pixels. Therefore, the created wrapper function used MSAA techniques in order to smooth the resulting output image for the HMD to solve the issue with inferior resolution and create a more pleasant usage experience.

4.3. Evaluation

Similar to the first project described in this thesis, the evaluation process of this second study also follows a multi step approach. First with a pre-questionnaire, followed by the
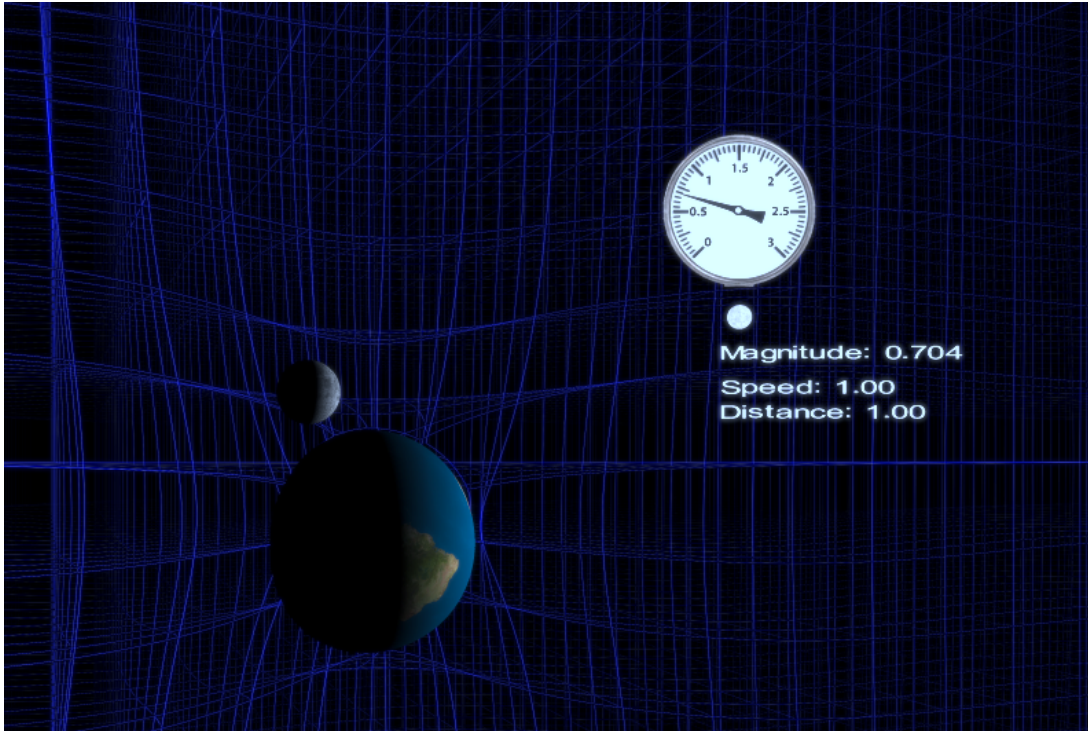
Figure 4.7.: Measuring Gauge on the users controllers position. The arrow moves according to the current gravitational waves effect. The numeric values underneath gives digital information about the same value and also the current settings for the binary star system.

the VRLE experience and closed up in a corresponding post-questionnaire. The study was carried out with n = 35 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 already 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 order to evaluate any change in understanding. In the following chapters more details about the design of this user study are going to be explained, followed by information about the test setting and used instruments. Afterwards the focus will follow through on how the study was actually conducted from start to finish. Then, insights into the participants and their demographics are given. Finally, the results are gonna be explained, focusing on the study questions first, which show gain of knowledge and understanding, and then on the corresponding immersion observations, which indicate feedback on usability and the users well-being during and after the simulation. The subchapter is closed up with a discussion about the gained insights.

The main research interest analysed in this approach is to find influences of visualization techniques in VR on the gain of visual information. Additionally, it is evaluated how well the chosen visualization technique of this project does in transmitting the

underlying theory in the form of a study question evaluation. Next to the analysis of understanding, correlations in the connected immersion questionnaire via GEQ need to be identified and evaluated. Therefore, the research questions of this project that evaluate its ability to transfer knowledge about gravitational waves with the devised study questions, are defined as follows:

- Analyse the influence of the chosen visualization technique in on the gain of visual information.
- Identify differences in understanding of basic attributes of gravitational waves before and after the VRLE with the devised study questions.
- Are there correlations between study question results and immersion evaluation response results of the GEQ?

4.3.1. Study Design

The study part of this research approach was designed with a *before and after* comparison setting, also called a pre-post study. In this evaluation design a group of participants is asked certain specifically devised study questions before and after some sort of intervention, in this case a VRLE experience. With this it should be possible to measure an impact of the intervention, in this case a difference in understanding and thus learning. In order to get such information the group of participants were asked to complete a corresponding pre- and post-questionnaire (see Section 3.3.2), respectively before and after the VRLE experience. Next to demographics in the pre-questionnaire and an evaluation of immersive impact of the VRLE in the post-questionnaire, both also contain the same study questions that evaluate the understanding of gravitational waves. These study questions represent an essential part of the evaluation approach and are described in more detail in the following section.

4.3.2. Setting and Instruments

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. In Figure 4.8 a user study participant during the process of exploration inside the VRLE can be seen.

Due to the extended GPU shader work in graphics calculation for the VR representation of omnipotent gravitational waves effects, OpenGL was used as the graphics API in combination with OpenVR as VR library to display everything in a HMD. During the study process the developed application was run on a Windows PC with an AMD Ryzen 7 processor, an NVidia GTX Titan V graphics card and a HTC Vive Pro Eye HMD as the immersive display.

To ensure proper data collection and for easier built in evaluation, both questionnaires were hosted on separately created Google Forms[6]. Both forms were linked via a
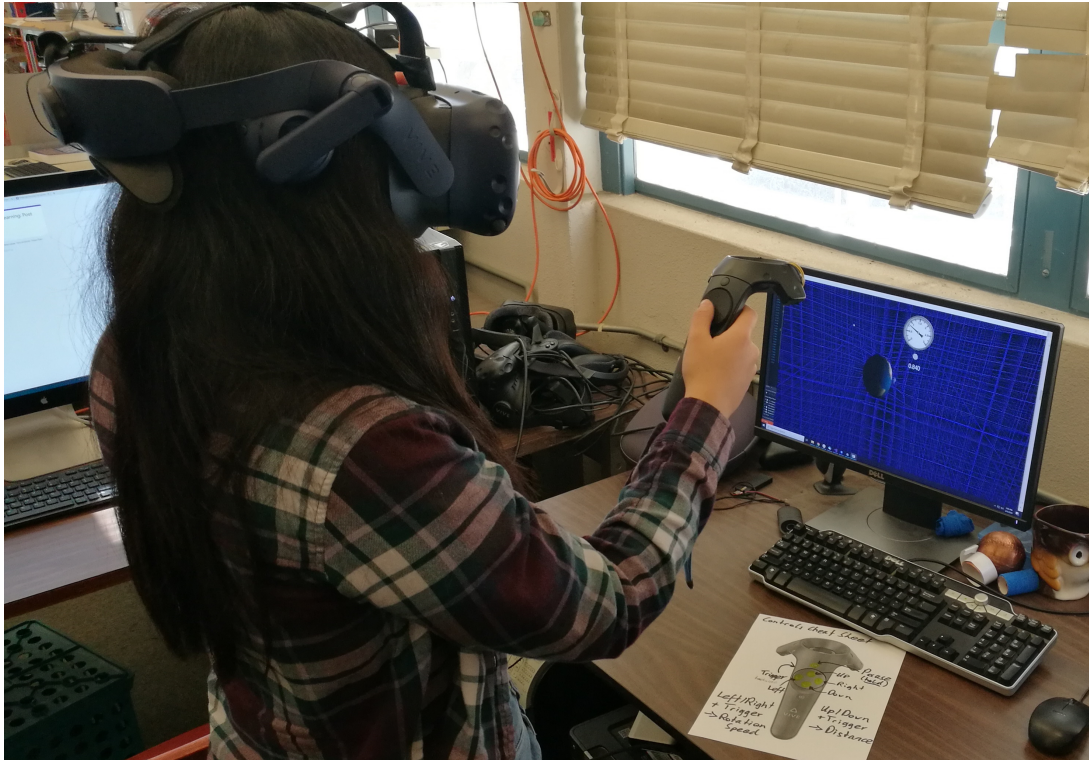
---

[6]https://www.google.com/forms/about/

Figure 4.8.: Study participant during VLE experience. In game view seen on screen on the right.

unique identifier that consists of a random five digit number which each participant drew from a pool of numbers before the start of the study process. The questions of the VR experience part of the post survey were designed in the form of the Game Immersion Questionnaire and Game Experience Questionnaire. These are known and tested frameworks for evaluating immersive experience of the user during and after the simulation. The corresponding answers are Likert-Scale based, evaluating each value from 1 to 5 with 1 being the lowest and 5 the strongest agreement (IJsselsteijn et al., 2013; Jennett et al., 2008).

The study questions are designed to quantify differences in understanding of core attributes of gravitational waves. They and all available answers are contained in both questionnaires, are taken from Lontschar, Pietroszek, et al. (2020) and are as follows:

Q1: What type of waves are Gravitational Waves? (Gif shows two wave types)

- Transverse and Longitudinal
- Transverse
- Longitudinal
- Other
- I don't know

Q2: How does the magnitude of the gravitational waves effect change if the radius between the rotating stars changes? (Rotation speed of the binary star system
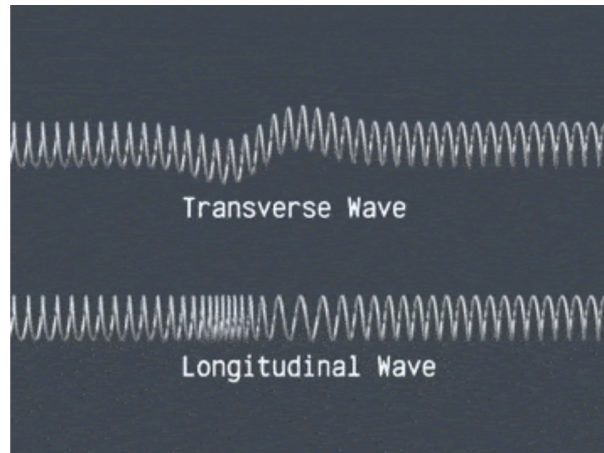
Figure 4.9.: One frame of the gif used to indicate wave types for question #1.

and frequency of the waves effect is not changing!)

- The magnitude of the waves effect gets higher with lower distance between the stars.
- The magnitude of the waves effect does not change with changed
- distance between the stars.
- The magnitude of the waves effect gets lower with higher distance between the stars.
- I don't know

Q3: What happens to a distant planet if the two stars collide, merge and would be on one place?

- The gravitational wave effect would fade out (decrease over time and then stop)
- The gravitational wave effect would become more intense (frequency and amplitude)
- The gravitational wave effect would become less intense (frequency and amplitude)
- The gravitational wave effect would stop
- The gravitational wave effect would not change as the mass of the system stays the same
- The gravitational wave effect change it's wavetype
- I don't know

Q4: How does the magnitude of the gravitational wave effect change if the rotation speed of the rotating stars changes? (Distance between the binary stars is not changing!)

- The frequency of the gravitational waves increases if the star system rotates slower, the amplitude stays the same

- The gravitational waves effect is not depending on the rotation speed of the binary stars
- The frequency of the gravitational waves effect increases if the stars rotate faster, the amplitude decreases
- The magnitude of the gravitational waves effect increases if the stars rotate faster, the frequency stays the same
- The frequency of the gravitational waves effect increases if the stars rotate faster
- The magnitude and frequency of the gravitational waves increase if the star system rotates faster
- The magnitude and frequency of the gravitational waves decrease if the stars rotate faster
- The magnitude and frequency of the gravitational waves effect decreases if the stars rotate faster
- I don't know

Q5: Which area in spacetime is most affected by the gravitational waves effect? (See Figure 4.10)

- Along the binary star rotation axis (up/down the y axis, see picture)
- Evenly the same, anywhere in space
- Along the binary star rotation plane (x-z plane, see picture)
- Exactly between the binary stars (see picture)

All answer possibilities were given in randomized order each time to not provide the exact same situation in pre- and post-survey, therefore removing the quick possibility to choose the same answer as last time and force participants to think first and carefully read through he answers before making a choice.

Each participant was tasked to answer the study questions in each of the questionnaires to the best of their knowledge and each question, safe the last, contained a possible answer "I don't know". During the post-questionnaire the participants were also allowed to re-visit the VRLE for further confirmation if they were still in doubt with some questions but remembered where the potential insights were hidden. For question five a screenshot of the corresponding part in the visualization was added for clarification about the possible answers, which contained "On the rotation plane of the binary stars" and "Along the rotation axis of the binary stars". This screenshot can be seen in Figure 4.10.

In order to create a non-blocking testing process, the questionnaire part was taken on a separate PC in order to give participants as much time as they desired for the VRLE experience. Because there were no specific requirements to this second device, other than the ability to open a conventional web browser, another desktop PC from the laboratory as well as a MacBook Pro of early 2018 was taken for this purpose, because it was available from the developers.
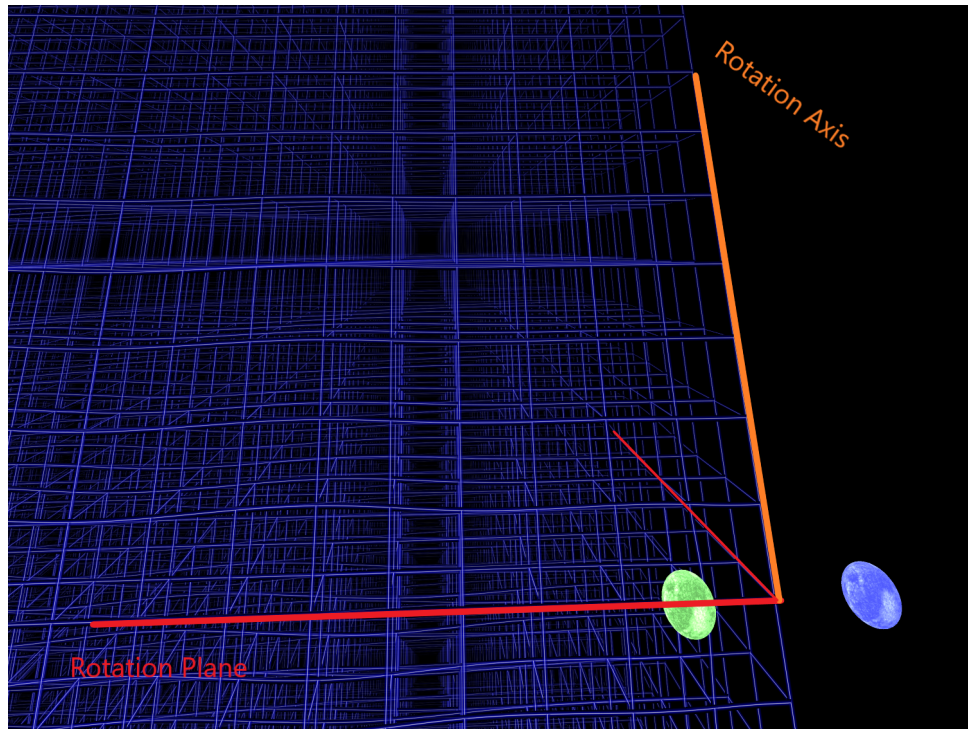
Figure 4.10.: The image used to indicate possible answers for question #5.

4.3.3. Procedure

Based on the devised study design and tools described in the previous sections the study was carried out. Participants registered for one of many 20 minute timeslots over the course of several days in order to take part in the study. The slots were prepared for sign up in a Doodle[7] form. On average most participants took around 8 to 10 minutes for exploration inside the VR experience and about 9 minutes for both questionnaires. The duration was not measured in detail but the initially chosen time of 20 minutes per timeslot proved to be sufficient and was therefore kept throughout the overall study process.

Each study participant followed the same multi-step process through the whole study approach. First a unique identifier number consisting of five random digits was drawn from a pool of IDs. Then a short verbal explanation of the studies content followed by the pre questionnaire. Each participant was encouraged to think through the study questions and answer them to the best of their understanding if they had any idea at all. There was the possibility to choose "I do not know the answer", but this was meant to be a last resort if they could not imagine any of the other answers to be correct. This answer represented a definite choice and was used in order to reduce some random noise in chance based correct answers that could happen, if participants were forced to choose an actual possibility. After the first questionnaire was finished, participants got a short introduction into what they are going to experience and how the controls

---

[7]https://doodle.com/free-online-appointment-scheduling

work. Everything is also explained visually in the VRLE, but a short introduction was deemed helpful when first testing samples and feedback were analysed and was therefore adopted for all participants thereafter. The first test samples were created with the help of colleagues in the lab and were only for feedback and functionality purposes and not recorded in the data sets.

After the practical part each user was given the possibility to explore the VRLE to their hearts content without a given time restriction. Theoretically the time frame was given with the assigned time slots of 20 minutes, but as they were sufficiently chosen no participant required additional overtime. During the exploration of the simulation participants were only guided by two main tasks that were given as follows:

T1: Explore the scene 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.

T2: Change the distance and period-time of the binary star system and observe the behaviour of gravitational wave-magnitude and distribution in succession.

While the direct effects of gravitational waves were visible in all the simulation elements, the goal of these tasks was to further illustrate the linear dependency of wave-amplitude and torque and overall fortify the understanding of correlations between gravitational waves source and effect. Furthermore, they were laid out to lead the participants into getting ideas about *where* to find the answers to the study questions that were introduced in Section 4.3.1 and especially to understand *why* the corresponding answers are correct.

After the participants finished their VRLE experience they were all asked to fill out the corresponding post-questionnaire containing the five study questions first, followed by the sets of GEQ and GIQ. While most participants were rather sure of the questions after seeking for the corresponding answers in the VRLE, some of them took advantage of the possibility to re-visit the simulation in order to clarify last doubts.

None of the participants were paid or in any way compensated for their time effort and participation was completely voluntarily and based on general interest in either the physics topic or the experience of a virtual reality simulation.

4.3.4. Study 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 4.11. The biggest part of the study participants were full-time students followed by students with a job on the side. Their age was in the range from 18 to a maximum of 34 years old with an average of 21.65 years old according to the given age ranges. 21 participants indicated to be male and 14 to be female. The most commonly represented ethnic groups were of Caucasian and Asian ancestry ($> 85\%$) and more than 90% of the participants did not yet finish any university degree. Three participants stated
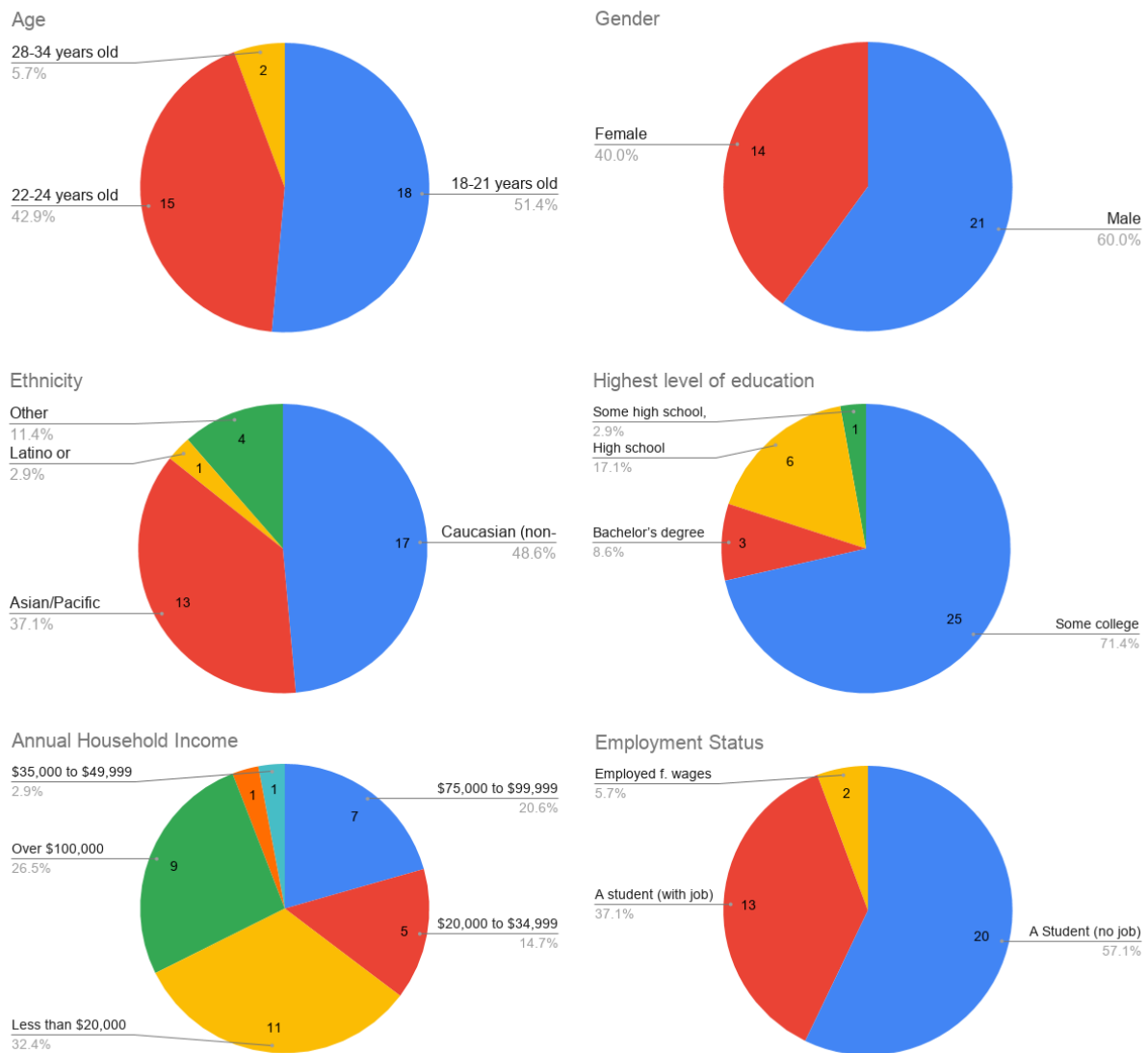
Figure 4.11.: Group demographics. The distribution of the participants age, level of education, employment status, ethnicity, gender and annual household income.

a bachelors title and therefore represent the ones with he highest finished level of education.

The distribution of previous VR experience as seen in Figure 4.12 indicates a fairly evenly spread level of indicated VR expertise. Only two participants stated having no prior experience with any kind of VR device and the biggest part specified only little experience, but three contributors thought of themselves to be experts in VR. The insights of this graph are important for the later evaluation of the results produced by the VR environment.
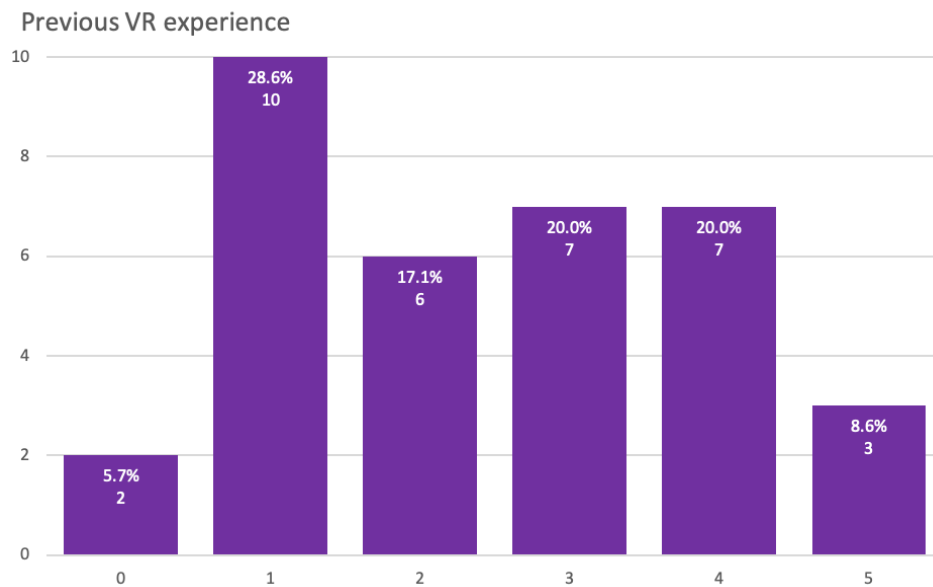
Figure 4.12.: Users self-perceived previous VR experience with any kind of VR device, before using the developed VR application. The histogram shows the amount of responses on the vertical axis and VR experience value from 0 to 5 on the horizontal axis.

4.3.5. Results and Discussion

Some parts of this subsection are based on the respective section of Lontschar, Pietroszek, et al. (2020).

Over the course of this study approach two main aspects of the study were recorded in accordance to the usage of the developed VRLE. The first of these aspects is a measure of understanding of gravitational waves attributes as the qualitative part. This was evaluated with five multiple-choice questions in a before and after comparison setting. The second aspect evaluates the immersive feedback and users well-being during and after the usage of the simulation. The second aspect includes insights from multiple questions of two sets with five-point Likert-Scale answers as the quantitative part of this study.

The following paragraphs and associated graphs are based on the corresponding parts of Lontschar, Pietroszek, et al. (2020).

Study question response evaluation

The acquired data gained with the evaluation of the results of the study questions immediately showed a striking increase in understanding of the topic. As seen in Figure 4.13 the average amount of each separate question for all participants shows an eminent gain of positive responses after the exploration of the simulation scene. The first five columns from the left show results for each separate question and the

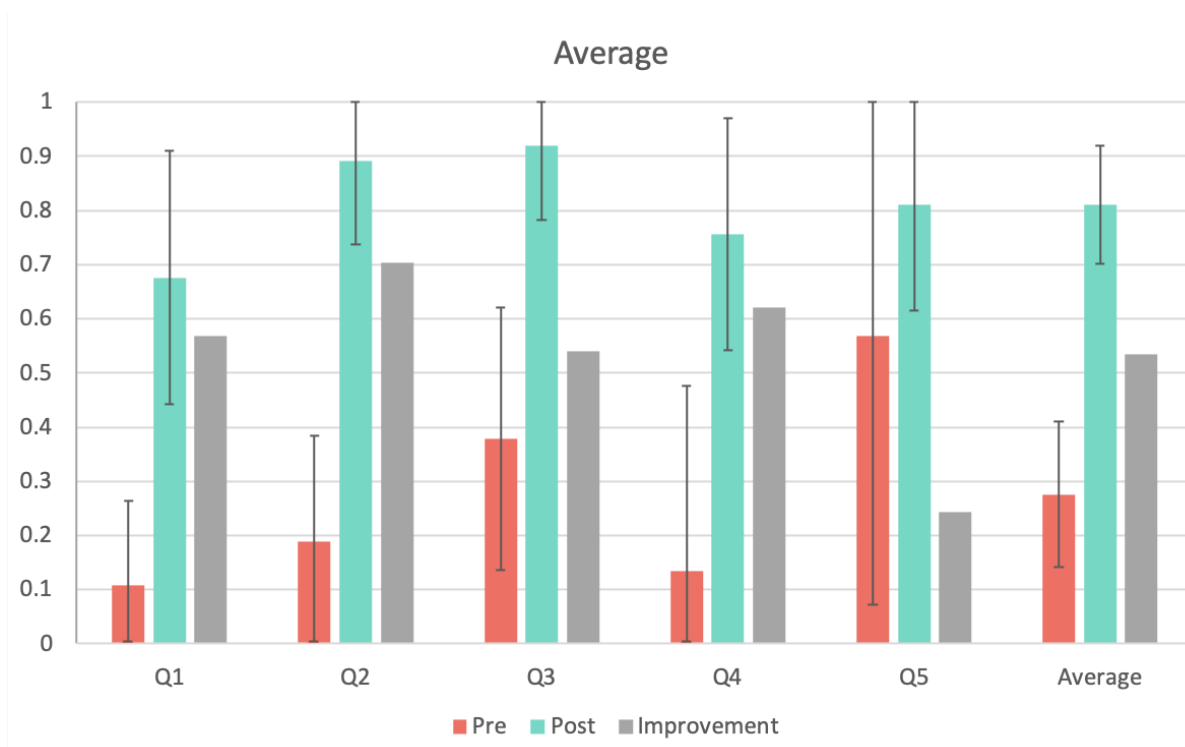right column displays the average over all questions, providing the first very positive insight.

Figure 4.13.: Result score for each question and all participants: pre-(orange) and post-questionnaire(cyan) results and improvement(grey).

An average value of 27.56% correctly chosen answers before the VLE was recorded whereas 81.08% could be seen afterwards, which sums up to an average increase of more than 50%. This represents an even better result than it was initially expected in an optimal 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 via verbal feedback of multiple participants that stated that their intuitions 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 types of waves were not entirely clear, even with the displayed visual representation in the form of an added gif to the question, which most likely lead to some slight skew in the collected results of question #1.

Looking at the average results of all participants already an overly positive result if the simulations influence can be identified. In order to confirm this some more detailed aspects of the gained data need to be evaluated as well. Therefore, in the following parts of this section the groups of best or worst participants, concerning the upper or

lower third of average increase of positive answers respectively, are being analysed in more detail.

Figure 4.14 and Figure 4.15 illustrate two mainly interesting aspects of the participants spectrum before and after the exploration of the virtual representation. In Figure 4.14 a) it is pretty impressive to see that even the group of participants that already brought a fairly good understanding into the study approach managed to improve for almost every study question. **Q5** indicates a reduction in understanding which most likely is connected to the "I don't know" answer not being available, thus introducing more uncertainty and random noise, as this group showed a 100% correct result for this question in the pre-survey. Because only one question showed a slightly negative development and a reason therefore can be found, the overall impression of the insights gained is absolutely positive. The group of participants that achieved the least correct answers prior to the VRLE (as seen in graph b) of this figure) managed to show an astounding improvement of 90% more correctly chosen answers in the post-questionnaire than before further fortifying the overly positive impressions gained so far. Figure 4.15 a) indicates that at least a third of participants were absolutely sure about the thought topic after learning about it in the provided simulation. Graph b) of this figure shows that even the participants that that managed achieve the lowest overall scores after the experience could improve their understanding by more than 20%, which can still be seen as a successful application.

Another important group of participants to be evaluated are the ones that improved the most and also the ones that did not improve much with the help of the developed application.

Figure 4.16 (a) illustrates an impressive difference in the ratio of correct to wrong answers, especially for the subgroup of participants that on average improved themselves the most. This also leads to the insight that especially people who have barely any or a wrong understanding of the research topic can benefit extensively from the implemented VR experience, as is confirmed in the similarity of Figure 4.14 b) as it most probably contains mostly the same users. Figure 4.16 (b) also seems familiar as it resembles a lot the results of the group that showed very high scores in the pre-surey. This makes sense as people who already have a good idea of the taught topic can not benefit in the same manner from the insights, as they do not learn much new knowledge to them.

What is an especially notable insight in those graphs: 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, which indicates that the application provides an especially good possibility to transfer new knowledge to people not familiar with the topic at all.

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%.
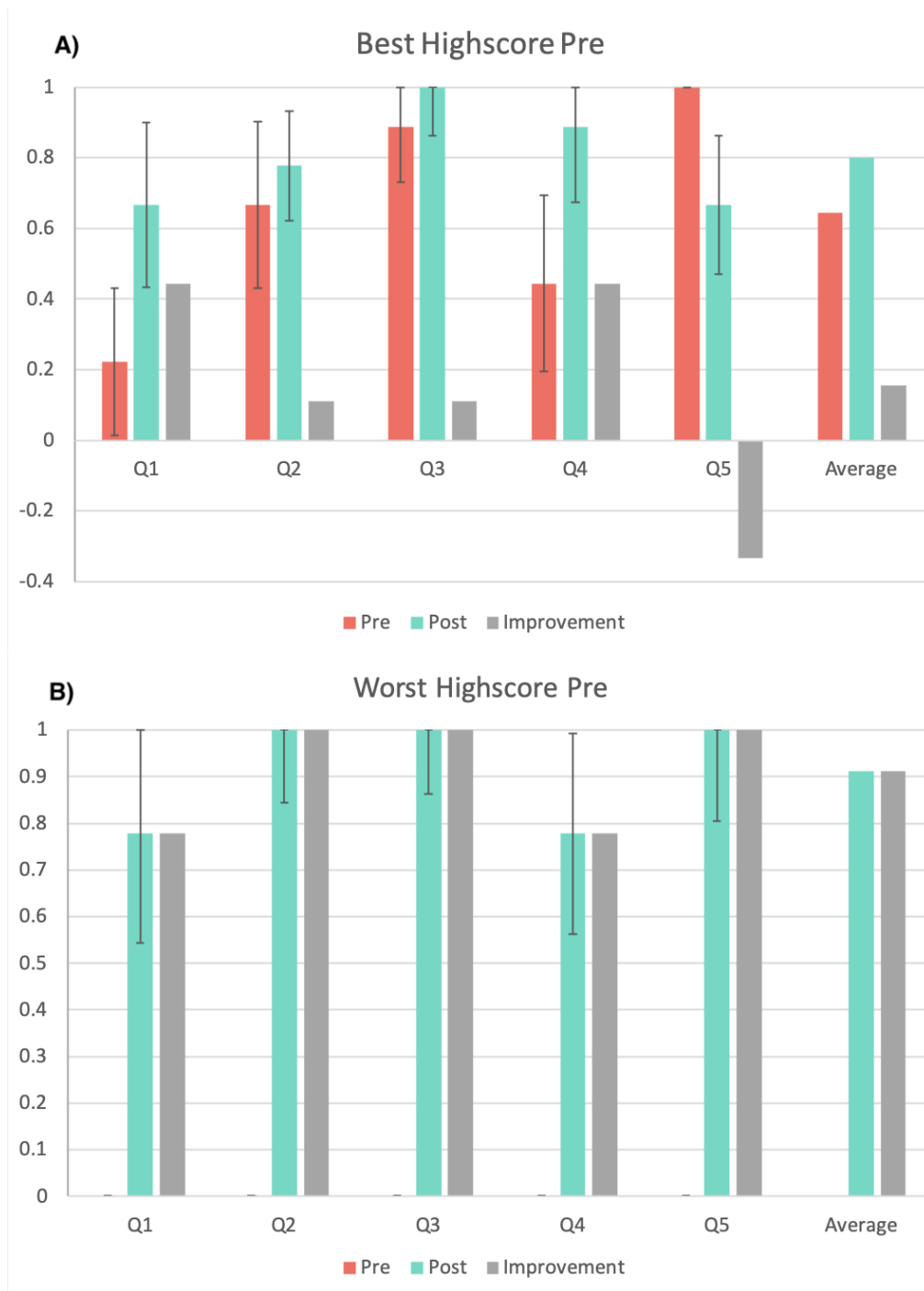
Figure 4.14.: Result scores for participants that showed the highest and lowest score before the VLE: pre-(orange), post-questionnaire(cyan) results and improvement(grey).
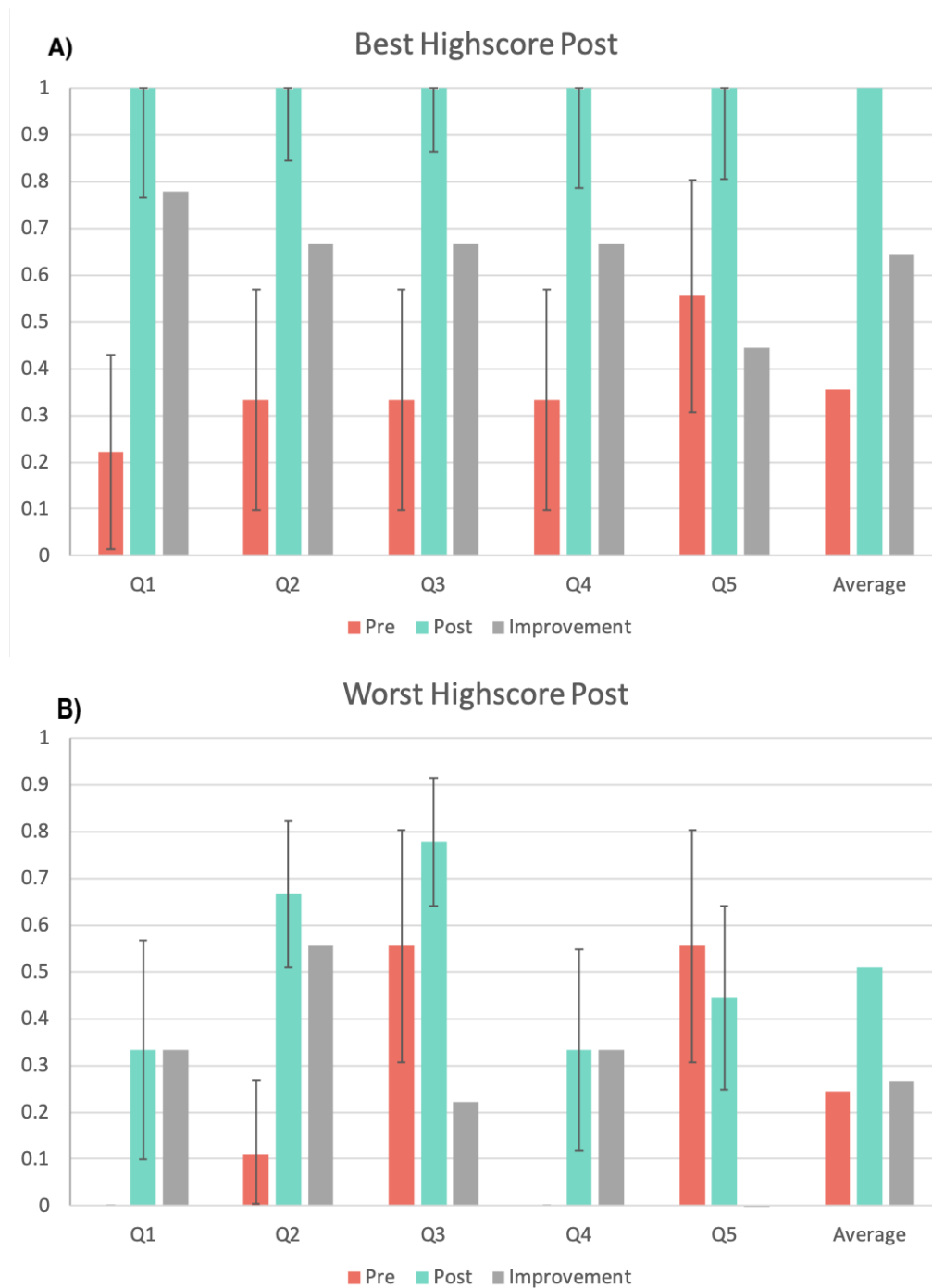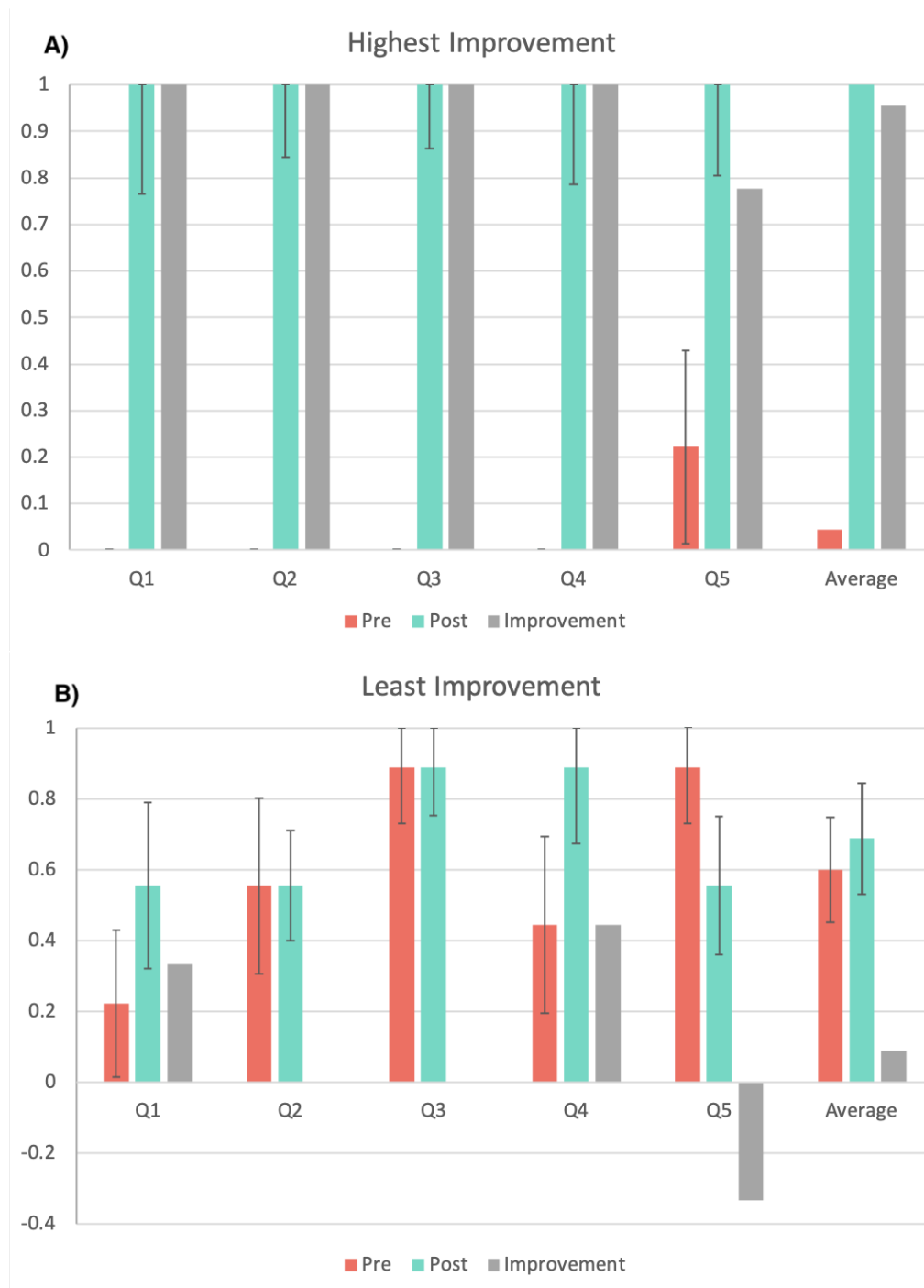
Figure 4.15.: Result scores for participants that showed the highest and lowest score after the VLE: pre-(orange) and post-questionnaire(cyan) results and improvement(grey).

Immersion and user experience evaluation

Conducting the Game Experience Questionnaire (GEQ), the immersion during the VLE experience followed by the Game Immersion Questionnaire(GIQ) measuring the

Figure 4.16.: Result scores for participants that improved the most and least af-
ter the VLE: pre-(orange) and post-questionnaire(cyan) and improve-
ment(grey).

immersive impression felt by the users after experiencing the simulation were assessed.
In this subsection following values are chosen from the questionnaire in order to

evaluate the users perception *during* the simulation:

- Competence
- Sensory and imaginative immersion
- Flow
- Tension and annoyance
- Challenge
- A summarized value of negative effects
- A summarized value of positive effects

And following values are chosen from the questionnaire in order to evaluate the users perception *after* exploring the developed VRLE:

- Basic attention
- Temporal dislocation
- Transportation
- Challenge
- Emotional Involvement
- Enjoyment

First looking at the average feedback values reported by all the participating people, Figure 4.17 give some first overview insights. While the graph shows that even some of the participants did not seem to feel overly competent in finishing the given tasks, on average they were still positively affected and stated a high sensory and imaginative immersion. It is especially positive that almost no one reported an annoyance value of more than zero and the overall negative effects reported were also particularly low. Part (b) of 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 study questions and remembering the gained impressions of the VRLE. According to verbal feedback many participants were also slightly overwhelmed by processing the gained information during and after the VLE experience but at the same time positively impressed by the visual impressions.

While the average of all reported values already gives some overview insights, same as in the previous subsection concerning the answers to the study questions the following graphs show the immersion values of the best and worst scoring groups of participants before and after the VRLE as well as the groups that improved the most and the least. Comparing the immersive responses of best and worst scoring participants of the pre-questionnaire as can be seen in Figure 4.18, 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
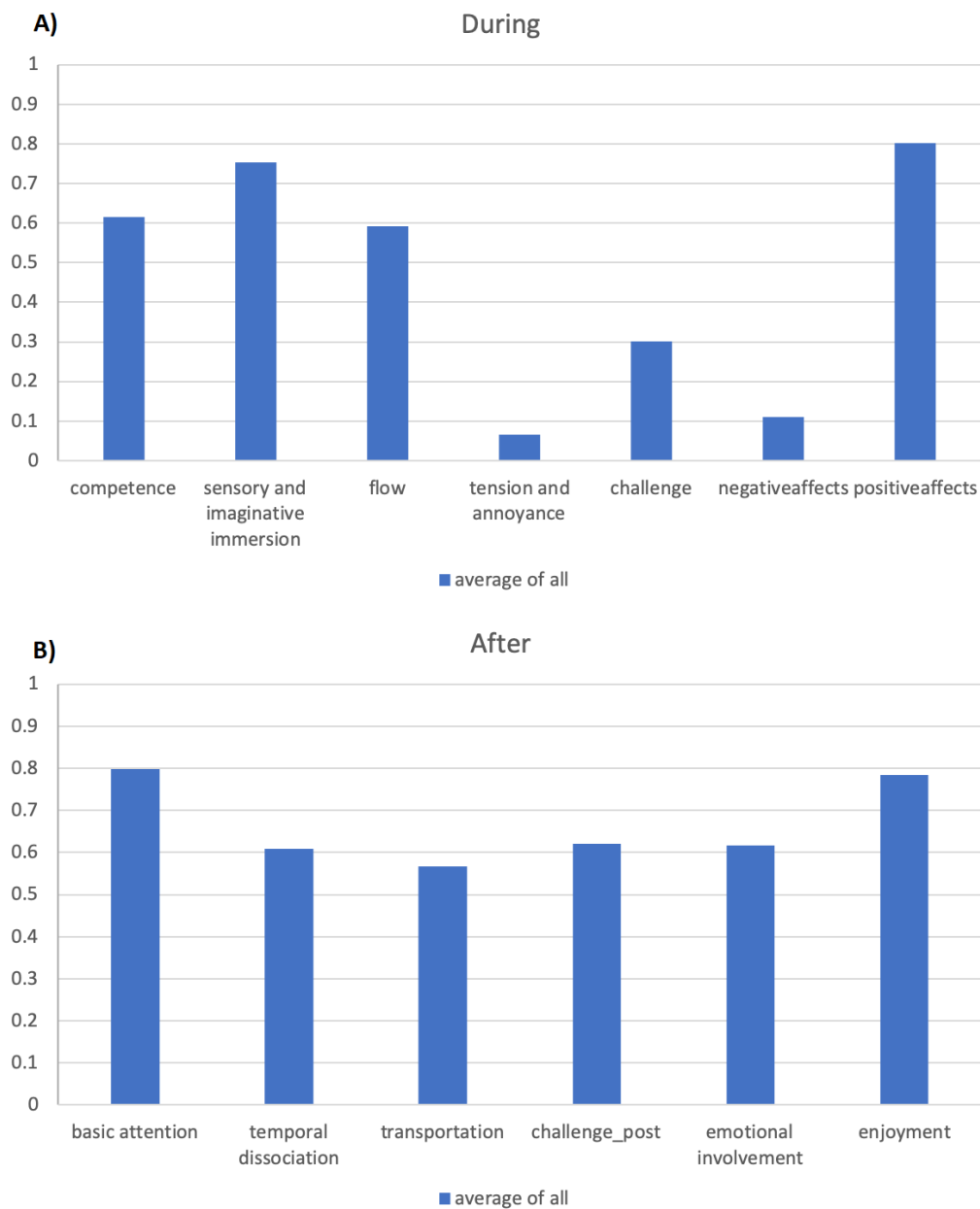
Figure 4.17.: Immersion level for all participants during and after the VLE. Each value is in the range from 0 (not at all) to 1 (absolutely).

score felt equally challenged with the simulation, even though they already brought some comparably good understanding of the subject. The assumption comes near that this is because most participants were not fully aware of their correct perception, as they were only told the correct results after finishing the post questionnaire and did not bring fundamental knowledge into the study.

A noteworthy tendency for participants who achieved the worst score after the VRLE to state an overall higher immersive involvement than their best scoring counterpart
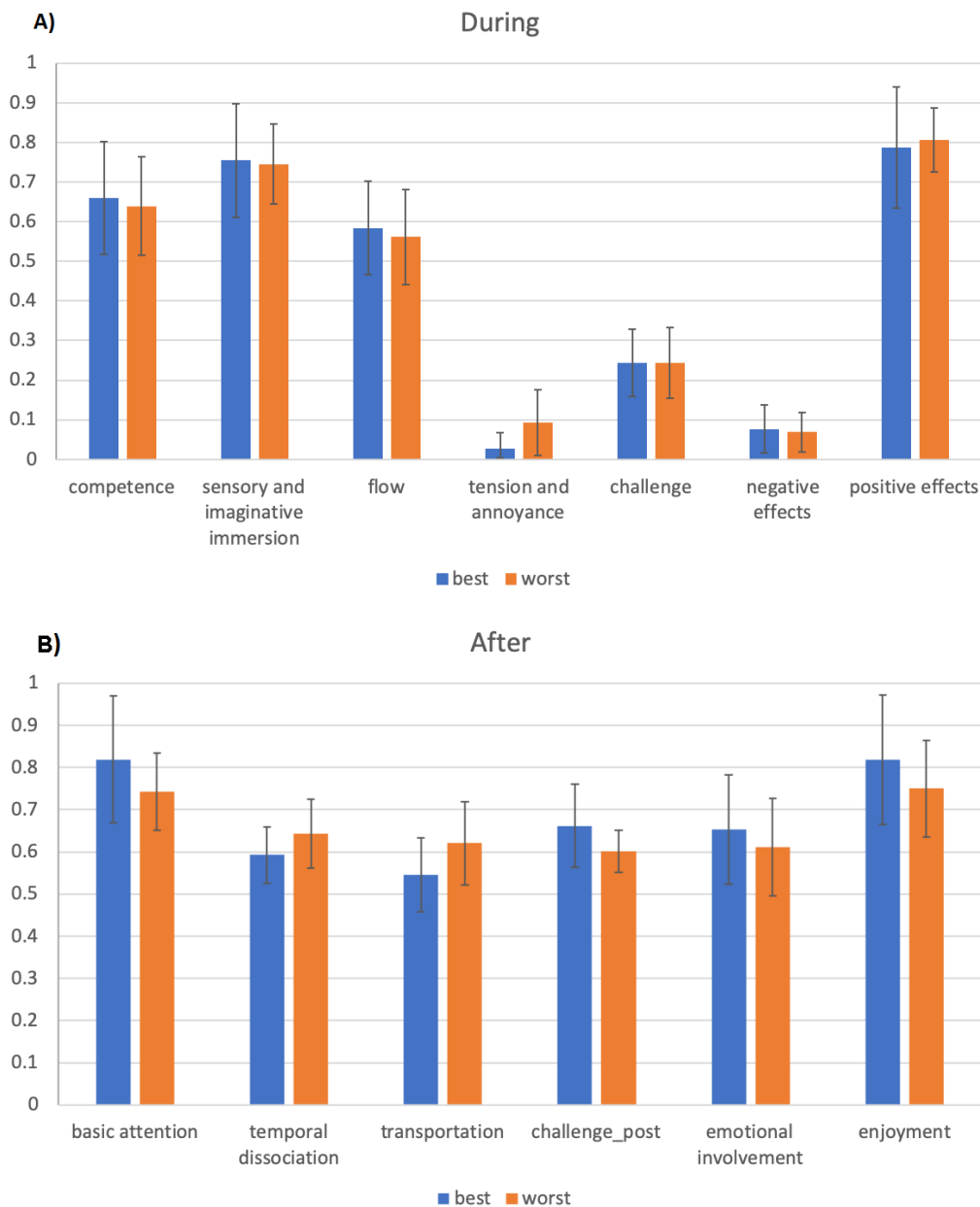
Figure 4.18.: Immersion level for participants that showed the highest and lowest
score before the VLE. Each value is in the range from 0 (not at all) to 1
(absolutely): best(blue) and worst(orange) third scoring participants.

could be identified, as can be seen in In Figure 4.19 a) and b). Moreover, the stated
feeling of higher competence and given attention to fulfilling the tasks is remarkable, as
the outcome of the study question evaluation would suggest the opposite. Observation
of the participants during the VRLE and verbal feedback indicated that some users
got distracted of the actual task at hand and therefore from interpreting the visual
input and its information by the strongly moving and colourful scenery. This could

also 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. Additionally, the figures show an expected tendency for participants who scored worse in the pre-survey part to feel challenged notably more than the ones that were already a bit familiar with the topic. Interestingly, the same group also reported higher involvement into the simulation overall which leads to the conclusion that even though it represents a topic that is harder to understand, it gives them more motivation to find the required answers.

In Figure 4.20 shows not many overly interesting additional insights to the previous graphs. Mostly all reported values are very similar and equal within the standard deviation. Only the reported basic attention seen in graph b) shows an interesting attribute where users that did not improve so well reported a slightly higher basic attention than the ones that improved a lot. While initially this seems counter-intuitive, this could be associated with the least improving users already bringing more understanding and thus also more attention into the simulation.

Restrictions and Limitations

As one of the most important limitations a lack of design expertise on game elements needs to be pointed out. During the development mostly free licenced assets found on the internet were used for various representations in the simulation. If more knowledge and routine in the creation of sprites and textures would have been present during the development of the application, most probably better immersive impressions could have been achieved.

Furthermore, while all calculations and physics interactions are based on theoretical formulas that were calculated accordingly, real world data from LIGO could further improve the accuracy of the simulated interactions. While the difference for the effects would most probably not make a change for the amateur user, an expanded and real data based simulation might provide appropriate starting points for novices of the field to deepen their understanding.

Discussion

The study question evaluation already in its preliminary stages showed excitingly good results of learning improvement, but in first testing runs with colleagues only some notes on paper were taken that were not taken into consideration in the end evaluation. After this very positive first feedback round, some last reported problems were solved and then the study was started. Over the course of the study it was impressive to see that already a small live evaluation that updated after every participant showed impressive improvements.

Overall, the evaluation of the end data showed a stunning increase of correctly chosen answers of more than 55% after experiencing the developed VRLE in comparison to before. Every single designed study question could improve understanding of specific aspects of gravitational waves to the users and was successful at that on average. A
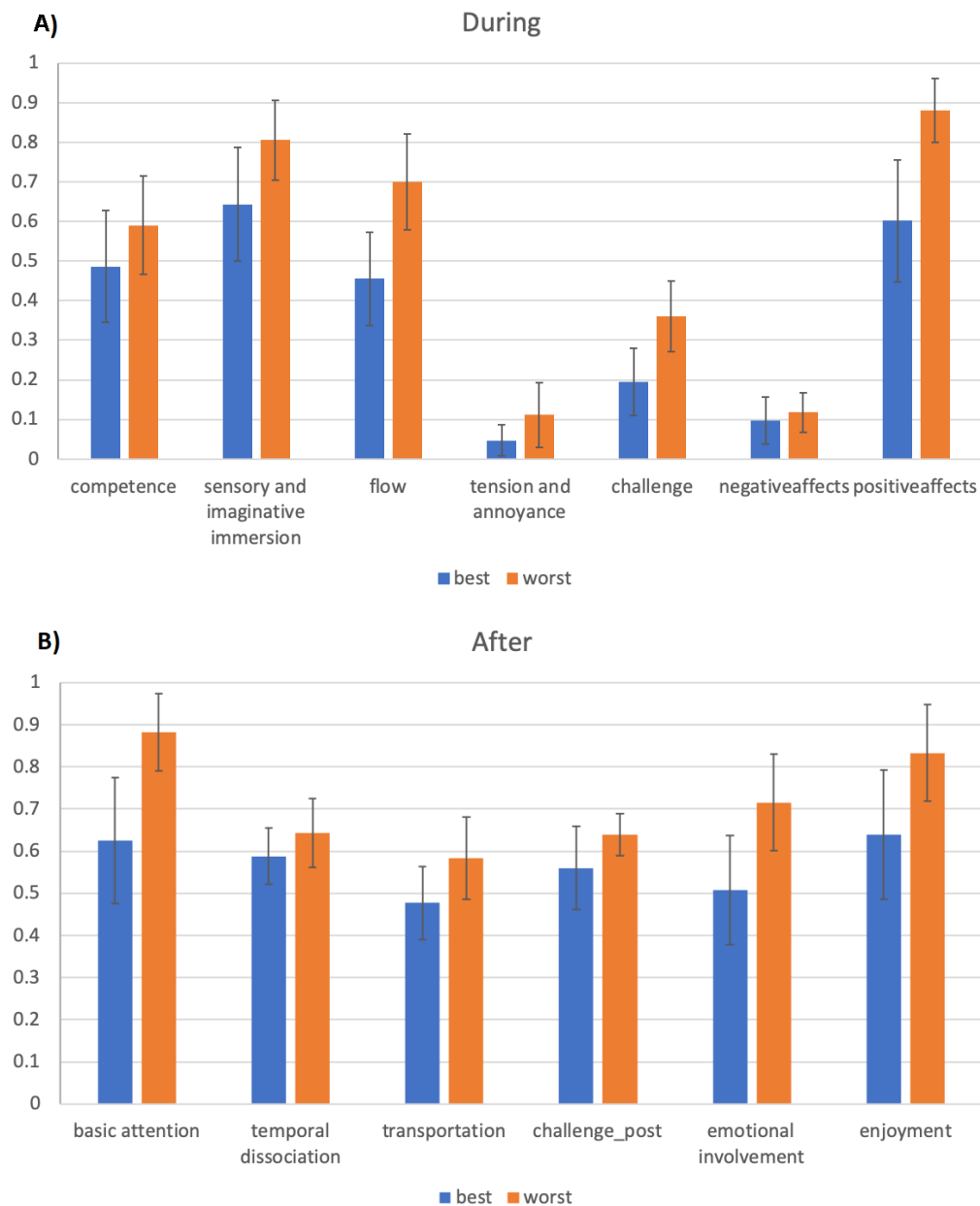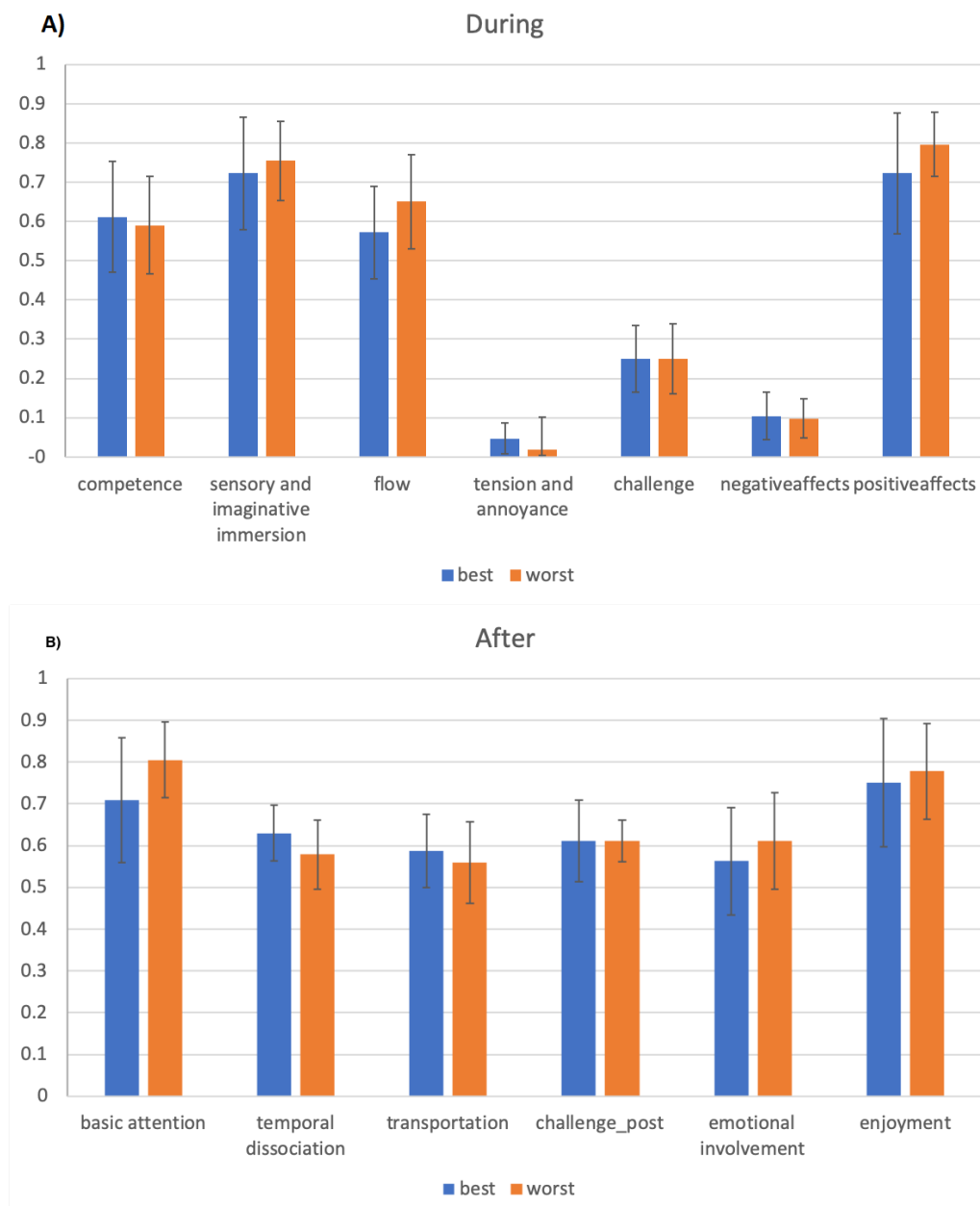
Figure 4.19.: Immersion level for participants that showed the highest and lowest improvement after the VLE. Each value is in the range from 0 (not at all) to 1 (absolutely): best(blue) and worst(orange) third scoring participants.

detailed look into specific sub groups of participants showed, that especially people who brought no or the wrong understanding of physics facts connected with the topic could benefit the most from the simulation. Even the group of participants that already had a good understanding could improve this by almost 20%, thus the conclusion comes near that mostly everyone of the participating users could benefit from the

Figure 4.20.: [Immersion level for participants that showed the highest and lowest improvement after experiencing the VRLE. Each value is in the range from 0 (not at all) to 1 (absolutely): best(blue) and worst(orange) third scoring participants.

devised visualization method in VR. Only question #5 showed a slightly worse result for the best group after the simulation compared to before. While this was worrying first it can be concluded that the negative trend is small enough to be explained with the missing answer "I don't know" to this question. Therefore, randomly chosen correct answers before the VRLE diminish the end result with chance based correct results and

users can, if not absolutely sure about their choice, be easily influenced by a previously taken choice.

Additional to the almost completely positive results regarding the study questions, the feedback gained from all users for the immersive impression and usability was also absolutely positive. Almost non existent negative values were reported for every aspect of the questionnaire and on average every user felt very engaged in solved the given exploration tasks while also feeling joy in the process. Thus, the created visual representation was not only effective but also enjoyable to use.

Finally, none of the participants involved in the study approach stated any dedicated educational degree in physics or even increased personal research interest on the topic. While this became a very good opportunity to show the effectiveness of the VRLE with amateur users, collaboration with a group of novices or experts in the testing process could give further interesting insights.

Compared with similar approaches taken in related work as discussed in Chapter 2.4 the evaluation results showed impressively positive results. Most likely the high-end HMD influenced the experience positively as comparable projects used lower-end HMDs like phone based ones in VIGOR (Kitagawa et al., 2017). Additionally, the information gained via the devised study questions is important, as it was found that similar projects were mainly only concerned with interest in the topic and increase or decrease thereof. Because of the small number of related works in the specific area of gravitational waves visualization in VR a good comparison of the technique can not be made, but the results indicate it to be an appropriate solution for the topic. Especially in comparison with non-immersive solutions.

4.4. Summary

In this chapter the three core aspects, design, development and evaluation, of the second project described in this thesis, concerning visualization of physics theorems, were explained in the respective subchapters.

Subchapter 4.1 the design process of this project was described. Starting with first idea about an interactive and immersive visualization of gravitational waves and the corresponding motivation to pursue it further. Followed by a detailed explanation of the identified requirements to the implementation and the expected target group that would be mainly intended to use the produced outcome. Lastly a detailed explanation of the conceptual design plan and the specific parts of the program that would make an appropriate application fulfilling the identified needs. Additionally, the most important tools and frameworks used during the development approach were explained in the last part of this subchapter, with some insights why OpenGL was the preferred graphics API and how some potential problems with resulting output images could be approached with anti aliasing techniques.

In Subchapter 4.2 a detailed explanation about the taken approach during the development of this project has 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 a general explanation about the realized VRLE. The essential underlying equations of gravitational waves have been pointed out and were explained shortly and a necessary scaling of those theoretical values was pointed out. Afterwards an overview of the initial view and all possible scene elements has been given, combined with insights why some of the elements have been created the way they are, with the earth and an orbiting moon as a relation point, the rotating binary star system and the user interface in the form of a measuring gauge. Insights into the creation and mechanics of the representations of space time have been given as a crucial core mechanic for the comprehensible visualization of gravitational waves effects. Afterwards, some practical background for the implementation of the rendering process of all scene elements with OpenGL shaders was provided. Finally a broad insight in the utilization of OpenVR has been given and how it was used to render the scene to a VR headset.

Subchapter 4.3 gives insights about the complete evaluation process of this project. 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 subchapter introduced insights into the gained data and what exactly the data tells, first concentrating on the research questions responses and thus the actual gained knowledge of the users, and second analysing the reported immersion values and putting them into relation to performance in previously mentioned question responses. The analysis of the created data from the user study and the contained study questions fortified the initial assumption of the importance of an appropriate visualization technique, as even a question about the wave types that, according to verbal feedback from participants, was hard to understand, showed a very positive development.

5. Lessons Learned

This chapter reflects on insights that came up during different phases of each project, including research, design, development and the evaluation phase. Some of these insights will also be further discussed in the following Chapter, where perspectives for potential improvements in the future are given.

5.1. Theory

During the extensive research conducted within this thesis, it quickly became clear how important a well established background of a scientific review is. Developments in the field of education are constantly in need to be evolved in order to keep up with the advancements of technologies. Virtual reality has often been proven to show significant advantages over traditional, sometimes even possibly outdated, teaching methods. Unfortunately, adopting VR in teaching remains a rare case, and the education institutions often can not be convinced to embrace technology-aided techniques universally. Therefore, it is important to show various possibilities and approaches when VR-assisted learning is superior to conventional methods. On the other hand, the aspects emerging with the inclusion of VR technologies in the teaching process can be not only positive, thus any potential shortcomings need to be addressed as well when designing such an application.

   A thorough research is also important for assessment of the results and setting up an appropriate outcome comparison. Considering the topics chosen for both projects, appropriate related work needs to be taken into consideration in order to prevent wrong decision-making and juxtaposition. Simple mechanical tasks cannot directly be compared to highly sophisticated surgery simulations but the insights from both approaches still can be related. The same goes for visualization techniques for physics theorems, where certain display methods have shown different effects depending on the specific domain they are applied in. Certain techniques can be adopted in various domains, while others are too field-specific and will not yield any quality results. All this can be discovered while doing the literature review and answer many questions before the actual designing and development begins.

5.2. Design and Development

Designing an application in accordance with all initial ideas and requirements is a great challenge known to many researchers. In order to fulfil possibly all the expectations,

appropriate requirements need to be identified meticulously and corresponding design decisions need to be taken and followed in order to ensure successful final outcome. While this is not always easy and often the alternatives to initial decisions only become apparent during the development process, having an explicit design plan helps to avoid unnecessary efforts in many cases. As OpenGL was used for the development of GraViz, many functionalities of the framework were already provided and essentially all possibilities in visual representations were available. While this was an utterly positive aspect of OpenGL, next to the resulting performance, being such a big collection of functionalities it is also not easy to get into working with it. Luckily one of the supervisors of the thesis was deeply connected with graphics programming and could provide great guidance for this, but still a big preparation effort with tutorials and such had to be made for the developer to be able to use OpenGL according to the needs of the project. Luckily many tutorials for this are available on different webpages[1][2], therefore next to lecture material there was plenty of explanation available, which was just time consuming to work through. A point to consider for future work is a switch to more recent alternatives to OpenGL. While so far there is no issue per se with it, developments in corresponding technologies suggest that DirectX would be a more future proof framework to learn. What mostly low-level all graphics frameworks have in common is a rendering pipeline with shaders, which was also used in the development part of GraViz. Getting to know how to work with shaders was one fundamental part to understand how to use OpenGL as such, but as it is a shared knowledge with other alternatives it also proved to be useful for future projects in graphics programming. Even though many advantages of low-level frameworks for visualizations could be used for the project, future work should also consider utilization of game engines for the development of such visualization. This would maybe be possible if more efficient algorithms can be used to transfer the knowledge of gravitational waves accurately.

An important factor was discovered in the development process concerning neglecting the true-to-life object alignment in the haptics project. The assumption was made that a visual channel received solely the VR headset would diminish the importance of object alignment; however, the analysis on the matter has shown that this was probably not the case. This point was proven to be an important feature to consider during the development. Lastly, it has to be said that many hours of debugging can potentially be saved if one thoroughly tests and validates a codebase from previous works and contributions. For example, a bug from a copied software class within the gravitational waves project introduced a completely invalid translation of HMD data to the developed application. Thus, only after spending a long time on debugging and searching within the newly written code, the error was finally detected in the adopted code piece.

---

[1]https://learnopengl.com/
[2]https://www.khronos.org/opengl/wiki/Getting_Started

5.3. Evaluation

In the first project that involved the setup being used outdoors, some external factors were not kept in mind originally. Infrared lighthouse tracking stations of VR headsets do not work well in sunlight and the interference completely disables tracking on a clear day. Such details are mainly not mentioned in related works due to tests almost always being conducted indoors, meaning such a requirement could not be devised originally from the background research and literature review. While in the end it was possible to use the setup in the evening hours when direct sunlight was gone, it still made the testing process more cumbersome and an alternative study environment might have been more preferable instead.

Using already known and established frameworks for evaluating immersive feedback of a devised application like the Game Experience Questionnaire is a straightforward way of getting important insights very quickly. It also allows to possibly have a great comparison with other works providing the assessment data from a study in the same format. While this seems to be a good initial choice, relatively recent developments in evaluation methods have shown that alternatives like the NASA-TLX questionnaire provide better insights in more meaningful evaluations than their predecessors. The Likert-Scale questions still brought sufficient insights to evaluate the performance. However, even small improvements like the inclusion of questions with an open answer field could have provided additional help in evaluating differences between MR and VR settings in the first project, documenting the feedback that was otherwise only in oral form.

For a dedicated research question evaluation the chosen multiple-choice questions of the second project provided an appropriate measurement for the evaluation of gained insights. While providing enough possible answers to choose from the random noise could be reduced significantly but other advancements like a confidence rating were missing and could have provided further helpful insights for the comparison of pre- and post- VRLE confidence.

6. Conclusion and Future Work

In this chapter insights and conclusions gained over the course of each project are summarized and future perspectives for more advanced approaches are given.

6.1. Conclusion

Teaching and learning is an ongoing development process for the receiving and the providing end alike and continuous technical advancements require the used techniques an frameworks to evolve as well in order to stay on par. In this thesis two important aspects have been thoroughly investigated and contributions in the form of published research papers have been made. Some main key points that were implemented are as follows:

- An affordable implementation of haptic feedback controls with standard equipment has been created and its positive influence in certain settings has been shown.
- Important core attributes about gravitational waves have been enclosed in five research questions that could be evaluated in a comparison study
- An understandable representation of space time has been created via a density grid
- An adjustable algorithm has been created that transfers gravitational waves effects on to a scene and teaches the complex topic with a cause effect setting.
- It has been shown how gamification elements increase positive feedback and engagement in learning environments.

6.1.1. Haptic Feedback in VRLEs

In the first part this thesis the research approach tried to find indications about mixed reality settings being strictly better or worse on an average analysis compared to learning in pure virtual reality, under the restrictions of the experiment setting and by investigating a simple mechanical task. It was indeed possible to see improvements in some areas, such as handling with objects of little weights, or situations where weight or form of the interact able objects vary, but a strictly positive or negative general effect could not be proven. The unwieldy nature of the heavier weights, combined with the unfamiliarity of throwing such an object, caused much interference in mixed reality and thus prevented proper measurement of learning and performance improvements connected to these parts of the study. An issue that was not present in pure virtual

reality in comparison. However, a distinctive trend for higher positive immersive values was observed for the MR group, which is explainable with the handling of real objects. At present, the findings of the taken approach show that in comparison with similar VR setups, haptic feedback for simple interactions such as throwing tasks, does indeed provide advantages to justify some extra cost and complications of setting it up, but this can not be seen as a general statement to always include it. A similar solution as provided in the presented approach in this thesis could easily implemented and be an appropriate solution for such applications, if the setting is fitting. For more complicated interactions or heavier objects, more refined hardware solutions would be necessary, but it is assumed that in this case it would also be advantageous. Perhaps in the future with better technology the achieved results can be substantially improved, making it an appropriate possibility (Lontschar, Deegan, et al., 2020).

6.1.2. Physics Visualization in VRLEs

A virtual learning environment to convey the subject of gravitational waves was developed with a corresponding evaluation system to measure its effectiveness in a quantitative manner. Identifying three areas of understanding: wave source, spatial irradiation distribution and wave type as well as measuring the perceived immersion, a pre- and post VRLE experience questionnaire conducted. Strikingly high results in transmission of the subject matter could be identified in the corresponding analysis of answers to the devised research questions. It could be successfully shown, that the developed immersive and interactive representation of this 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 for general interest. The developed representation of space time as a density grid could be confirmed to be easily understandable for the amateur physicist. 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. As such, the developed simulation can be seen as an appropriate introductory application for this topic in teaching or for personal interest in research out of private curiosity (Lontschar, Pietroszek, et al., 2020).

6.2. Future Work

6.2.1. Haptic Feedback in VRLEs

The goal of the first part of this thesis was to identify general influence of haptic feedback in VRLEs towards learning outcome. The assumption was that a general tendency should be identifiable in an appropriate setting with the corresponding equipment that provides a fitting haptic feedback information channel to the users. One of the main concerns regarding the outcome of the analysed data was an identified skew because of some issues in usability with the available tools. Connectivity between the created

controller and the thrown objects became an issue due to outside influences like dew at times. Even though tendencies for some parts of the tested application could be identified, like the better immersive feeling in MR when changing weights of thrown objects or interacting with medium weight items and corresponding score developments, it is intended 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 similar to surgery simulations or fitting games without the common help of artificially adjusted placement to overcome inaccuracies of any means of controls. This said, the main point to concentrate on would be more advanced haptic tools that should be created specifically for this kind of usage while still being minimalistic and easily available, instead of makeshift tools like in the approach taken the described project. Connected to advanced controls a correction of visual alignment should also be included, as it was suspected that inaccuracies of virtual placement over real world position was introducing negative effects on intuitive impressions for the users (Lontschar, Deegan, et al., 2020).

6.2.2. Visualization Techniques in VRLEs

In the second part of this thesis the implementation of an immersive representation of space-time was used to convey core understanding of gravitational waves, their effects and the influence of attribute changes in their source, in this example a binary star system. The evaluation already showed impressive results with the devised research questions. While no direct expansion on this projects codebase is planned for the upcoming future, follow up approaches on the topic should encompass further extension into more detailed gravitational waves insights by using data of real events like event of the collision of a binary black hole system that was measured and detected in 2016. To achieve this a collaboration with LIGO is being discussed. Not only would this create the possibility to device a simulation that is following exact data that is available, but with a new approach taken from a very small code base, it would increase motivation to thrive into different simulation techniques and leave more room for new ideas instead of having to adapt old implementations. The density grid representation already proofed to be an appropriate display mechanic and more sophisticated rendering processes could increase the impressions gained and also provide more possibilities for more advanced insights. Next to more accurate descriptions it would also be a possibility to work on the algorithms used to represent the morphing of space time according to gravitational waves and with that create more efficient versions of the application that do not need low-level graphics engines to run. Overall, a collaboration with physics experts during active development on an advanced project would be a very important to gain more insights and even better results.

Appendix

Appendix A.

USB Contents

On the USB stick attached to this thesis a copy of both practical projects and their theory parts are included.

A.1. Practical Part

- Unity 2018 installer.
- An executable file of the latest version of the GraViz project and all necessary libraries.
- Latest version of the haptic feedback throwing project.

A.2. Theoretical Part

- The latest version of this thesis in PDF format.
- The created study data of both projects.
- The questionnaire data of both projects.

List of Figures

List of Tables

Bibliography

Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., . . . et al. (2016). Observation of gravitational waves from a binary black hole merger. *Physical Review Letters*, *116*(6). doi:10.1103/physrevlett.116.061102

Abbott, B., Abbott, R., Adhikari, R., Ageev, A., Allen, B., Amin, R., . . . Armandula, H., et al. (2004). Analysis of ligo data for gravitational waves from binary neutron stars. *Physical Review D*, *69*(12), 122001.

Abdoli Sejzi, A. (2015). Augmented reality and virtual learning environment. *Journal of Applied Science Research (JASR)*, *11*, 1–5.

Adelsberger, H. H., Bick, M., & Pawlowski, J. M. (2000). Design principle for teaching simulation with explorative learning environments. In *2000 winter simulation conference proceedings (cat. no.00ch37165)* (Vol. 2, 1684–1691 vol.2).

Alaneme, G. C., Olayiwola, P. O., & Reju, C. O. (2010). Combining traditional learning and the e-learning methods in higher distance education: Assessing learners' preference. In *2010 4th international conference on distance learning and education* (pp. 187–190).

Allen, G., Andersson, N., Kokkotas, K. D., & Schutz, B. F. (1998). Gravitational waves from pulsating stars: Evolving the perturbation equations for a relativistic star. *Physical Review D*, *58*(12), 124012.

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, *6*(4), 355–385.

Bailey, M. (2009). Using gpu shaders for visualization. *IEEE Computer Graphics and Applications*, *29*(5), 96–100.

Bailey, M. (2011). Using gpu shaders for visualization, part 2. *IEEE computer graphics and applications*, *31*(2), 67–73.

Bailey, M. (2013). Using gpu shaders for visualization, part 3. *IEEE Computer Graphics and Applications*, *33*(3), 5–11.

Bark, K., Hyman, E., Tan, F., Cha, E., Jax, S. A., Buxbaum, L. J., & Kuchenbecker, K. J. (2015). Effects of vibrotactile feedback on human learning of arm motions. *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society*, *23*(1), 51–63. doi:10.1109/TNSRE.2014. 2327229

Basdogan, C., Ho, C. .-.-., & Srinivasan, M. A. (2001). Virtual environments for medical training: Graphical and haptic simulation of laparoscopic common bile duct exploration. *IEEE/ASME Transactions on Mechatronics*, *6*(3), 269–285.

Belleman, R. B., Belleman, R. G., Stolk, B., & Vries, R. D. (2001). Immersive virtual reality on commodity hardware. In *Proceedings of the 7th annual conference of the advanced school for computing and imaging* (pp. 297–304).

Bliss, J., & Ogborn, J. (1989). Tools for exploratory learning: A research programme*. *Journal of Computer Assisted Learning, 5*(1), 37–50. doi:10.1111/j.1365-2729.1989. tb00196.x. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1365-2729.1989.tb00196.x

Bondi, H. (1960). Gravitational waves in general relativity. *Nature, 186*(4724), 535–535.

Bondi, H., Van der Burg, M. G. J., & Metzner, A. (1962). Gravitational waves in general relativity, vii. waves from axi-symmetric isolated system. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 269*(1336), 21–52.

Bouzit, Burdea, Popescu, & Boian. (2002). The rutgers master ii-new design force-feedback glove. *IEEE/ASME Transactions on Mechatronics, 7*(2), 256–263.

Bowen Loftin, R. (1994). Virtual environments for aerospace training. In *Proceedings of wescon '94* (pp. 384–387).

Brown, T., Lomsdalen, J., Humer, I., & Eckhardt, C. (2019). Immersive learning for scale and order of magnitude in newtonian mechanics. (pp. 30–42). doi:10.1007/978-3-030-23089-0_3

Bunt, A., Conati, C., & Muldner, K. (2004). Scaffolding self-explanation to improve learning in exploratory learning environments. In J. C. Lester, R. M. Vicari, & F. Paraguaçu (Eds.), *Intelligent tutoring systems* (pp. 656–667). Berlin, Heidelberg: Springer Berlin Heidelberg.

Burdea, G. (1999). Haptic feedback for virtual reality. *2*.

Burdea, & Coiffet. (2003). *Virtual reality technology*. Wiley - IEEE. Wiley. Retrieved from https://books.google.com/books?id=oxWgPZbcz4AC

Bybee, R. W. (2010). What is stem education? *Science, 329*(5995), 996–996. doi:10.1126/ science.1194998. eprint: https://science.sciencemag.org/content/329/5995/996. full.pdf

Callaghan, V., Gardner, M., Horan, B., Scott, J., Shen, L., & Wang, M. (2008). A mixed reality teaching and learning environment. (pp. 54–65). doi:10.1007/978-3-540-85170-7_5

Carr, M. (1997). Visualization with opengl: 3d made easy. *IEEE Antennas and Propagation Magazine, 39*(4), 116–120.

Castelvecchi, D., & Witze, A. (2016). Measurements of general relativistic effects in the binary pulsar psr1913 + 16. *Nature*, 1476–4687. doi:10.1038/nature.2016.19361

Castro, R. (2019). Blended learning in higher education: Trends and capabilities. *Education and Information Technologies, 24*(4), 2523–2546. doi:10.1007/s10639-019-09886-3

Cervantes-Cota, J., Galindo-Uribarri, S., & Smoot, G. (2016). A brief history of gravitational waves. *Universe, 2*(3), 22. doi:10.3390/universe2030022

Chai, C. S. (2019). Teacher professional development for science, technology, engineering and mathematics (stem) education: A review from the perspectives of technological pedagogical content (tpack). *The Asia-Pacific Education Researcher, 28*(1), 5–13. doi:10.1007/s40299-018-0400-7

Checa, D., & Bustillo, A. (2020). Advantages and limits of virtual reality in learning processes: Briviesca in the fifteenth century. *Virtual Reality*, *24*(1), 151–161. doi:10. 1007/s10055-019-00389-7

Chen, L., Ali Babar, M., & Nuseibeh, B. (2013). Characterizing architecturally significant requirements. *IEEE Software*, *30*(2), 38–45.

Chu, G., Humer, I., & Eckhardt, C. (2019). Special relativity in immersive learning. (pp. 16–29). doi:10.1007/978-3-030-23089-0_2

Cichocki, A., Cincotti, F., Kauhanen, L., Aloise, F., Palomäki, T., Caporusso, N., ... Millán, J. R. (2007). Vibrotactile feedback for brain-computer interface operation. *Computational Intelligence and Neuroscience*, *2007*, 048937. doi:10.1155/2007/48937

Cook, D. A. (2007). Web-based learning: Pros, cons and controversies. *Clinical Medicine*, *7*(1), 37–42. doi:10.7861/clinmedicine.7-1-37. eprint: https://www.rcpjournals. org/content/7/1/37.full.pdf

Cosco, F., Garre, C., Bruno, F., Muzzupappa, M., & Otaduy, M. A. (2012). Visuo-haptic mixed reality with unobstructed tool-hand integration. *IEEE transactions on visualization and computer graphics*, *19*(1), 159–172.

Covaci, A. [A.], Olivier, A., & Multon, F. (2015). Visual perspective and feedback guidance for vr free-throw training. *IEEE Computer Graphics and Applications*, *35*(5), 55–65.

Covaci, A. [Alexandra], Postelnicu, C.-C., Panfir, A. N., & Talaba, D. (2012). A virtual reality simulator for basketball free-throw skills development. In L. M. Camarinha-Matos, E. Shahamatnia, & G. Nunes (Eds.), *Technological innovation for value creation* (pp. 105–112). Berlin, Heidelberg: Springer Berlin Heidelberg.

Crespo, L. M., & Reinkensmeyer, D. J. (2008). Haptic guidance can enhance motor learning of a steering task. *Journal of Motor Behavior*, *40*(6), 545–557. PMID: 18980907. doi:10.3200/JMBR.40.6.545-557. eprint: https://doi.org/10.3200/JMBR.40.6.545-557

Cruz-Neira, C., Sandin, D. J., & DeFanti, T. A. (1993). Surround-screen projection-based virtual reality: The design and implementation of the cave. In *Proceedings of the 20th annual conference on computer graphics and interactive techniques* (pp. 135–142). SIGGRAPH '93. doi:10.1145/166117.166134

Dattalo, A., Humer, I., Tahai, M., Pietroszek, K., Sueda, S., & Eckhardt, C. (2018). Interactive large structure n-body gravity simulation for immersive learning in virtual reality. *iLRN2018 Montana*. doi:10.3217/978-3-85125-609-3-09

de Freitas, S., & Neumann, T. (2009). The use of 'exploratory learning' for supporting immersive learning in virtual environments. *Computers & Education*, *52*(2), 343–352. doi:https://doi.org/10.1016/j.compedu.2008.09.010

Delgado, F. J., & Noyes, M. (2017). Nasa's hybrid reality lab: One giant leap for full dive. Retrieved from https://ntrs.nasa.gov/search.jsp?R=20170005616

Demian, P., & Morrice, J. (2012). The use of virtual learning environments and their impact on academic performance. *Engineering Education*, *7*(1), 11–19. doi:10.11120/ ened.2012.07010011

Díaz, P., Zarraonandía, T., Sánchez-Francisco, M., Aedo, I., & Onorati, T. (2019). Do low cost virtual reality devices support learning acquisition? a comparative study of two different vr devices. In *Proceedings of the xx international conference on human computer interaction*. Interacción '19. doi:10.1145/3335595.3335629

Duncan, A. (2009). A call to teaching: Secretary arne duncan's remarks at the rotunda at the university of virginia. *Retrieved November*, 9, 2009.

Edwards, L. D. (2012). *Computers and exploratory learning*. Springer Science & Business Media.

Faktorovich, A. (2019). You could have written this book: Babbling about gravitational waves. *Pennsylvania Literary Journal*, 11(1), 104.

Frid, E., Bresin, R., Pysander, E.-L. S., & Moll, J. (2017). An exploratory study on the effect of auditory feedback on gaze behavior in a virtual throwing task with and without haptic feedback. *Sound and Music Computing (SMC)*, 242–249.

Frid, E., Moll, J., Bresin, R., & Sallnäs Pysander, E.-L. (2019). Haptic feedback combined with movement sonification using a friction sound improves task performance in a virtual throwing task. *Journal on Multimodal User Interfaces*, 13(4), 279–290. doi:10.1007/s12193-018-0264-4

Haas, J. K. (2014). A history of the unity game engine.

Hameed, S., Badii, A., & Cullen, A. J. (2008). Effective e-learning integration with traditional learning in a blended learning environment. In *European and mediterranean conference on information systems* (pp. 25–26). Citeseer.

Hammesfahr, A. et al. (2000). Lisa, laser interferometer space antenna: A cornerstone mission for the observation of gravitational waves, system and technology study report. *white book*, 7–16.

Han, I., & Black, J. B. (2011). Incorporating haptic feedback in simulation for learning physics. *Computers & Education*, 57(4), 2281–2290. doi:https://doi.org/10.1016/j.compedu.2011.06.012

Hunter, J. D. (2007). Matplotlib: A 2d graphics environment. *Computing in science & engineering*, 9(3), 90–95. Retrieved from https://matplotlib.org/

IJsselsteijn, W., de Kort, Y., & Poels, K. (2013). *The game experience questionnaire*. Technische Universiteit Eindhoven.

Jennett, C., Cox, A. L., Cairns, P., Dhoparee, S., Epps, A., Tijs, T., & Walton, A. (2008). Measuring and defining the experience of immersion in games. *International Journal of Human-Computer Studies*, 66(9), 641–661. doi:https://doi.org/10.1016/j.ijhcs.2008.04.004

Jimenez, J., Gutierrez, D., Yang, J., Reshetov, A., Demoreuille, P., Berghoff, T., . . . Lottes, T., et al. (2011). Filtering approaches for real-time anti-aliasing. *ACM SIGGRAPH Courses*, 2(3), 4.

Kapferer, W., & Riser, T. (2008). Visualization needs and techniques for astrophysical simulations. *New Journal of Physics*, 10(12), 125008. doi:10.1088/1367-2630/10/12/125008

Kapp, K. M. (2012). *The gamification of learning and instruction: Game-based methods and strategies for training and education*. John Wiley & Sons.

Khaled, W., REICHLING, S., BRUHNS, O. T., BOESE, H., BAUMANN, M., MONKMAN, G., ... ERMERT, H. (2004). Palpation imaging using a haptic system for virtual reality applications in medicine. In *Perspective in image-guided surgery* (pp. 407–414). doi:10.1142/9789812702678_0055

Kim, J. H., Park, S.-T., Lee, H., & Yuk, K.-C. (2001). Virtual reality simulations in physics education. *3*.

Kim, J. T., & Lee, W.-H. (2015). Dynamical model for gamification of learning (dmgl). *Multimedia Tools and Applications*, *74*(19), 8483–8493. doi:10.1007/s11042-013-1612-8

Kiryakova, G., Angelova, N., & Yordanova, L. (2014). Gamification in education. Proceedings of 9th International Balkan Education and Science Conference.

Kitagawa, M., Kesden, M., Tran, N., Sivampillai Venlayudam, T., Urquhart, M., & Malina, R. (2017). Vigor: Virtual interaction with gravitational waves to observe relativity. In S. Lackey & J. Chen (Eds.), *Virtual, augmented and mixed reality* (pp. 404–416). Cham: Springer International Publishing.

Kolb, D. A. (1984). Experiential learning: Experience as the source of learning and development.

Kondo, T. (2006). Augmented reality and virtual learning environment. *Proceedings of E-Learn*, *11*, 83–87.

Kreimeier, J., Hammer, S., Friedmann, D., Karg, P., Bühner, C., Bankel, L., & Götzelmann, T. (2019). Evaluation of different types of haptic feedback influencing the task-based presence and performance in virtual reality. In *Proceedings of the 12th acm international conference on pervasive technologies related to assistive environments* (pp. 289–298). PETRA '19. doi:10.1145/3316782.3321536

Kuenzi, J. J. (2008). Science, technology, engineering, and mathematics (stem) education: Background, federal policy, and legislative action.

Lahav, O., & Mioduser, D. (2008). Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. *International Journal of Human-Computer Studies*, *66*(1), 23–35. doi:https://doi.org/10.1016/j.ijhcs.2007.08.001

Li, Y. (2019). Five years of development in pursuing excellence in quality and global impact to become the first journal in stem education covered in ssci. *International Journal of STEM Education*, *6*(1), 42. doi:10.1186/s40594-019-0198-8

Li, Y., Wang, K., Xiao, Y., & Froyd, J. E. (2020). Research and trends in stem education: A systematic review of journal publications. *International Journal of STEM Education*, *7*(1), 11. doi:10.1186/s40594-020-00207-6

Loftin, R. B., Engleberg, M., & Benedetti, R. (1993). Applying virtual reality in education: A prototypical virtual physics laboratory. In *Proceedings of 1993 ieee research properties in virtual reality symposium* (pp. 67–74).

Lontschar, S., Deegan, D., Humer, I., Pietroszek, K., & Eckhardt, C. (2020). Analysis of haptic feedback and its influences in virtual reality learning environments. In *2020 6th international conference of the immersive learning research network (ilrn)* (pp. 171–177).

Lontschar, S., Pietroszek, K., Humer, I., & Eckhardt, C. (2020). An immersive and interactive visualization of gravitational waves. In *2020 6th international conference of the immersive learning research network (ilrn)* (pp. 178–184).

Madden, J., Pandita, S., Schuldt, J. P., Kim, B., S. Won, A., & Holmes, N. G. (2020). Ready student one: Exploring the predictors of student learning in virtual reality. *PLOS ONE, 15*(3), 1–26. doi:10.1371/journal.pone.0229788

MaroonVR. (2020). Retrieved August 7, 2020, from https://maroon.tugraz.at/

Martí-Parreño, J., Seguí-Mas, D., & Seguí-Mas, E. (2016). Teachers' attitude towards and actual use of gamification. *Procedia - Social and Behavioral Sciences, 228*, 682–688. 2nd International Conference on Higher Education Advances,HEAd'16, 21-23 June 2016, València, Spain. doi:https://doi.org/10.1016/j.sbspro.2016.07.104

McKinney, W. et al. (2010). Data structures for statistical computing in python. In *Proceedings of the 9th python in science conference* (Vol. 445, pp. 51–56). Austin, TX. Retrieved from https://pandas.pydata.org/

Milbergs, E. (2004). Measuring innovation for national prosperity. *Washington, DC: Center for Accelerating Innovation*. Retrieved from https://innovate.typepad.com/innovation/files/innovation_framework_report_3.00%20January%202004%20%20Update.pdf

Moro, C., Štromberga, Z., & Stirling, A. (2017). Virtualisation devices for student learning: Comparison between desktop-based (oculus rift) and mobile-based (gear vr) virtual reality in medical and health science education. *Australasian Journal of Educational Technology, 33*(6). doi:10.14742/ajet.3840

Mosquera, C. K., Steinmaurer, A., Eckhardt, C., & Guetl, C. (2020). Immersively learning object oriented programming concepts with scool. In *2020 6th international conference of the immersive learning research network (ilrn)* (pp. 124–131).

Nazarenko, A. L. (2015). Blended learning vs traditional learning: What works? (a case study research). *Procedia - Social and Behavioral Sciences, 200*, 77–82. The XXVI Annual International Academic Conference, Language and Culture, 27–30 October 2015. doi:https://doi.org/10.1016/j.sbspro.2015.08.018

Njoo, M., & De Jong, T. (1993). Exploratory learning with a computer simulation for control theory: Learning processes and instructional support. *Journal of Research in Science Teaching, 30*(8), 821–844. doi:10.1002/tea.3660300803. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/tea.3660300803

Oliphant, T. E. (2006). *A guide to numpy.* Trelgol Publishing USA. Retrieved from https://numpy.org/

Olson, S., & Riordan, D. G. (2012). Engage to excel: Producing one million additional college graduates with degrees in science, technology, engineering, and mathematics. report to the president. *Executive Office of the President.*

Paisley, V. (2013). Gamification of tertiary courses: An exploratory study of learning and engagement. In *Proceedings of ascilite - australian society for computers in learning in tertiary education annual conference 2013* (pp. 671–675). Australasian Society for Computers in Learning in Tertiary Education. Retrieved from https://www.learntechlib.org/p/171196

Pan, Z., Cheok, A. D., Yang, H., Zhu, J., & Shi, J. (2006a). Virtual reality and mixed reality for virtual learning environments. *Computers & Graphics*, *30*(1), 20–28. doi:https://doi.org/10.1016/j.cag.2005.10.004

Pan, Z., Cheok, A. D., Yang, H., Zhu, J., & Shi, J. (2006b). Virtual reality and mixed reality for virtual learning environments. *Computers & Graphics*, *30*(1), 20–28. doi:https://doi.org/10.1016/j.cag.2005.10.004

Pan, Z., Cheok, A., Yang, H., Zhu, J., & Shi, J. (2006). Virtual reality and mixed reality for virtual learning environments. *Computers & Graphics*, *30*, 20–28. doi:10.1016/j.cag.2005.10.004

Pirker, J., Holly, M. S., Hipp, P., König, C., Jeitler, D., & Gütl, C. (2018). Improving physics education through different immersive and engaging laboratory setups. In M. E. Auer & T. Tsiatsos (Eds.), *Interactive mobile communication technologies and learning* (pp. 443–454). Cham: Springer International Publishing.

Pirker, J., Lesjak, I., & Guetl, C. (2017). Maroon vr: A room-scale physics laboratory experience. In *2017 ieee 17th international conference on advanced learning technologies (icalt)* (pp. 482–484).

Pirker, J., Lesjak, I., Parger, M., & Gütl, C. (2018). An educational physics laboratory in mobile versus room scale virtual reality - a comparative study. In M. E. Auer & D. G. Zutin (Eds.), *Online engineering & internet of things* (pp. 1029–1043). Cham: Springer International Publishing.

Poincaré, H. (1905). The principles of mathematical physics. *The Monist*, 1–24.

Reisoğlu, I., Topu, B., Yılmaz, R., Yılmaz, T. K., & Göktaş, Y. (2017). 3d virtual learning environments in education: A meta-review. *Asia Pacific Education Review*, *18*(1), 81–100.

Rieman, J. (1996). A field study of exploratory learning strategies. *ACM Trans. Comput.-Hum. Interact. 3*(3), 189–218. doi:10.1145/234526.234527

Rittle-Johnson, B., & Alibali, M. W. (1999). Conceptual and procedural knowledge of mathematics: Does one lead to the other? *Journal of Educational Psychology*, *91*(1), 175–189. doi:10.1037/0022-0663.91.1.175

Sahni, J. (2019). Does blended learning enhance student engagement? evidence from higher education. *Journal of e-Learning and Higher Education*, *2019*, 1–14.

Schmidt, B., & Stewart, S. (2009). Implementing the virtual reality learning environment: Second life. *Nurse Educator*, *34*(4). doi:10.1097/NNE.0b013e3181aabbe8

Shafranovich, Y. (2005). Common format and mime type for comma-separated values (csv) files. Retrieved from https://en.wikipedia.org/wiki/Comma-separated_values

Song, A., Dan Morris, A., Colgate, J., & Peshkin, M. (2005). Real time stiffness display interface device for perception of virtual soft object. In *2005 ieee/rsj international conference on intelligent robots and systems, iros* (pp. 1128–1132). 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS. IEEE IRS/RSJ International Conference on Intelligent Robots and Systems, IROS 2005 ; Conference date: 02-08-2005 Through 06-08-2005. doi:10.1109/IROS.2005.1545131

Squire, K., Barnett, M., Grant, J., & Higginbotham, T. (2004). Electromagnetism super-charged!: Learning physics with digital simulation games. *Proceedings of the 6th International Conference on Learning Sciences.*

Taylor, E. F., & Wheeler, J. A. (1975). Introduction to general relativity.

Taylor, J. M., J. H.; Weisberg. (1979). Measurements of general relativistic effects in the binary pulsar psr1913 + 16. *Nature, 277,* 437–440. doi:10.1038/277437a0

Taylor, J. M., J. H.; Weisberg. (1982). A new test of general relativity - gravitational radiation and the binary pulsar psr 1913+16. *Astrophysical Journal, 253,* 22. doi:10.1086/159690

Technologies, U. (2019). Unity (Version 2019.2.17f1). Retrieved October 1, 2019, from https://unity.com/

Thorsteinsson, G., & Shavinina, L. (2013). Developing an understanding of the pedagogy of using a virtual reality learning environment (vrle) to support innovation education. *The Routledge International Handbook of Innovation Education. Edited by LV Shavinina. Oxford: Routledge. ISBN-10, 415682215,* 456–470.

Trafford, P., & Shirota, Y. (2011). Ubiquitous e-Learning: Designing Web Systems for Economics and Business Mathematics. *Gakushuin Economic Papers, 48*(2), 111–128. Retrieved from https://ideas.repec.org/a/abc/gakuep/48-2-2.html

Tynjälä, P. (1999). Towards expert knowledge? a comparison between a constructivist and a traditional learning environment in the university. *International Journal of Educational Research, 31*(5), 357–442. doi:https://doi.org/10.1016/S0883-0355(99)00012-9

Ullrich, S., & Kuhlen, T. (2012). Haptic palpation for medical simulation in virtual environments. *IEEE Transactions on Visualization and Computer Graphics, 18*(4), 617–625.

van der Meijden, O., & Schijven, M. (2009). The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: A current review. *Surgical endoscopy, 23,* 1180–90. doi:10.1007/s00464-008-0298-x

Van Rossum, G. (2020). *The python library reference, release 3.8.2.* Python Software Foundation. Retrieved from https://docs.python.org/3/library/csv.html

Våpenstad, C., Hofstad, E. F., Langø, T., Mårvik, R., & Chmarra, M. K. (2013a). Perceiving haptic feedback in virtual reality simulators. *Surgical Endoscopy, 27*(7), 2391–2397. doi:10.1007/s00464-012-2745-y

Våpenstad, C., Hofstad, E., Langø, T., Mårvik, R., & Chmarra, M. (2013b). Perceiving haptic feedback in virtual reality simulators. *Surgical endoscopy, 27.* doi:10.1007/s00464-012-2745-y

Vergara, D., Rubio, M. P., Lorenzo, M., & Rodríguez, S. (2020). On the importance of the design of virtual reality learning environments. In R. Gennari, P. Vittorini, F. De la Prieta, T. Di Mascio, M. Temperini, R. Azambuja Silveira, & D. A. Ovalle Carranza (Eds.), *Methodologies and intelligent systems for technology enhanced learning, 9th international conference* (pp. 146–152). Cham: Springer International Publishing.

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., . . . Contributors, S. 1. 0. (2020). SciPy 1.0: Fundamental Algorithms for Scientific

Computing in Python. *Nature Methods*. doi:https://doi.org/10.1038/s41592-019-0686-2

Weber, J. (2004). *General relativity and gravitational waves*. Courier Corporation.

Weisberg, J. M., & Huang, Y. (2016). Relativistic measurements from timing the binary pulsar psr b1913+16. *The Astrophysical Journal*, *829*(1), 55. doi:10.3847/0004-637x/829/1/55

Woo, M., Neider, J., Davis, T., & Shreiner, D. (1999). *Opengl programming guide: The official guide to learning opengl, version 1.2*. Addison-Wesley Longman Publishing Co., Inc. Retrieved from https://www.opengl.org/

Yakunin, K. N., Marronetti, P., Mezzacappa, A., Bruenn, S. W., Lee, C.-T., Chertkow, M. A., ... Messer, O. B., et al. (2010). Gravitational waves from core collapse supernovae. *Classical and Quantum Gravity*, *27*(19), 194005.

Yarman, T. (2006). The end results of general relativity theory via just energy conservation and quantum mechanics. *Foundations of Physics Letters*, *19*(7), 675–693.

Yoshikawa, T., & Ueda, H. (1996). Haptic virtual reality: Display of operating feel of dynamic virtual objects. In G. Giralt & G. Hirzinger (Eds.), *Robotics research* (pp. 214–221). London: Springer London.

Yuen, K. K., Choi, S. H., & Yang, X. B. (2010). A full-immersive cave-based vr simulation system of forklift truck operations for safety training. *Computer-Aided Design and Applications*, *7*(2), 235–245. doi:10.3722/cadaps.2010.235-245. eprint: https://www.tandfonline.com/doi/pdf/10.3722/cadaps.2010.235-245

Zeidler, D. L. (2016). Stem education: A deficit framework for the twenty first century? a sociocultural socioscientific response. *Cultural Studies of Science Education*, *11*(1), 11–26. doi:10.1007/s11422-014-9578-z

Zeidler, D. L., Sadler, T. D., Simmons, M. L., & Howes, E. V. (2005). Beyond sts: A research-based framework for socioscientific issues education. *Science education*, *89*(3), 357–377.