Isabel Lesjak, BSc

Design and Evaluation of Interactive Physics Visualisations in Augmented Reality

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Supervisor

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

Co-Supervisors

Ass. Prof. Dipl.-Ing. Dr.techn. Johanna Pirker, BSc

Prof. David Lowe, University of Sydney

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

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Betreuer

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

Mitbetreuer

Ass. Prof. Dipl.-Ing. Dr.techn. Johanna Pirker, BSc

Prof. David Lowe, University of Sydney

Institut für Interactive Systems und Data Science
Institutsvorstand: Univ.-Prof. Dipl-Inf. Dr. Stefanie Lindstaedt

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Abstract

Today's rapidly changing world is evolving with ongoing technological innovation and cutting-edge research advancing the state of science. Due to these fast-paced changes, professionals with experience, know-how and skills in Science, Technology, Engineering, and Mathematics (STEM) are now especially in high demand. Therefore, it is important to ensure that current and future generations of students become more interested and motivated in studying STEM subjects such as physics or chemistry. With traditional, more passive teaching methods such as lectures or textbooks alone, students often find it difficult to understand abstract concepts and invisible phenomena such as magnetism, optics, or quantum mechanics. As part of an active learning approach, interactive visualisations and digital simulations can support students' conceptual understanding of physics phenomena by enabling them to interact directly with virtual representations of phenomena and thus involving them actively in the learning process.

Active Learning can also be enhanced by various modern technologies in order to meet the demands of today's digitally-adept generation of learners who prefer a flexible way of "learning by doing". In physics classes with theoretical formulas and complex experiments, immersive and interactive technologies such as Virtual Reality and Augmented Reality can be used to create virtual learning environments which are more easily accessible and interesting for students. Especially Augmented Reality allows students to learn from physical phenomena occurring within their immediate surroundings, by merging the real with the virtual world.

This master thesis deals with the design, implementation and evaluation of interactive physics visualisations in Augmented Reality (AR). To begin with, we have established a first version of a framework which helps to choose appropriate visual augmentations for certain educational purposes and learning activities. Based on this theoretical foundation, we have implemented an AR application in two versions, for marker-less AR on the Microsoft Hololens and for marker-based AR on an Android smartphone. In essence, this AR application augments real and virtual magnets with visual representation of their magnetic field and enables students to explore, observe and interactively adjust its properties. A first evaluation with A/B testing by 20 study participants has compared the two versions of the AR application with regards to user experience, interactivity, learning progress, and motivation. Our results indicate that Augmented Reality technology, in particular on mobile phones, can be a useful tool for improving students learning experience and making physics education more interactive and accessible.

Kurzfassung

Die heutige Welt entwickelt sich durch technologische Innovation und Spitzenforschung in der Wissenschaft ständig weiter. Aufgrund dieser rasanten Veränderungen sind Fachleute mit Erfahrung, Know-how und Fähigkeiten in den Bereichen Mathematik, Informatik, Naturwissenschaft und Technik (MINT) mittlerweile besonders gefragt. Deswegen ist es unter anderem wichtig, sicherzustellen, dass die gegenwärtige und zukünftige Generation von Schülern und Studenten mehr Interesse und Motivation für MINT-Fächer wie Physik oder Chemie entwickelt. Mit traditionellen, passiven Lehrmethoden wie Vorlesungen oder Lehrbüchern allein fällt es den Lernenden oft schwer, abstrakte Konzepte und unsichtbare Phänomene wie Magnetismus, Optik oder Quantenmechanik zu verstehen. Der Ansatz des aktiven Lernens beinhaltet unter anderem interaktive Visualisierungen und digitale Simulationen. Diese können das konzeptuelle Verständnis für physikalische Phänomene fördern, indem Lernende direkt mit virtuellen Darstellungen interagieren und somit aktiv in den Lernprozess eingebunden werden.

Aktives Lernen kann auch durch verschiedene moderne Technologien unterstützt werden, um den Anforderungen der heutigen Generation für eine flexible, digitale Art des Lernens gerecht zu werden. Im Physikunterricht können theoretische Formeln und komplexe Experimente mit immersiven und interaktiven Technologien wie Virtual Reality und Augmented Reality erweitert werden. Dies schafft virtuelle Lernumgebungen, die für Lernende leichter zugänglich und zugleich interessanter sind. Insbesondere die Augmented Reality Technologie ermöglicht es nun durch die Verschmelzung der realen mit der virtuellen Welt von physikalischen Phänomenen zu lernen, die in unmittelbarer Umgebung auftreten.

Diese Masterarbeit beschäftigt sich mit dem Entwurf, der Implementierung und der Evaluierung interaktiver physikalischer Visualisierungen in Augmented Reality (AR). Zu Beginn wird eine erste Version eines Frameworks erstellt, das bei der Auswahl geeigneter visueller Erweiterungen in AR für bestimmte Zwecke und Lernaktivitäten unterstützen soll. Basierend auf dieser theoretischen Grundlage haben wir eine AR-Anwendung in zwei Versionen implementiert: für markerlose AR auf der Microsoft Hololens sowie für marker-basierte AR auf einem Android-Smartphone. Im Wesentlichen erweitert diese AR-Anwendung reale und virtuelle Magneten um eine visuelle Darstellung ihres Magnetfeldes. Mit der AR-Anwendung ist es möglich, diverse Eigenschaften des Magnetfeldes zu beobachten und interaktiv zu verändern. In einer ersten Evaluierung mit A/B-Testungen durch 20 Studienteilnehmer wurden die beiden Versionen der AR-Anwendung im Hinblick auf Benutzererfahrung, Interaktivität, Lernfortschritt und Motivation verglichen. Unsere Ergebnisse deuten darauf hin, dass die Augmented-Reality-Technologie, insbesondere auf Smartphones, ein nützliches Werkzeug sein kann, um das Lernerlebnis zu verbessern und den Physikunterricht interaktiver und zugänglicher zu gestalten.

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1 Introduction

Professionals with know-how in the fields of Science, Technology, Engineering, and Mathematics (STEM) are increasingly in demand in today's rapidly transforming world. However, designing STEM education in an engaging and interesting way is still a challenging task. Traditional didactic approaches such as lecturing convey knowledge through passive, one-way communication from teacher to student, which results in poor conceptual understanding and limited problem-solving abilities among students (Black, 1993). Students often find science classes boring and difficult and therefore lose interest and motivation to further study STEM subjects, which in turn results in a lack of graduates with STEM degrees (Olson & Riordan, 2012).

To counter this issue, more modern approaches such as active learning emphasize "learning by doing" and actively involve students in the learning process by requiring them to engage in activities and think about what they are doing (Bonwell & Eison, 1991). This interactive engagement with hands-on activities such as for instance laboratory experiments with simulations and collaborative group work with peer discussions has been proven more effective in improving conceptual understanding and increasing student motivation than conventional lecturing (Hake, 1998).

Active learning can be enhanced by technology to meet the needs of today's new generation of learners who have grown up surrounded by digital media and thus require a more flexible, digital and self-directed learning experience (Pirker, 2017). For example, in physics classes, interactive simulations and digital visualisations can be used to make usually invisible phenomena visible and to enable experiments which would otherwise be too dangerous or too expensive (Lunce, 2006). Additionally, immersive technologies such as Virtual Reality and Augmented Reality provide a way to create more motivating learning environments, keeping learners engaged and focused in a so-called "flow" experience (Csikszentmihalyi, Abuhamdeh, & Nakamura, 2014).

By augmenting the physical world with virtual entities, Augmented Reality technology changes our perception of reality and thus has significant potential; not only to disrupt a range of existing business sectors and industries, but also to enhance educational environments and open up new forms of immersive and interactive learning.

1.1 Motivation and Goals

In contrast to Virtual Reality which immerses users in a completely virtual environment, Augmented Reality (AR) does not isolate users from their physical surroundings. AR merges the real with the virtual world, making it possible to stay connected to the real world while also viewing superimposed virtual content, such as watching augmented sound waves being emitted from a music-playing audio speaker. This makes it easier to establish mental connections between observed phenomena and theoretical concepts and also facilitates the transfer of skills into real-life situations (Observatory of Educational Innovation, 2018).

This thesis focuses on Augmented Reality in the educational context by establishing a theoretical framework to facilitate the creation of visual AR learning experiences. Building upon previous theoretical work in the area of augmented laboratories by Lowe and Liu (2017), a novel framework for visual augmentations in Augmented Reality within learning contexts has been modelled and categorically tested. It can be used as a framework or tool to decide which type of visual augmentations should be used in an AR experience in order to ensure the purpose of AR and desired learning outcome are met.

Based on this design framework, an interactive physics experience in AR with visual augmentations for magnetism has been implemented as a first prototype and proof-of-concept for the applicability of this framework. Using these implementations, we investigate the difference in user reaction (motivation, engagement, satisfaction) towards the AR experience on two different AR devices, (1) the head-mounted AR headset called Microsoft Hololens (1st generation) and (2) an Android smartphone.

The main contributions of this thesis are:

- Proposal of a new framework to meaningfully employ the use of visual augmentations in learning contexts
- Development of an AR application in two versions, one for the Microsoft Hololens and one for an Android smartphone
- Comparative user evaluation with 20 participants, investigating user experience, interactivity, learning progress and motivation for the developed AR application on both AR devices

1.2 Structure and Methodology

This thesis is structured into three main parts: In the first part, necessary background knowledge as well as relevant related work are presented (Chapter 2). The second part constitutes the practical work: building upon prior research, a novel design framework providing guidance for implementing visual augmentations in learning contexts is then introduced (Chapter 3). This is followed by the requirements, design decisions and implementation details of the developed AR applications (Chapter 4). In the third part, the user evaluation and the obtained results are discussed (Chapter 5). Figure 1.1 provides a visual outline of this thesis' main structure.

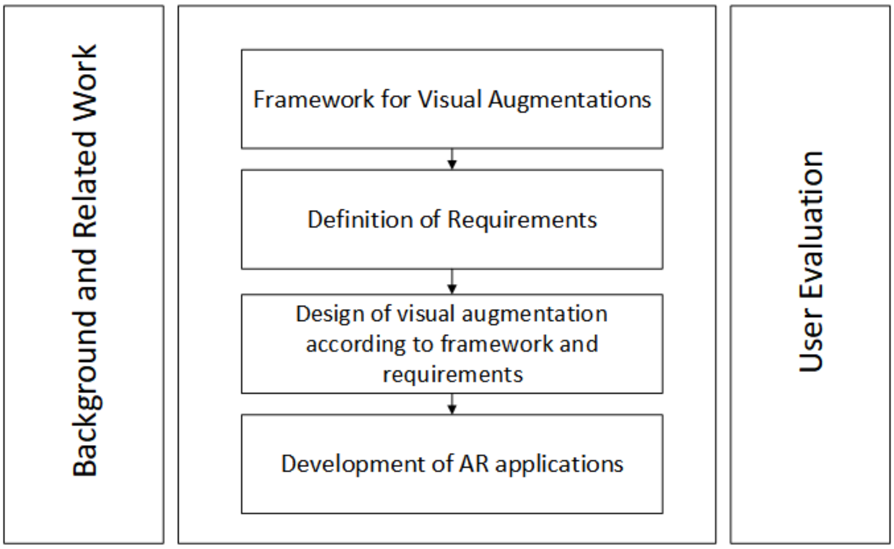

Figure 1.1: The structure of this thesis. The theoretical work provides the basis for the practical work, which is then evaluated through user studies.

Chapter 2 gives an overview on pedagogical models and technological tools for learning in STEM education, with a particular focus on the subject of physics. After contrasting the traditional learning approach with more modern, active learning methods, we describe mobile learning, game-based learning as well as Virtual Reality and Augmented Reality as useful technologies to enhance learning for the new generation of learners. Given the focus of this thesis, we then explore the topic of Augmented Reality in more detail by discussing definitions, application domains and state-of-the-art hardware and software. More specifically, we have a closer look at the use of Augmented Reality in science education by presenting a review of selected, existing Augmented Reality applications and discussing current challenges, benefits and affordances of AR technology.

Chapter 3 introduces a preliminary version of a framework for choosing suitable visual augmentations when designing learning experiences in AR. We argue that it is important to consider the learning activity in relation to the purpose of its augmentation and provide a list of recommended visual augmentation types to choose from.

Chapter 4 deals with the practical aspect of this thesis. We specify the target group and the functional and non-functional requirements for the developed AR applications. We also present the conceptual architecture and implementation differences behind the applications, which were implemented for two different platforms (Microsoft Hololens and Android smartphone).

Chapter 5 presents the set-up of the evaluation study with 20 participants and its resulting findings. We describe the evaluation method and participant pool and analyze the participant's answers questionnaires and interviews in order to answer this thesis' research questions centred around differences in user reactions towards different types of AR.

Chapter 6 discusses problems that arose during the phases of literature research, development and evaluation and notes down lessons learned by dealing with these problems. Finally, Chapter 7 summarises this thesis' results and provides an outlook with ideas for possible future work.

2 Background and Related Work

Professionals skilled in science, technology, engineering, and mathematics (STEM) are vital to ensure ongoing scientific innovation and technological progress. However, there is a significant lack of STEM graduates as many students lose interest and motivation to study STEM subjects. Therefore it is necessary to make STEM classes more engaging and interesting to the new generation of learners. This chapter presents different learning approaches and technological tools to improve STEM education, with a particular focus on teaching physics by means of Augmented Reality technology.

2.1 Learning and Teaching in STEM

In today's rapidly changing world, STEM skills are vital to innovate and stay competitive in the globalised market. Without an increase in STEM professionals, technology-driven countries like the U.S risk to fall behind other rising countries like China and India in economic development (Atkinson & Mayo, 2010). Therefore, it is important to make STEM education more engaging and appealing to the youth again by using innovative learning approaches and new technologies which meet the needs of a new generation of learners.

Learning and teaching in the fields of science, technology, engineering, and mathematics is a challenging task. While teachers find it difficult to explain abstract concepts and theoretical formula, students struggle to relate the taught content to real-world phenomena and often loose interest and motivation to study STEM subjects. This results in high failure and drop-out rates in STEM classes and consequently, a lack of sufficient university graduates with STEM degrees to fill the growing demand in the job market (Olson & Riordan, 2012).

One of the STEM subjects that students find particularly difficult and work-intensive is Physics (Angell, Guttersrud, Henriksen, & Isnes, 2004). The subject of Physics involves many theoretical equations and complex concepts of scientific phenomena that are usually invisible, such as electromagnetism or wave propagation. Therefore it is often difficult for students to gain a good conceptual understanding of these topics and to relate physics theory to real-life situations or observations in the laboratory (Scheucher, Bayley, Gütl, & Harward, 2009). In physics education, traditional lecturing is still a common instruction method, even though previous research has demonstrated that interactive learning approaches are more effective in increasing student engagement and improving learning outcomes (Hake, 1998; Knight and Wood, 2005; Deslauriers, Schelew, and Wieman, 2011).

Apart from expository instruction, physics education can be enhanced by including activities such as hands-on experiments, self-determined learning, laboratory sessions, and the use of interactive computer simulations to visualise complex phenomena (Y.-F. Lee, Guo, & Ho, 2008).

The following sections will introduce different learning approaches and tools to teaching and learning in STEM education, comparing traditional teaching methods to more modern, interactive approaches.

2.1.1 Traditional Learning

One of the most common conventional instruction methods is lecturing. During lectures, teachers and textbooks act as primary source of knowledge while students sit and listen, memorize facts and recite formulas, often without gaining a proper understanding of the taught content. Furthermore, lecturers are usually presenting solutions to problems or derivations of formulas instead of teaching students the vital skill of how to solve or derive these on their own (Freedman, 1996).

The traditional didactic approach of lecturing is underpinned by the behaviorist learning theory, according to which external stimuli elicit observable responses which can be measured. In the context of learning, new knowledge is transmitted to students by teachers via direct instruction (the stimulus) and students demonstrate their acquired knowledge through their performance on tests and assignments (the response) (McLeod, 2003).

However, as this lecturing approach does not actively involve students and mostly relies on one-way communication from teacher to student, students themselves remain passive participants in the learning process, which in turn results in poor conceptual understanding and limited problem-solving abilities (Black, 1993). Another issue applies to the use of traditional textbooks: in a study with Korean high school students, Kim and Pak (2002) have shown that students still have difficulties in conceptual understanding of basic mechanics, even after solving 1000 traditional physics textbook problems. This indicates that the ability to apply learned formulas and pathways to solve given problems does not automatically result in a better understanding of the underlying concepts.

Yet another drawback arising through conventional lecturing is the fact that students often have difficulties to relate different concepts to another and to connect physics theory and formal equations to observable phenomena in the real world (McDermott, 1993).

During physics classes in particular, teaching is not limited to lecturing only. Apart from lecturing theoretical content, it is also common to illustrate scientific concepts bv performing experiments and acquire practical skills by working in a laboratory environment. While these experiments and laboratory experiences help students to relate theory content to real life and allow them to acquire essential skills in handling real equipment, such a physics laboratory with hands-on experiments might not always be readily available, accessible or scalable to many students, given the high amount of monetary, temporal and spatial resources required to run and maintain physical lab classes with experiments (Daineko, Dmitriyev, & Ipalakova, 2017). When dealing with real equipment, students also tend to be afraid of damaging equipment or hurting themselves (Wieman, Adams, & Perkins, 2008). In addition, experiments involving concepts such as nuclear radiation (Park, Lee, Yuk, & Lee, 2005) make them too unsafe and too expensive to be performed within educational institutions.

In order to overcome these issues and facilitate learning, especially in STEM disciplines, it is thus important to actively involve students in practical hands-on activities and enhance these through the use of various technologies. As was already stated by the ancient Chinese philosopher Confucius, learning by doing is essential to understanding: *"I hear and I forget. I see and I remember. I do and I understand"*. Moreover, a large-scale study with more than 6000 participants by Hake (1998) has shown that using interactive engagement methods in class leads to an above-average improvement in students' conceptual understanding and problem-solving ability, well beyond the average improvement obtained in traditional lecture courses. The following section introduces the active learning model and various approaches to incorporate active learning in the classroom in more detail.

2.1.2 Active Learning

Active Learning is an instructional approach which engages learners in the learning process by requiring them to perform activities and actively think about what they are doing (Bonwell & Eison, 1991). Within a classroom, active learning among students can be promoted through activities and interactions that actively involve students in doing something; such as short exercises, group discussions, note-taking, debates, or feedback sessions.

This student-centred, participatory approach to learning stands in contrast to the more traditional instructional setting of a classroom lecture where students passively listen to their instructors. The paradigm of active learning can be based upon the constructivist learning theory which essentially states that *"people learn by constructing their own understanding and knowledge of the world through experience and reflecting upon that experience"* (Harasim, 2017). Instead of passively receiving knowledge by another authority, learners themselves are actively involved in creating knowledge by engaging in experiences, integrating newly gained information into their existing body of knowledge and socially interacting with others.

Prince (2004) mentions several studies that have demonstrated the effectiveness of active learning in improving information retention and student's performance on test scores which are measuring conceptual understanding. More recently, a meta-analysis of 225 studies investigating traditional lecturing compared to active learning in STEM undergraduate education has shown that active learning can increase student's average examination scores by 6 percent and that the failure rate for students receiving only traditional lecturing is 1.5 times higher than for those involved in active learning (Freeman et al., 2014).

Active learning can be incorporated into the classroom through a wide variety of instructional strategies. According to Bonwell and Eison (1991), active learning can be encouraged by simple modifications of traditional lectures or by adopting alternative formats of instruction that do not involve lecturing. Strategies mentioned by Bonwell and Eison (1991) include pausing lectures to let students take notes or complete short exercises, followed by peer discussions or changing the traditional frontal lecture to a feedback lecture or a guided lecture. For large classes, active learning can be promoted by incorporating in-class discussions, visual-based instruction, in-class writing, case studies and other instructional strategies such as cooperative learning, debates, drama, role play, simulations, and peer teaching. For college classrooms in particular, Faust and Paulson (1998) have reviewed a wide range of active learning techniques, ranging from individual exercises, question and answer activities to immediate-feedback techniques, critical thinking motivators, and cooperative learning strategies. Furthermore, popular pedagogical models which rely on active learning include problem-based learning, discovery-based learning, inquiry-based learning, project-based learning and case-based learning (Cattaneo, 2017).

In the next sections, the following five approaches to active learning are being described in more detail: Technology-Enhanced Active Learning, Motivational Active Learning, inquiry-based learning, experiential learning as well as exploratory learning. These specific approaches were chosen because they have already been applied successfully within science classes or in virtual learning environments, and as such are relevant to this thesis' focus on physics education with Augmented Reality.

Technology-Enabled Active Learning

In order to facilitate active learning in the today's modern classroom, the potential of digital technology and e-learning tools to engage, immerse and motivate learners should not be neglected. Through the use of interactive 3D simulations and visualisations, gamified learning environments, collaborative, virtual worlds, virtual or remote laboratories it is possible to let students carry out hands-on activities and reflect upon these.

A modern approach to Active Learning which makes use of technology is "Technology-Enabled Active Learning" (TEAL), an instructional method pioneered by Professor John Belcher in 2001, in order to improve the learning experience in freshman physics classes at Massachussetts Institute of Technology (R. B. Y. J. Dori & Belcher, 2006). The use of visualisations and collaboration between peers are key features of TEAL. To incorporate TEAL into the physics class, the classroom was custom-designed with shared desks and desktop computers to enable collaborative group exercises and interactive 2D and 3D visualisations of electromagnetic phenomena. Specifically, available software and hardware technology (such as computers, 3D programs, measurement devices, personal response system) are used to incorporate visualisations, collaborative group work, hands-on experiments as well as conceptual questions followed by peer discussions into the classroom lecture.

Previous research by Y. J. Dori and Belcher (2005) and Shieh (2012) has investigated the impact of TEAL on students and has shown that the use of TEAL does indeed have a positive impact, as it increased student performance on test scores and also resulted in better conceptual understanding of physics phenomena, while managing to raise students' interest in physics classes.

Motivational Active Learning

Based on the TEAL model, Pirker, Riffnaller-Schiefer, and Gütl (2014) have developed a pedagogical model called Motivational Active Learning (MAL). It combines interactive engagement and collaboration strategies from TEAL with motivational gamification elements in order to increase student motivation in class. The key features of MAL are collaborative learning (students solve tasks in small groups of 2-4), constant interactions between instructor and students, immediate and motivational feedback (use of leaderboard, points instead of grades), error tolerance (possibility to repeat quizzes) and adaptive course content (instructor adjusts lecturing speed and content according to student feedback).

The MAL model was first applied and evaluated in a computer science class on ”Information Search and Retrieval” at Graz University of Technology in the year 2013. Hereby, the traditional lecture was broken down into ”mini lectures”, each one preceded by a concept question and ending with a concept quiz. At the beginning of each class a recap quiz led by the instructor was used to revise content taught in the previous lesson. Further motivational activities integrated into each lesson included discussion questions, small programming and calculation tasks as well as reflection questions. The evaluation of this course showed that students are indeed being motivated by the MAL approach. However, it is still necessary to take into account a range of different learning activities in order to meet the specific demands of different learner types (Pirker, 2017).

Inquiry-based Learning

Spronken-Smith (2012) argue that inquiry-based learning is a subset of active learning because it requires students to actively participate in the learning process by asking and answering questions or finding solutions to problems. As opposed to traditional lecturing, which is a rather topic-driven process, learning through inquiry is a problem-driven, or question-driven approach. This makes learners responsible for their own learning and seeking new knowledge. Teachers only act as guides or facilitators to the inquiry process, they do not convey knowledge merely through lecturing. In inquiry-based learning, the learners construct problems by formulating questions or hypotheses, testing these through experimentation and observations, collecting data and drawing conclusions. This is a process which is similar to the scientific method used by researchers (Pedaste et al., 2015).

The different phases of inquiry-based learning are often shown in an inquiry cycle. Since varying definitions of an inquiry cycle have been presented in literature, Pedaste et al. (2015) have developed a synthesized inquiry cycle, combining the core features of existing inquiry cycles. It consists of five general phases, nine sub-phases and different possible pathways to go through these phases, as shown in Figure 2.1. The inquiry-cycle starts with the Orientation phase, where students are introduced to the topic or the problem to be investigated. Next, in the Conceptualisation phase, the students form key concepts and refine research questions either through open questioning or generating hypotheses. The following Investigation phase allows students to either explore phenomena or perform experiments, and then interpret the gathered data, before coming to a conclusion in the Conclusion phase. Finally, the Discussion phase is possible throughout the whole inquiry process and can happen in the form of reflection activities or direct communication with others.

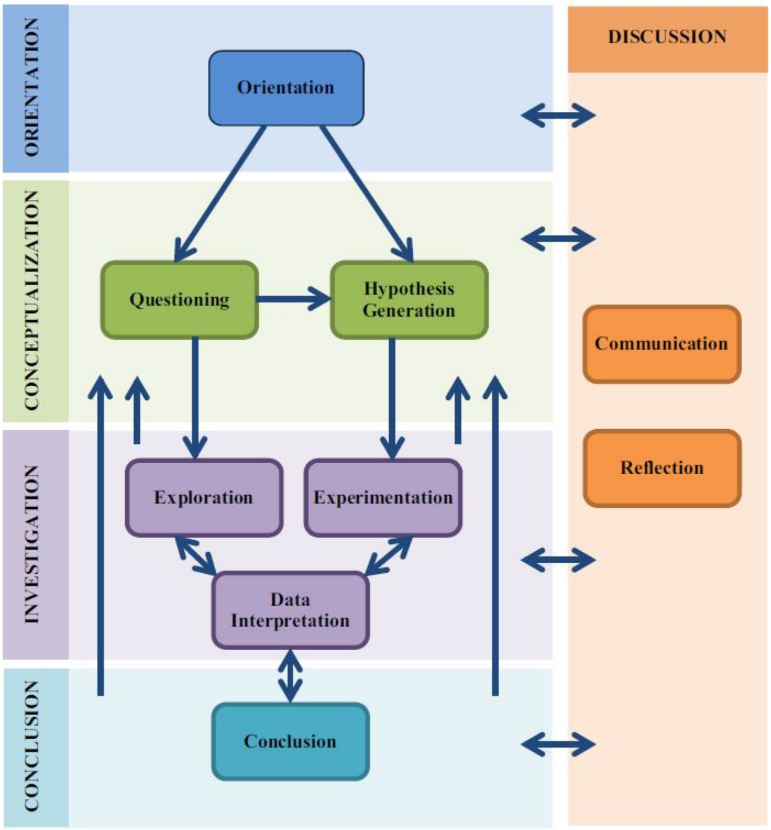

Figure 2.1: Inquiry-based learning cycle, reprinted from Pedaste et al. (2015)

Experiential Learning

Another learning strategy that can be used to involve students in active learning is Experiential Learning. Experiential Learning is a holistic learning model introduced in 1984 by D. Kolb (1984) which emphasises the importance of experience during the learning process. According to D. A. Kolb, Boyatzis, Mainemelis, et al. (2001), learning occurs when "*knowledge is created through the transformation of experience*". More specifically, it is necessary to first grasp and then transform experiences in order to construct knowledge.

Ideally, experiential learning occurs cyclically in four stages, according to the Experiential Learning Cycle shown in Figure 2.2. These four stages are (1) Concrete Experience (CE), (2) Reflective Observation (RO), (3) Abstract Conceptualisation

(AO) and (4) Active Experimentation (AE). First, the learner engages in making a concrete, hands-on experience, which is then observed and reflected upon. Next, the learner uses these reflections to form abstract concepts and create mental models. Finally, the newly gained knowledge is applied and tested by acting and experimenting in different situations, which in turn again leads to the formation of new experiences.

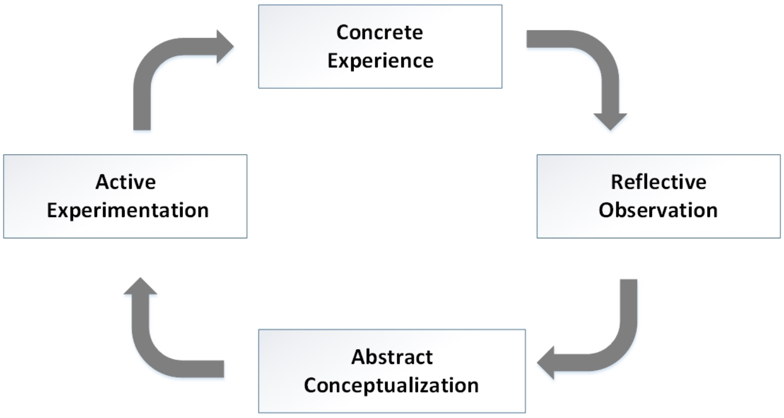

Figure 2.2: Experiential Learning Cycle, recreated from D. A. Kolb, Boyatzis, Mainemelis, et al. (2001)

Exploratory Learning

The Exploratory Learning Model, which was introduced by De Freitas and Neumann (2009), builds upon the Experiential Learning Model by adding "exploration" as a fifth element to the cycle of learning in order to address additional learning possibilities that have arisen within immersive and 3D environments. During this exploration phase, learners should observe and explore both their virtual and physical environment and engage in communication, collaboration and social interaction with others. As can be seen in Figure 2.3, learners can engage in exploration by observing, performing activities, learning, or interacting, before this is followed by a phase of reflection. The use of immersive, virtual environments effectively enables these range of activities to take place more easily.

Since virtual learning environments are more easily adaptable and do not require a rigid choreography as in a physical classroom setting, tutors and teachers can design and customise immersive learning experiences with various tasks and activities, which are time and cost-effective by being easily replicable at virtually no extra resource. This is why the addition of an exploration phase becomes crucial: By including an exploration phase in the learning process, learners can then experience and explore the learning environment not only at their own pace but also complete activities according to their own preferences, needs and habits, as they do not have to adhere to one pre-determined sequence of activities. Therefore, exploratory learning gives greater control to learners and empowers them to gather knowledge and gain experience in their individual way. The use of 3D immersive environments for exploratory learning is an example of technology-enhanced learning, which is becoming relevant in order to appeal to the needs and desires of a new generation of learners.

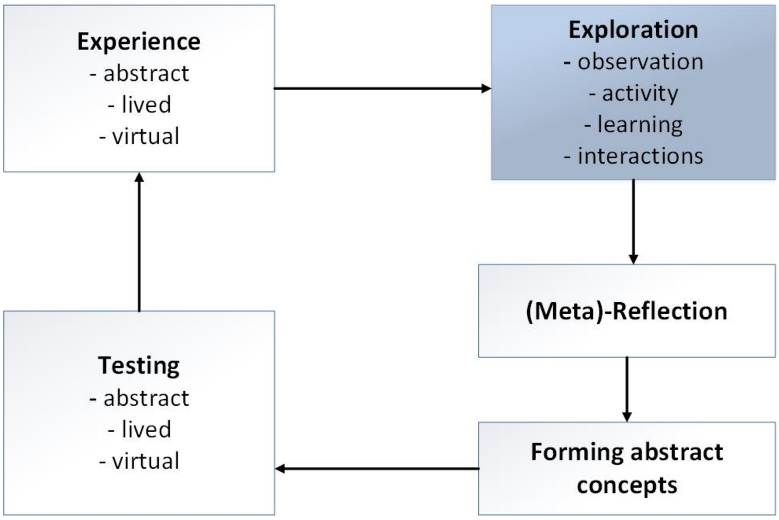

Figure 2.3: Exploratory Learning Model, recreated from De Freitas and Neumann (2009)

2.1.3 A New Generation of Learners

Today's students represent a new generation of learners: they are the so-called "digital natives" who have grown up surrounded by digital media such as smartphones, mobile apps, the Internet, video games, and social media. The ubiquitous access to information and constant availability of these technologies have resulted in different characteristics, preferences and expectations towards learning. According to Prensky (2001), digital native learners nowadays have shorter attention spans, like to engage in multi-tasking and want to access any information quickly and in a direct way. They prefer visual over textual content as well as learning by doing and collaborating with peers, rather than listening to a lecturer or reading a textbook. They also expect digital tools to be an integral part of their (learning) environment. As observed by Pirker (2017), this new generation of learners *"requires an online and digital learning environment, which supports social interaction and allows self-regulated learning in a mobile and flexible way."*

The ongoing development in the area of Information and Communication technologies (ICT) has been supporting these emerging demands towards learning and making it possible to learn digitally, anywhere and at any time, thus giving rise to a new form of learning called e-learning. According to Horton (2011), e-learning refers to any form of learning which is supported by electronic technologies. There are different varieties of e-learning, ranging from standalone online courses, educational games, simulations, to mobile learning, social learning, and virtual classroom courses (Horton, 2011). Further types of e-learning technologies include Learning Management Systems (Gros & García-Peñalvo, 2016), adaptive learning and Intelligent Tutoring systems (Oxman, Wong, & Innovations, 2014), gamification (Hammer & Lee, 2011), Massive Open Online Courses and cloud-based tools (Chang, Gütl, & Ebner, 2018), as well as virtual and remote laboratories (Sancristobal et al., 2012) and immersive media such as Virtual Reality, Augmented Reality, and Mixed Reality (Dede, Jacobson, & Richards, 2017).

Looking at the wide variety of available e-learning tools, several information and communication technologies are particularly relevant to create more mobile, flexible, and self-regulated learning experiences. The wide prevalence of mobile devices such as smartphones and tablets has enabled mobile learning, while the success of video games in engaging users has led to the adoption of gamification strategies for educational purposes. The rise of immersive technologies such as Virtual Reality and Augmented Reality makes it possible to create interactive learning experiences which are necessary to keep learners engaged. As these selected four technologies (mobile learning, gamification, Virtual Reality, and Augmented Reality) allow to meet the current demand towards more mobile, flexible and engaging learning experiences, they will be discussed in further detail in the following sections.

2.2 Technologies for Learning and Teaching in STEM

This section describes technologies to enhance learning and make it more interesting, interactive and engaging for today's new generation of learners. Physics education in particular, with its emphasis on complex phenomena and practical lab work, can benefit from modern technologies to aid learning and teaching.

2.2.1 Mobile Learning

Mobile learning has been defined as *"learning across multiple contexts, through social and content interactions, using personal electronic devices"* (Crompton, 2013). For example, mobile learning on smartphones is a convenient method to make the learning process more flexible as learning is not restricted to a physical classroom with a human teacher anymore. Instead, information, apps and course contents can now be accessed from anywhere and at any time, all from a device that fits into everyone's pocket. Today, smartphones have become an essential part of everyday life, as there are now more than 3 billion smartphone users worldwide, and this number is projected to grow further in the upcoming years, as reported by Newzoo (2018).

A review by Crompton and Traxler (2015) presents different examples and case studies showing how mobile learning can be effectively applied in STEM subjects. Especially the use of widely available and affordable smartphones or tablets can, for instance, support outdoor learning activities, facilitate the development of learning content in underdeveloped countries, or augment learners' surroundings with contextual content via the smartphone camera. Another comprehensive meta-analysis on trends in mobile-learning research is given by Chee, Yahaya, Ibrahim, and Hasan (2017).

In physics education, modern smartphones may also be used as experimental tools to conduct scientific experiments, since smartphones are usually equipped with sensors for measuring acceleration, orientation, magnetic field strength, light intensity as well as a GPS and a microphone, with corresponding apps available[1] to read out and interpret sensor measurements. Previous research has reported on smartphones being successfully used to analyse gravitational acceleration (Kuhn & Vogt, 2013b), different types of sound waves (Kuhn & Vogt, 2013a), and pendulum phenomena (Vogt & Kuhn, 2012).

While mobile learning already enables a more flexible "anytime, anywhere" way of learning, going beyond the borders of a real classroom, it is still a challenge to keep learners attentive, motivated and engaged. Enhancing learning environments with educational games or elements from game design is one way to improve motivation and engagement in STEM education. The next section discusses digital game-based learning as well as gamification strategies in more detail.

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[1] `https://www.rotoview.com/sensor_kinetics_android.htm`

2.2.2 Digital Game-Based Learning

One way to make learning more fun and motivating is through incorporating the element of play. Engaging in play is an important factor to foster children's cognitive development, as described by Piaget (1973). For example, playful learning can already take place at a playground: while children climb up ladders, go down slides, or rock on swings, various physical forces such as gravity, friction or inertia are always at play and therefore, the fundamental concepts of Newton's laws of motion can easily be observed and explored (e.g. experiencing inertia by jumping off a swing in motion and trying to stand still).

Furthermore, playing video games is an activity that many people enjoy spending many hours on doing. What makes video games so compelling and fun to play is, among others, the fact that they provide challenges that are neither too easy nor too difficult to master and continuously adapt to the player's current skill level while also allowing for riskless trial and error (Plass, Homer, & Kinzer, 2015). In other words, highly motivating and engaging video games are those designed to adapt in difficulty and operate at the upper limit of a player's growing competence, also called the player's zone of proximal development (Vygotsky, 1980). Video games also provide contextual information just-in-time, at places where it is needed, and allow players to assume new identities by role-playing different characters and actively participate in another virtual world (Gee, 2003).

Given the fact that video games have been highly successful in engaging players and keeping them focused for longer periods of time, it is not surprising that gaming principles and game elements have been transferred into the classroom environment. As summarized by Shaffer, Squire, Halverson, and Gee (2005), video games can become powerful contexts for learning because of the following reasons: they allow students to engage in situated learning, gain social skills, assume new identities and develop shared values within their gaming community; all of which helps them to gain expertise knowledge and become an expert in a certain area.

The educational potential of games as a medium for learning is used in a didactic approach called digital game-based learning (DGBL). According to Prensky (2001), digital game-based learning refers to the use of games and their motivational aspects for an educational purpose, to promote learning. More specifically, according to Plass et al. (2015) DGBL can be seen as *"a type of game play with defined learning outcomes"* which addresses four types of engagement; namely, cognitive, affective, behavioral, and socio-cultural engagement. In order to develop serious games - effective educational games which are both fun to play and instructive - it is important to strike a sound balance between the actual learning content that should be conveyed and the amount of game elements and game mechanics in use to make the learning process more playful (Plass, Perlin, & Nordlinger, 2010).

With their virtual content and adaptable difficulty levels, games bring abstract concepts to life, encourage trial and error, and provide immediate feedback as well as scaffolding suited to individual student needs, all of which makes games an ideal option to teach STEM subjects more effectively, both inside and outside of the classroom (Rapini, 2012). An example for game-based learning in Computer Science education is ″sCool″, a mobile, adaptive learning game designed to teach computational thinking and programming skills in Python (Kojic et al., 2018). It consists of a mobile application, adapting to students' different play styles in order to support explorative learning, and a web interface with tools to facilitate content creation for educators and provide useful learner analytics and student assessment options. In a preliminary study, this sCool platform was rated by both students and teachers as highly immersive, engaging and user-friendly. Similarly, another evaluation of ″sCool″ by Steinmaurer, Pirker, and Gütl (2019) indicated high motivation to learn programming among learners, though it also revealed prevalent issues in transferring the studied computational concepts into other, similar problem-solving contexts.

Looking at physics education, a notable example for game-based learning is a game called ″Newton's playground″ (Shute, Ventura, & Kim, 2013), where players have to move a ball towards a target location by drawing objects, which are then brought to life, acting like real objects according to the laws of gravity and motion. Regarding the effectiveness of game-based learning, Kapp (2012) extensively summarizes prior research from various meta-analysis studies in his book ″The Gamification of Learning and Instruction″ , overall concluding that instructional games, when designed with clear learning objectives and the right level of uncertainty (for rewards) in mind, indeed are beneficial for learning and enhance motivation among learners.

Since developing educational games for game-based learning can be quite costly and time-consuming (Dicheva, 2017), another approach to enhance learning with games is by means of gamification. Learning can be made more fun and motivational through the use of gamification, which refers to the ″use of game design elements in non-game contexts″ (Deterding, Dixon, Khaled, & Nacke, 2011). For instance, by rewarding score points for completing existing tasks like math homework which might otherwise feel boring or tedious to complete. In the educational context, the following game design elements have been widely used to enhance learning: points (as a measure of success), levels and progress bars (as a measure of progression), leaderboards (to create competition), badges, prizes and rewards, a narrative storyline, as well as clear and immediate feedback (Nah, Zeng, Telaprolu, Ayyappa, & Eschenbrenner, 2014).

Previous studies have reported on the positive impact of gamification on students knowledge retention and intrinsic motivation (Buckley & Doyle, 2016) and its benefits for improving student engagement, as indicated by higher class attendance and greater interaction with online course materials (Barata, Gama, Jorge, & Gonçalves, 2013).

In the fields of STEM, simulations and visualisations are often used to illustrate complex concepts, (invisible) physical phenomena, or dangerous experiments (Lunce, 2006). For instance, previous research by Wieman et al. (2008) has revealed that well designed, interactive simulations of science experiments can effectively encourage self-driven, exploratory and playful learning among students, without becoming too overwhelming or in danger of breaking down, as it is often the case when dealing with real experiments and physical equipment.

When designing simulations, it is important to consider both the pedagogical as well as the motivational design aspects of simulations. As a matter of fact, even the scientifically most accurate simulation is of little use if learners are loosing interest in engaging with it. For this purpose, Pirker and Gütl (2015) have introduced a framework for the gamification of (existing) science simulations, based on the analysis of successful examples. In order to gamify simulations, it is recommended to add possibilities for (i) interactivity, (ii) feedback, and (iii) single or multiple game participants. The addition of gamification elements such as challenges, missions, or puzzles encourages ongoing, continuous user interaction. As users interact with simulations, they should receive feedback in the form of badges, points, rewards, or leaderboard information. Simulations can also be designed for more than one user, which provides potential for collaborative and competitive behavior (e.g. with high-score rankings on leaderboards or group assignments for missions).

Playful learning in gamified environments is not the only way to enhance motivation and engagement among learners. Learning environments that achieve feelings of immersion, presence and flow are also highly motivational and engaging. The next sections give an overview of Virtual Reality and Augmented Reality, both technologies which can make learning more immersive and interactive.

2.2.3 Virtual Reality Environments

The potential of Virtual Reality (VR) technology to create immersive and engaging user experiences should not be overlooked. Virtual Reality can be defined as the *"use of computer graphics systems in combination with various display and interface devices to provide the effect of immersion in the interactive 3D computer-generated environment"* (Pan, Cheok, Yang, Zhu, & Shi, 2006). Essentially, two key features of VR are interactivity and immersion. Through the use of hardware controllers for user input as well as sensors for tracking users position, it is possible to detect and react to user input in real time. Interacting with a realistic virtual environment provides a greater feeling of immersion for users. As defined by Brockmyer et al. (2009), immersion describes the technical capability of a system to make users feel present in or being a part of the virtual environment. The feeling of presence itself is an individual human response to immersion and refers to *"the subjective experience of being in one place or environment, even when one is physically situated in another"* (Witmer & Singer, 1998).

Another experience which can be facilitated by the use of VR technology is the flow experience. The concept of flow has been described by Csikszentmihalyi (2008) as an optimal state of mind where someone is completely engaged and focused on an activity, as the challenges or problems at hand exactly match the personal skill level, making it neither too easy nor too difficult to tackle .

Virtual reality-based instruction has been shown as an effective means towards fostering learning in K-12 and higher education (Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014). One example of effective educational use of VR in the STEM field is "Maroon", a three-dimensional, virtual physics laboratory with simulations, visualisations and interactive experiments centered around the topics of electromagnetism and wave propagation. It has been developed in different versions, ranging from a non-VR, desktop-based version to a fully immersive room-scale VR and a more portable, affordable mobile VR setup (Pirker, Holly, Lesjak, Kopf, & Gütl, 2019). In a comparative study, Pirker, Lesjak, Parger, and Gütl (2018) have demonstrated that learning with Maroon in VR is experienced as more engaging and interesting, especially in the room-scale version of the immersive physics laboratory.

Virtual reality can be used to make virtual laboratories like "Maroon" feel more immersive and interactive. The use of virtual laboratories within science education has been extensively reviewed by Potkonjak et al. (2016), who argue that virtual laboratories are superior to remote laboratories due to their cost-effectiveness and flexibility. Virtual laboratories provide the possibility for visualising invisible phenomena, enable simultaneous multi-user access and dynamic configuration changes, and also allow for users to make mistakes without real damage as consequence.

While VR technology is able to fully immerse users in computer-generated digital environments, this also results in one major drawback of VR environments: isolating its users from the real, physical world. As users experience purely digital versions of experiments or physical phenomena, it might be difficult to also transfer gained knowledge towards other real situations and apply skills within real-world contexts (Observatory of Educational Innovation, 2018). Further disadvantages of Virtual Reality include the possibility of experiencing motion-sickness as negative side-effect (Brigham, 2017), lower credibility of virtual simulations as compared to remote or real laboratory situations (Cooper, 2000; Zhao, 2011), as well as the time-consuming effort required to completely recreate virtual models of real situations rather than simply complementing it with augmentations (Beaudouin-Lafon, 1994).

With the potential of Augmented Reality technologies, it is possible to overcome current issues of Virtual Reality and bridge this gap by merging virtual content with the real, physical world. The next sections will give an overview of Augmented Reality environments and its use in education.

2.2.4 Augmented Reality Environments

In contrast to Virtual Reality, which fully immerses the user into a completely virtual world, Augmented Reality does not disconnect the user from the physical, real world. Instead, it overlays reality, or rather the perception of reality, with virtual entities like information, data, objects, process visualisations, manufacturing steps or even human avatars. Augmented Reality enables users to interact with their surroundings in a realistic and multimodal way through visualisations, audio, and haptics.

Definition and Applications

The term "Augmented Reality" (AR) as such was coined in 1992 by Tom Caudell and David Mizzel. In the context of aircraft manufacturing, they describe Augmented Reality as a technology to "*augment the visual field of the user with information necessary in the performance of the current task*" (Caudell & Mizell, 1992).

In a widely cited definition for Augmented Reality, Azuma (1997) defines AR as a technology that enhances user's perception of reality by superimposing 3D virtual objects onto the 3-D physical environment in real-time. Specifically, the three main characteristics of Augmented Reality technology are (1) the combination of real and virtual, (2) the real-time interactivity, and (3) the registration of objects in 3D space.

Milgram, Takemura, Utsumi, and Kishino (1995) have established the well-known Reality-Virtuality continuum, which encompasses four different stages

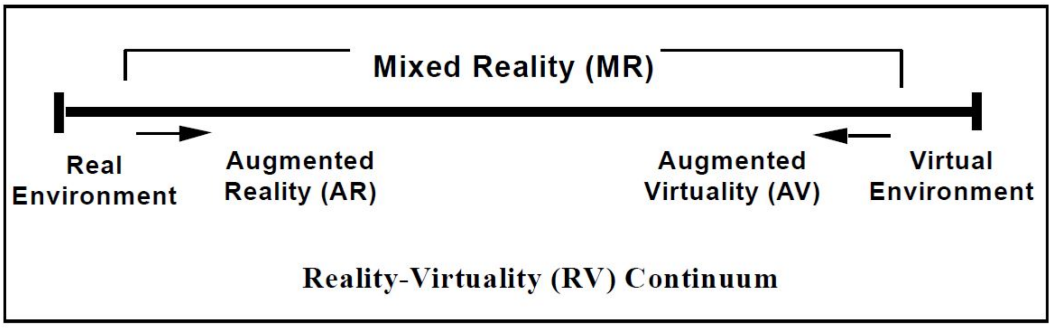

Figure 2.4: Reality-Virtuality Continuum, reprinted from Milgram, Takemura, Utsumi, and Kishino, 1995

under the umbrella term "Mixed Reality": Real environment, Augmented Reality, Augmented Virtuality, and Virtual Reality, as illustrated in Figure 2.4. This continuum ranges from a completely real world to a completely virtual world. As can be seen, Augmented Reality lies closer to real environment, since it is enhancing reality by overlaying it with virtual entities. In contrast, Augmented Virtuality is located closer to purely virtual environments, as it visualises real objects from the physical world within virtual environments. In a broad sense, the authors describe Augmented Reality as "*augmenting natural feedback to the operator with simulated cues*", whereas in a more specific, technology-oriented definition, AR is being defined as "*a form of virtual reality where the participant's head-mounted display is transparent, allowing a clear view of the real world*" (Milgram et al., 1995).

By augmenting the physical world with virtual entities, Augmented Reality technology changes our perception of reality and therefore it has significant potential to not only create new forms of entertainment and enhance learning environments, but also to disrupt a wide range of existing business sectors and industries. The pervasive influence of Augmented Reality can be seen in the wide range of Augmented Reality applications present in various domains of life nowadays, as mentioned in the following list with references to prior work:

- Education and training (K. Lee, 2012; M. Wang, Callaghan, Bernhardt, White, & Peña-Rios, 2018)
- Gaming (Geroimenko, 2019) and entertainment (Huang, Jiang, Liu, & Wang, 2011)
- Medicine (Peters, Linte, Yaniv, & Williams, 2018) and surgery (Vávra et al., 2017)
- Fashion (Logaldo, 2016) and retail (Bonetti, Warnaby, & Quinn, 2018)

- Assembly (X. Wang, Ong, & Nee, 2016) and maintenance (Palmarini, Erkoyuncu, Roy, & Torabmostaedi, 2018)
- Construction (Heinzel, Azhar, & Nadeem, 2017) and architecture (X. Wang, 2009)
- Tourism (El Choubassi, Nestares, Wu, Kozintsev, & Haussecker, 2010) and cultural heritage (Vlahakis et al., 2002)
- Sports training (Kajastila & Hämäläinen, 2014) and competition broadcasting (Bozyer, 2015)
- Military (Livingston et al., 2011) and marketing (Rajappa & Raj, 2016)

Given the large prevalence of AR applications in these domains, the mainstream use of AR among the general public is not surprising. Several popular consumer smartphone applications include features that use AR for various everyday tasks. Some of the more well-known applications are listed below:

- Walking navigation with the aid of AR in Google Maps (see the "Google Maps Live View" feature on compatible smartphones[2])
- Capturing photos with AR lenses on Snapchat[3]
- Authoring custom content for face filters and AR effects on Facebook and Instagram via the software Spark AR Studio[4]
- Playing the location-based mobile game Pokémon Go in AR mode[5], where users navigate the real world to find and catch virtual Pokemons

In order to create applications and facilitate AR experiences like those mentioned above, it is necessary to rely on enabling technology behind fundamental Augmented Reality, which lies in a variety of tracking approaches, display technologies and software components.

Technological aspects of Augmented Reality

From a tracking point of view, Augmented Reality applications can be classified into two distinct categories: (1) marker-based (or image-based) AR and (2) marker-less (or location-based) AR. The former makes use of image targets, also called fiducial markers (Billinghurst, Clark, Lee, et al., 2015) to correctly anchor virtual objects within the physical world, while the latter does not require any type of marker to accomplish this, but uses location data from GPS or other sensors instead. Registering targets or environmental features and tracking their positions enables the accurate alignment of virtual objects within 3D space,

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[2] `https://support.google.com/maps/answer/9332056`

[3] `https://support.snapchat.com/en-US/article/face-world-lenses`

[4] `https://sparkar.facebook.com/ar-studio/`

[5] `https://www.pokemongo.com/en-us`

which is one of the defining characteristics of AR, as described by Azuma (1997).

In order to fulfill another fundamental characteristic of AR according to Azuma (1997), it is necessary to merge the real with the virtual world view. This can be achieved through various display devices, such as optical see-through displays, video-based displays, and surface-projection displays (Billinghurst et al., 2015). One of the most affordable ways to experience AR is through smartphones or tablets (with cameras and GPS sensors) which provide an augmented view of the world on a mobile display screen (Chatzopoulos, Bermejo, Huang, & Hui, 2017). However, using these handheld devices to experience AR comes with the drawback of hands-free use not being possible, which is where the benefit of head-mounted displays (HMD) comes in, enabling users to wear the display on the head and interact with their surroundings through eye gaze and intuitive hand gestures.

In addition to appropriate hardware devices, software tools are also required to create the technical illusion of virtual objects co-existing within physical reality. To give an overview of the technical environment necessary for AR, a few selected state-of-the-art hardware devices, followed by relevant software tools for experiencing and creating AR environments will be briefly described in the following paragraphs.

The **Microsoft Hololens** was released in its initial version in March 2016 (Ramos, Korb, & Okada, 2019). It was not sold to private consumers, but it was available as Development Edition and Commercial Suite[6], targeted towards research institutions, developers and business enterprises. The Microsoft Hololens marks a major milestone in cutting-edge technology as it is the *first, fully untethered* holographic computer that projects and anchors holograms onto real-world objects and surfaces, using spatial mapping techniques. User interaction is possible in various ways: through eye gaze input, hand gestures, voice commands, and clicks on a one-button bluetooth-connected controller. However, one major drawback of the Hololens 1 is its rather small field of view of only 34° diagonal FOV (corresponds to a 30° horizontal FOV and 17.5° vertical FOV), which is very limited compared to typical human vision which has a (binocular) field of view of almost 180° (Bishoff & Kavoussi, 2016).

Its successor, the **Microsoft Hololens 2**[7] has recently been released in February 2019 and is currently available at a retail price of USD 3,500. This second version of the HMD has been upgraded with improved and new features such as eye tracking, hand recognition, a twice-as-large field of view (52° diagonal FOV, or

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[6] `https://www.microsoft.com/en-gb/p/microsoft-hololens-development-edition/8xf18pqz17ts`

[7] `https://www.microsoft.com/en-gb/hololens`

43° horizontal FOV and 29° vertical FOV, as reported by Heaney (2019)) as well as better ergonomics due to the flip up visor and weight centering at the back of the head (O'Connor et al., 2019). Even though this second version is also not being sold to private consumers, a variety of educational applications for the Hololens are already available for download in the Microsoft Store[8].

One major competitor of the Microsoft Hololens is the **Magic Leap 1**[9], which was released in August 2018 (Rony Abovitz, 2019) and currently retails for USD 2,295. Its main distinguishing feature is its light weight of only 316 grams (compared to the weight of the Hololens 2 at 556 grams), which is made possible since the Magic Leap 1 comes with an external, high-performance pocket computer called "Lightpack" for computing and processing, which is attached to the HMD via a cable and rests on the user's hip (Leap, 2019). Therefore, it is being branded as a "wearable spatial computer" (Leap, 2019), with a diagonal field of view of 50° (or 40° horizontal FOV and 30° vertical FOV, as reported by Heaney (2019)). Additional features include advanced hand, eye and head tracking, spatial audio, spatial understanding and memory as well as a touch-pad-enabled control with haptic feedback and 6 degrees of freedom for interaction. Figure 2.5 depicts the Magic Leap 1 and the Hololens 1 head-mounted display devices next to each other. Figure 2.6 illustrates the differences in horizontal and vertical field of view for the Microsoft Hololens 1, the Microsoft Hololens 2 and the Magic Leap 1, respectively. In order to provide a relative perspective of the limited field of view of these AR headsets, Figure 2.7 shows the field of view of Hololens 2 (which is already double the size from Hololens 1) which appears as a small fraction in relation to the field of view offered by typical consumer VR headsets. However, even modern VR headsets such as the HTC Vive with a 110° FOV (Soffel, Zank, & Kunz, 2016) only encompass a subset of the full 180° field of view we as humans usually experience through our eyes. This relatively small field of view of AR headsets in comparison to human vision is one of the major reasons why current AR experiences do not feel completely realistic yet, as augmented content is being cut off as soon as it is located outside of the head-mounted display's field of view (Zimmer, Bertram, Büntig, Drochtert, & Geiger, 2017).

Apart from hardware devices, appropriate software tools are also required to develop realistic AR experiences. First of all, **Unity3D**[10] is a popular cross-platform game development engine which enables the creation of three-dimensional, interactive environments. In order to allow for cross-platform development

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[8] `https://blogs.msdn.microsoft.com/uk_faculty_connection/2018/02/28/hololens-mr-apps-for-education/`

[9] `https://www.magicleap.com/`

[10] `https://unity3d.com/unity`

Figure 2.5: Comparison of AR HMDs: Magic Leap (left) next to Microsoft Hololens (right), reprinted from 4Experience (2019).

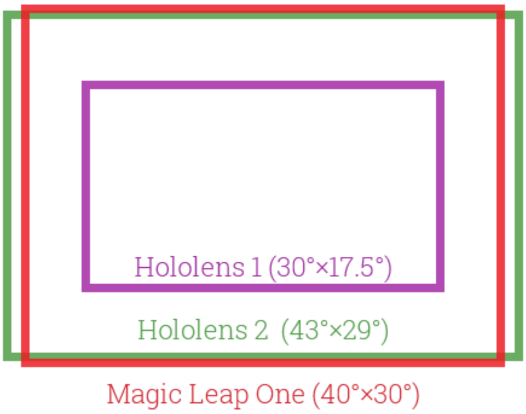

Figure 2.6: Comparison of Field of View for Magic Leap 1, Hololens 1, and Hololens 2, reprinted from Heaney (2019).

within one Unity project for multiple, different AR devices, the Unity package **ARFoundation**[11] can be used.

Recent versions of Unity3D already integrate the **Vuforia Engine**[12], which is one of the most widely used software development kits for AR. Vuforia employs computer vision technology to recognize and track pre-defined image targets and superimpose 3D objects onto them in real-time. Further major software development kits for mobile AR include **ARKit 3**[13] for iOS devices as well as

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[11] `https://docs.unity3d.com/Packages/com.unity.xr.arfoundation@2.2/manual/index.html#about-ar-foundation`

[12] `https://library.vuforia.com/getting-started/overview.html`

[13] `https://developer.apple.com/augmented-reality/arkit/`

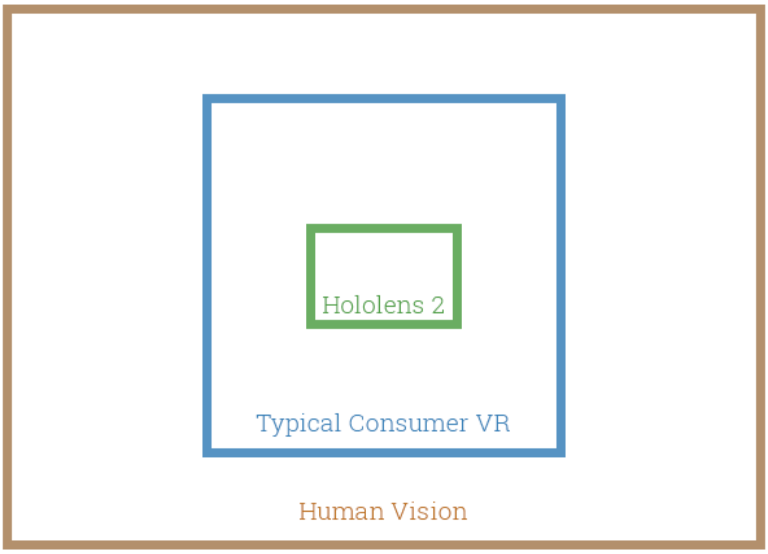

Figure 2.7: Comparison of Field of View for Human Vision, Consumer VR and Hololens 2, reprinted from Heaney (2019).

ARCore[14], the equivalent SDK for Android devices. In order to develop applications for the Microsoft Hololens and other mixed reality headsets, Microsoft offers the **Mixed Reality Toolkit**[15], providing a set of core components and building blocks for user interfaces and user interaction. This toolkit actually presents a major, paradigm-shifting update to its previous version, which is called **HoloToolkit** [16].

Given the availability of appropriate hardware and software tools as mentioned above, it is possible to create useful AR content to improve science education. In the following section, we describe relevant prior work on the use of AR in science education. In particular, we focus on existing AR applications to teach and learn physics.

2.3 Augmented Reality in Science Education

Augmented Reality technology has already found its way into STEM education, as an useful aid to visually support the representation of abstract concepts and illustrate complex topics in 3D. A systematic review on studies about the use

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[14] `https://developers.google.com/ar`

[15] `https://github.com/microsoft/MixedRealityToolkit-Unity`

[16] `https://github.com/microsoft/MixedRealityToolkit-Unity/wiki/HoloToolKit-2017-vs-MixedRealityToolkit-v2`

of AR in STEM education has been conducted by M.-B. Ibáñez and Delgado-Kloos (2018), who have investigated and summarised 28 publications (published between 2010 to 2017) describing AR applications and the corresponding evaluations thereof with students in different levels of education. According to the results of their review, Augmented Reality is most commonly employed for exploration and simulation activities to support the understanding of science phenomena. The 28 reviewed publications used the three following main instructional approaches within AR-based learning environments: (1) instruction through presentation, (2) instruction through self-guided discovery as well as (3) instruction through cooperation and collaboration. Specifically, five main instructional techniques used in these approaches were identified as: observation, inquiry, game, role-play, and concept maps. The main learning outcomes evaluated by the reviewed studies are cognitive as well as affective outcomes, assessing how students acquire and retain knowledge and which emotions they feel. Problems reported in the studies include the need for additional technical training to prepare students and teachers for working with AR technology, possible student distraction related to the novelty effect of AR experiences as well as frequently occurring usability issues, such as slow, non-intuitive system interfaces lacking immediate feedback.

More recently, Garzón, Pavón, and Baldiris (2019) have published a review with a meta-analysis of 61 studies (published between 2012 and 2018) on educational AR applications. In general, their reviews shows the steady growth of publications in the field of AR and also the increasing development and use of AR applications, which, according to the authors, might be related to the wide proliferation of mobile devices capable of displaying AR. Their results from quantitative data analysis indicate a "medium" impact of AR on learning effectiveness and also point out the lack of accessibility features for users with special needs in existing AR applications. Overall, the three most commonly reported advantages of AR in educational settings are improved learning performance (as measured by test scores), followed by an increased motivation to learn, and the possibility to visualize abstract concepts and invisible phenomena, which improves conceptual understanding. Likewise, the most reported disadvantages are related to the complexity of AR systems (which may feel overwhelming to less tech-savy people), technical difficulties while using and managing AR systems as well potential student distraction arising from multi-tasking, all of which might contribute to another challenge Augmented Reality is currently facing: teacher's resistance towards integrating it into the current classroom experience.

Similarly, another review by Knierim, Kosch, Hoppe, and Schmidt (2018) addresses current challenges and future opportunities for Mixed Reality (VR and AR) technologies in education. These immersive technologies have the potential to lower the workload of instructors, as virtual content can be displayed just in time, in a personalized and context-appropriate way for individual students, who can thus acquire new knowledge independently from the availability of external instructors. Especially AR technology, with its blending of real and virtual worlds, can offer cognitive assistance as virtual information can now be presented simultaneously and in view with the physical environment, e.g. during practical laboratory sessions or a lecture recital. However, the type, amount and placement of virtual content within the user's field of view needs to be carefully considered in order to avoid visual information overload and provide an effective learning experience (Diaz, Hincapié, & Moreno, 2015). Another challenge arises with teachers' and students' acceptance towards using emerging technologies like AR and VR for teaching and learning. In addition to these pedagogical challenges, currently available hardware for AR experiences still suffers from technological limitations such as limited field of view, low battery life, and poor user ergonomics for prolonged wear. Even though state-of-the-art hardware devices like the Microsoft Hololens already support multimodal input gestures for user interaction (speech, hand gestures, physical controllers), from a technical point of view it is still a challenge to enable meaningful collaborative interaction among multiple users.

Nevertheless, AR as such is generally beneficial for facilitating collaboration as the very nature of AR essentially makes it possible to combine the real with the virtual world, which then allows learners to simultaneously view digital learning content and maintain face-to-face contact with their peers in the same space (Bujak et al., 2013). Apart from enabling simultaneous views of real surroundings and virtual environments, the use of Augmented Reality can also facilitate other useful aids to improve learning. A prior literature review by Wu, Lee, Chang, and Liang (2013) has identified the five major affordances of AR technology as (1) providing different 3D perspectives, (2) enabling ubiquitous, collaborative and situated learning, (3) increasing the feeling of presence, immersion and immediacy, (4) making the invisible visible, and (5) connecting formal with informal learning. Another key pedagogical affordance of Augmented Reality is the ability to re-scale virtual content (Bower, Howe, McCredie, Robinson, & Grover, 2014). Virtual objects, such as chemical molecules or solar planets, which are originally too small or too large to be examined in the classroom, can be scaled to an appropriate size to be manipulated by students.

The pedagogical value of Augmented Reality is further indicated in literature. For example, Bower et al. (2014) mention that Augmented Reality is particularly useful to support constructivist learning, situated learning, game-based learning, as well as inquiry-based learning. Similarly, Cheng and Tsai (2013) argue that the utilisation of AR within science education can be divided into to main approaches: (1) image-based AR and (2) location-based AR. While image-based AR supports the spatial ability and conceptual understanding of students, location-based AR is better suited to enhance inquiry-based learning activities, such as collecting data outdoors or testing a hypothesis in a laboratory. Regarding the pedagogical impact of educational augmented reality experiences, recent studies with experimental and control groups have shown a significant increase in student motivation (T. Khan, Johnston, & Ophoff, 2019), a positive effect on learning attitude and learning outcomes (Cai, Chiang, Sun, Lin, & Lee, 2017) and higher levels of flow (M. B. Ibáñez, Di Serio, Villarán, & Kloos, 2014) when engaging with educational content in AR.

In order to contribute to the body of prior research discussed above, we also give an exemplary and non-comprehensive overview on existing Augmented Reality applications for science education, with a particular focus on physics education. For this purpose, we have performed a search query on Google Scholar for papers published between 2015 and 2019, which include the keywords *"Augmented Reality" AND "physics" OR "STEM"*. As a result, a total of 16 publications related to our own work have been selected and are being presented in the form of Table 2.2 for 10 applications running on AR HMDs (Microsoft Hololens and others) and in the form of Table 2.1 for an additional 6 applications implemented on mobile, hand-held devices, i.e. smartphones and tablets.

Table 2.1: Overview of papers investigating AR applications on hand-held devices (smartphones, tablets)

Publication	**Topic**	**Type of AR**	**Visualisations**	**Learning tasks**	**Purpose of AR**
Andersson et al. (2016)	Sound waves	Mobile, marker-based	sound waves (transverse, longitudinal), sphere (sound propagation)	observation, conceptual understanding	make invisible visible
Barraza et al. (2015)	Maths: Quadratic equations	Mobile, marker-based	parabola graph, virtual sliders	observation, interaction	provide multiple perspectives on equation plot (from all angles)
Beheshti et al. (2017)	Electricity	Mobile, marker-based	electrons and ions, virtual buttons, text, virtual instrument (multimeter)	observation, interaction, prediction, exploration, explanation	make invisible visible, simultaneous views (circuit + electrons)
Daineko et al. (2018)	Mechanics	Mobile, marker-based	virtual ball with trajectory, virtual arrows, numbers, text input	observation, interaction, concept question	make invisible visible (stone flight trajectory)
T. Wang et al. (2018)	Optic waves (double-slit)	Mobile, marker-based	virtual instruments (light source, screen, slit), numbers, laser beam	observation, interaction	increased mobility and flexibility of double-slit experiment
Wozniak et al. (2015)	Optics (light ray)	Mobile, marker-based	virtual instruments (light source, screens, lens), trajectory of light ray	observation, interaction	make invisible visible (light rays), easily accessible preparation for lab sessions

Table 2.2: Overview of papers investigating AR applications on head-mounted displays

Publication	**Topic**	**Type of AR**	**Visualisations**	**Learning tasks**	**Purpose of AR**
Bodensiek et al. (2019)	Electrodynamics (fine beam tube)	Hololens, markerless	magnetic field, electron beam, numbers, buttons, virtual ruler	data collection, calculation	make invisible visible, simplify and improve measurement handling, provide immediate feedback to user action
Dass et al. (2018)	Programming: Path finding, Hilbert, debugging	Hololens + Mobile, not stated	text, virtual arrows, virtual buttons	observation, interaction	simplify user input, immediate feedback (predictive code execution)
Khan et al. (2018)	Newtonian Physics (Mathland)	Hololens, marker-based	predicted ball trajectory, actual ball trajectory (trail and strobe effect)	observation, interaction	enable real-life like interactions with virtual objects, experience mathematical phenomena in a constructionist way
Lukowicz et al. (2015)	Acoustics	Google Glass, markerless	scatterplot graph for fill level/frequency, numbers, text, virtual slider	observation, data collection	simplify experiment conduction, simultaneous views (equipment + data)
Matsutomo et al. (2017)	Magnetism (2 magnets)	HMD, marker-based	virtual magnets, magnetic field lines, iron core, cone plot	observation, interaction	make invisible visible, show interaction between 2 moving magnets
Minaskan et al. (2019)	Object Motion and Collision (Airtable pucks)	Hololens + projector, marker-based	numbers (Hololens), color-coded pathlines (projector)	observation, interaction	simplify data computation, display live data on velocity
Radu and Schneider (2019)	Electromagnetism (audio speaker)	Hololens, marker-based	magnetic field lines, sound waves, moving electrons, text, graph	observation, interaction	make invisible visible, simultaneous views (magnetism + electricity)
Strzys et al. (2018)	Heat Conduction (metal rod)	Hololens, marker-based	temperature, numbers, buttons, graph	observation, calculation	make invisible visible, simultaneous views (equipment + data)

Continued on next page

Table 2.2, *Continued from previous page*

Publication	**Topic**	**Type of AR**	**Visualisations**	**Learning tasks**	**Purpose of AR**
Ueda and Kawada (2019)	Magnetic Field	Hololens, markerless	magnetic field lines, azimuth needles	observation, interaction	make invisible visible, possibility for shared virtual experience among multiple users
Yoon et al. (2017)	Aerodynamics	AR mirror, markerless	virtual ball, virtual arrows for airflow	observation, conceptual understanding	make invisible visible (air flow)

As can be seen in the selection of AR applications presented above in Table 2.1 and Table 2.2, educational content in a variety of different science topics, mostly related to physics, is being augmented. The selected AR applications for head-mounted displays and projective AR devices are implemented using both marker-less and marker-based AR, while the selected mobile AR applications rely on marker-based AR only. Most selected visualisations employ the use of AR in order to make invisible phenomena visible and to facilitate interactive observation as a learning task.

In the field of physics, Augmented Reality can help to make abstract and invisible concepts such as heat conduction, energy, or electromagnetism visible to the human eye. One way of enhancing conceptual understanding of complex physical phenomena like these is through incorporating dynamic visual representations in Augmented Reality, as is illustrated in the following examples being described in more detail.

For instance, Strzys et al. (2018) have developed a Microsoft Hololens application which augments the temperature and heat conduction along a metal rod in real-time, using data captured by an Infrafred-camera. Essentially, this represents an extension of human vision by changing the representation of a quantity, as humans can generally not see heat nor temperature. By using the Microsoft Hololens to directly overlay the augmentation on physical parts within users' field of view, cognitive load is reduced and the split attention effect can be avoided (Dixon, Terton, & Greenaway, 2018). In a pilot study, Strzys et al. (2018) also investigated the effect of the use of Mixed Reality on learning with a total of 59 students (divided into experimental and control groups) and concluded that using the Microsoft Hololens has a limited, yet positive impact on improving students' understanding of heat transfer and thermal conduction. Currently, expensive hardware costs for the Microsoft Hololens as well as high necessary programming effort to integrate sensor data still pose open challenges for a wider use of augmented experiments in science laboratories. There is potential for future research to augment other, more complex science experiments and further validate the impact of AR on reducing cognitive load and improving conceptual understanding.

With regards to magnetism, a Hololens application visualizing virtual bar magnets, magnetic field lines (in 2D and 3D) and azimuth needles (varying in brightness to indicate the strength of a magnetic force) has been developed by a Japanese researcher and former physics teacher who has also evaluated this application with 300 students at 10 schools in 5 countries. In a blog post, the developer Ueda (2018) reported on high student satisfaction and interest when using this Hololens application to teach concepts about the strength and direction of magnetic fields. The same developer also published a scientific paper on this work, written in Japanese language (Ueda & Kawada, 2018).

This application has been released for download in the Microsoft Store as "HoloMagnet"[17]. Currently, the code of this Hololens application is also available open-source on GitHub[18], with open issues indicating that there is the demand for porting the same application to several other AR platforms, such as the Magic Leap headset or Android smartphones using ARCore.

Similarly, Matsutomo, Manabe, Cingoski, and Noguchi (2017) implement an innovative approach towards real-time 3D visualisation of magnetic field lines from multiple electromagnetic sources. Their application runs on an unnamed HMD with an attached web camera, allowing users to move virtual magnets via physical, tangible markers and observe the resulting interference phenomena. These markers are used to identify the positioning of the virtual magnets. Then, the magnetic field distribution is calculated in real-time via a combination of several mathematical methods which ensures that magnetic field lines are accurately drawn and dynamically updated in real-time, even during interactive movement of the virtual magnets via the markers.

Concerning the topic of electrodynamics, Bodensiek, Sonntag, Wendorff, Albuquerque, and Magnor (2019) have developed an experimental setup with a fine beam tube where the Microsoft Hololens is used to record and display measurement data. Here, a virtual ruler is used to determine the radius of an electron beam, supplemented by visualisations of predicted electron beams and a magnetic field as vector plot. This augmented lab experiment with virtual instruments resulted in more accurate measurement results when compared to measurements taken using a physical ruler. The only issue mentioned by the authors is the need to adapt external lighting conditions in order to ensure good visibility of all holograms.

Augmented reality has also been implemented for use in unstructured learning activities. Radu and Schneider (2019) have developed a collaborative Hololens application to let students explore the internal physics phenomena hidden inside audio speakers, with visualisations for multiple phenomena: amplification, magnetic fields and electricity. They evaluated different versions of the experimental setup with varying levels of (educational) AR content (including non-AR), among them a scaffolding version, which sequentially adds educational AR content to the learning experience. Results have shown that augmented versions are significantly more effective in improving student's attitudes towards learning physics and spatial understanding, probably due to the possibility for simultaneous exposure to multiple concepts. However, the study results also indicate that the use of AR might not always be more effective for an already well-designed experiment, as participants in non-AR conditions

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[17] `https://www.microsoft.com/de-at/p/holomagnet3/9pff2nq2t708`

[18] `https://github.com/feel-physics/HoloMagnet3`

also reported motivation, learning gain and positive attitudes. Concepts such as the relationship between physical motion and magnetic fields were even understood better in the absence of AR, as rich visualisations might have distracted students from the kinesthetic information.

In another study, Minaskan, Rambach, Pagani, and Stricker (2019) have enhanced a traditional physics experiment with colliding pucks on an airtable with two versions of Augmented Reality: a HMD-based single user experience with the Microsoft Hololens in a university's physics laboratory as well as a shared, multi-user experience using projective AR in a science museum. The aim was to make users understand the laws behind object motion and collision, by augmenting the experiment with numerical values (Hololens) and color-coded pathlines (projective AR) for angular velocity, velocity and kinetic energy. The results of their evaluation have shown that projective AR with a fixed, wide-angle camera is better suited to augment this dynamic, fast-motion experiment, as the limited field of view of the Hololens makes it very difficult to follow and track objects at high velocity. Instead, an HMD like the Microsoft Hololens is more suitable to augment stable experiments with static elements.

Looking at conveying the laws of optics, T. Wang, Zhang, Xue, and Cai (2018) have presented a virtual version of the well-known double-slit experiment with optic waves, which can be performed at any time, from anywhere on smartphone or tablet devices, thus eliminating the need for special lab equipment and lab hours. The visualisations of a light source, light ray, fluorescent screen and double slit also allow users to adjust parameters and observe changing light phenomena, while numerical values of relevant parameters (distance, wavelength) and the corresponding mathematical formulas are displayed alongside. Preliminary pilot tests have demonstrated that this use of AR facilitates teaching as it makes students more interested and attracted towards the experiment, a fact which should be further evaluated with a larger sample size and integrated into an inquiry-based learning activity.

Similarly, Wozniak, Vauderwange, Curticapean, Javahiraly, and Israel (2015) propose a marker-based mobile application to perform light and optics experiments in Augmented Reality. Through visualisations of a virtual optical bench, light source and screen, users can observe refraction and reflection along the path of light ray and also interact with the experiment by moving and adjusting lens type, focal length, refractive index and other characteristics.

Augmented Reality also has the potential to embody mathematical concepts in everyday, physical surroundings. The paper by M. Khan, Trujano, Choudhury, and Maes, 2018 presents an innovative application which uses a Microsoft Hololens in combination with a custom-built arm controller and object controller for tangible user interaction. It allows users to interact with virtual objects just like in real-life, e.g. by moving their physical arm to throw a virtual ball. In this application, users learn about Newtonian physics (an area of applied mathematics) by constructing and manipulating their own virtual world with virtual force fields, ramps, cubes, ropes and balls.

Overall, these selected examples provide AR content for learning about a wide range of different science topics, mostly within the field of physics. In conclusion, the 16 examined related works (as listed in Table 2.1 and Table 2.2 and partly described in more detail in the preceding paragraphs) can be analysed as follows:

Almost all of the selected papers are describing learning scenarios where the user's task is to observe a certain physical phenomena which is being augmented with one or multiple types of visual representations. More specifically, Augmented Reality is used to enable observation of usually invisible concepts (such as magnetic field lines, light waves, or electrons and ions) in a real-life context and in situations where these phenomena are occurring naturally (such as sound waves being emitted from an audio speaker). As seen in literature, another important occurring feature of the developed AR apps is the interactivity they offer to users who can interact either with the virtual AR content itself or control it through two-dimensional UI elements (on mobile displays).

A commonly stated benefit resulting from the use of augmented reality for educational experiences is the possibility to maintain a simultaneous view on both physical equipment and generated data or scientific quantities, thus ensuring spatial continuity and avoiding a split attention effect. Additionally, applications for HMDs such as the Microsoft Hololens also offer the benefit of hands-free use, whereas AR applications designed for smartphones or tablets provide better mobility and easier access due to the wide prevalence of handheld mobile devices.

Even though existing literature has already pointed out the potential of AR to improve science education, there are still open problems to be addressed. These are mostly related to technical aspects (such as high hardware costs and limited field of view for HMDs, necessary programming skills to author AR experiences, tracking stability) and usability issues such as non-intuitive or too small interfaces and the possibility of distraction due to the novelty effect of AR technology.

Regarding the tracking technology for AR, the reviewed applications indicate a trend towards marker-based AR with fiducial markers which is being employed by each of the reviewed applications for mobile devices and the majority of those for head-mounted displays; whereas only four of the reviewed applications are relying on marker-less AR, which uses location data or natural environment features for tracking.

While the implementation and evaluation of augmented reality applications is thoroughly described from a technical and methodological point of view by most examined papers, the underlying didactic concepts and instructional strategies (if applicable) were mostly not stated explicitly, but might be vaguely inferred from usage or learning task descriptions. Hence, the two main occurring pedagogical approaches are inquiry-based learning and exploratory learning, as described earlier in Section 2.1.2. The selected AR applications either encourage learners to freely explore and observe (multiple) representations of simulated phenomena, or to engage in scientific inquiry by making predictions, collecting data, changing parameters and examining phenomena under varying conditions.

However, one limitation notable among this range of related work is the lack of multi-platform availability, with only two applications implemented to run on two different AR devices (Minaskan et al. (2019), Dass, Kim, Ford, Agarwal, and Chau (2018)). Moreover, the experimental setup of most studies compares an AR condition to a non-AR condition. Among our reviewed studies, only Dass et al. (2018) evaluate an AR experience on two different AR devices, comparing a Microsoft Hololens against an iPhone.

Another relevant issue to be considered is the fact that most of the reviewed publications do not explicitly state why Augmented Reality in particular, and not some other technology, has been chosen to enhance a learning experience. Instead, most AR applications are implemented without relying on a (design) guideline or framework to consider which type of visual augmentations are indeed meaningful to support learning tasks and achieve a certain educational purpose. When designing an AR application, it is useful to think about the relation between a learning task at hand and the specific purpose of using AR to enhance it. It is important to consider the reason for employing AR technology, for example by stating which kind of action or affordance is enabled or improved through the use of AR and considering whether this helps learners in achieving certain tasks. In this context, it can be useful to know which type of visualisation is recommended for effective augmentation of a specific learning task, given the wide range of possible visualisation types[19].

By drafting a framework for recommended AR visualisations in learning contexts and using it to develop interactive AR experiences on magnetism accordingly, followed by a preliminary user evaluation on Microsoft Hololens as well as on an Android smartphone, this thesis aims to facilitate the design of useful learning visualisations in AR, make augmented physics education accessible to

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[19] These thoughts have been discussed by the thesis author and research colleagues during research meetings in January and March 2019 at the University of Sydney and are further discussed in Chapter 3.

a broader audience and contribute towards a better understanding of hands-free and handheld AR applications.

2.4 Summary

Today's world is transforming rapidly and professionals with skills in Science, Engineering, Technology, and Mathematics are more in demand than ever. However, there is a lack of graduates with STEM degrees as students often lose interest and motivation to study these subjects. In order to counter this development, it is important to make STEM education more engaging and interesting to a new generation of learners who have grown up surrounded by digital media. Instead of relying on passive lecturing, today's learners need to be actively involved in the learning process in a student-centred, teaching approach called "active learning", which has been shown as more effective to improve learning performance. It can be encouraged through various strategies: Technology-Enabled Active Learning (TEAL) integrates visualisations, simulations, hands-on experiments, and collaborative group work into lectures to make the traditional physics class more interactive and engaging. Motivational Active Learning (MAL) supplements the TEAL approach with various gamification elements to increase student motivation. In inquiry-based learning, students actively construct their own knowledge by solving problems and answering questions, in a process similar to the scientific method. Learning by doing essentially involves the creation of experiences which is important for experiential learning and exploratory learning within immersive environments. In order to create a more flexible, digital and self-directed learning experience for today's students, these pedagogical models can be supported by various technologies: The wide prevalence of smartphones makes information available anywhere and at anytime, thus enabling mobile learning. Digital game-based learning uses educational games and gamification strategies to encourage trial and error and provide immediate feedback and adaptive scaffolding, which keeps learners engaged and motivated. Virtual Reality technology enables the creation of highly motivational, immersive and interactive learning environments, such as the virtual physics laboratory "MaroonVR". While Virtual Reality completely immerses users into a purely digital environment, Augmented Reality does not disconnect users from the real world. Instead, AR overlays the real world with virtual entities and enables natural, real-time user interaction. A wide variety of (educational) applications use image-based or location-based AR on handheld devices, projective displays, or head-mounted displays such as the Microsoft Hololens. In science education, Augmented Reality enhances exploration or inquiry-based activities where it is used to make usually invisible phenomena visible and illustrate abstract concepts in 3D, while allowing students to maintain a simultaneous view of their physical surroundings. This improves students' conceptual and spatial understanding and makes it easier to connect the observed phenomena to real-life situations.

In order to facilitate the design and development of meaningful augmented reality applications for education, the next chapter proposes a framework providing guidance on the use of AR visualisations within learning contexts.

3 Towards a Framework for Visual Augmentation in Education

Augmented Reality (AR) as such is not fully immersive per se, but it has the power to combine the real with the virtual world. The use of AR now makes it possible to overlay the real world with interactive visualisations and simulations of otherwise invisible physical phenomena (such as magnetic field lines, heat or nuclear atoms) or abstract concepts, such as complex geometric shapes or polynomial equations (Barraza Castillo, Cruz Sánchez, & Vergara Villegas, 2015). These simulations and visualisations can be used to promote active learning, which is a learning approach known to improve student engagement and learning outcomes (Freeman et al., 2014). When designing educational augmented reality applications, it can be overwhelming or difficult to choose which type of visual augmentations to include in order to provide a meaningful learning experience where Augmented Reality is actually aiding the learning activity and not hindering it with information overload (Pascoal & Guerreiro, 2017). Therefore, this chapter aims to propose a preliminary framework for deciding which kind of visual augmentations to use in order to achieve different, educational augmentation purposes.

3.1 Theoretical Basis

Understanding abstract and complex phenomena is an integral part of STEM education (Sari, Sumantri, & Bachtiar, 2018). Yet, it can be challenging to convey an understanding of these phenomena within the limited, two-dimensional realm of textbooks and blackboards (Strayer, 2007). Augmented Reality can be a valuable tool to represent interactive visualisations of these phenomena within three-dimensional space, thus supporting conceptual and spatial understanding. In accordance with the exploratory learning model established by De Freitas and Neumann (2009) and discussed in Section 2.1.2 of this thesis, users are free to explore and interact with visualised phenomena from multiple perspectives and view them in multiple representations. For instance, using Augmented Reality, the magnetic field surrounding a magnet can be observed from different angles and through multiple visual representations, i.e. in the form of an iron filling, a vector field, or magnetic flux lines. Given the many possibilities for visual representation of scientific concepts, determining which type of visual augmentation to choose in order to create an effective learning experience can be a difficult and overwhelming task. Hence, it could be useful to be able to rely on a framework offering a list of possible visual augmentation types, including a mapping to which different augmentation purpose the individual visual augmentation types are suited for.

Prior work has already proposed two ways for classifying visual augmentation types in the context of science laboratory settings: according to Lowe and Liu (2017), the "role of augmented reality in laboratory experimentation" can be categorised according to (1) the nature of their augmentation functionality ("enabling an augmented perception of reality, or creating an artificial environment") or to (2) the nature of augmentation information ("text, 2D, or 3D visualisations"). Based upon this categorisation, Lowe and Liu (2017) then identified specific classes of experimental augmentation (such as annotations, phenomena representation, virtual equipment) as well as meaningful opportunities for augmentation[1] within educational laboratories (such as comparative modelling, making the invisible visible).

While Lowe and Liu (2017) provide both a classification system as well as exemplary classes of visual augmentation types, the authors only indicate that the presented augmentation types "might be feasible and useful" - they do not offer any recommendations or suggestions on when to use which kind of augmentation type. For visual augmentations and visualisations in general, a careful consideration of their purpose should drive their design (Andrews, Pirker, & Sabol, 2014). In order to design meaningful learning experiences, it is important to consider which visual augmentation types are suitable for augmenting a learning activity in such a way that a certain purpose can be achieved.

Building upon the augmentation opportunities and examples established by Lowe and Liu (2017), this thesis tries to fill the existing gap by presenting a framework called **"Advanced EDU-AR-VIZ Framework"**. This framework can be used as a structured workflow, providing guidance for choosing appropriate visual augmentations to effectively reach educational goals.

The following three questions form the theoretical backbone for the proposed framework:

1. **What** kind of learning activity should be augmented?

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[1] In our own work, we later refer to these mentioned opportunities as *augmentation purpose*.

2. **Why** is augmentation needed for this learning activity? (i.e. What purpose does the augmentation fulfill?)
3. **How** can this learning activity be augmented? (i.e. Which types of visual augmentations are recommendable and which ones are not recommendable, in order to fulfill a certain augmentation purpose)

These three questions can be seen as an orientation for developers of educational AR applications. Before starting the design process, they should ask themselves these questions. Our proposed framework itself may then be used as a starting point to find possible answers to the second and third question.

The first question deals with **learning activities**, such as for instance the question-driven activities of inquiry-based learning, an active learning approach which is frequently supported by Augmented Reality technology and described in more detail in Section 2.1.2. Hereby, one should consider the mentioned learning activities within a broader context, as each learning activity, or rather a sequence of coordinated learning activities, can help to achieve a particular learning goal (Hawryszkiewycz, 2003).

The second question deals with the **purpose of augmentation**. A learning activity should be augmented not just for the sake of using AR technology, but rather to achieve a specific purpose, which ultimately leads to a better educational outcome (Lowe & Liu, 2017). Hereby, our framework proposes four distinct purposes to choose from which are listed below. These purposes have been adapted from previous work published by Lowe and Liu (2017), who listed these as examples to illustrate the opportunities for augmentation within laboratory settings:

- Make the Invisible Visible
- Enable Comparative Modelling
- Draw User Attention
- Create Artificial Reality

The third question arises from a list of possible high-level **visual augmentation types** and the corresponding, specific examples for each type. These examples have been collected through a review of related work in Chapter 2 and are presented below in Table 3.1, categorised into different classes of visual augmentation types.

Table 3.1: Overview of visual augmentation types and corresponding examples with sources.

Visual augmentation type	Examples	Sources
Add virtual information to physical object	overlay organ locations and names on top of a body, display current velocity of moving objects	K. Lee (2012); Minaskan et al. (2019)
Represent physical phenomena	magnetic field around a magnet visualised with field lines, azimuth compass needles, or vector field; false-color representation of temperature; moving electrons and ions; sound waves	Ueda and Kawada (2018), Matsutomo et al. (2017); Strzys et al. (2018); Radu and Schneider (2019), Beheshti, Kim, Ecanow, and Horn (2017); Andersson, Anker, Dunford, Lundqvist, and Weiss (2016);
Visualise alternative model for comparison	visualize "ghost" model, visualize predicted vs. actual trajectory of motion	Lowe and Liu (2017); M. Khan et al. (2018), Daineko et al. (2018);
Visualise simulated scenarios	virtual version of double slit and optical lens experiment; dynamically changing parabola equation, airflow around virtual ball	T. Wang et al. (2018), Wozniak et al. (2015); Barraza Castillo et al. (2015); Yoon, Anderson, Lin, and Elinich (2017);
Display hint	highlight important physical area	Lowe and Liu (2017),
Display instructions	step-by-step text, animations	Dass et al. (2018), Lukowicz et al. (2015); Diaz et al. (2015)
Modify space	visualize virtual liquids or virtual instruments (ruler, scale, multimeter)	Lowe and Liu (2017); Bodensiek et al. (2019); Lukowicz et al. (2015); Beheshti et al. (2017)
Modify time	visualize process in slow-motion	Tao et al. (2018)

Each of these visual augmentation types can be recommended to achieve one of the augmentation purposes mentioned previously. It is important to distinguish between these visual augmentations, seeing them as distinct types suited for different purposes. For instance, visual augmentations which add virtual information to a physical object might be more useful to aid the observation of usually invisible physical phenomena, such as the magnetic field around a bar magnet. Other augmentation types such as visualising "ghost" models, might be more suited for comparative modelling when generating and testing a hypothesis, i.e. when the user has entered a formula calculating the trajectory of motion of a ball and wants to test this prediction against the actual flight trajectory.

3.2 Practical Workflow

Bringing these three questions together, a systematic workflow for using the framework can be established, as illustrated in Figure 3.1. First, select which learning activity is to be augmented, then decide on the purpose of the augmentation and based on this purpose, select one of the recommended visual augmentation types, with concrete examples of each type listed in Table 3.1.

Figure 3.1: Schematic process with three questions guiding towards the right visual augmentation.

These three questions visualised as workflow in Figure 3.1 are related to each other as follows: Each mentioned learning activity can be augmented to achieve a certain purpose. In turn, each purpose of augmentation can be fulfilled by certain visual augmentation types. Employed correctly, this makes sure that the included augmentations indeed serve a specific purpose, i.e. there is a good reason why a certain learning activity is being augmented with a particular visual representation in AR.

Due to the limited scope of this thesis, our proposed framework only deals with the latter two questions in more detail, by providing a list of possible visual augmentation types (as high-level concepts, with specific examples) for each of the four mentioned augmentation purposes. The first question, dealing with the kind of learning activities which shall be augmented, is left open to be addressed by future work. Future work should investigate which kind of learning activities can be put into relation with specific purposes of augmentation, i.e. which augmentation purpose makes sense for which learning activity. Furthermore, researchers are encouraged to find and validate recommended visual augmentation types which can fulfill the corresponding augmentation purpose for a particular learning activity.

In order to better illustrate the current state of the proposed framework, it is presented in a visual form in Table 3.2. Two possible visual augmentation types (as high-level concepts, specified with examples in Table 3.1) are recommended for each of the four augmentation purposes, which themselves are being described in more detail by Lowe and Liu (2017).

To explain the **"Advanced EDU-AR-VIZ Framework"** more specifically, each of the visual augmentation types is being listed with concrete examples and

ADVANCED EDU-AR-VIZ FRAMEWORK

	Augmentation Purpose (adapted from Lowe & Liu, 2017)			
	1) Make Invisible Visible	**2) Comparative Modelling**	**3) Draw User Attention**	**4) Create artificial reality**
Visual Augmentation Type	Add virtual information to physical object	Visualise alternative model for comparison	Display hint	Modify space
	Represent physical phenomena	Visualise simulated scenarios	Display instructions	Modify time

Table 3.2: Framework for choosing appropriate visual representations (listed here as high-level concepts) to fulfill a particular augmentation purpose.

corresponding sources in Table 3.1, some of which are being described in more detail in the following paragraphs:

In order to make invisible things visible, it can be useful to add virtual information to physical objects. Virtual information can encompass various forms such as text, numbers, models, or symbols. Properties of physical objects which can not be directly observed thus become visible to learners. For example, a swinging, physical pendulum can be augmented with virtual, dynamic vectors showing the usually invisible forces of gravity and tension (Lowe & Liu, 2017); or a human body can be overlaid with virtual organs and their corresponding names to support the study of anatomy (K. Lee, 2012).

Physical phenomena such as magnetism, heat, or electricity are usually invisible and therefore augmentation can be used as a visualisation tool to depict them in multiple representations. For instance, a bar magnet can be augmented with virtual magnetic field lines, azimuth compass needles, iron fillings or vector field arrows to illustrate its surrounding magnetic field (Ueda & Kawada, 2018; Matsutomo et al., 2017). Another example is the visualisation of heat and current temperature on a metal rod, using a false-color representation, which is essentially extending human vision to a new realm of ”seeing” heat and temperature (Strzys et al., 2018).

In order to enable comparative modelling, Augmented Reality can be used to ”merge both real and virtual experiments” (Lowe & Liu, 2017). For example, when students predict the path of a swinging pendulum by generating a formula for its motion, then this predicted ”ghost” model is being visualised on top of a real pendulum for comparison. Similarly, the trajectory of motion of a virtual ball can be visualised with a ”trail and strobe” effect and then these snapshots can be compared to one another to show a change in velocity and motion (M. Khan et al., 2018).

In a broader sense, comparative modelling can also be achieved by simulating virtual scenarios, such as the virtual version of a real experiment showing light refraction and reflection through an optical lens (T. Wang et al., 2018). Students can carry out the virtual version of the experiment outside of school as practice and preparation for the real experiment in the laboratory (Wozniak et al., 2015).

In order to draw user's attention to important events or areas whenever necessary, displaying (textual) hints or instructions can be a useful augmentation type. For example, a virtual arrow indicating into which direction the user should be looking next or highlighting a currently selected virtual object can help users to orient themselves in the augmented world. While performing or setting up an experiment, the corresponding instructions (in the form of animations or text) can be displayed step by step and just-in-time at the correct location, thus avoiding the split attention effect (Strzys et al., 2018).

Finally, Augmented Reality can be used to create an artificial version of reality, by visualising something that would otherwise not be present in the context and thus modifying space, or modifying time. For example, virtual instruments such as a ruler used with Augmented Reality can replace the need for a physical ruler and even lead to more accurate measurements, as investigated in a publication by Bodensiek et al. (2019). Similarly, the path of motion of an object can be visualised as a trace played back in slow-motion, thus adding an additional fourth dimension (i.e. time) to three-dimensional visualisations (Tao et al., 2018).

To validate the practical application of the proposed framework, this thesis aims to examine only one particular visual augmentation type, namely the representation of physical phenomena in order to make the invisible visible, and investigate via user evaluations whether this is a recommendable augmentation or not. To this end, we consider the example of a magnet and its magnetic field as practical application, as discussed in Chapter 4 of the thesis. Now, in our proposed framework we have hypothesized that visual augmentations of the type *"add virtual information to physical object"* or the type *"represent physical phenomena"* are recommendable to fulfill the purpose of *making the invisible visible*. In order to validate this hypothetical claim, we design an augmentation which adds virtual field lines and a vector field to a physical or virtual magnet. Then we evaluate the effectiveness and usability of such a visual augmentation through empirical user studies, as discussed later in Chapter 5.

Similar to this approach, future work should, for instance, investigate whether it is recommendable to visualise predicted models to enable comparative modelling; or whether it is recommended to display animations rather than textual hints in order to gain users' attention. Ultimately, a complete framework should offer guidance and support learning by making it easier to make design decisions for effective visual augmentations which are not just fun to look at, but also educationally appropriate for specific learning activities because these are being meaningfully enhanced by the chosen augmentations.

3.3 Summary

In this chapter, a preliminary framework to choose educational augmentations in order to achieve certain augmentation purposes for learning activities has been proposed. The core of the framework rests on three guiding questions, which together try to answer the question of how to choose appropriate visual augmentations, according to specific learning tasks and purpose of augmentation.

It is important to note that the framework presented in this chapter is not complete. Instead, it only presents possible answers to two of the three guiding questions, together with several hypothetical recommended visual augmentation types for each augmentation purpose. Only one particular case is being validated through a practical implementation and evaluation.

The remaining possible combinations of purpose of augmentation and visual augmentation types still need to be validated by future work in order to find out if the proposed visual augmentations are indeed recommendable (or not recommendable) to achieve particular purposes. Moreover, this framework should be extended to include a mapping from augmentation purpose to learning activities as an additional dimension. Researchers should see this framework as a starting point for future work and design their AR applications in such a way that this framework can be extended with further useful recommendations for visual augmentations, and even non-visual augmentations, in areas such as sound and haptics.

The following chapter will consider the practical application of the proposed framework with one example application being implemented according to the framework's workflow.

4 Design and Development

This chapter provides an overview about the design and development of an multi-platform Augmented Reality (AR) application, running on Android smartphones as well as on the Microsoft Hololens. This AR application has been implemented as a single, demonstrative use case to illustrate the usefulness of the visual augmentation framework described in the previous chapter. As a starting point, we outline the fundamental design decisions taken while adhering to suggestions from the visual augmentation framework and discuss an existing, educational Virtual Reality (VR) application, which has served as a content-wise inspiration. Next, we describe the target user group, before defining both functional as well as non-functional requirements of the AR application and presenting the conceptual design of the AR application. Then we briefly present the software tools and frameworks used in order to implement the chosen design, followed by an explanation of the application's conceptual architecture and further relevant implementation details.

4.1 Basis and Motivation

In order to validate the practical application of the ”Advanced EDU-AR-VIZ Framework” proposed in Chapter 3, we are addressing the following three questions according to the workflow suggested by the framework: (1) what to augment, (2) why to augment it, and finally, (3) how to augment it. More specifically, we start the design process of our AR application by first determining what kind of learning activity is to be augmented, then justifying the planned augmentation with a particular purpose (suited to aid the learning activity), before deciding to implement a particular visual augmentation type which, according to our framework, is (tentatively) recommended to fulfill the aforementioned augmentation purpose.

To begin with, we have drawn inspiration from an existing, multi-platform Virtual Reality physics laboratory called ”MaroonVR” in order to determine the scientific content and type of the learning activity we wish to augment. MaroonVR offers interactive experiments with simulations and visualisations on electromagnetism concepts and allows students observe and explore these usually invisible concepts in a completely virtual, immersive environment using Virtual Reality technology (Pirker et al., 2019). The particular variant of MaroonVR from which we draw inspiration is designed to offer a room-scale VR experience on the HTC Vive[1] VR headset. In previous user studies, Pirker, Holly, et al. (2018) and Pirker, Lesjak, Parger, and Gütl (2018) have already evaluated the effectiveness of MaroonVR and shown its positive impact in increasing student's motivation, engagement and learning outcomes in physics classes. According to Pirker, Lesjak, and Gütl (2017), visualising complex physics phenomena such as electric charge and magnetic field lines in a dynamic and three-dimensional way supports students conceptual understanding. Moreover, showing these visualisations in immersive Virtual Reality avoids distractions from the outside world and therefore helps students to focus better on the learning task at hand.

While both Virtual Reality and Augmented Reality have the potential to transform the learning process, it is important to note that VR and AR are two fundamentally different technologies, with different educational use cases applying to each. Learning environments in VR make it possible to immersively experience scenarios which are too dangerous, too expensive, or too difficult to experience in real reality. Using VR, it is possible to easily re-create settings which are not readily available in real-life classroom settings, such as looking at a Tesla coil in its full size, navigating the solar system or operating a nuclear reactor. Augmented Reality, in contrast, can be particularly useful to further incorporate the physical environment into the learning process by extending currently already existing learning environments with an additional augmented dimension. Instead of re-creating a full artificial (virtual) reality, AR can be used to augment existing real-life set-ups, such as printed textbooks, printed hand-outs or physical laboratory experiments which are usually already present in classrooms anyway. AR applications enable learners to immediately try out the augmentations in relevant situations. For example while reading a textbook containing image markers, learners can point their smartphone at these image markers, and then printed, static content is brought to life in the form of dynamic, interactive visualisations in three-dimensional space.

For our proposed Augmented Reality application (which should be regarded as a first proof-of-concept prototype, rather than a fully-fledged augmented version of a physics laboratory), we have decided to visually augment the magnetic field around magnets, which is one of the visualisations also available in the virtual MaroonVR laboratory. In both, the Virtual Reality environment of MaroonVR and our proposed AR application alike, the addressed learning activity is to actively explore and observe such electromagnetic phenomena like magnetic field strength and magnetic field lines. As discussed in Chapter

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[1] `https://www.vive.com/eu/product/vive/`

2, the act of observation can be regarded as one phase in the inquiry-based learning cycle, a learning method common in scientific subjects (Pedaste et al., 2015), while active exploration is a crucial element during exploratory learning in immersive environments (De Freitas & Neumann, 2009). To answer the first question of our framework (i.e. what learning activity to augment), we can state that the learning activity to be augmented by our AR application is the *observation and exploration* of magnetic fields around magnets.

As far as the second question of our framework is concerned (i.e. why to augment something?), we can refer to one of four augmentation purposes proposed in our framework to find an answer. In our practical example, the purpose of augmentation is to *make the invisible visible*, i.e. to visualise the usually invisible magnetic field around magnets using AR, which supports the aforementioned learning activity of observation and exploration. With the aid of AR, learners can easily view and interact with a three-dimensional representation of a magnetic field around a magnet without being isolated from the physical world, allowing them to connect the observed phenomena towards real-life situations such as examining real magnets.

According to our proposed framework depicted in Table 3.2, there are two visual augmentation types recommended to achieve our chosen augmentation purpose of visualising the invisible: augmentations that (a) add virtual information to physical object or (b) represent physical phenomena. As we develop our AR application only as an initial prototype, we have decided to implement only one particular visual augmentation type in this first prototypical stage, namely the representation of physical phenomena in the form of virtual field lines and vector field arrows around virtual magnets. This *representation of physical phenomena* constitutes the answer to the third question of our framework, regarding possible visual augmentation types. Ultimately, we plan to investigate whether this particular visual augmentation is indeed recommendable or not by evaluating its usability and user satisfaction via experimental studies, as discussed later in Chapter 5.

Summing up, our Augmented Reality app is designed to facilitate the observation and exploration of magnetic fields by making them visible in the form of magnetic field lines and vector fields around bar magnets. We have decided to implement our AR app on two different AR devices, which are (1) the Microsoft Hololens[2], a state-of-the-art AR headset and (2) the Google Pixel 3a[3], a mid-end Android smartphone released in May 2019. The reason why we have decided to implement our AR app on two different AR devices is to explore and investigate the different use cases for different types of AR. Two fundamentally different

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[2] `https://docs.microsoft.com/en-us/hololens/hololens1-hardware`

[3] `https://store.google.com/?srp=/product/pixel_3a`

approaches towards AR are employed on each of our chosen AR devices. On the mobile, hand-held Android smartphone the marker-based AR approach is being used, i.e. the interaction with AR content happens indirectly through a tangible interface, such as a printed marker image acting as image target for the virtual content. On the hands-free, head-mounted Microsoft Hololens device, marker-less AR is employed, i.e. the virtual content is not attached to any markers, but instead anchored in physical space and users can interact with the virtual content directly via hand gestures.

When designing an Augmented Reality experience, it is also important to consider which features it should include to meet the needs of its users. The following sections will elaborate on its primary audience and the resulting software requirements.

4.2 Target User Group

The main target user group are high-school students aged 15 to 18 who are learning about magnetism according to their school's physics curriculum. These students often find studying STEM subjects such as physics uninteresting and difficult, struggling to understand abstract concepts and complex formula (Angell et al., 2004). In addition, today's generation of students prefers to learn in a more visual, flexible and engaging way (Prensky, 2001). The nature of Augmented Reality, especially on mobile phones, addresses the need for a visual-based and flexible learning mode and also makes it easier to understand abstract concepts and relate mental models to real life by augmenting the physical world with interactive, virtual visualisations and simulations, which can be more exciting and interesting for learners than traditional static textbooks. As our AR application is being developed for educational use in schools and universities, teachers and educators are naturally also part of the target group. Nevertheless, the experimental nature of the developed AR applications should be of interest of anyone who wants to explore and visualise interactive magnets and magnetic fields in three-dimensional space. Based on the aforementioned characteristics and needs of the primary target audience, the following sections will define and analyse requirements of an AR application designed with the target group in mind.

4.3 Requirement Analysis

According to Sommerville (2011), requirements analysis is the process of defining the necessary features and behaviour of a system, according to the needs of its primary target audience. While functional requirements describe what a user should be able to do in the system, non-functional requirements provide a view on how a system should (or should not) behave, with regards to factors such as performance, usability, resource usage, availability, or compatibility.

4.3.1 Functional Requirements

The following functional requirements have been identified for our AR application (henceforth abbreviated as "app"), with general requirements which are valid for both mobile and HMD version of the app, and specific requirements only applying to the individual devices.

General requirements

1. The app should represent the physics phenomena of magnetism by visualising the invisible magnetic field around a virtual or a physical bar magnet.
2. This magnetic field around a magnet should be visualised using two different representations which form part of the visual augmentation:
    a. Magnetic field lines
    b. Vector field with directional arrows
3. Users should be able to
    a) observe the magnet and its magnetic field from multiple viewpoints and different angles.
    b) observe the magnetic field around one single magnet.
    c) observe the interacting magnetic field between two magnets.
    d) explore the behaviour of two magnets repelling each other.
    e) explore the behaviour of two magnets attracting each other.
    f) move the magnets along two or more dimensions.
    g) toggle on and off the two different representations of the magnetic field.
    h) dynamically adjust the field strength of a magnet.
    i) see the currently set field strength of the selected magnet.

Specific requirements for Android smartphone

1. The user moves and rotates the magnets indirectly by moving the printed image targets, onto which virtual magnets are overlaid on top of the physical, real magnets that are attached to these targets.
2. The user selects a magnet via touch input onto the mobile device's display.
3. The user receives visual feedback on which magnet has currently been selected.
4. The user activates and deactivates different representations of the magnetic field by touching persistent two-dimensional UI elements on the mobile screen.

Specific requirements for Microsoft Hololens

1. User interaction with virtual elements happens via a combination of gaze and certain pre-defined hand gestures ("gaze and commit" input model, according to Microsoft (2019)).
2. The user moves the virtual magnets directly with the hands by selecting and dragging them to the desired physical space.
3. The user receives visual feedback on the state of their user interaction (recognized gaze, recognized hand gesture) via a changing appearance of a virtual cursor.
4. The user activates and deactivates different representations of the magnetic field by interacting with static UI elements which are anchored into physical space at a fixed location.
5. The virtual hologram persists in its alignment in physical space and keeps its position even if users look away and look at it again.

4.3.2 Non-functional Requirements

The following non-functional requirements addressing both AR devices, the Microsoft Hololens and the Android smartphone, have been identified as follows:

1. The application should be user-friendly and intuitive to handle for students and teachers alike.
2. The visual augmentations should be visible within the limited field of view of the device displays.
3. The application should display realistic and scientifically correct visualisations.

4. The application should operate at a sufficient frame rate of 30 frames per second (FPS) on mobile smartphones and 60 FPS on Microsoft Hololens to provide a stutter-free visualisation without significant lag or delay in rendering.
5. The application should be able to run for about 5 minutes consecutively without causing overheating on the respective devices.
6. The application should not suddenly crash.
7. The HMD version of the application should run on Microsoft Hololens 1.
8. The mobile version of the application should run on Android smartphones released in 2018 or later, which have at least 2 GB of RAM.
9. The developed application should not make use of any paid third-party assets from the Unity Asset store or other sources.

Based on this list of identified functional and non-functional requirements, the following section introduces the conceptual design of our AR application.

4.4 Conceptual Design

Conceptually, the AR application has been designed in the form of five integrated layers, resulting in two different variants of the final AR application, as shown in Figure 4.1. Even though the two variants of the final AR application are being deployed onto fundamentally different AR devices, they do share the same inherent conceptual design. Each layer of the conceptual design is going to be further explained in the following paragraphs.

First of all, the initial layer contains the model design of the visual augmentation itself, with two three-dimensional models of virtual magnets each with their surrounding magnetic field lines as well as a vector field with directional arrows in the background. A schematic representation of the complete model in Unity3D is depicted in Figure 4.2 and Figure 4.3.

After having designed the look of the visual augmentation by modelling virtual objects, now the behaviour of these models has to be determined by associating the models with realistic physics. In the physics layer, we make use of the existing physics implementation for magnetic field behaviour in the MaroonVR project (available online as open-source code[4]) in order to ensure a realistic simulation of magnets and magnetic fields. Background knowledge on the underlying physics concepts and information on how the corresponding theoretical formulas have been implemented is discussed in the master's thesis by Holly (2019).

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[4] `https://github.com/GamesResearchTUG/Maroon`

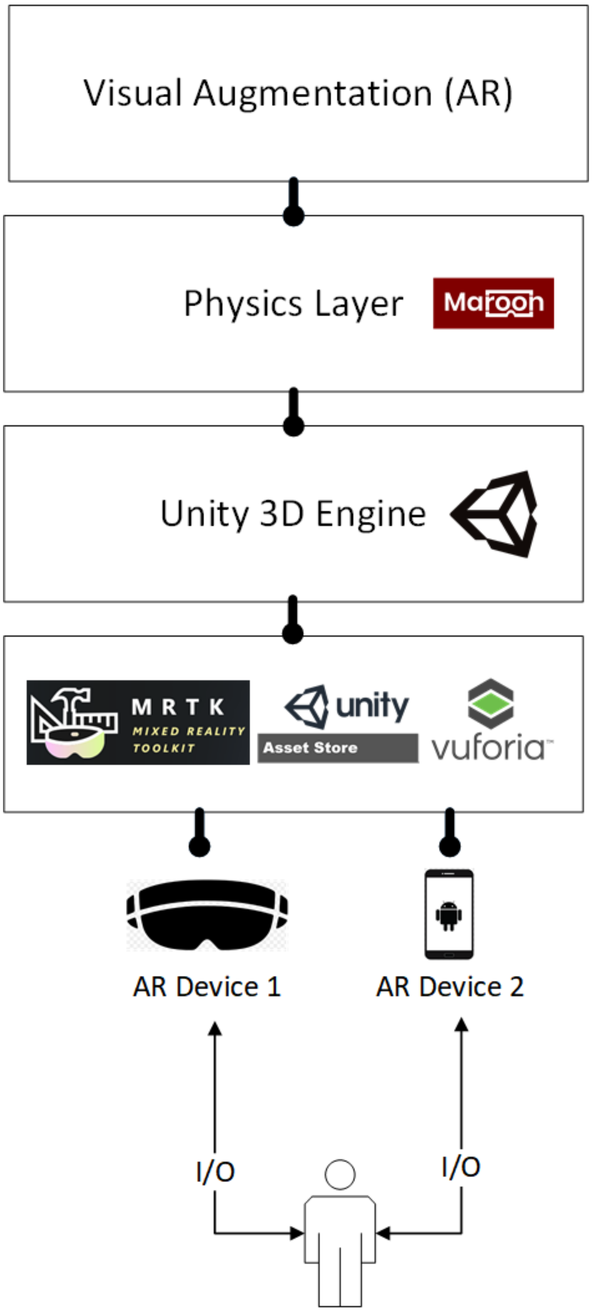

Figure 4.1: The conceptual design for the developed AR application.

Next, the 3D objects and code from the first two layers have to be assembled into one scene of a Unity project which is created with the Unity3D Engine. A Unity project contains all code scripts, 3D models, materials, textures, plug-ins and other assets necessary to create a virtual AR environment by placing and arranging the respective content as game objects within a scene. Figure 4.4

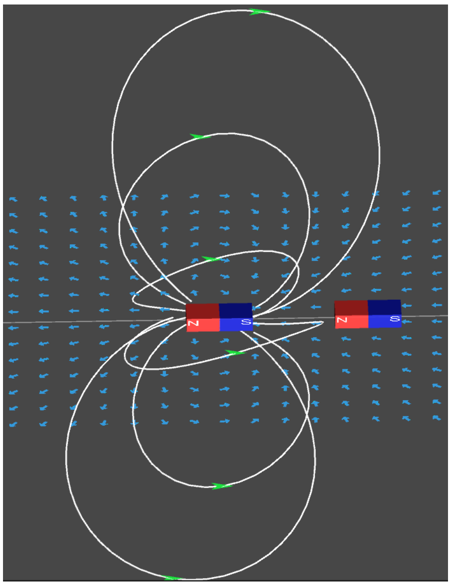

Figure 4.2: Visual augmentation model of magnets with and without field lines in Unity3D.

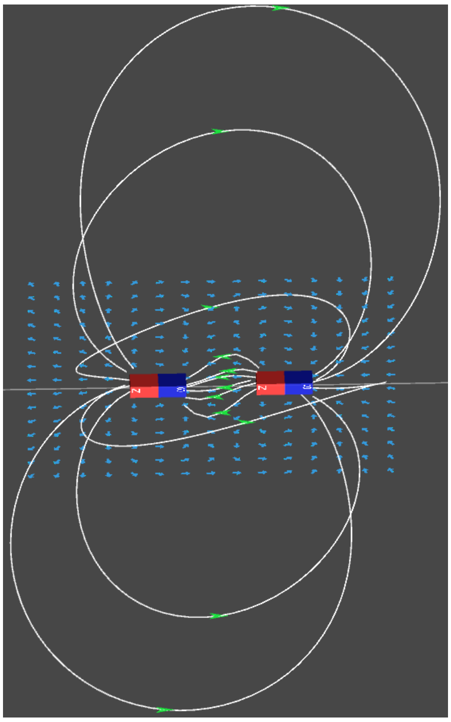

Figure 4.3: Visual augmentation model of two magnets with interacting field lines in Unity 3D.

shows an example of the hierarchical order of game objects within our Unity scene. Within this Unity scene, we have further extended code scripts and adapted 3D models with extra functionality to make them suitable for use in AR. This Unity3D game engine layer also provides the basis to enable the import of additional third-party code, as part of the next layer.

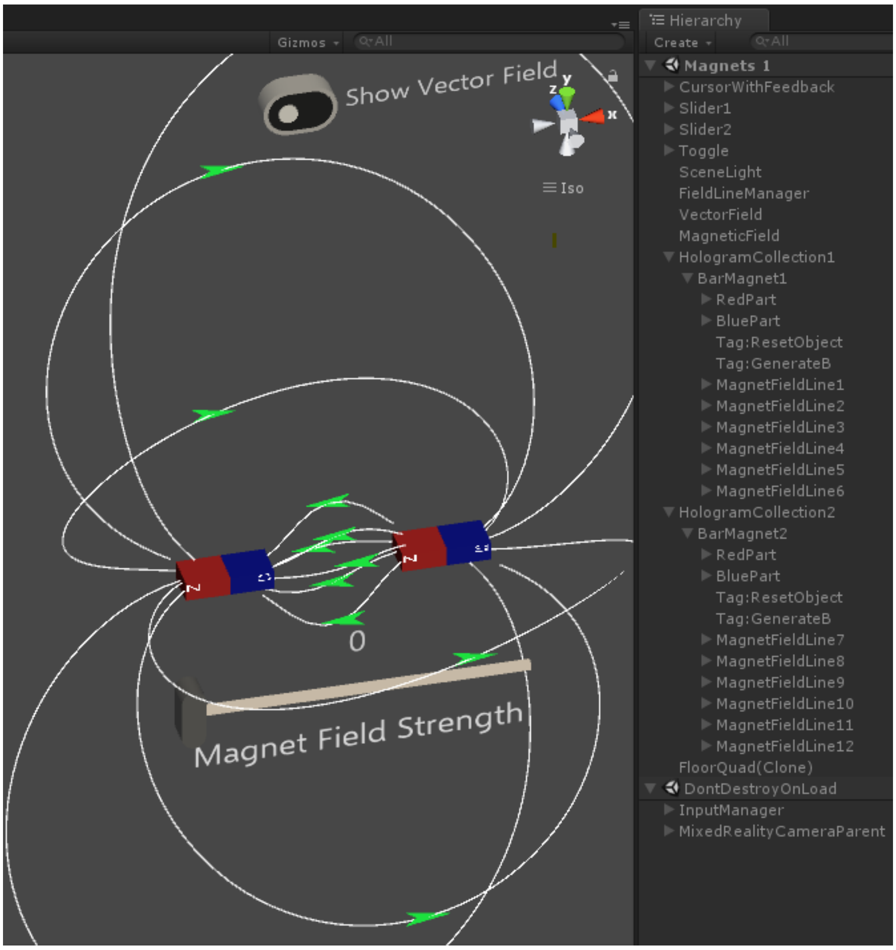

Figure 4.4: The hierarchy of game objects in the Unity scene. The `HologramCollection` game objects contains the modelled magnet and its magnetic field lines.

The next layer deals with third-party frameworks (in the form of SDKs and Unity packages) which had to be integrated into the aforementioned Unity project in order to provide functionality for user interaction through user interface elements and in order to enable marker-less as well as marker-based registration and tracking for the correct alignment of virtual objects within the physical environment. Depending on the device for which the AR application was designed to run on, different frameworks had to be used: for the marker-based mobile AR application, Vuforia with Image Targets and UI assets from the Unity Asset Store were used, whereas the marker-less Hololens AR application required the use of the HoloToolKit framework. These third-party tools are being discussed in more detail in Section 4.5.

The final layer of our conceptual design involves building and deploying the developed AR application onto two different AR devices, (1) the Microsoft Hololens and (2) an Android Smartphone, as illustrated by the corresponding device icons in Figure 4.1. Input from the user reaches these devices through different input modalities: users interact with the augmented content either through head gaze and hand gestures (in the Hololens app) or through touch input or movement of physical image markers and real magnets (in the mobile app). The output from these devices is also represented in two different ways: on the mobile device, virtual 3D content is presented on a 2D display, whereas on the Hololens device, the virtual 3D content is projected onto a 2D display with additional depth information, in such a way that the 3D holograms appear to be anchored within the physical environment.

4.5 Chosen Tools and Frameworks

In order to implement the aforementioned conceptual design, it was necessary to rely on a development set-up that allows for iterative implementation of a multi-platform learning environment with three-dimensional virtual objects. Unity3D[5] is a popular game engine which natively supports cross-platform development for our chosen AR devices. Moreover, it enables the seamless import of 2D/3D model objects and other assets and it also includes a built-in physics engine. Given the fact that the existing MaroonVR project[6] has already been developed using Unity3D and since we use part of its code basis to implement the physics behaviour of our AR application, we have also chosen to use Unity3D (more specifically, the Unity 2017.4.13f1 version) as our main development tool. For efficiently writing new code and adapting existing code in the C# language, we have decided to use the free Community edition of Visual Studio 2017[7] as IDE, mainly because this tool was also a necessary pre-requisite in order to build and deploy the app solution onto the Microsoft Hololens device.

Since the mobile version of our app relies on marker-based AR, some specific tools were necessary for development on the mobile platform. As explained in Chapter 2, marker-based AR relies on fiducial markers such as feature-rich printed images or distinctive 3D objects to overlay augmented content on top. In order to generate printable image targets, an online Augmented Reality

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[5] `https://store.unity.com/products/unity-personal`

[6] `https://github.com/GamesResearchTUG/Maroon`

[7] `https://visualstudio.microsoft.com/de/downloads/`

Marker generator by Brosvision[8] has been used. In order to recognize these image targets and to overlay them with the corresponding virtual objects, we make use of the Vuforia SDK[9] as it was already natively integrated into the Unity3D engine. In order to enable an ad-hoc demonstration of the developed AR application, we have included a printed version of the custom image targets used for our mobile AR application in Figure 4.5.

An additional requirement for the mobile AR application is to provide users with feedback on which virtual object (magnet) they have currently selected via touch input. This was achieved by highlighting selected magnets with a colored outline, a visual effect provided by the third-party plugin "Outline Effect"[10] which was downloaded from the official Unity Asset Store.

For the Hololens version of our AR application which uses marker-less AR, we have used the 2017 version of Microsoft's official Hololens framework called "HoloToolKit", which has later been extensively updated and re-named to "MixedRealityToolkit"[11]. It contains basic components, UI building blocks and code scripts for the correct alignment of virtual holograms within the user's physical surroundings and for user interactions with virtual holograms through head gaze, hand gestures and voice commands.

4.6 Conceptual Architecture and Implementation

After having made decisions on the conceptual design, now the conceptual design has to be implemented in a concrete manner with the chosen tools for development, resulting in a more refined conceptual architecture. The AR application has been developed based upon the work by Holly (2019) who has previously implemented the physics for calculating a magnetic field and rendering magnetic field lines and vector fields around electromagnetic objects. Based on this work, our own, original contributions include the following main aspects:

- Performance optimization to enable a smooth user experience on the targeted AR devices (1)
- Design of a bar magnet with a North and a South pole as a virtual 3D model (2)

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[8] `https://www.brosvision.com/ar-marker-generator/`

[9] `https://developer.vuforia.com/downloads/sdk`

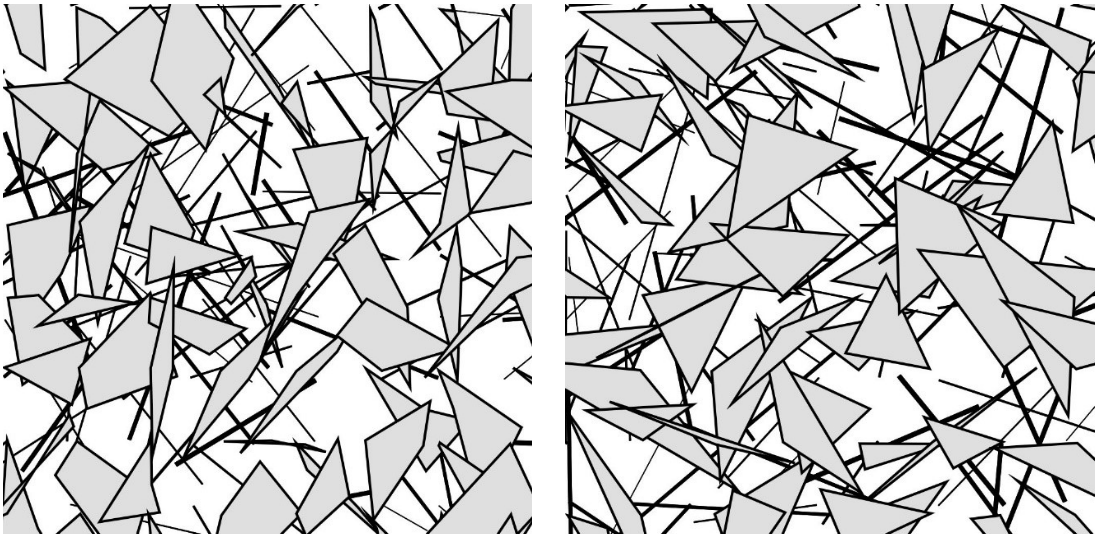
[10] `https://assetstore.unity.com/packages/vfx/shaders/fullscreen-camera-effects/outline-effect-78608`

[11] `https://github.com/microsoft/MixedRealityToolkit-Unity/wiki/HoloToolKit-2017-vs-MixedRealityToolkit-v2`

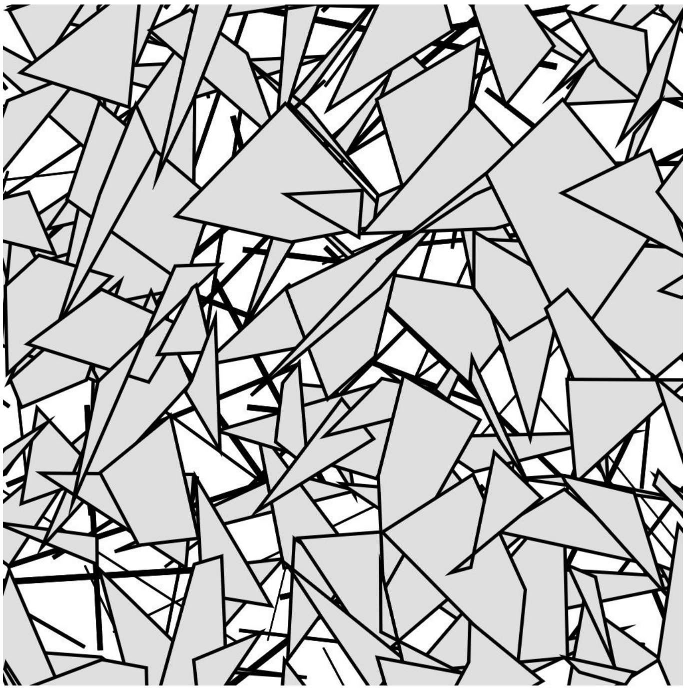
- Design of an user interface with UI elements suitable for the respective AR devices (3)
- Major adaptions related to the use of AR (4)
  - Addition of a second magnet into the scene and adjusting the resulting interaction between two movable magnets and their field lines (5)
  - Adaption of the calculation and rendering of magnetic field lines (6)
  - Adaption of the modelling and rotation for vector field arrows (7)

In the above list, the numbers in parentheses indicate the corresponding element in Figure 4.6, which shows an overview of the application's conceptual architecture. There, the parts highlighted in green color indicate our own code contributions which have been integrated into code scripts from the MaroonVR project (Holly, 2019), along with marker-less and marker-based tracking functionality and user interface elements which are provided by third-party frameworks and plugins. All these necessary code adaptions and feature extensions have been fully integrated together in a single Unity project, hence the depiction as a jigsaw puzzle in Figure 4.6. Overall, our contributions are extending the existing physics simulation for electromagnetic objects in MaroonVR with the functionality to visualize dynamically changing magnetic field lines for two interacting magnets in AR while also adapting it with specific user interfaces to enable an interactive user experience on two different AR devices.

To give an overview of the implemented conceptual architecture, Figure 4.7 shows a simplified UML class diagram with the relevant classes for visual augmentation and user input functionality. Regarding the classes related to magnets, an object of the class `Magnet` inherits functionality from the `ElectroMagneticObject` base class. Then the `MagneticField` object (which implements the `IField` interface) collects all producers of the type `ElectroMagneticObject` in a scene and calculates the resulting magnetic field at each position. With regards to the user interface classes, the two UI components `Slider` and `Toggle` are listening for user input events and sending values changed by users to the `HandleUserInput` object class, which in turn updates the `Magnet` and `VectorField` object accordingly with the respective values. Our scene also contains a `FieldLineManager` object which, together with the `CloseFieldLine` class, calculates the positions for each of the 12 `FieldLine` objects attached to a `Magnet` object, before the `AdvancedLineRenderer` object renders them visually. Furthermore, if the toggle for vector field visualisation is switched on, the `VectorField` object instantiates single vector field arrow objects, each of them containing the `VectorArrowController` script. For dynamically rotating these arrows, the `VectorFieldManager` object with its `Update` function is there to call the `triggerArrowRotation` function of the `VectorField` in each frame.



(a) Vuforia Image target for first magnet (b) Vuforia Image target for second magnet



(c) Vuforia Image target for vector field

Figure 4.5: Custom Vuforia Image Targets for the developed mobile AR application, re-printed here to make it possible to directly experience the visual augmentation being overlaid onto the image targets if the mobile AR application is installed on an available Android smartphone.

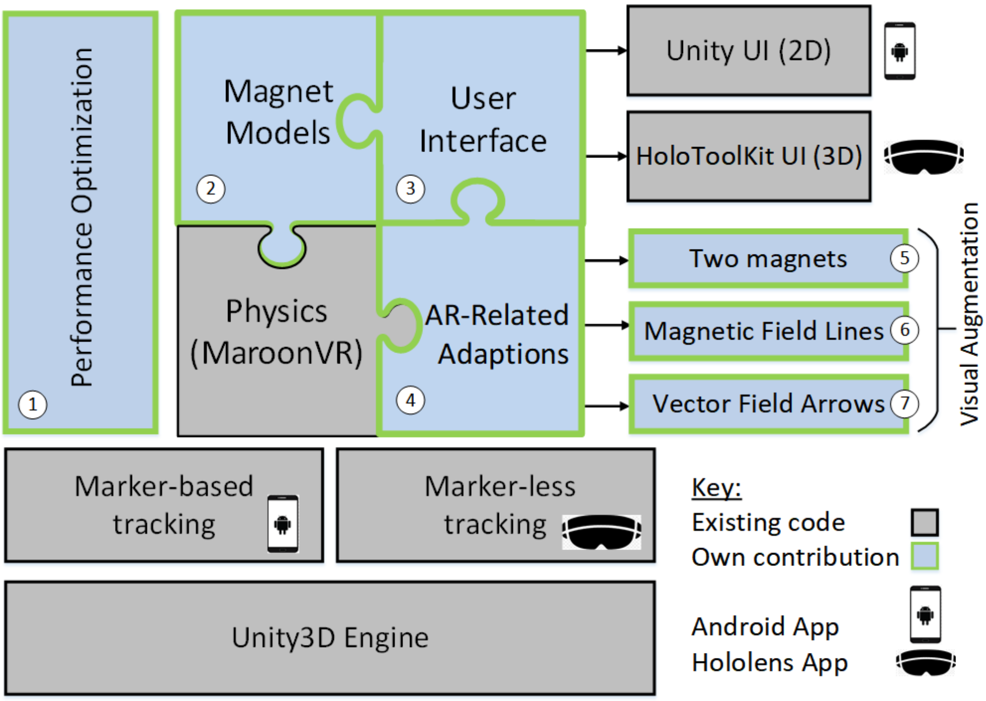
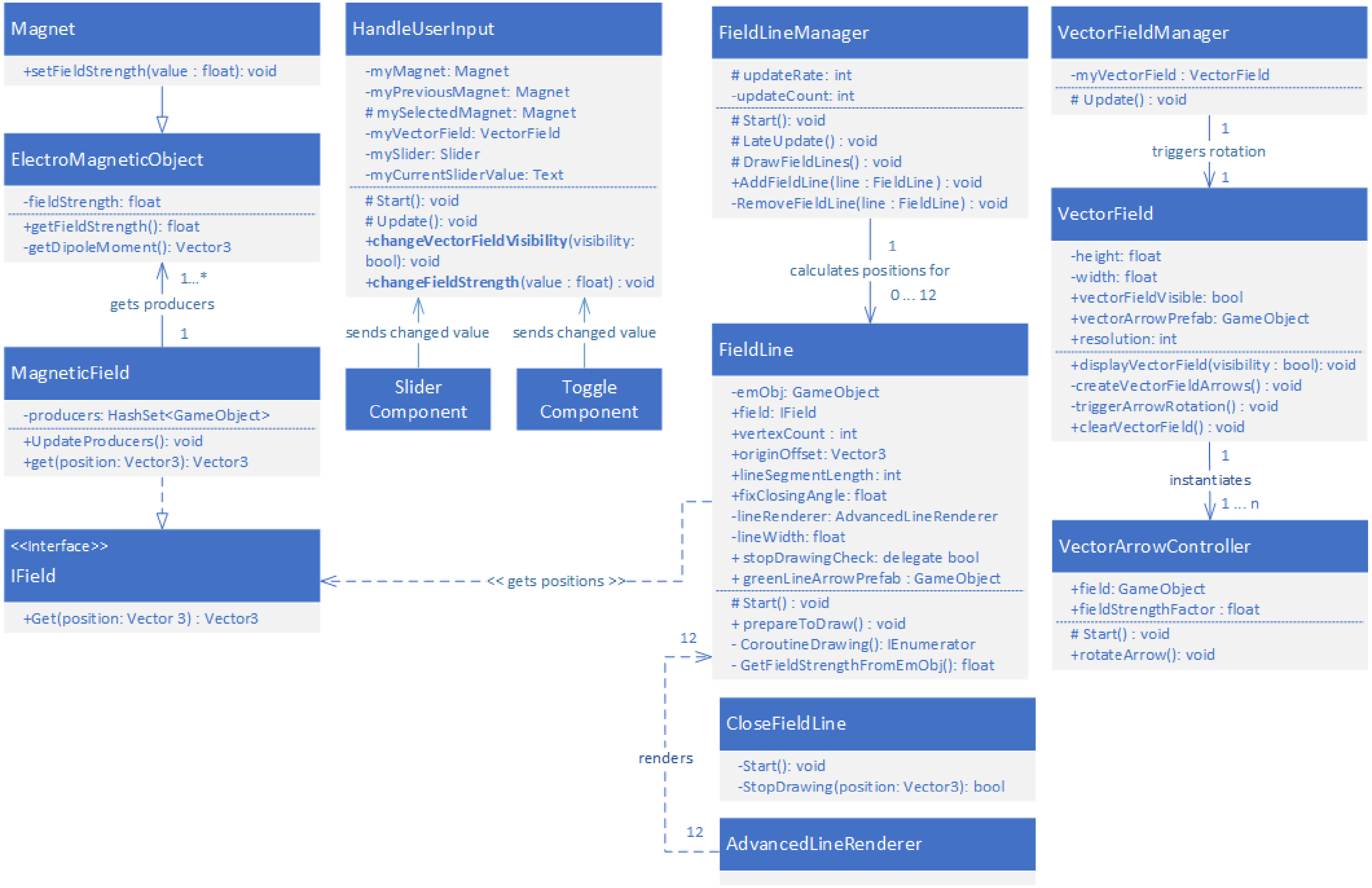


Figure 4.6: The conceptual architecture for the developed AR application, with newly developed components highlighted with a green surrounding line to indicate our own contribution.

Figure 4.7: UML Class Diagram with classes related to Magnet, Field Lines, Vector Field and UI components.



The following sections will further elaborate on those selected implementation details which are relevant to our own contribution.

Performance Optimization

It was necessary to perform some performance optimization in order to make the AR application execute smoothly on the Microsoft Hololens, with its limited computational power (1 GHz processor, 2GB RAM according to the official specification[12]). The code for calculating and rendering magnetic field lines and vector field arrows has been initially written by Holly (2019) to be executed on the HTC Vive, a VR headset which relies on a high-end computer to perform calculations and render 3D objects. In order to execute the same code on an untethered, stand-alone AR device such as the Microsoft Hololens, it was necessary to tweak the existing code with several performance optimizations:

First of all, we have lowered the update rate for the rendering of field lines, i.e. each field line is only re-drawn every 30th frame instead of every single frame, which would cause jitter and lag in visualisation due to significant computational overhead. With a frame rate of 60 FPS on the Hololens, this results in the field lines being re-drawn approximately twice per second, which is sufficient to generate a relatively fluid user experience. In addition, Microsoft's officially recommended settings[13] for the development of Hololens apps in Unity have been applied, such as using the single pass instanced rendering method for optimizing CPU and GPU resources as every 3D object has to be rendered twice - once for each eye - to be displayed on the Hololens device. Further optimization has occurred on the level of creating the models of objects: in order to render hundreds of vector field arrows more efficiently, we have used an unlit and double-sided Shader with scripts provided by the local company zarG Byte[14] to create the vector field arrows as quad objects with only 4 polygons instead of 3D objects with a high polygon count each.

Magnet Models

The magnet models shown in Figure 4.2 and 4.3 have been specially designed for the AR application as simple 3D objects constructed out of two cubes, colored in red and blue and overlaid with the text characters "N" and "S" to indicate the North and South pole of the magnet. The magnet's magnetic field lines are

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[12] `https://docs.microsoft.com/en-us/hololens/hololens1-hardware`

[13] `https://docs.microsoft.com/en-us/windows/mixed-reality/recommended-settings-for-unity`

[14] `https://www.zargbyte.com/`

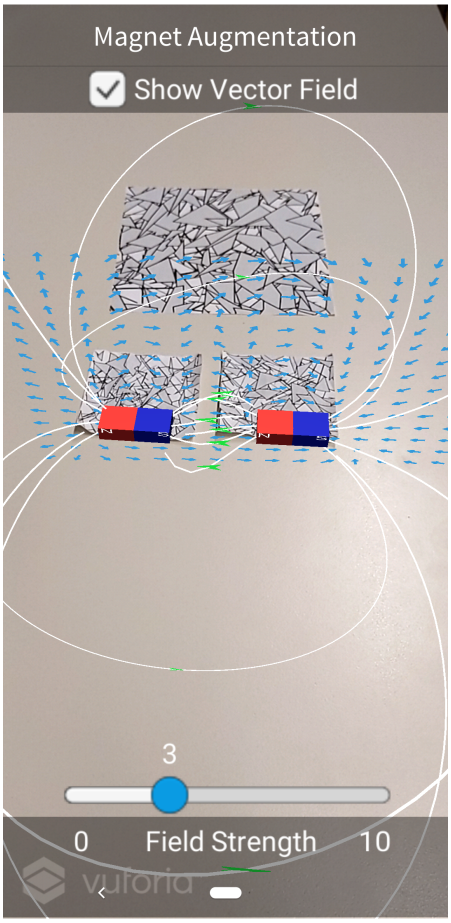


Figure 4.8: Screenshot of mobile AR application, showing the magnetic field of two magnets attracting each other.

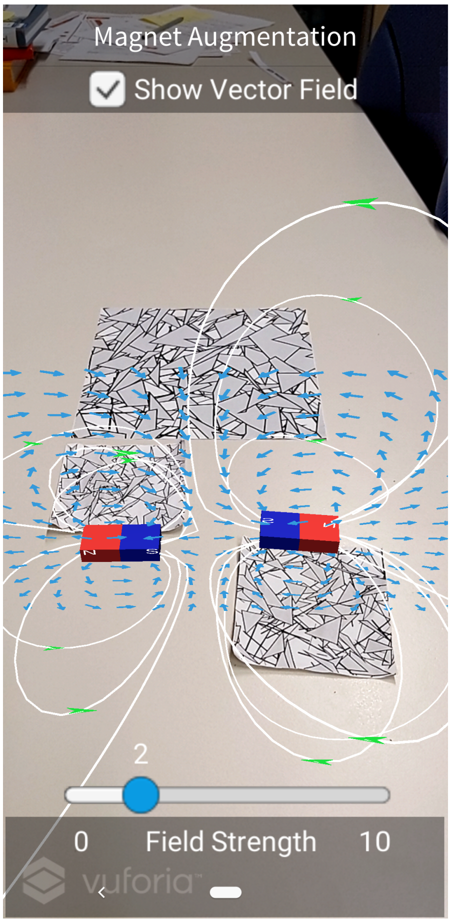


Figure 4.9: Screenshot of mobile AR application, showing the magnetic field of two magnets repelling each other.

rendered by the `AdvancedLineRenderer` object and also include a green arrow on top of the field line to indicate the direction of the field line. In addition to the magnet models, a vector field with blue vector field arrows is included in order to provide an alternative visual representation of the magnetic field. Figure 4.8 and Figure 4.9 show the magnet models as Augmented Reality content when viewed on the display of the mobile device. In comparison, Figure 4.10 and Figure 4.11 show the magnet models as Augmented Reality content when viewed through the Microsoft Hololens.

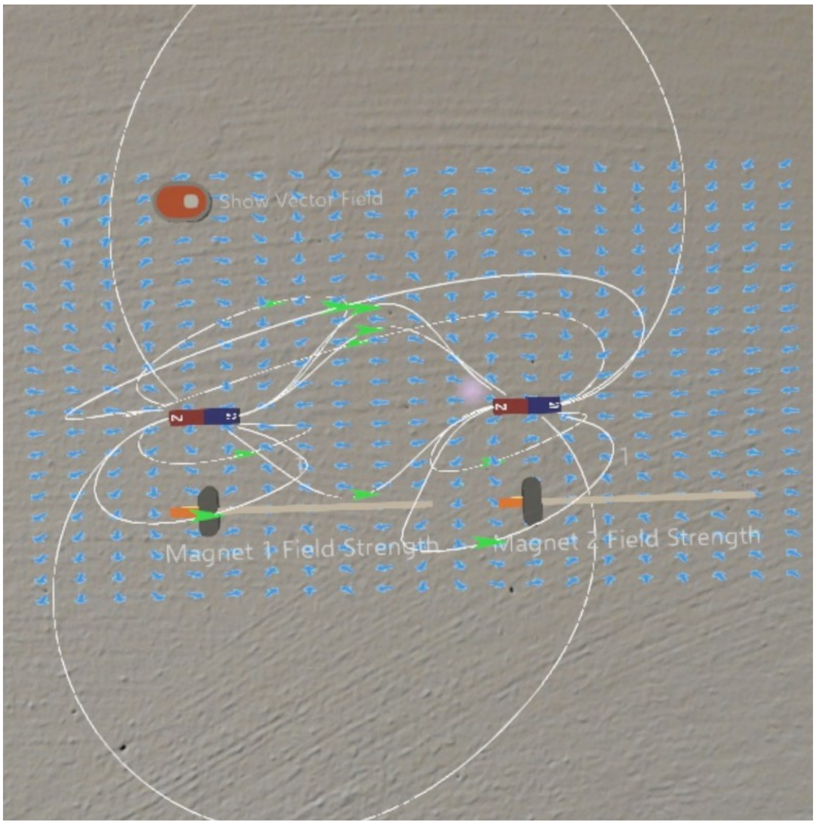


Figure 4.10: Screenshot of Hololens AR application, showing the magnetic field of two magnets attracting each other.

User Interface

Due to the different nature of the device displays, the user interface for the AR application on the Microsoft Hololens has to be different from the AR application's user interface on mobile devices. For the mobile device with its 2D display, we have decided to use Unity UI elements which are provided as standard assets within the Unity3D engine. As depicted in Figure 4.13b the mobile application currently contains two UI elements: a toggle switch to turn the visualisation of the vector field on and off, as well as a slider to adjust the field strength of a magnet to a value between 0 and 10. For the Hololens, it is not recommendable to use these standard Unity UI elements as they are provided as 2D elements overlaid on a screen canvas, which look distorted when viewed through the Hololens display. Hence, to stay in accordance with the three-dimensional, holographic nature of holograms, we have decided to use appropriate 3D UI elements for the Hololens AR application. We have included two interactable sliders (one for each magnet) and an interactable toggle. These UI elements are included as customizable prefabs within the HoloToolKit

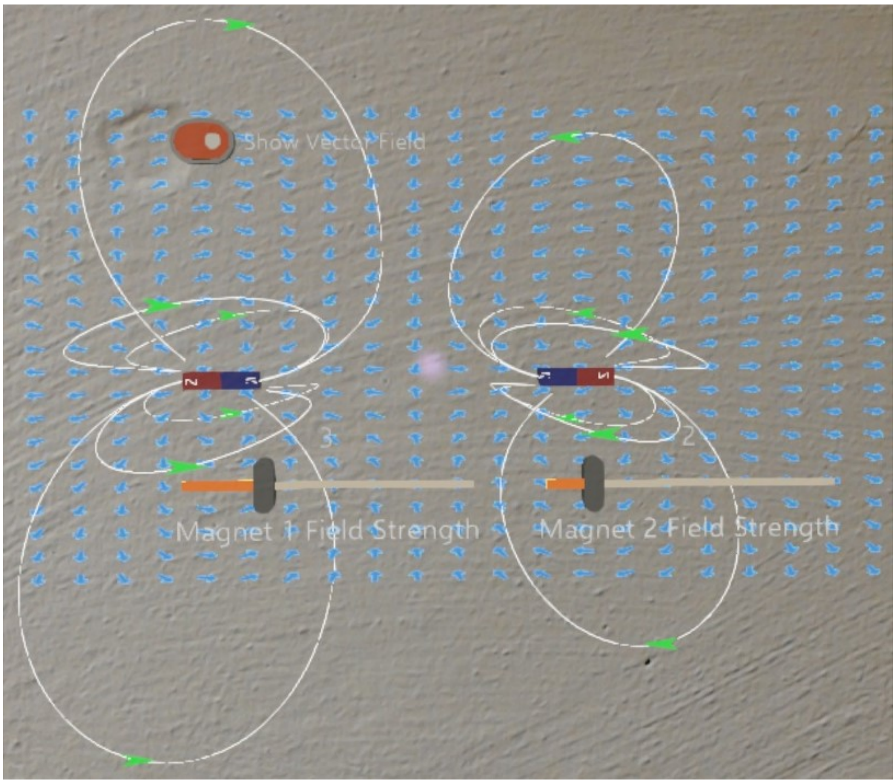


Figure 4.11: Screenshot of Hololens AR application, showing the magnetic field of two magnets repelling each other.

framework. Figure 4.13a shows a screenshot of these three-dimensional UI elements within the Unity scene.

Overall, these described UI elements create an interactive user interface to enable direct user interaction with the virtual content in AR. The general sequence of events occurring during user interaction is illustrated within the sequence diagram in Figure 4.14. On mobile devices, user interaction occurs via touch input on displays and via movement of the printed image targets which act as tangible interfaces. The user can move the virtual magnets and the vector field indirectly by moving the printed image targets. The user can also set the field strength of magnets via a standard Unity UI Slider (after selecting a magnet via touch input). Once the user selects a virtual magnet by tapping it on the smartphone display, this user input is detected and thus the selected magnet is set as the magnet to be adjusted and also highlighted in green color in order to provide immediate feedback to the user, as illustrated in Figure 4.16. Then the user drags the handle of the slider to a certain point between 0 and 10 on the slider range, which triggers the `Slider` component's `OnValueChanged()` function to send an event to the `HandleUserInput` object, which in turn executes the `changeFieldStrength()` function to change the current field strength of the selected magnet to the value which the user has just set on the `Slider` object. Similar to the user interaction with the slider, users can interact with an Unity UI `Toggle` object to turn the visualisation of the vector field on or off. This `Toggle` UI element follows the same sequence of events for user interaction as the `Slider` element, but instead of numeric values it uses boolean values to refer to its ″on″ and ″off″ state. The ″on″ state is indicated with a checkmark within the Toggle and the ″off″ state is indicated by the absence of this checkmark, as illustrated in Figure 4.15 and Figure 4.16.

On the Hololens, the user interaction occurs through a so-called ″gaze-and-commit″ pattern: first, the users turns his head gaze towards the hologram to be selected and then performs one of the pre-defined hand gestures depicted in Figure 4.12. In order to move a magnet hologram, the user performs the ″Air tap″ gesture (which is in fact a combination of the ″Ready″ gesture followed by the ″Tap″ gesture, according to Tang, Au, and Leung (2018)) and then performs the ″drag″ gesture to move the magnet to the desired position. In order to change the field strength of a magnet or to toggle the visualisation of the vector field the user essentially follows almost the same sequential process as described in Figure 4.14 for the mobile device. However, instead of touching the UI elements through a device display, the user simply performs the ″ready″, ″tap″, ″hold″ and ″drag″ hand gestures in mid-air. Additionally, there is no need to select a particular magnet first because on the Hololens application a separate, individual slider is available for each magnet. This is facilitated due to the screen-less and thus relatively big frame of action offered by the Hololens device: even though it has a small field of view, it allows the anchoring of these sliders as holograms anywhere in the physical world instead of having to contain them within the limited area of a mobile device display.

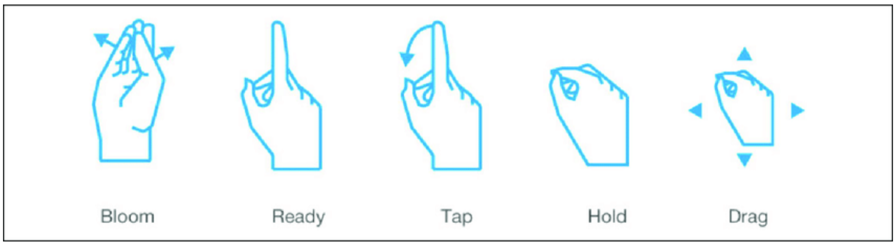
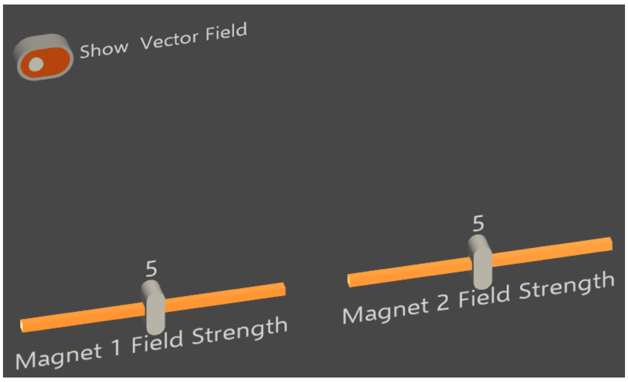


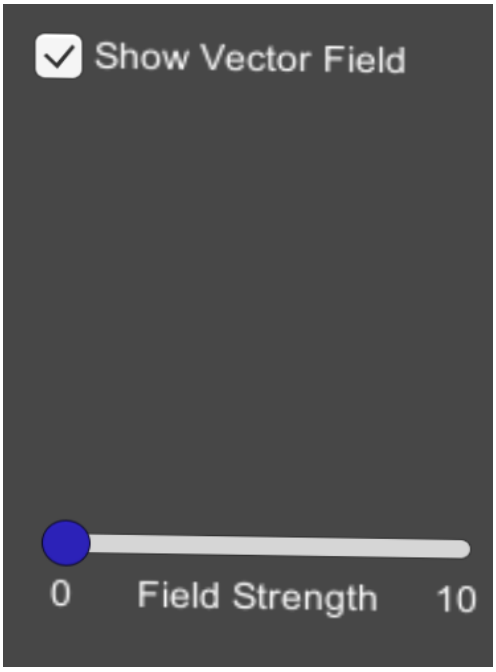
Figure 4.12: The pre-defined hand gestures which are recognized by the Hololens 1, re-printed from Tang, Au, and Leung (2018).

AR-Related Adaptions

As the existing physics implementation has been initially developed by Pirker et al. (2017) and later refined by Holly (2019) specifically for a room-scale



(a) 3D UI elements on the Hololens application, depicted slightly skewed to convey the three-dimensionality of the UI



(b) 2D UI elements on the mobile application

Figure 4.13: Screenshot in Unity3D showing the user interface elements

Virtual Reality experience on the HTC Vive, the fundamental shift from VR to AR technology has also required several adaptions and changes related to the fundamental nature of AR and its different possibilities for user interaction.

The previous magnet experiments in MaroonVR only involve the use of one magnet, without visualising the interacting magnetic field between two magnets which can either repel or attract each other. Our work has extended this by

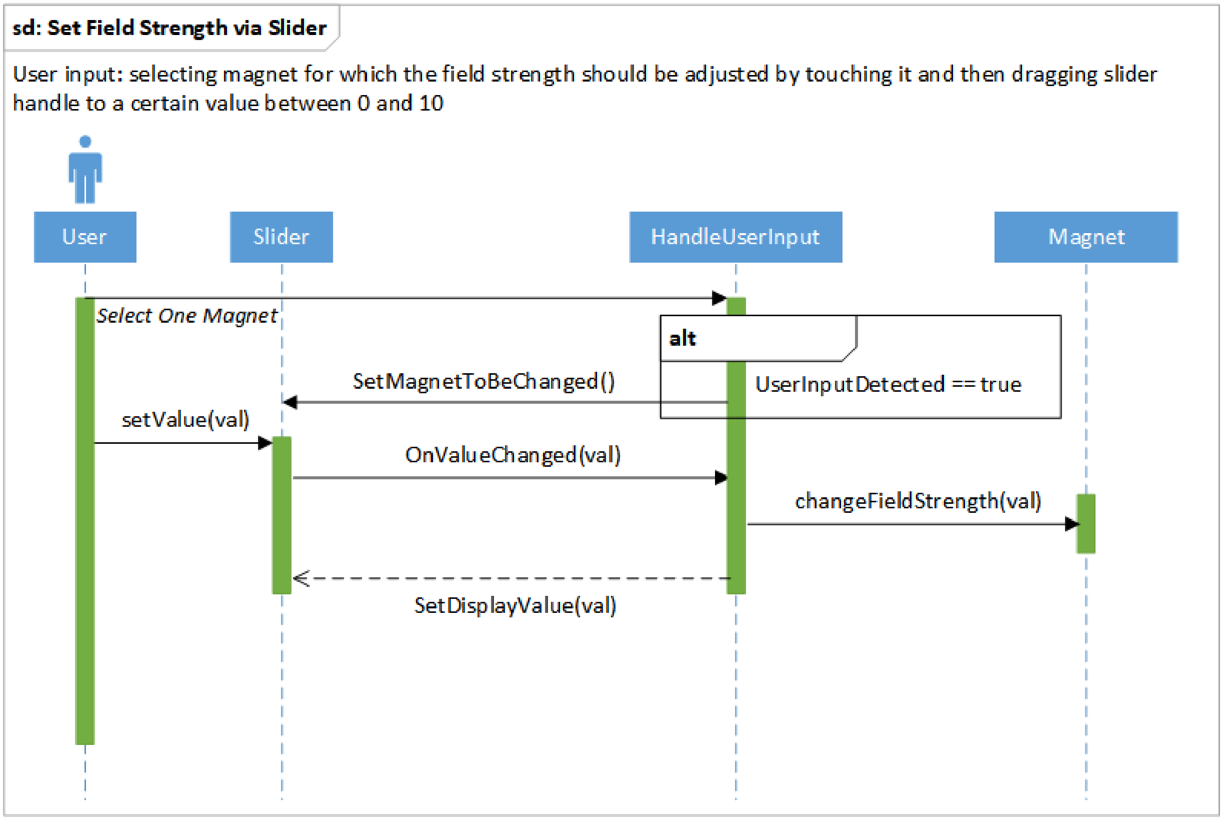


Figure 4.14: Sequence diagram showing the events for setting the field strength of a magnet.

integrating two magnets and visualising magnetic field lines and the vector field for two interacting magnets. In order to allow for more than one magnet in the scene, it was also necessary to further adapt the calculation and rendering of field lines in order to make them interact with each other dynamically and in real-time.

In order to avoid computational overhead during the calculation and rendering of these dynamically changing field lines, the functions for calculating and drawing fieldlines have been re-implemented as a co-routine in the `FieldLine` object. This means that the calculation of positions for field lines and the rendering of these calculated lines are now not completed in one single frame anymore but instead split up over multiple frames and yielding inbetween without blocking resources which allows for other functions to be executed as well.

Furthermore, in MaroonVR, the rotation of magnets was disabled while the movement of magnets had also been restricted along the horizontal axis. This had previously made it possible to calculate just one field line and clone this single field line around one axis in a symmetric way. However, in AR, it is

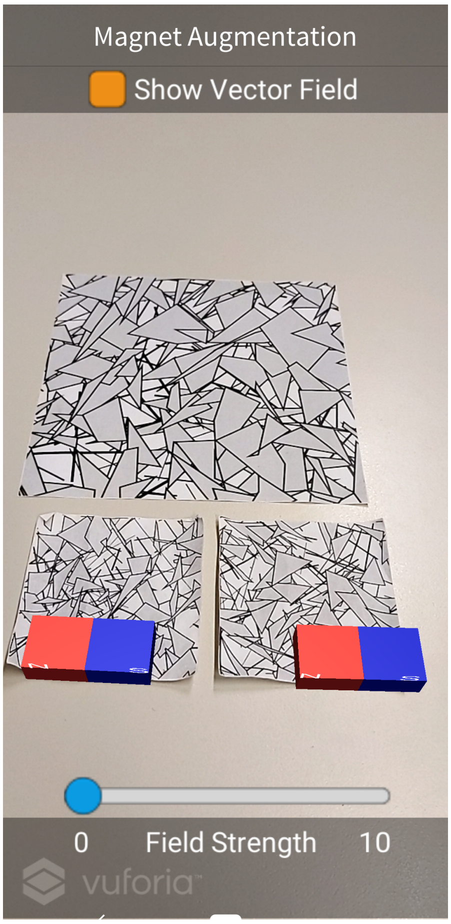


Figure 4.15: Screenshot of mobile AR application, showing the two magnets and the user interface.

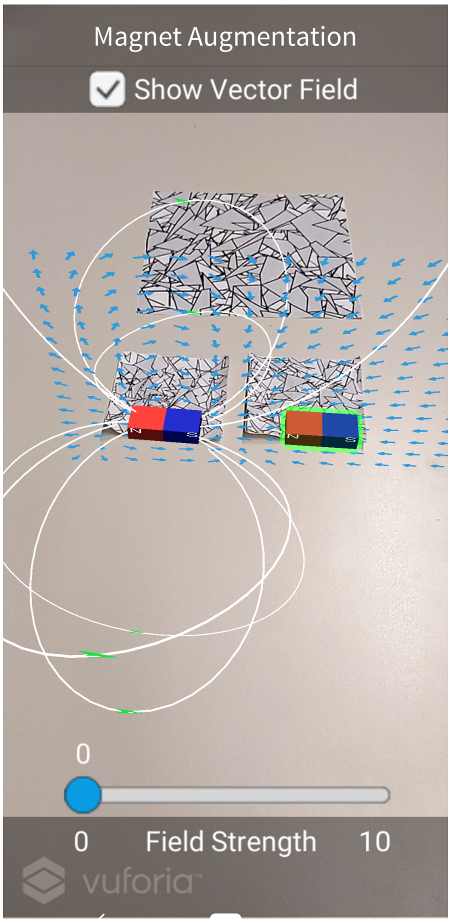


Figure 4.16: Screenshot of mobile AR application, showing the selection of one magnet (highlighted in green) and visible field lines and vector field.

naturally possible to move and rotate magnets along up to three axes: horizontally, vertically, and longitudinally. Especially when using marker-based AR with a tangible, physical object acting as marker, it is in fact not possible to restrict the user's movement in any way at all. Just like in real life, users of the AR application are free to position and rotate virtual objects in any way they want. This happens, for example, by physically positioning and rotating virtual magnets indirectly via moving printed image markers and real magnets or directly via performing the corresponding hand gestures on the Hololens. This greater range of possible movement and rotation occurring during the user interaction with two magnets has led to problems with the existing implementation for "cloning" field lines, therefore requiring the refactoring of code which involved the placement of six individual field lines per magnet and individually calculating their directions instead of cloning from one line.

On mobile devices, another code adaption related to the vector field was necessary due to Vuforia's non-changeable Image Target[15] behaviour, which by design disables certain functions of game objects which are placed as child objects of these Image Target objects. As can be seen in Figure 4.7, the `Vector Field` object is responsible for instantiating individual vector field arrows (each containing the `VectorArrowController` script) and arranging them on their respective positions within the vector field. Each vector field arrow has to change its rotation dynamically, depending on the position of the magnet and its current magnetic field strength. However, as the `Vector Field` object (containing all the single vector field arrows) is a child object of the Vuforia Image Target object within the scene hierarchy, it is not possible to directly call the `triggerArrowRotation` function of the `Vector Field` object in each frame, so that the rotation of the individual arrows would be triggered. Therefore it was necessary to implement a new object called `VectorFieldManager` and place it on the same hierarchy level as the Vuforia Image Target object, in order to be able to externally trigger the rotation of each vector field arrow within every frame.

4.7 Summary

This chapter has discussed the conceptual design and the development of an Augmented Reality application for two different AR devices, the Microsoft Hololens and an Android smartphone. In accordance with the visual augmentation framework developed in Chapter 3, we have carefully designed our AR

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[15] `https://library.vuforia.com/articles/Training/Image-Target-Guide`

application to facilitate the observation and exploration of magnets by augmenting them with visual representations of their usually invisible magnetic field. Our framework suggests that representing physical phenomena, such as magnetic field behaviour, is a recommendable visual augmentation type to fulfill the purpose of making the invisible visible using AR. The validity of this recommendation will be further evaluated through user studies in the following chapter.

The AR application has been developed using Unity3D and is targeted targeted towards educational use in high schools and universities. It exists in two variants: (1) a hand-held and easily accessible mobile version on an Android smartphone using marker-based AR, and (2) a hands-free, head-mounted version on the Microsoft Hololens using marker-less AR. An analysis of functional and non-functional requirements has shown that the AR application should generally provide an user-friendly and realistic visual augmentation of magnets and magnetic fields, but with individual user interfaces specifically designed for the two different AR devices. The conceptual design of the AR application includes five main layers with 3D models, physics, game engine, third-party plug-ins, and the resulting builds for each AR device. The AR application has been developed partly based on the physics implementation in MaroonVR (Holly, 2019). As part of our own contribution, we have integrated several performance optimizations, model and user interface design as well as major code adaptions related to the use of AR into the conceptual architecture of the implemented system. The next chapter discusses the evaluation with test users of the AR application.

5 User Evaluation

This chapter discusses the comparative user evaluation of our developed AR application. We investigate the user experience and learning experience of our AR application on two different AR devices: the Microsoft Hololens and the Android smartphone are being evaluated in comparison to each other. Through the means of A/B split testing with 20 participants, our study aims to compare the two different variants of the AR application in order to find out about the differences in user reaction between marker-based AR on a mobile, hand-held device and marker-less AR on a hands-free, untethered and head-mounted device. Our findings present users overall impression with regards to user experience, interactivity and learning experience.

5.1 Research Goals

The main goal of this study is to compare the user reaction towards AR on two different AR devices, (1) the Microsoft Hololens with marker-less AR and (2) the smartphone with marker-based AR. To investigate the overall user reaction, we focus on the following three main areas in which users may show neutral, positive or negative reactions:

- **User Experience**: usability and user satisfaction
- **Interactivity**: user interaction with different input modalities
- **Learning Progress** and **Motivation**

Through a comparative evaluation, we seek to answer the following two research questions (RQ):

RQ1: Are users more satisfied with the Hololens AR application or with the mobile AR application? In other words, which version of the AR application provides the superior interactive user experience?
RQ2: Which version of the AR application leads to (more) learning progress and (higher) learning motivation?

In order to answer these two research questions we mainly rely on qualitative self-reporting by users and quantitative questionnaires validated by previous research (Helin, Kuula, Vizzi, Karjalainen, & Vovk, 2018), in combination with an assessment quiz to test theoretical physics knowledge and potential learning outcomes on magnets and magnetic fields.

5.2 Material and Setup

To test the AR application with study participants, we use two hardware devices: the Microsoft Hololens 1 device and the Samsung A40 smartphone which features an almost bezel-less 5.9 inch Super AMOLED display and 4GB of RAM[1]. Since a better visibility of holograms can be ensured when physical surroundings are not too bright, our test sessions with users have been conducted in a closed office space with dimmed lighting and an empty 1m x 1m white wall space for the Hololens experience (see Figure 5.1). The mobile AR application also requires the participants to use printed image targets and real magnets to interact with the augmented content, as shown in Figure 5.2.

Figure 5.1: The test setup for the Hololens AR application, showing a study participant performing a gesture while viewing the holographic content which is anchored on the white wall space in front of her.

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[1] https://www.samsung.com/uk/smartphones/galaxy-a40/SM-A405FZKDBTU/

Figure 5.2: The test setup for the mobile AR application, showing a study participant pointing the smartphone at two real magnets which are tracked by the attached custom-printed image targets.

5.3 Method and Procedure

For the evaluation of our AR application which has been developed as prototypical proof-of-concept (for details see Chapter 4), we have conducted a first experimental study with A/B and B/A testing for a total of 20 subjects (sample size n=20). Our study setup involves two experimental conditions, with the two AR devices (described in the preceding Section 5.2) as independent variables. The following six specific user tasks were carried out by each subject in both experimental conditions:

T1: look around in the AR application, have a look from different perspectives and make sure you see all AR content in your device's respective field of view (for the Hololens app: also walk around in physical space)
T2: adjust the field strength of one magnet to the value 1
T3: adjust the field strength of another magnet to the value 2
T4: switch the visualisation of the vector field on, off, and on again
T5: move the virtual magnets (for the mobile app: move the real magnets) around as you like
T6: explore and observe as you like, adjust the parameters freely

With regards to the A/B testing set-up, the study participants are divided into two groups for split testing. The first group of 10 participants first tests the AR application on device A and then on device B, whereas the second group of 10 participants tests it in reverse order; first using device B and then using device A. Device A refers to the Microsoft Hololens and device B refers to the Android smartphone.

The procedure of the user study is as follows: first, the participants are asked to fill out a pre-questionnaire with questions regarding demographic information and their previous experience with computers and Augmented Reality. Then the participants have to fill out a worksheet with their answers to five theoretical questions about magnetism and also indicate the confidence level of their answers on a range between 1 (not very confident, unsure about answer) to 5 (very confident, very sure about the answer). The theoretical questions on the worksheet are designed to assess user's conceptual understanding of magnetic fields and are listed as follows:

Q1: Draw the magnetic field lines and their direction between the following constellation of magnets: (an illustration of two horizontal magnets attracting each other)
Q2: Draw the magnetic field lines and their direction between the following constellation of magnets: (an illustration of two horizontal magnets repelling each other)
Q3: Can you explain the relationship between field strength and magnetic field lines?
Q4: What other representations of magnetic fields do you know?
Q5: How is the vector field of a magnet aligned?

For the last three questions, users were free to choose words and/or a sketch to provide their answer. These questions are asked as a form of pre-test in order to record the state and confidence level of participant's existing knowledge, prior to their exposure to the AR application, which ideally helps them to learn new knowledge or consolidate existing knowledge. Before starting the practical hands-on part of the evaluation, the participants using the Hololens device also receive a short introduction and practical demonstration to learn the hand gestures necessary to operate the AR application on the Microsoft Hololens.

For the practical part, all participants test the AR application on one AR device and carry out the aforementioned six user tasks T1 to T6. Afterwards they again fill out the same worksheet with answers and confidence levels to the same five theoretical questions as before, together with an additional sixth open-ended question asking them what they have learned in terms of physics after using the AR application. This allows us to detect potential learning progress and a change in confidence levels after experiencing the AR application, i.e. whether the users answers remain the same, are more correct or more false or whether their confidence in knowledge has increased or decreased after using the AR application for the first time. This post-assessment using the worksheet is only done *once* after the users have initially experienced the AR application on their respective first AR device. Thereby, we try to assess the educational effectiveness of the single AR applications independently from each other and avoid overflowing (knowledge) biases. Overall, 10 participants filled out the printed post-assessment worksheet on paper after first testing the AR application on the Hololens, whereas another 10 participants filled it out after first testing the AR application on the smartphone.

In addition to this educational assessment, the participants are then also asked to assess their individual user experience with regards to user interaction and learning experience on that AR device by filling out a first online post-questionnaire consisting of eight open-ended questions on their overall impression and 17 single-choice Likert-scaled questions for rating their learning experience and further motivation to learn with this AR application. In order to gain insights into the usability and user satisfaction with the AR application, participants were further asked to answer a total of 30 relevant single-choice questions from two standardized usability questionnaires. This completes the testing for the first AR device.

Next, another test run with the second AR device follows, where the same six user tasks have to be carried out. Afterwards, users do *not* fill out the printed post-quiz assessment worksheet again. Instead, it is followed by the same online post-questionnaires as in the previous test run with the first device. Finally, after having experienced both versions of the AR application, the participants have to fill out a final online survey with open-ended questions asking them to compare their experiences on each device and indicate their preference for one version. This concludes the test session.

Methodology and Constraints

The participants were not paid for their participation in the user study, they volunteered to take part themselves. The time it took one study participant to complete one whole test session with all questionnaires and both AR applications varied between 45 to 60 minutes, depending on the amount of questions raised by participants, who sometimes also experienced difficulties in user interaction, especially when dealing with hand gestures for the Hololens device and the necessity to adjust the headset's fit to the head. On average, study participants spent around 10 minutes for successfully completing the six mentioned user tasks on the Hololens application, whereas they spent significantly less time performing the same six user tasks in the mobile AR application. Nevertheless, no official time limit has been communicated to the study participants while they were experiencing the AR application itself. All test sessions with participants were conducted over the course of three days in the beginning of March 2020.

The experimental study involves the use of several survey techniques and questionnaires, some of which were adapted in order to only include question items which are relevant for the developed AR application. Using these survey and questionnaires, we aim to fulfill the aforementioned research goal by comparing users' reaction towards the AR application on two devices, the smartphone and the Microsoft Hololens. Hereby, we are focussing on the areas of user experience, interactivity, and learning experience. The following list maps our chosen questionnaires and surveys to specific research questions from these focus areas:

- Regarding User Experience and Interactivity, are users more satisfied with the Hololens AR application or with the mobile AR application?
    - the System Usability Scale by Brooke et al. (1996). It contains 10 statement items to be rated on a five-point Likert-Scale and is a common, often-used questionnaire for HCI evaluation of AR systems (Dünser and Billinghurst (2011), Helin et al. (2018)).
    - the Questionnaire for User Interaction Satisfaction by Chin, Diehl, and Norman (1988), which has also been validated as effective tool for comparative evaluations of software applications (Harper and Norman (1993), Helin et al. (2018)). Our adapted version contains 20 items (out of 41 items in the original version) to be rated on a 5-point Likert-Scale.
    - 12 open-ended questions asking users about their subjective opinion, positive and negative aspects of their individual AR experience with each device.
- Regarding Learning Experience, which version of the AR application leads to (more) learning progress and (higher) motivation?
    - a practical worksheet with up to six theoretical questions about magnets and the relationship between magnetic field lines and field strength. It is administered twice as pre- and post-test in order to be able to assess learning progress (in the form of potentially improved correctness of answers and potentially increased confidence in conceptual knowledge) after using one version of the AR application for the first time.

  - 17 single-choice questions[2] with a five-point Likert-Scale, asking users about their learning experience with the AR application and their motivation for using AR to learn.

5.4 Participants

Overall, there were 20 persons (among them 4 female) participating in this study, with their age (AVG=26.95, SD=3.27) ranging from 23 to 35 years. 10 participants started to test the AR application on the Microsoft Hololens first, whereas the other 10 participants started to test the AR application on the Android smartphone. Exactly half of the participants had a visual aid in the form of glasses, which they could also keep wearing while working with the quite adjustable Hololens headset. The participants were recruited from Graz University of Technology, University of Graz and FH Joanneum. Among the 20 participants, there were 16 students in the area of Computer Science or Software Engineering and Management, two students from non-technical studies as well as two working professionals in the field of IT and research. The current educational level of the 18 students ranged from Bachelor (5 participants) and Master (7 participants) to PhD (6 participants) level.

Regarding their usage of computers, most of them rated themselves as experts (AVG=4.6, SD=0.94) and indicated that a graphically rich learning environment is more or less important to them (AVG=3.9, SD=0.91). With regards to the usage of Virtual Reality (AVG=2.75, SD=1.25) and Augmented Reality (AVG=2.4, SD=1.31) however, the study participants did not see themselves as advanced users nor experts. This lack of expertise is also reflected in more specific questions about their experience with AR headsets. While most participants had indeed already heard about Microsoft Hololens 1 (18 participants) and Microsoft Hololens 2 (13 participants), the number of those who had actually previously used the Hololens 1 (11 participants) or the Hololens 2 (1 participant) was much lower. Moreover, 9 participants stated that they had not used any of four mentioned AR head-mounted devices so far, which indicates that almost 50 percent of our study participants were novice users of AR headsets such as the Microsoft Hololens. This fact is important to consider when interpreting the results, since the limited time span for this comparative study did not allow us to provide novice users with additional training, which could have helped to counteract a potential novelty effect towards the AR technology on the Microsoft Hololens (Huynh, Ibrahim, Chang, Höllerer, & O’Donovan, 2018).

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[2] These questions have previously been used in various publications (i.e. Pirker, Lesjak, Parger, and Gütl (2018)) with a comparative evaluation of the MaroonVR system, on which we have based part of our own implementation.

The same pattern is visible when asking participants about their previous usage experience with mobile AR applications, i.e. marker-less or marker-based iOS and Android applications on tablets or smartphones. Again, 9 participants stated they had not yet used such types of AR applications at all, while 8 participants had already used Android-based AR applications, and 3 participants had used marker-less AR applications on iOS.

In contrast, when participants were asked to indicate whether they had already used the AR features of four popular consumer mobile apps (i.e. Instagram Face Effects, Snapchat Face Lenses, AR mode in Google Maps and in Pokemon Go), only four participants stated that they had not yet used any of these AR features. In fact, 10 out of 20 participants reported that they had indeed already used Snapchat Face Lenses, which is an example of a marker-less AR feature in the Snapchat app using facial recognition to overlay users' faces with virtual content such as sun-glasses. This discrepancy in recognized usage and non-usage of AR might be due to the fact that users are not yet fully aware that AR technology is powering these standard features in popular social sharing and gaming apps.

When asked about their physics knowledge, only 2 participants rated themselves as being an expert in physics (AVG=2.90, SD=1.07). 18 participants regularly use e-learning tools for learning, while only 7 participants use simulations of experiments for learning. All 20 participants except one agreed that using an Augmented Reality environment for learning physics is a good idea. The next section discusses qualitative and quantitative results from the comparative evaluation with these 20 participants.

5.5 Results

In total, we have evaluated written feedback and online questionnaire answers from 20 study participants, henceforth also referred to as "users". We focus on analyzing qualitative and quantitative results in the area of User Experience, Interactivity, Learning Progress and Motivation. Qualitative results consist of participant's answers to open-ended questions, whereas quantitative results contain calculated average scores and standard deviation from single-choice Likert-scale questions. The following sections present these findings in more detail.

5.5.1 User Experience, Usability and User Satisfaction

The subjective user experience was first evaluated using open-ended questions asking users about their overall impression, their opinion on the use of AR, and their likes and dislikes for each of the two versions of AR application. The following paragraphs compare the qualitative findings for both AR applications.

When asked about their overall impression, most users found the Hololens AR application interesting and exciting to use, even though the novice Hololens users among them did remark some difficulties with technical aspects such as specific user controls and limited field of view of the device, as relayed in statements such as *"Hard to control the objects using HoloLens gestures"*, *"Bit annoying regarding controls, but overall fun."* and *"The Design and interaction system is pretty well, however the lack of high FOV in hololens is pretty annoying and reduce the user experience."*. Similarly, users of the mobile AR application generally found it easy to use and well designed, apart from some minor bugs regarding usability.

Regarding the use of hands-free, marker-less AR in the context of learning physics, the majority of users had a positive opinion, stating that it is generally a good idea and helps them in improving their conceptual understanding of invisible phenomena, as expressed in one statement: *"It was nice that something invisible (i.e. field lines) could be understood quite intuitively. I think this could be very helpful in combination with real physical items."*. Similarly, the majority of users also had a positive opinion regarding the use of hand-held, marker-based mobile AR in the context of learning physics, whereby several users were specifically pointing out the useful advantages of a mobile AR solution over a traditional textbook solution, as illustrated in the following statement: *"Change of field strength etc. not possible on normal piece of paper or book, switching on and off of vector fields helpful for visualization."*.

Positive and Negative User Feedback

For the Hololens AR application, users especially liked the fact that they could see the visual augmentation in all three dimensions and thus it was possible to walk around in physical space and view the augmented content (i.e. static magnets anchored in physical space) from different angles and various perspectives, as exemplified in a user's statement: *"Easier to understand 3D interactions, e.g. walk around magnets, magnets stay still while you walk around and look at it at different angles."*. In contrast, when using the mobile AR application users especially liked the fact that this version combines virtual features (strength of magnet; field line and vector field visualization) with physical features (weight of real magnets, attracting/repelling force), thus offering a real-time, realistic and interactive experience between real-world-objects and the visual augmentation in AR. For example, a user reported to like *"that I could move around with the phone and the physical magnets and see the impact in real time."*

As far as negative feedback for the Hololens AR application is concerned, users mainly did not appreciate the limited field of view, the necessity to use specific hand gestures, as well as the setup of the Hololens headset itself which sometimes required additional adjusting to fit the users' head. Moreover, one user specifically noted that *"The experience of using hololense was taking away attention from the physics lecture."* which might indicate that AR experiences on the Hololens could even distract students from educational content due to its unconventional, novel user interface. Concerning negative feedback for the mobile AR application, user's complaints were referring to several issues. First of all, the frequent loss of marker tracking which occured when printed image targets were not in view of the camera. Due to the hand-held nature of the smartphone device, only one hand was free for interacting with the real magnets and this was disliked by several users. Sometimes, users negatively commented on the non-intuitive need to first select a magnet before being able to change its field strength.

System Usability

In addition to evaluating the individual user experience by collecting subjective reports from users, we have also assessed the perceived usability of the AR application in a quantifiable way through two standardised questionnaires, the System Usability Scale (SUS) with 10 items and an adapted version of the Questionnaire for User Interaction Satisfaction (QUIS) with 20 items.

For the **System Usability Scale**, users had to rate 10 statement items on a range from 1 (strongly disagree) to 5 (strongly agree). These metric results from the System Usability Scale survey were then computed according to the standardized formula established by Brooke et al. (1996). Overall, the 20 study participants rated the **mobile AR application (SUS AVG=80.875, SD=11.244)** with a higher average SUS score than the **Hololens AR application (SUS AVG=70.375, SD=18.813)**. The mobile SUS score falls into the *"Good"* range, whereas the Hololens SUS score is lower and lies within the *"Okay"* range, as can be seen in the reference interpretation depicted in Figure 5.3. Moreover, the Hololens SUS Score has a relatively higher standard deviation of 18.813, compared to the mobile SUS' standard deviation of 11.244. This reflects the fact that users opinions about the Hololens AR application were more divided and spread over a greater range, depending on users individual experience and potential previous experience in interacting with holograms. Nevertheless, the computed SUS scores for both AR applications are still above the overall average SUS score of 68 (Brooke, 2013).

For the mobile AR application, none of the 20 study participants has given it a non-acceptable, low SUS score below 60, whereas for the Hololens AR application a total of six users gave it an usability rating of less than 60 which means that to those users, the Hololens system's usability is still marginally low or even non-acceptable, according to the SUS interpretation scale in Figure 5.3.

The difference in SUS scores between the two versions of the AR application might result from the fact that not every user had previous hands-on experience with the Microsoft Hololens. Therefore, especially novice users were not always able to adapt to the relatively novel input method with head gaze and hand gestures on the Hololens right away, even after they had received a short technical demonstration prior to putting on the AR headset. Whereas users were already used to the conventional, more "haptic" way for interacting with the mobile AR application, users testing the Hololens struggled more and sometimes even required assistance on how to adequately perform or correct their hand gestures so that these were recognized by the Hololens. Moreover, the head-mounted nature of the Hololens glasses means that its users were essentially trying to get used to the physicality of a wearable device while also interacting with the software. This might have biased their opinion towards the usability of the overall system, taking into account both hardware and software instead of being able to separately evaluate the software AR application as such. Problems with the Hololens headset sliding downwards due to not having been fitted properly or causing discomfort due to its heaviness may also have distracted users and tilted their user experience for the Hololens AR application towards a slightly more negative light.

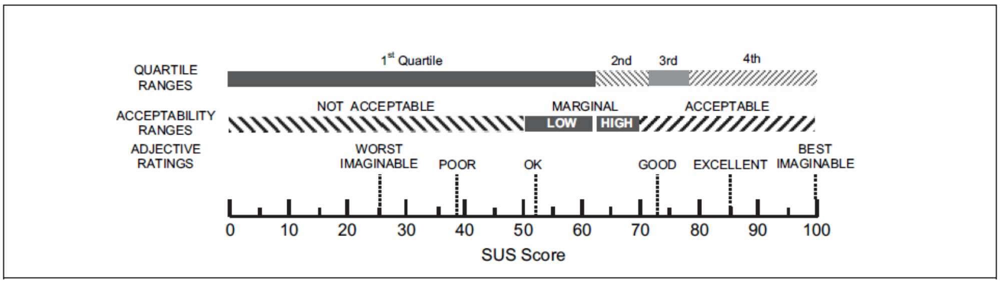

Figure 5.3: The reference scale for SUS scores, reprinted from Bangor, Kortum, and Miller (2009)

User Interaction Satisfaction

In order to measure user satisfaction with specific interactive aspects of the user interface, we conduct our evaluation with an adapted version of the Questionnaire for User Interaction Satisfaction (QUIS). It contains 20 statement items divided into five categories about the overall user reaction to the system, the screen interface, learning, system capabilities, as well as usability and user interface. Users were asked to rate each statement on a range from 1 to 5. Each statement had the same-sized 5-point Likert-Scale, but the individual continuum ranges were polar opposites and labelled differently for each statement. An overview of the QUIS results is shown in Table 5.1.

With regards to the overall user reaction to the system, users found the mobile AR application to be less frustrating and thus more satisfying (AVG=4.30, SD=0.91) than the Hololens AR application (AVG=3.80, SD=1.24). The higher standard deviation at SD=1.24 for the Hololens average also indicates that this user reaction rating differed over a greater range for the Hololens app, given the varying previous Hololens experience of the users.

Moreover, users also rated the mobile AR application slightly more "wonderful, easy, and flexible" than the Hololens AR application, as can be seen by comparing the average score values in Table 5.1. This might be due to the fact that the users were already quite familiar with the user interface and user interaction on a smartphone. In fact, they found learning to operate the system way more easy on the mobile application (AVG=4.65, SD=0.49) than on the Hololens application (AVG=3.95, SD=1.10) .

In contrast, the users perceived the Hololens AR application to be a bit more "stimulating" (AVG=4.50, SD=0.76) than the mobile AR application (AVG=3.95, SD=0.60). This might be related to the novelty effect of the Hololens and its novel user interface which made the AR experience more exciting, but also more frustrating, especially for almost half of the users who had never used the Hololens before. Other areas where users rated the Hololens application higher (albeit only slightly higher) than the mobile AR application were regarding a better use of colors, a clearer organization of information on the screen, easier remembering of names and use of commands as well as better system feedback and a more gracious system response to errors.

Table 5.1: Overview and comparison of average scores and standard deviations on QUIS statements between Hololens and mobile AR application.

			Hololens AR app		**Mobile AR app**	
Nr.	**Statement**	**Range Continuum**	AVG	SD	AVG	SD
1	Overall User Reaction to the System	terrible (1) ... wonderful (5)	4.10	0.72	4.35	0.67
2	Overall User Reaction to the System	difficult (1) ... easy (5)	4.15	1.09	4.50	0.61
3	Overall User Reaction to the System	frustrating (1) ... satisfying (5)	3.80	1.24	4.30	0.91
4	Overall User Reaction to the System	inadequate power (1) . . . ... adequate power (5)	4.10	1.02	4.55	0.86
5	Overall User Reaction to the System	dull (1) ... stimulating (5)	4.50	0.76	3.95	0.60
6	Overall User Reaction to the System	rigid (1) ... flexible (5)	3.60	1.10	3.95	1.05
7	Characters on the computer screen are	hard to read (1) ... easy to read (5)	3.90	1.17	4.25	1.12
8	Highlighting on the screen simplifies task	not at all (1) ... very much (5)	4.15	0.75	4.25	0.85
9	Organization of information on the screen is	confusing (1) ... very clear (5)	3.95	1.05	3.90	1.07
10	Learning to operate the system is	difficult (1) ... easy (5)	3.95	1.10	4.65	0.49
11	Exploring new features by trial and error is	difficult (1) ... easy (5)	4.15	0.93	4.45	0.76
12	Remembering names and use of commands is	difficult (1) ... easy (5)	4.50	0.76	4.35	0.93
13	Tasks can be performed in a straight-forward manner	never (1) ... always (5)	4.15	0.99	4.25	0.72
14	System speed is	too slow (1) ... fast enough (5)	4.45	0.94	4.45	0.89
15	System reliability is	unreliable (1) ... reliable (5)	3.50	1.15	4.05	0.76
16	Correcting your mistakes is	difficult (1) ... easy (5)	3.95	0.89	4.60	0.60
17	Experienced and inexperienced users needs are taken into consideration:	never (1) ... always (5)	3.35	1.18	3.65	1.14
18	Use of colors is	poor (1) ... good (5)	4.20	0.70	4.15	0.81
19	System feedback is	poor (1) ... good (5)	4.10	0.79	3.75	1.16
20	System response to errors	awkward (1) ... gracious (5)	3.75	0.97	3.50	1.00

5.5.2 Interactivity and User Interactions

After having a look at the overall user experience of the developed AR application, we want to focus specifically on its interactivity and also the differences in user interaction possibilities on the Hololens device and the smartphone device. As discussed in Chapter 2, one of the fundamental characteristics of AR, according to Azuma (1997), is its real-time interactivity. In other words, the nature of AR technology makes it possible for users to engage with it in a very interactive way as it reacts to users input in real-time. In order to find out how users experienced the different kinds of user interactions in our AR application, we asked them open-ended questions to reflect about their interaction experience.

User Interaction on the Hololens - Hand Gestures with Head Gaze

For the interactive Hololens AR application, user interaction happens through a combination of head gaze and hand gestures. Feedback from users regarding this type of user interaction was in fact mostly rather negative, as 18 out of 20 study participants mentioned one or more negative issues when asked about how they had experienced this kind of interaction within the Hololens AR application. Users perceived the hand gestures to be very un-intuitive and difficult to perform. For instance, one user stated that it was *"A little annoying, hand gestures seemed to be laggy and unresponsive at times"*. The fact that users were not too fond of having to interact via hand gestures could be due to the fact that the Hololens system does not recognize hand gestures immediately or even not at all if these are not performed in a very specific way within a certain space frame in front of your body, as described by Microsoft (2019) and expressed by one user's observation: *"[...] it seemed like the headset expected me to do something in one exact way and if it's not done like that it doesn't work."*. Another user's remark concerns the user interaction with the slider UI elements: as there is one separate slider for each magnet, it could be helpful to also visually highlight the corresponding magnet (that is changing its field strength) while the user is actively adjusting the relevant slider on the Hololens AR application. In addition, one participant noted that the three-dimensional sliders were partly obstructing the vector field augmentation, depending on the user's viewing point - therefore, both virtual sliders should be positioned sufficiently below the vector field.

User Interaction on the Smartphone - Image Targets and Magnets

For the interactive mobile AR application, user interaction happens through a physical, real interface which is more *tangible* (i.e. touchable and concrete) than the more unusual interface on the Hololens. More specifically, users do not just touch and point into thin air like with the Hololens - instead, they interact in a more commonly used way, via touch input on the tangible smartphone display and direct movement of printed image targets and physical, real magnets attached to these image targets. These real magnets were then overlaid with virtual magnets and visual representations of their magnetic field. When users were asked how they liked interacting in this way, their responses were generally more positive than for the Hololens application. Users found this rather familiar way of interacting with a smartphone and real, physical objects relatively easy to understand and use. The only issue they mentioned in the context of interacting with magnets concerns the frequent loss of tracking of the printed image targets (to which the real magnets were attached), because the augmented content disappeared as soon as the smartphone camera was not pointed exactly onto the image targets anymore or as soon as the image targets were partially obstructed by hands or other objects. Therefore, this required users to re-adjust the smartphone position frequently in order to re-enable the tracking functionality. One user also remarked that *"the magnets clinging to one another made it sometimes hard to interact with the printed targets."*.

User Interaction on the Smartphone - Touch Input on Smartphone Display

Users of the mobile AR application also generally enjoyed the easy-to-use interaction through touch input (i.e. tapping and dragging fingers on the smartphone display), describing it as *"pretty classic touchscreen stuff"* and *"No problems here, felt like a standard app"*. The only issue occurring here is the fact that the necessity of selecting a magnet and how to do so was not always clear to users. This was, in fact also a frequent observation made during the live test sessions with study participants: several users of the mobile AR application did not intuitively know that a magnet has actually first to be selected via a tap on the touch display before its field strength can be set via the UI slider. Users were trying to set the field strength via the UI slider a few times without having selected a magnet first and then appeared confused about the apparent lack of an appropriate system reaction and missing feedback after their input. After letting the users try a few times, a few of them figured it out themselves, whereas others eventually did require a hint from the study conductor. In any case, this revelation resulted in some "Aha!" reactions from users who seemed surprised, yet satisfied once they had comprehended that the corresponding magnet is always highlighted with a green outline after they had correctly selected it.

When interacting with UI elements on the smartphone display, users of the mobile AR application sometimes had troubles fine-tuning the field strength to an exact value by dragging the slider handle to a certain value between the range of 0 and 10. It was not always possible to land at the desired value right away, which required users to overshoot and then re-adjust the slider handle downwards again. One user has suggested to replace the slider element with two plus and minus buttons for incrementally increasing and decreasing the value by 1.

Yet another aspect which had not been considered while planning this evaluation is the fact that user interaction can take place even in unintended or unexpected ways. Some users decided right away to launch and use the mobile AR application in landscape mode instead of in portrait mode. In fact, the landscape mode indeed provided a better camera angle and field of view for users. However, we then asked all users to stick to portrait mode during testing, as the UI elements in the mobile AR application had previously not been designed with auto-rotation or horizontal viewing in mind.

5.5.3 Learning Progress and Motivation

The evaluation of learning progress and motivation towards learning was done separately. First of all, the learning motivation of study participants has been assessed by themselves after each AR experience. As can be seen in Table 5.2, participants rated their learning experience and motivation on a five-point Likert-scale between 1 (fully disagree) and 5 (fully agree). In general, users showed strong motivation to learn with both variants of the AR application as they perceived each of them as interesting, engaging and useful tool to supplement regular learning.

Motivation and Preference

When comparing the average ratings for the Hololens AR app and the mobile AR app, it appears that users would rather like to learn with the mobile AR application (AVG=4.10, SD=0.85) than with the Hololens AR application (AVG=4.05, SD=1), albeit there is only a minor difference in the average ratings. In addition, users also think that the mobile AR application makes learning more fun (AVG=4.85, SD=0.37) than the Hololens AR application does (AVG=4.45, SD=0.83). In accordance with this finding, users preference to learn with an AR environment inside the classroom is indeed higher for the mobile AR application (AVG=4.2, SD=1.11) than for the Hololens AR application (AVG=3.6, SD=1.23). The same preference pattern applies to learning outside the classroom.

However, when users have to choose between learning physics with traditional methods or with the AR application, they still tend to favour the Hololens version (AVG=4.25, SD=1.16) rather than the mobile version (AVG=3.9, SD=1.02) of the AR application. Moreover, users perceived the physics simulations to be more engaging when viewed through the Hololens display (AVG=4.5, SD=0.83) than through the smartphone display (AVG=4.15, SD=0.93). This could be interpreted as an effect of the relative novelty of the Hololens user experience.

After having experienced the two versions of the AR application on both AR devices, study participants were ultimately asked to directly compare these and choose their preferred one. Overall, the majority of users prefers the mobile AR application, which again aligns with the aforementioned analysis of findings from Table 5.2. In total, 12 out of 20 users indicated a preference for the mobile AR application on Android, with almost all responses justifying their preference with the fact that the mobile AR application was *"easier to use"* and *"not as cumbersome"* to use as the Hololens. The remaining 8 users preferred the Hololens AR application, mostly citing reasons such as the possibility of hands-free use and a better-designed UI operating in 3D. One user also stated that *"the static image projection is easier to look at than the constantly updating Android app."*

Learning Progress

In addition to evaluating the motivation of learners, we also aimed to assess potential learning progress of study participants. This was done by requiring all study participants to fill out a short pre-quiz with knowledge questions before they tested their first AR application, and to answer the same post-quiz once again right after they had tested their first AR application. These knowledge questions address the conceptual understanding of magnetism as physics phenomena. In addition to answering these knowledge questions, study participants were also asked to rate their individual confidence level on a scale from 1 (not confident, unsure) to 5 (very confident, sure) regarding the correctness for each of their answers. The subsequent comparison and interpretation of the combined pre- and post-quiz answers has revealed the following analysis:

- Participants with sufficient prior knowledge who thus scored mostly correct answers on the pre-quiz, also had mostly correct answers afterwards

Table 5.2: Learning Experience and Motivation in Hololens AR app and Mobile AR app rated on a Likert scale between 1 (fully disagree) and 5 (fully agree)

	Hololens AR app		**Mobile AR app**	
Statement	**AVG**	**SD**	**AVG**	**SD**
I would like to learn with the AR application	4.05	1.00	4.10	0.85
It is a good idea to use the AR application for learning	4.40	0.88	4.50	0.69
The AR application is a good supplement to regular learning	4.50	0.61	4.65	0.67
I learned something with the AR application	4.30	0.92	4.45	0.69
The AR application makes the content more interesting	4.75	0.44	4.70	0.57
The AR application makes the content easier to understand	4.40	0.60	4.50	0.61
The AR application makes learning more engaging	4.30	0.86	4.65	0.59
The AR application makes learning more fun	4.45	0.83	4.85	0.37
The AR application makes learning more interesting	4.40	0.82	4.65	0.81
The experience with the AR application inspired me to learn more about physics	3.20	1.40	3.35	1.09
Learning with the AR application was more motivating than ordinary exercises	4.40	0.88	4.50	0.69
I would rather like to learn Physics with the AR application than with traditional methods	4.25	1.16	3.90	1.02
I find regular physics classes boring	2.25	1.12	2.40	1.23
Seeing the physics simulations through the Hololens / the smartphone display was engaging	4.50	0.83	4.15	0.93
Seeing the physics simulations through the Hololens / the smartphone display was interesting	4.40	0.75	4.50	0.76
I would like to learn with the AR application in the classroom	3.60	1.23	4.20	1.11
I would like to learn with the AR application outside of the classroom, i.e. at home	3.80	1.11	4.10	1.12

in the post-quiz. In addition, the AR experience managed to further increase their confidence (which had already been rather high previously) as well.
- Participants with insufficient, inexistent or incorrect prior knowledge did not always manage to learn and gain enough knowledge using the AR application. Subsequently, their answers in the post-quiz would not always be correct. Nevertheless the subjective confidence regarding the correctness of their answers increased for almost everyone, even when answers in the post-quiz were still wrong.
- Participants with little prior knowledge and low confidence were able to gain more new knowledge and more confidence than those who already previously had a confident knowledge about magnets and magnetism.
- Participants were almost always equally confident or more confident about their given answer after they had experienced either AR application, regardless of the actual correctness of their answer.

When analyzing the users' answers to selected knowledge questions and comparing their correctness with regard to the AR application used by study participants to learn, it seems like users learn slightly better using the mobile AR application. As illustrated in Figure 5.4, 60% of users who first used the mobile AR application (sample size n=10) could subsequently correctly draw the magnetic field lines around two attracting magnets. In comparison, only 50 percent of users who first used the Hololens AR application (sample size n=10) could give a correct answer to the same question.

In another question, the users were asked to describe the relationship between magnetic field strength and magnetic field lines. Once again, the same pattern as before can be observed. As depicted in Figure 5.5, after using the mobile AR application, 70% of users has given a correct answer to this questions, while the remaining 30% has given a wrong answer. In contrast, only 50% of users gave a correct answer to this question after using the Hololens AR application. Here, the remaining users have given either a wrong answer (10%), an almost correct answer (30%) or no answer at all (10%).

When users were asked about what they had learned in terms of physics right after using the AR application for the first time, users mainly mentioned that they had now learned how to draw a magnetic field and also that the magnetic field lines run from the North to the South pole. Most of them were quite confident (rated as confidence level 4 or 5) with their answer. Some relevant answers from users are listed here:

- *"magnetic lines and field correlations influence strong/low magnets"*
- *"correct drawing of magnetic field lines, how the field strength influences magnetic field lines, another representation using vector lines"*

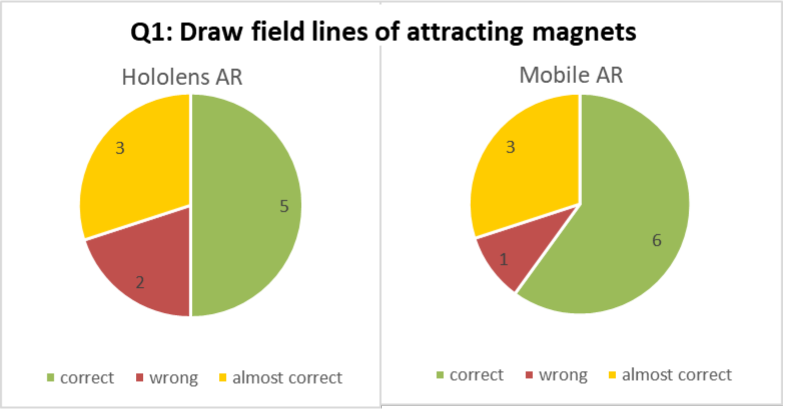

Figure 5.4: Distribution of answer correctness for the question "Draw the magnetic field lines of this magnet constellation (inserted image of 2 model magnets with opposing poles)

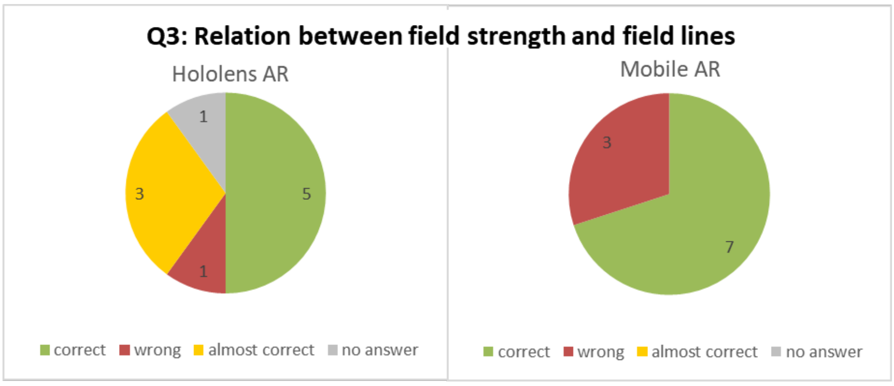

Figure 5.5: Distribution of answer correctness for the question "What is the relationship between magnetic field strength and magnetic field lines?

- *"compared to theory, there is more haptic feedback, one can feel the force of attraction and magnets repelling each other"*
- *"how to draw a magnetic field"*
- *"that I was correct in my assumptions"*
- *"It was a really good representation of forces that are at work. It also helps show the notation used to draw those forces."*
- *"North to South (not the other way around)"*
- *"I know better understand magnetic field lines and magnetic vector fields and how they are visualised"*
- *"it's north to south"*

Besides asking users to describe what they have learned, in the next section we also investigate learning outcomes in connection with the design of our AR application which includes recommended visual augmentation types according to our proposed framework from Chapter 3.

5.5.4 Usefulness of the Framework for Visual Augmentation in Education

As discussed in Chapter 3, we have implemented and evaluated one particular visual augmentation type in order to achieve the augmentation purpose of making invisible phenomena visible. By doing so, we attempt a preliminary, partial test of the usefulness of one part of our proposed framework, which is depicted in Table 3.2. The recommended visual augmentation type which we have chosen to evaluate is essentially the representation of physical phenomena, i.e. in our case the usually invisible magnetic fields around magnets.

After the practical application of the framework by implementing the AR application, its perceived usefulness and effectiveness has also been assessed by evaluating it with users. Looking at the overall user feedback, none of them has explicitly stated that the included visualisation of magnetic field lines, vector field and virtual magnets is detrimental to their learning experience or that they would like to see it removed and replaced with another visual augmentation. In fact, users agree that it makes sense to visualize magnetic fields in a dynamic way (changing according to field strength), as this would, for instance, not be possible within static images in textbooks.

Nevertheless, it is still questionable whether the included visual augmentation is enough in its current form. While users enjoyed seeing virtual magnetic field lines and the vector field around magnets, they were later often not able to answer the assessment question asking them what other representations of the magnetic field they know of. This might indicate that the mere representation of physical phenomena without any additional information did not make users really aware about the underlying meaning. For instance, users struggle to recognise and associate the visible vector field with directional arrows as a valid visual representation of a magnetic field. To counteract this, the existing visual augmentation could be expanded by the display of textual hints and instructions, which are the recommended visual augmentation types to draw users attention, according to our proposed framework discussed in Chapter 3.

Furthermore, the design of the existing visual augmentation itself might also have already influenced the learning outcome of users. One part of the visual augmentation which was often overlooked by users on both AR applications alike are the green directional lines on top of the white magnetic field lines, as depicted in Figure 4.3. Most of the users did not seem to notice these relatively small, three-dimensional arrows, which also manifests itself in their answers to the theoretical questions on the worksheet: rarely did users indicate a direction when drawing field lines. The few users who did notice the green arrows have remarked that the direction of field lines is not very well visible when depicted with the green arrows, especially not on mobile where these lines with arrows are re-rendered in every frame and therefore become difficult to focus on.

In general, our proposed framework has definitely aided us in choosing one appropriate visual augmentation to support learning in the first place. Users already benefit from the fact that our visual augmentation is available as such in the AR application, as they can now interact with a visual representation of usually invisible magnetic fields. However, including just one appropriate visual augmentation type only might not be enough. Given the fact that users were not able to learn all of the conveyed content in the intended way, the addition of other types of visual augmentation according to our proposed framework in Chapter 3 should be considered for future work in order to enhance conceptual understanding and improve learning outcomes more effectively.

5.6 Limitations

The main limitation of our comparative evaluation is its rather small sample size. The number of 20 participants is relatively low and the participants are not directly representative of our main target group (i.e. high school students). Moreover, we do not yet provide a long-term evaluation about the impact of AR on learning outcomes. Due to the small sample size and time constraints, we were also not able to conduct a statistical analysis in order to confirm whether our results are actually statistically significant or not. Similarly, in order to be able to fully confirm the usefulness of our proposed framework for visual augmentation, additional evaluation by comparing different visual augmentation types next to each other and further interviews with experts on visual learning would also be required.

Moreover, the evaluation with study participants is also impacted by several limitations inherent within the implemented AR application software and the hardware devices it is being executed on.

Software

From a software perspective, the tested AR application has not been designed as a sophisticated, fully-featured system to meet all expectations of users but rather as a proof-of-concept for visual augmentation in the form of a first prototype with basic functionality and experimental features, which were sometimes limited due to restrictions in official software SDKs and other frameworks.

Contrary to fully released software, our AR application has not been extensively tested for quality assurance by ourselves. Therefore, it is evident that hidden usability issues and runtime bugs were being encountered live by users who participated in our comparative evaluation study. Another flaw which was noticed by a few users during their test sessions is the fact that magnetic field lines were re-rendered more frequently in the mobile AR application (updates every frame) than in the Hololens AR application (updates every 30th frame), where the update rate had to be sampled down to ensure a fluid, optimal performance without a frame rate drop. This difference makes the former application appear more reactive and dynamic than the latter.

Hardware

In addition to these software limitations, there are also hardware differences between our chosen AR devices which might bias users perception and influence the comparability in between them. Both AR devices, the Microsoft Hololens and the Android smartphone, come with advantages and disadvantages alike. While the Hololens' major drawback is its rather small field of view, its head-mounted setup provides users with the benefit of having both hands free to also interact with real objects. However, even though their hands were free, users were not using this potential to grab and move real magnets, like they did while using the mobile AR application. As explained in Chapter 4, our work mainly focuses on comparing marker-less AR on the Hololens with marker-based AR on the smartphone, therefore we did not implement any marker-based nor marker-less tracking of real magnets in the Hololens application. This was done for the mobile application instead where real magnets are detected and tracked indirectly through their attached printed markers. However, moving real magnets while viewing their augmentations through the smartphone display still comes with the disadvantage that only one hand is free to move magnets around, given the hand-held nature of the smartphone. An ideal AR application removing this kind of limitation would consist of a Hololens AR application featuring real-time object detection and marker-less tracking of various kinds of real magnets in different sizes as well as the use of voice commands as an alternative interaction option in case hand gestures do not work properly.

5.7 Discussion

Overall, this evaluation has provided useful insights towards the user and learning experience of our developed AR application. We are now able to answer the aforementioned research questions, albeit without claiming any statistical significance or any validated correlation due to the lack of statistical analysis.

With regards to RQ1 which investigates which AR application provides the better user experience, i.e. which one is has a more satisfying and interactive user experience, it can be said that the mobile AR application is the overall winner. This is reflected in its comparatively higher SUS score and its higher ratings on the QUIS survey. Additionally, more study participants have chosen the mobile application as their preferred AR application. As far as interactivity is concerned, users have also given more positive or mostly positive feedback about the mobile AR application, finding it more easy to use and less frustrating than the Hololens AR application.

As far as RQ2 is concerned, which examines the learning progress and motivation on both AR applications, the same resulting pattern applies. Again, it seems like that users are able to learn and gain knowledge better with the mobile AR application, as reflected in the slightly higher number of correct answers to assessment questions in the post-quiz. Moreover, users have also indicated that they are more motivated to learn with the mobile AR application, which they would also prefer to use for learning inside and outside of the classroom alike.

In conclusion, the AR application provides an interesting and engaging way to learn the concept of magnetism. Nevertheless, the existing UI on both AR applications can benefit from additional improvements in order to further enhance the overall user experience. While the existing visual augmentation already supports learning by representing invisible magnetic fields, the AR application should still be extended with further explanatory augmentations in order to enhance conceptual understanding and ensure effective learning outcomes for all users.

As the Hololens technology itself is still in its infancy, dealing with major usability problems and being costly and difficult to purchase, it is for now not worth it to employ large-scale educational experiences with the Hololens in classrooms. Given the wide prevalence of easy-to-use and flexible smartphones nowadays, it makes sense to further pursue the development for learning with mobile Augmented Reality applications instead.

6 Lessons Learned

This chapter reflects critically on the creation process of the whole thesis and presents lessons learned while working on this thesis. These learned lessons will also be incorporated for conducting future work.

6.1 Literature Research

As part of a comprehensive literature survey, we have presented various learning models and technologies for STEM education, with a particular focus on physics. As an alternative to traditional teaching methods, active learning methods enhanced with immersive and interactive technologies such as Virtual Reality or Augmented Reality has been proven useful to meet the needs of a new generation of learners. Both Virtual as well as Augmented Reality have advantages and disadvantages and are well suited for different educational use cases. In science education, the use of AR has not yet spread as far as the use of other e-learning technologies with more technological acceptance, even though prior research has already been investigating the effects of AR vs. non-AR environments on learning. Our literature research further contributes to analyzing the use of Augmented Reality in a more distinguished approach, by comparing existing marker-based with marker-less AR applications in science education and using this as a basis to develop a framework for the effective design and use of educational visual augmentations.

When attempting to develop a new model or framework, it is also crucial to base it on existing literature and back up claims with empirical evidence. The value of a well-grounded and extensive literature research shows itself here, since existing examples retrieved from previous literature research can be used to justify and illustrate the content of new frameworks or models.

6.2 Design and Development

The testing part of the development process was rather cumbersome, as many functionalities, especially related to UI, were not testable within the Unity Editor. Therefore, each time a change occured, it was necessary to deploy a new build onto the respective AR device, which has consumed a lot of time overall.

When designing interactive holographic experiences for the Microsoft Hololens, it is of utter importance to consider the correct sizing and placement of virtual objects within the scene due to the limited field of view of the Hololens. Objects should not be placed too far apart from each other and each object should ideally be small enough to fit into the whole viewframe at once.

For AR applications using the Vuforia SDK, it is required to enable the "WSA Internet Client" property within Unity Player Settings, or else the image targets will not be recognized (without an internet connection to the Vuforia Target Manager).

Script Execution Order is important if the nature of the application changes, i.e. if virtual content is suddenly being placed after a tap instead of being loaded into the scene right away. In addition, it is important to test all possible user interactions on the AR device, such as rotating or scaling virtual objects. In this way, otherwise dormant bugs might be discovered and fixed.

As soon as virtual objects become dynamic in the sense that they can be moved along more than one fixed axis, it is crucial to take the use case of rotated objects into consideration for computational calculations and rendering methods. For example, the rotation of the virtual magnet within world space coordinates directly affects the rendering of field lines as well as the rotation of vector arrows, so the correct Quaternion functions from Unity need to be used to always return the appropriate angle.

Coroutines are an efficient way to spread complex, computationally intensive calculations such as the position of the field line segments over multiple frames without blocking other running functions such as tracking of virtual objects. Converting the drawing of field lines into a coroutine rather than executing it as a normal function to be completed in one frame has made this visual augmentation appear more smooth and fluid, especially on the Hololens device.

6.3 Evaluation

During the test sessions, it is necessary that physical surroundings have the appropriate lighting conditions (not too bright, no fully turned on lights in the evening) so that small or thin holograms (like directional vector field arrows) are easy to see.

In addition to considering the surrounding environment, it is important to consider the time it takes for complete newbies to learn the hand gestures specific to the Hololens, as these do not come intuitive to everyone. Hence, a training session prior to starting the experiment where users spend some time in the official ”Learn Gestures” app on the Hololens could also serve to familiarize novice users with the Hololens-specific gestures and diminish a potential novelty effect which might taint their user experience.

Moreover, even experienced Hololens users sometimes had trouble performing hand gestures in such a way that they were recognized right away. Therefore it is recommended to implement the use of relevant voice commands as a fall-back option for user interaction in case the hand gestures are not working properly. Furthermore, a second fall-back option in case that voice commands do not work would be to pair the official Bluetooth-connected clicker with the Hololens. This clicker can then act like a single-buttoned mouse. Alternatively, a real Bluetooth mouse and Bluetooth keyboard can also both be paired with the Hololens and subsequently used for user interaction, without the need to implement any additional input handling in the Hololens application.

Another lesson learned was the necessity to deal with the declining ability among study participants to read thoroughly and take in information precisely, step by step. This lesson was learned through the printed worksheets which were used to assess learning progress. These worksheets contained textual questions (each question on a separate page, thus leading to a high page count), some descriptive text as well as illustrative models of magnets. Overall, the printed worksheet package consisted of 14 pages stapled-together and was handed to the participants as such. First of all, participants did not exhibit a lot of enthusiasm when seeing this stack of paper. They sometimes flicked through the pages quickly to peek at other questions and were generally concerned about being confronted with a seemingly high workload. In future user evaluations, these concerns should be alleviated pre-emptively by first explaining the complete evaluation procedure step-by-step to the participants and then handing them the questions page by page instead of all at once in order to not overwhelm them.

As far as the questions and descriptive text on the worksheet itself are concerned, it was noted that not every participant had the patience or the attention to properly read through the text, sometimes missing or mis-reading important contextual information or misunderstanding the question itself. This leads us to the assumption that questions should be phrased as simple and as unambiguous as possible. Furthermore, important parts of text or questions should be emphasized in different font styles. For instance, two questions consisted of different printed constellations of magnet models in black-and-white-color, with their poles indicated with the letter N or S only. When users were asked to draw field lines around these magnet constellations, some of them were confused since both constellations appeared to be the same to them. An additional color-coding of the magnets poles in red and blue colors would probably avoid this confusion and help users to recognize these magnets as attracting or repelling each other.

7 Conclusion

This final chapter presents several ideas for future work as an outlook, before summarizing the thesis contents in order to provide a well-rounded conclusion to this research work.

7.1 Future Work

First of all, we are planning a large-scale evaluation with more participants and users from the target group (high-school students), possibly also as long-term evaluation to evaluate learning progress over a longer period of time. For this purpose, the integration of an automated assessment system with quiz questions and user tasks would be useful.

In its current state, our developed AR application only augments straight bar magnets. In future versions, it should provide additional visual content and also use augmentation in combination with other real objects. For instance, the augmentation of other common types of magnets such as horseshoe magnets shall be supported as well. As we have seen from our user evaluation in Chapter 5, the use of real objects such as the two bar magnets has been received quite well among users of the mobile AR application. Additional areas where it makes sense to augment physical phenomena are for example experiments involving mechanics. Using Augmented Reality, one can depict the forces acting on real objects which are being moved by users (i.e. operating a model crane with weights). Other examples include augmenting the acting forces when riding a bike, or visualising balls rolling down a ramp at different speeds with augmented force vectors indicating gravity, acceleration, and velocity.

In addition to expanding the reach of our AR application towards other subject domains and with new educational content, future work will also aim at integrating new features (some of which were requested by users during the evaluation phase) into the existing AR application to further enhance it. One major extra feature which would probably lead to a ”wow-effect” among users is the visualisation of the vector field as color-gradient heat-map. By providing a colored heatmap visualisation of the vector field arrows, the vector field augmentation then would not only show the direction of the field (via the direction of the individual field arrows) but also the strength of the magnetic field at the arrow positions within the vector field. Overall, the use color of (red color for arrows closer to magnet, to indicate high field strength and green color for vector field arrows further away from the magnet, indicating weaker field strength) or also the use of varying brightness and size of vector field arrows can be helpful to convey additional properties about the magnetic field within the same visual augmentation type.

Future work should not just adapt existing visual content but also extend it by introducing other forms of visual augmentation within the AR application. As already discussed in Chapter 3 and Chapter 5, it is suggested to also include textual annotations for the virtual content in order to make the visible evident and avoid confusion among users. Often users see the augmented content without really being able to call what they see by name, so during the assessment questions they struggle to relate the visuals to the corresponding physical quantity by name (i.e. users asked whether the blue arrows that they had seen were indeed supposed to show the vector field). Therefore, the virtual objects should include tool-tip like textboxes with their corresponding names, so that users can immediately see what part of the visual augmentation depicts the field lines, which part is the vector field, and so on. Similarly, one should also provide users with status messages (e.g. ”magnet tracked/lost”), textual hints or instructions with explanations such as the need to select a magnet first before being able to set its field strength on the mobile AR application.

Another important feature which should be considered in future work is the use of analytics and logging of user behaviour in order to better understand how users are interacting with the AR system. Especially on the Microsoft Hololens, which already tracks users head gaze, this can be combined with spatial mapping of the physical room in which users execute the AR application, in order to create a heatmap of the holograms and areas at which users are most often looking at and interacting with. Ultimately, the use of analytics and statistics (i.e. how many seconds a user has looked at a certain object) could also aid in a detailed investigation and reconstruction of users learning behaviour.

With regards to learning with the AR application, it would be useful to also include an (automated) assessment system. This system could, for instance, ask users to answer theoretical questions just-in-time and in the correct context, namely while they are experiencing the physics phenomena in AR. Instead of later filling out a paper-printed worksheet, situated learning could be assessed through the integration of an augmented, guided assessment quiz within the AR application itself.

The addition of an assessment system also suggests to include more pedagogical guidance in virtual form so that learners can use the app on their own without having to rely on explanations from external teachers. For instance, an intelligent virtual ”physics professor”, similar to Microsoft Office’s ancient ”Clippy” avatar, could appear at various stages and adapt its output accordingly in order to provide users with tasks, instructions and explanations or relevant hints.

7.2 Summary and Conclusion

Learning and teaching in STEM subjects is not an easy task. At the same time, training a sufficient number of STEM graduates and professionals is important in order to keep up with today’s rapidly changing and innovating world pace. Given the fact that students nowadays often lose interest or drop out from lectured STEM classes, active learning is one proven methodology to counteract this movement by actively engaging and motivating students to be more directly involved in the learning process.

The active learning approach can be enhanced with various technologies, such as mobile learning, game-based learning, Virtual Reality or Augmented Reality. Especially Augmented Reality, which merges the real with the virtual world, enables learners to engage in exploratory, inquiry-based and situated learning with their existing learning environment while also staying in touch with physical surroundings and peers for collaboration. In particular for learning physics, this connection to reality can be useful to establish a connection between abstract concepts and observable natural phenomena, such as the haptic force between attracting magnets and the usually invisible concept of the magnetic field surrounding these magnets.

This thesis has presented the design and the evaluation of interactive physics visualisations in Augmented Reality. Based on an extensive literature research, we have started our design process by working towards a framework for visual augmentations in (science) education which should facilitate the creation of meaningful educational AR applications. We argue that certain visual augmentation types are recommended to fulfill certain augmentation purposes which in turn can be matched to aid specific learning activities. Using our proposed ”Advanced EDU-AR-VIZ Framework” established in Chapter 3, we have decided to design and implement a first prototypical AR application for two different AR devices: the Microsoft Hololens and the Android smartphone. In essence, our AR application incorporates the representation of physical phenomena as visual augmentation type in order to achieve the purpose of making the invisible visible.

Using marker-based and marker-less AR respectively, the two device-specific versions of our AR application can augment physical and virtual bar magnets with representations of their magnetic field (in the form of virtual magnetic field lines and vector fields), while also enabling users to dynamically adjust parameters and interact with virtual objects. User interaction on the two AR devices happens through different input modalities, enabled by the respective user interfaces.

In a preliminary study, we have evaluated the AR application with 20 university students. First results from the evaluation have shown that the use of Augmented Reality technology indeed has potential to engage and motivate students to learn more about physics phenomena as it enables students to interact with dynamic, three-dimensional virtual content or even with augmented real objects from all perspectives. Generally, both versions of the AR application have received positive feedback from users. However, there is still room for improvement for both versions regarding the overall need for additional visual augmentation types and fixing prevailing issues with usability on both platforms, as well as addressing the stability of tracking (for mobile AR application) and alternative user controls (for Hololens AR application).

While the appearance of interactive holograms in the Hololens AR application definitely manages to excite users more about novel possibilities in Augmented Reality, the mobile AR application on smartphones is the more promising version to facilitate a comprehensive educational use of AR in classrooms. Especially given the wide prevalence of mobile learning on smartphones, mobile Augmented Reality can be used in combination with existing materials and thus enhance textbooks and laboratory setups with an additional virtual and interactive dimension.

Appendix

Appendix A.

Contents of DVD

The DVD attached in the back cover of this thesis contains the source files for the practical part as well as the theoretical part .

A1) Theoretical part

- The PDF version of this thesis
- Blank template of the online questionnaire files
- Blank template of the printed assessment worksheet given to study participants
- All evaluation questionnaire files (.lss) with answers exported from Lime Survey
- Two examples of assessment worksheets filled out by users as scanned PDF file
- An Excel sheet with the performed calculations to analyze evaluation results

A2) Practical part

- Unity 2017.4 installation file
- A PDF with the printable custom image targets for the mobile Android AR application
- The final version of the AR application in two builds:
  - the Android build (.apk file)
  - the Hololens build (.appx file)

Appendix B.

Installation Guide

B1) System requirements for running the AR application

- for the Hololens AR application:
  - the Microsoft Hololens 1 device
  - with at least 100 MB of free disk space
  - and an active Internet connection
- the mobile AR application:
  - an Android smartphone running Android 8 or higher
  - with at least 2GB of RAM
  - and a functional rear-facing camera

B2) Installation of the AR Application

- for the Hololens AR application:
  - connect the Hololens device via USB cable to your PC
  - follow the official documentation[1] for installing custom apps on the Microsoft Hololens
- the mobile AR application
  - copy the `MagnetAR.apk` file onto your Android smartphone
  - navigate to the file on your phone and long-tap to install
  - When prompted with a system pop-up, agree to "Allow installation of apps from unknown sources"

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[1] https://docs.microsoft.com/en-us/hololens/holographic-custom-apps

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