

Dissertation

Interactive Augmented Reality for Student-Centered, Explorative, and Collaborative Human Gross Anatomy Education

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Technische Universität München

Fakultät für Informatik

Lehrstuhl für Informatikanwendungen in der Medizin

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Abstract

The study of human gross anatomy forms an integral part of basic medical training and is considered an essential prerequisite for all postgraduate medical specialties. However, due to the complexity and diversity of the subject, acquiring knowledge of human gross anatomy is a complex and laborious endeavor for medical students. Consequently, establishing best practices for the learning and teaching of gross anatomy within a modern curriculum for students is a challenging and constantly debated topic. Today's pedagogical landscape in anatomy education encompasses a variety of established learning resources, including cadaver dissections, traditional lectures, anatomy textbooks and atlases, 3D models, and computer-based e-learning resources. In recent years, Augmented Reality (AR) has become increasingly prevalent in many different domains. In the context of anatomy education, AR-based learning offers unique opportunities to create an interactive, student-centered, and collaborative learning environment, combining several of the benefits from other educational paradigms. Therefore, the goal of the present thesis is to investigate the potential of AR as a complementary learning resource for human gross anatomy, and to study whether and under what circumstances AR-based anatomy learning can be effectively integrated into a modern undergraduate anatomy curriculum as a complementary learning resource. For this purpose, two novel AR solutions are proposed: the AR *Magic Mirror* platform and the *VesARlius* application. While the former is a screen-based virtual mirror system that allows users to interact with 3D virtual anatomy models superimposed on their digital mirror image, *VesARlius* is an head-mounted display (HMD)-based AR solution that enables users to engage in a collaborative and synchronized anatomy learning environment that includes an advanced user interface (UI) and a number of different paradigms to facilitate collaboration. In a series of experimental user studies, both AR solutions were integrated into the medical curriculum and evaluated in realistic learning environments with a large number of medical students. Furthermore, the specific advantages of using these two novel solutions for gross anatomy learning purposes were determined by comparing them with established anatomy learning resources. In addition to the technical and evaluation results, this thesis also presents the findings of two user studies addressing two perceptual phenomena associated with the proposed AR solutions. In the context of the AR *Magic Mirror* platform, the differences between a (regular) *Reversing* and a *Non-Reversing Magic Mirror* were investigated as two different design concepts, including the underlying psychological effects and the implications for user perception, anatomical knowledge transfer, and interaction. In the case of *VesARlius*, the limited field of view (FoV) of the HMD was considered a major limitation of the application. Therefore, a number of novel visualization techniques are proposed in this thesis to guide the user's attention towards virtual objects outside the FoV in HMD-based AR applications. In summary, this thesis represents an important first step towards a wide-ranging adoption of AR-based anatomy learning and the establishment of AR as an important and indispensable resource for gross anatomy learning in undergraduate studies.

Zusammenfassung

Das Studium der menschlichen Anatomie ist ein integraler Bestandteil der medizinischen Grundausbildung und gilt als wesentliche Voraussetzung für alle Fachrichtungen nach dem Studium. Aufgrund der Komplexität und Vielfalt des Faches ist der Erwerb von anatomischen Kenntnissen für Medizinstudenten jedoch ein komplexes und arbeitsintensives Unterfangen. Folglich ist die Etablierung optimaler Praktiken für die Anatomieausbildung innerhalb eines modernen Curriculums ein herausforderndes und ständig diskutiertes Thema. Heutzutage gibt es eine Vielzahl etablierter Lernressourcen, darunter Präparationskurse, traditionelle Vorlesungen, Lehrbücher und -atlanten, 3D-Modelle und computergestützte E-Learning-Ressourcen. In den letzten Jahren hat Augmented Reality (AR) in vielen Bereichen zunehmend an Bedeutung gewonnen. Im Kontext der Anatomieausbildung bietet AR-basiertes Lernen einzigartige Möglichkeiten, eine interaktive, studierendenzentrierte und kollaborative Lernumgebung zu schaffen, die die Vorteile anderer Lehrparadigmen kombiniert. Ziel der vorliegenden Dissertation ist es daher, das Potenzial von AR als ergänzende Lernressource für die Anatomielehre zu beleuchten und zu untersuchen, ob und unter welchen Umständen AR-basiertes Anatomie-Lernen als ergänzende Lernressource effektiv in einen modernen Lehrplan integriert werden kann. Zu diesem Zweck werden zwei neuartige AR-Lösungen vorgestellt: die *AR Magic Mirror*-Plattform und die *VesARlius*-Anwendung. Erstere ist ein bildschirmbasiertes *Virtual Mirror*-System, das es den Benutzern erlaubt, mit virtuellen 3D-Anatomie-Modellen zu interagieren, die ihrem digitalen Spiegelbild überlagert sind. Bei *VesARlius* handelt es sich um eine auf einem Head Mounted Display (HMD) basierende AR-Lösung, die eine kollaborative und synchronisierte Anatomie-Lernumgebung bietet, bestehend aus einer fortschrittlichen Benutzeroberfläche (UI) und einer Reihe verschiedener Paradigmen zur Zusammenarbeit. In mehreren Benutzerstudien wurden beide AR-Lösungen in den medizinischen Lehrplan integriert und in realistischen Lernumgebungen mit einer großen Zahl von Medizinstudenten evaluiert. Darüber hinaus wurden die Vorteile des Einsatzes dieser beiden AR-Lösungen für die Anatomielehre bestimmt, indem sie mit etablierten Lernressourcen verglichen wurden. Zusätzlich zu den technischen und Evaluationsergebnissen werden in dieser Dissertation auch die Ergebnisse von zwei Benutzerstudien vorgestellt, die sich mit zwei Wahrnehmungsphänomenen im Zusammenhang mit den vorgeschlagenen AR-Lösungen befassen. Im Kontext der *AR Magic Mirror*-Plattform wurden die Unterschiede zwischen einem (regulären) *Reversing* und einem *Non-Reversing Magic Mirror* untersucht, einschließlich der zugrundeliegenden psychologischen Effekte und der Implikationen für die Benutzerwahrnehmung, den anatomischen Wissenstransfer und die Interaktion. Im Fall von *VesARlius* wurde das begrenzte Sichtfeld des HMD als eine wesentliche Einschränkung der Anwendung angesehen. Daher wurden eine Reihe neuartiger Visualisierungstechniken entwickelt, um die Aufmerksamkeit des Benutzers bei HMD-basierten AR-Anwendungen auf virtuelle Objekte außerhalb des Sichtfeldes zu lenken. Zusammenfassend stellt diese Arbeit einen wichtigen ersten Schritt zur Etablierung von AR als bedeutsame und unverzichtbare Ressource für das Anatomiestudium dar.

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Introduction

” *anat·o·my.*

Latin anatomia, Greek anatomē, "dissection", from ana, "apart", + tomē, "cutting"

1. *The morphologic structure of an organism.*
2. *The science of the morphology or structure of organisms.*

— Farlex Partner Medical Dictionary

Anatomy is a branch of natural science that is concerned with studying the morphologic structure of living organisms. In the context of medical education, the study of topographic (gross) human anatomy forms a cornerstone of medical training and is taught alongside other basic disciplines such as physiology, biochemistry, and histology during the preclinical part of the curriculum in the majority of medical schools around the world. A solid understanding of gross anatomy forms the basis for the clinical part of the curriculum and is considered an essential prerequisite for all postgraduate medical specialties. In a recent study, the relevance of human gross anatomy was evaluated by surveying medical professionals from various disciplines [8]. Gross anatomy was considered the most important discipline for surgical specialties, for understanding different types of disorders, as well as for daily clinical activities such as physical examination, diagnosis formation, and interpretation of radiological section images. These perceptions are shared by medical students, who consider gross anatomy an essential knowledge platform for clinical medicine at all stages of their education [328].

1.1 Motivation

Given the profound importance of gross anatomy for the medical profession, the fundamental question that arises is the following: ***What is the best way to learn and teach human gross anatomy?*** From a historical standpoint, the dissection of cadavers has been one of the most relevant anatomy teaching paradigms throughout the centuries. Until today, dissection courses remain an indispensable instructional unit for teaching anatomy in many undergraduate curricula [445]. Hands-on dissection courses are associated with a number of specific advantages. Among others, they stimulate active learning [496], prepare students for clinical practice and encounters with death [142, 360], and support them in developing manual skills [249], a 3-dimensional (3D) perspective of anatomical structures [10], as well as teamwork competency and empathy [55]. Additionally, cadaver dissections provide an unmatched level of realism by preserving the texture and haptic sensation of anatomical structures which closely resemble those within a living human body [305]. Despite these benefits, there is an ongoing debate about whether dissection courses should still comprise an integral part of modern undergraduate curricula [249, 313, 359]. Critics have argued that the high inconveniences of cadaver dissections in terms of cost [36], time [11], access to cadavers

[312], health related concerns due to the exposure to formaldehyde [87], as well as ethical and legal issues [133] do not justify their continued use. As a result, many institutions have officially abandoned dissection courses in lieu of alternative anatomy teaching paradigms [119, 169, 308, 310]. Prosections (examining previously dissected anatomy specimens) and more recently plastination (a specific way of preserving prosections) have been proposed as two alternative teaching paradigms that can either fully replace or supplement full body dissections [30, 111, 219, 500]. While the actual hands-on experience of dissecting anatomical structures is not incorporated, observing prosections and plastinated specimens requires fewer cadavers and is superior to full body dissections in terms of time-efficiency, allowing students to observe more anatomical variations if several specimens are available [342, 361, 464].

Alongside dissection or prosection courses, didactic lectures have formed the basic framework of anatomy courses for centuries and they remain the most prevalent teaching pedagogy at present [445]. Concomitantly, medical students employ anatomy textbooks for consolidating, reviewing, and increasing retention rates of the lecture contents. However, this traditional anatomy teaching approach has been criticized by many as an inefficient, passive, and outdated form of learning that is purely focused on delivering content [217, 257, 363, 445, 469]. Therefore, medical educators and students alike frequently turn to additional teaching and learning paradigms. These include computer-based learning (CBL) resources that contain digital 3D representations and interactive animations of anatomical models [21, 211, 235, 238, 396], plastic or 3D-printed anatomy models [271, 378], as well as peer examinations on living anatomy such as body painting [20, 95, 311] or ultrasound courses [69, 214].

Another popular paradigm for complementing traditional anatomy education is the incorporation of medical imaging and radiology. Generally, these topics are taught only during the clinical part of the medical curriculum, resulting in a large time lapse between anatomy and radiology education [182, 400, 442]. Early integration of medical imaging into preclinical anatomy and dissection courses has been recognized as an effective avenue for increasing students' understanding of both radiology and gross anatomy alike as previously learned concepts can be correlated with clinically relevant content [161, 318, 331, 367, 419]. Furthermore, such integrated courses have been shown to increase students' motivation and interest in gross anatomy [333] as well as their understanding of spatial relationships [285].

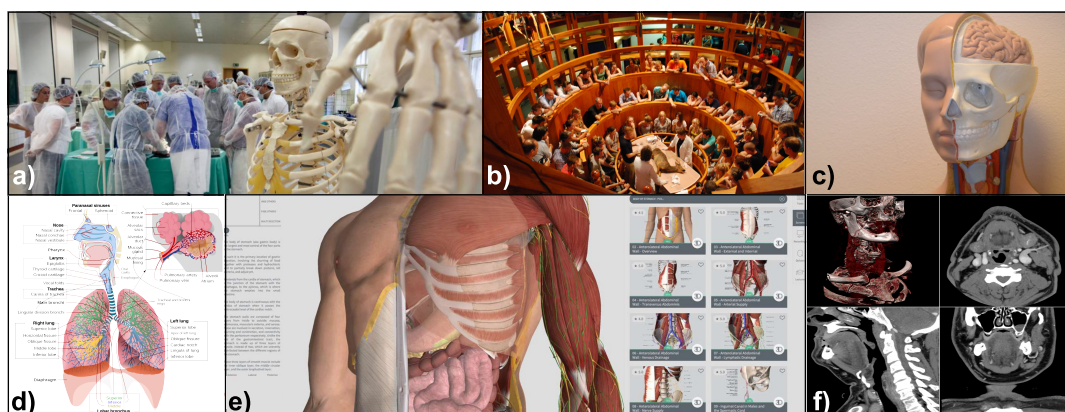


Fig. 1.1. Overview of the most relevant modalities of anatomy education: a) cadaver dissection course; b) traditional anatomy lecture; c) plastic 3D model; d) example content from anatomy textbook; e) computer-based learning resource; f) radiology images from computed tomography (CT).

In recent years, both Virtual Reality (VR) and Augmented Reality (AR) have been established as two novel categories of anatomy education paradigms that offer completely new ways for student-centered, interactive, and collaborative anatomy learning [3, 86, 110]. While VR is characterized by a complete immersion of the user in a simulated virtual environment, AR seamlessly incorporates digital, computer-generated content into the user's view to enhance perception of the real world [12, 13]. For the former, several studies have demonstrated the effectiveness of VR in the context of anatomy education and reported benefits over traditional learning paradigms [91, 325, 340]. However, advanced VR technology is generally associated with a more complex hardware setup, requiring a dedicated VR workstation as well as a tethered head-mounted display (HMD). AR on the other hand offers a set of distinct advantages over VR, making it a considerably more favorable choice for complementing traditional teaching modalities in the context of an undergraduate anatomy curriculum. First of all, different categories of AR systems with varying levels of cost and technical complexity exist, ranging from low-cost mobile AR systems over spatial AR to sophisticated HMD-based solutions [45]. This wide range of options enables institutions to choose the most appropriate form of AR based on their specific requirements. Secondly, the nature of AR to provide an unobstructed view of the real world facilitates the integration of such systems into existing educational settings, in particular for collaborative teaching and learning scenarios. Lastly, perceptual challenges such as motion sickness or eye-fatigue are a common problem for VR systems which do not occur in AR scenarios [7, 184, 200].

Coming back to the initially posed question, an all-in-one solution suitable for serving every aspect of human gross anatomy training in an optimal way does not exist. Instead, medical students are supplied with a plethora of different learning and teaching paradigms, every one of them with specific benefits and limitations. Figure 1.1 provides an overview of the most important educational resources that are used by medical students for anatomy learning today. In recent years, a consensus developed among medical education specialists stating that a modern gross anatomy curriculum should incorporate multimodal learning possibilities where traditional anatomy learning paradigms are complemented by innovative approaches to yield the best possible learning outcome [133, 217, 445]. Especially today, when many experts lament a decline in undergraduate anatomy knowledge due to reductions in allocated time, teaching staff, and cadaver dissections, modern anatomy curricula that incorporate novel learning concepts can counteract this trend [185, 352, 431, 469]. In such modern anatomy curricula of the future, AR has the potential to occupy a position of significant importance as it combines several of the benefits from other learning modalities. Instead of physical anatomy models, computer-generated 3D equivalents can be visualized efficiently in AR and enable various types of intuitive user interaction. Such digital 3D models can even be superimposed directly onto the surface of a tracked person, similar to the manual and time-consuming body painting approach. Additionally, the integration of clinically relevant medical image data can be achieved easily, both in the form of static 2D slices or interactive 3D volumes. Therefore, it is very intriguing to study the benefits of AR-based anatomy learning in more detail and investigate whether and under what circumstances AR can be integrated effectively into a modern undergraduate anatomy curriculum.

1.2 Objectives

The overall goal of this thesis is to investigate the potential of AR as a complementary educational resource in the context of undergraduate gross anatomy learning. In order to achieve this goal, novel state-of-the-art AR solutions have to be developed, which meet the complex and multifaceted requirements of contemporary anatomy education to enable interactive, engaging, and explorative anatomy learning, placing the user at the center of the learning experience. In addition to developing these novel AR solutions, another important objective of this thesis is their validation with the intended target audience—primarily medical students at the beginning of their studies—to ensure that these novel AR solutions can indeed be applied effectively for the study of gross anatomy. For this purpose, the developed AR solutions have to be integrated into a realistic curricular framework and thoroughly evaluated by a large number of students. In addition to these objectives, this thesis aims to identify the particular advantages and benefits of AR-based anatomy learning, requiring a number of experimental user studies in which these novel solutions are compared with established anatomy learning resources. Finally, this thesis will take a look at the remaining challenges and limitations of AR-based anatomy training and explore approaches to limit the impact of these shortcomings.

1.3 Contributions

Considering the objectives formulated above, the contributions of this thesis primarily revolve around two novel solutions that are proposed for AR-based anatomy learning: the AR *Magic Mirror* platform and the *VesARlius* application. While both solutions allow the user to explore highly realistic virtual models of anatomical structures as well as radiological section images, both are tailored to very specific learning scenarios due to their different conceptual designs and unique functionalities. In the following, a summary of the major contributions of this thesis is provided.

The Magic Mirror Anatomy Learning Platform

The first contribution of this thesis is the AR *Magic Mirror* platform, a screen-based virtual mirror system that allows the user to interact with 3D anatomy models that are superimposed *in-situ* onto the digital mirror image of the user, enabling a self-directed and personalized anatomy learning experience. While similar systems have been presented previously, the proposed implementation of the AR *Magic Mirror* platform incorporates a series of novel functionalities, including real-time skeletal animation, improved interactive gesture control, and an advanced perceptual *in-situ* visualization.

In addition to these technical contributions, this thesis presents an in-depth analysis of the perceptual differences between a *Reversing* and a *Non-Reversing Magic Mirror* (RMM vs. NRMM) as two distinct conceptual designs for the AR *Magic Mirror* platform. Within the framework of an experimental user study, the different effects of these two designs on both user interaction and general perception in the context of AR-based anatomy learning are compared.

The third major contribution related to the AR *Magic Mirror* is the evaluation of the platform and its integration into the medical curriculum. Three different user studies are presented within this thesis, in which the AR *Magic Mirror* platform was validated with a total of **1701** medical students in a realistic curricular framework. In addition, these comparative studies investigate the individual benefits of AR-based anatomy learning with the *Magic Mirror* platform compared to both traditional and other modern anatomy learning resources.

The VesARlius Anatomy Learning Application

The second novel solution for AR-based anatomy learning presented in this thesis is the *VesARlius* application, an HMD-based solution developed for the Microsoft HoloLens that allows medical students to engage in a team-based, collaborative learning environment. Unlike the AR *Magic Mirror* platform, which is limited to a single user interacting with the system simultaneously, *VesARlius* incorporates a number of different collaboration paradigms allowing multiple students to work together and explore the system's content in a collaborative and synchronized learning environment.

Similar to the AR *Magic Mirror* platform, the evaluation of *VesARlius* constitutes an essential contribution of this thesis. Two experimental user studies are presented, in which the application was integrated into the medical curriculum. The first study was aimed at determining the potential of *VesARlius* to enable collaborative anatomy learning in teams of co-located students and to serve as an additional educational resource in the context of anatomical education. In the second study, the specific advantages of running *VesARlius* on the HoloLens compared to a standalone application running on a regular desktop computer were evaluated.

A particular limitation of the HoloLens and all current HMD's is the restricted field of view (FoV), resulting in some parts of the *VesARlius* user interface not being visible under certain circumstances. In order to guide the attention of the users towards virtual objects located outside the visible FoV, both within *VesARlius* as well as general-purpose HMD-based AR applications, this thesis proposes a number of novel visualization techniques that are evaluated and compared with other existing visual guidance approaches during two experimental user studies. Lastly, another major contribution in the context of *VesARlius* and out-of-view object visualization is the development of a novel algorithm for classifying different head rotation trajectories.

1.4 Organization

This section provides a concise overview of the organization of the present thesis. Chapter 2 provides the necessary background information relevant for understanding the contributions presented in this thesis, including a comprehensive overview of the history of anatomy education in section 2.1, an overview of AR and its enabling technologies in section 2.2, as well as an exhaustive review of the literature and state of the art in both AR and VR anatomy education in section 2.3. In chapter 3, the AR *Magic Mirror* platform is introduced, starting with a description of the general concept and the technical aspects of the system in the sections 3.1 and 3.2, to the study of *Reversing* and *Non-Reversing Magic Mirrors* in section 3.3, and finally the evaluation of the AR *Magic Mirror* platform and the integration of the

system into the medical curriculum in section 3.4. Chapter 4 is entirely dedicated to the *VesARlius* application and again contains an initial section on the general concept and technical functionalities of the application (section 4.1), followed by a description of the two evaluation studies conducted within the medical curriculum in section 4.2, and finally a detailed analysis of visualization techniques for guiding the attention of users towards out-of-view objects in HMD-based AR environments in section 4.3. Chapter 5 contains both a meta discussion about the meaning and relevance of the obtained thesis results and an outlook on future research directions, both for the AR *Magic Mirror* platform in section 5.1 and for the *VesARlius* application in section 5.2. Additionally, section 5.3 briefly considers the future of AR-based anatomy learning in light of the results presented in this thesis. Finally, section 6 concludes this thesis with a short summary of the key findings.

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In order to develop novel teaching solutions for contemporary anatomy education that serve the needs of medical students, it is important to understand the historical developments in anatomy education that have taken place over time. Therefore, this chapter opens with a comprehensive overview of the history of anatomy education in section 2.1, starting from the very beginnings of anatomy teaching in ancient civilizations to the diverse and multi-faceted educational environment of the 21st century. Against the background of these historical developments and the growing emergence of digital teaching methods, debates on how anatomy should be taught in a modern curriculum are increasingly taking place today. To address a number of remaining challenges in contemporary anatomy education, this thesis proposes novel teaching solutions that are based on Augmented Reality (AR). Section 2.2 introduces the fundamental concepts of AR, including its key enabling technologies that are essential in the development of an AR system. Finally, section 2.3 provides a comprehensive overview of the literature and the state of the art in anatomy education, before section 2.4 concludes with a summary of the main considerations of this chapter.

2.1 History of Anatomy Education

In historical terms, anatomical education has undergone a long evolutionary process which culminated in the systematic teaching of human gross anatomy as an empirical science within today's medical training institutions. For the purpose of better understanding both the complex and multifaceted educational landscape that exists in anatomy today as well as ongoing debates of best teaching practices in anatomy, one has to embark on a journey through time. Throughout the entire history of humanity, acquiring comprehensive insights about the form and structure of the human body with the purpose of applying this knowledge for the treatment of various health conditions as well as for teaching it to future generations has been a fascinating and compelling quest. This history of anatomy and its education is characterized by the mysticism, superstition, and religious beliefs of ancient world views, long periods of slow and stagnating knowledge increase, as well as by radical paradigm shifts that fundamentally changed the way anatomy is practiced and taught. Interestingly, for the most part of that history, the main focus of attention has been the role of dissections and learning anatomy undergoing a traditional apprenticeship model. Only very recently, novel concepts for teaching and learning anatomy were established, driven mainly by technological advances.

2.1.1 Ancient Civilizations

While the very first records conveying a certain degree of anatomical knowledge were scratched and painted on the walls of caves during prehistoric times [287, 467], the actual origins of medicine and anatomical sciences have emerged over the course of several millennia from the cradles of human civilization in Ancient India, Ancient China, Mesopotamia, and Ancient Egypt.

Ancient India

In Ancient India, the earliest evidence of anatomical knowledge dates back to the Vedic Age (c.1500 – c.500 BCE) and was derived mainly from religious sacrifices of both men and animals [280, 507]. This knowledge was passed along primarily within religious hymns and texts containing very primitive lists of bodily parts [507]. Later on, the practice of medicine was taught from *Guru* to *Sishya* in a teacher-disciple relationship [208, 280]. While religious laws prohibited human dissections, famous Ancient Indian physician and surgeon *Susrata* who lived in the 6th century BCE was a proponent of studying the dead body as a means of acquiring anatomical knowledge and published systematic methods for the dissection of the human body in his treatises [327, 365, 443, 507].

Ancient China

The Ancient Chinese civilization was bound by the doctrine of Confucianism and concepts of traditional Chinese medicine such as the balance of energetic forces and harmony of the universe [279]. Human dissections were generally prohibited, hence anatomical knowledge was very limited. One exception is the *Yellow Emperor's Inner Canon of Medicine (Huangdi Neijing)*, a famous medical treatise traditionally attributed to the mythical Emperor *Huang Di* (c.2696 – c.2598 BCE). However, the manuscript is generally dated to the first or second

century BCE and multiple authors are believed to have composed the canon for a long period of time [198, 473, 498]. The document suggests some basic understanding of blood circulation in the body much before it was discovered by William Harvey [279, 282].

Mesopotamia

In Mesopotamia, the practice of medicine—though strongly influenced by magico-religious aspects—was an established profession that included diagnosis, the application of pharmaceuticals, as well as the treatment of wounds [76, 456]. Mesopotamians only possessed very limited anatomical knowledge which was mainly derived from animals [513]. In particular, ancient Babylonian priests considered the liver as the seat of the soul and performed detailed analyses of sheep specimens [299]. Dissections of humans or animals for scientific reasons were not performed [337, 388]. However, it is generally considered that medical practices in Mesopotamia influenced the Ancient Egyptians [388].

Ancient Egypt

Despite previously mentioned early insights in medicine and anatomy from other ancient civilizations, the origins of anatomical studies are generally attributed to the Ancient Egyptian civilization around 3000 BCE [80]. According to their belief in the immortality of the soul and a rebirth after death, the procedures of embalming and mummification were practiced which required the evisceration of human bodies through a small incision and consequently an accurate awareness of the precise topographic anatomy [67, 171]. Therefore, the Ancient Egyptian embalmers can be considered the precursors of today's anatomists and their preparations of cadavers as the first rudimentary dissections [80]. However, as their procedures were motivated by purely ritual and religious motives, studying the extracted organs was not considered relevant to them. While no papyrus strictly devoted to anatomical studies is known, several others accurately document various aspects of anatomy, surgical procedures, and Ancient Egyptian medicine in general [281]. These medical scriptures, including the famous *Edwin Smith Papyrus*, were studied by Ancient Egyptian physicians who received their medical training within temple schools studying various disciplines of medical practice, including patient interrogation, inspection, and examination, as well as palpation and treatment [128, 344, 398]. However, anatomical knowledge was still very limited and diseases—in accordance with all other Ancient civilizations—were believed to originate from external, supernatural interventions and evil spirits [512]. During the *Ptolemaic Kingdom* founded in 305 BCE, Alexandria was established as the cultural and intellectual capital of Hellenistic Egypt that attracted philosophers, scientists, and physicians from around the world. Several impactful anatomists from classical antiquity traveled to Egypt for conducting their anatomical research in Alexandria where they got acquainted with the Ancient Egyptian sources [281]. These unique circumstances in Alexandria, combined with the long tradition of Ancient Egyptian medical knowledge, formed the ideal breeding ground for the future developments of human anatomy as a scientific discipline during Hellenistic Greece and the Roman Empire [80].

2.1.2 Classical Antiquity

The Ancient Greek civilization began to emerge around 800 BCE and is known for initiating one of the most impactful paradigm shifts in the history of medicine. Previously tied to

magic and superstition, the medical practice transformed into a more rational, objective, and empiric discipline with a strong focus on anatomy. While medical education was primarily dominated by a master-apprentice relationship and formalized medical curricula did not exist, the first centers of medical excellence as the earliest precursors to modern medical schools were established in Ancient Greece and later in Hellenistic Alexandria. Historically, this period is also characterized by a vast increase in anatomical knowledge—though often times still erroneous—resulting predominantly from systematic dissections of both animals and human cadavers. Knowledge about anatomy continuously increased in both Ancient Greece and the Roman Empire over the course of several centuries until it reached its peak with the studies from *Galen of Pergamon* whose theories about the human body dominated medical practice and education for more than 1500 years until the Renaissance.

Religious vs. Rational Medicine

In Ancient Greek literature, the very first occurrence of anatomy education appears in Homer's *Iliad* (around the 8th century BCE). In the epic poem, the centaur *Chiron* teaches the secrets of wounds and pain relief to *Asclepius*, son of Apollon and God of Medicine in both Greek and Roman mythology [132, 425]. In dedication to his healing powers, Asclepius was worshiped in hundreds of healing temples known as Asclepieia throughout Ancient Greece [226]. Asclepieia served both as centers of medical education for temple physicians, also known as *Asclepiads*, as well as sacred healing sanctuaries for patients [124, 283]. The medical knowledge in these Asclepieia was orally transmitted from a chosen temple physician to his disciple with the help of supernatural guidance by the gods [253]. In addition to temple physicians practicing and teaching religious medicine in Asclepieia, another group of medical practitioners was abundant in Ancient Greece that viewed medicine as a manual craft. The physicians of this group received a strictly empirical training, whereby the medical knowledge transfer again took place according to a master-apprenticeship model—often times from father to son—, which primarily concentrated on the practical aspects of medicine with the apprentice observing and assisting his master in patient treatment [132, 193]. However, due to limited anatomical knowledge, internal non-traumatic diseases could not be understood and consequently treated rationally, such that craftsman physicians often declared patients as hopeless, declined to treat them, and instead transferred them to Asclepieia to avoid criticism and loss of reputation [116]. In the course of time, the importance of rational medicine steadily increased, although the Asclepiads continued their practice for a long time and were only forced to abandon it when early Christianity regarded it as a pagan rite [132].

Emergence of the First Medical Schools

A somewhat more scientific and theoretical approach to medicine, which complemented the rational craft tradition, started to emerge from the regions of *Magna Graecia* (modern day Southern Italy and Sicily) and Southwestern *Asia Minor* (modern day Anatolia) [175, 345]. In these regions, the first medical schools started to emerge, often times as part of philosophical schools of thought, which were generally characterized by a loose formation of an influential medical practitioner and his followers [380]. One of the earliest and most renowned medical schools was located in Croton, with the natural philosopher and physician *Alcmaeon of Croton* (fl. 5th or 6th century BCE [125, 262, 274]) as its most famous and outstanding representative [107]. Alcmaeon is attributed with pioneering the idea of placing the center of intelligence and perception into the brain instead of the heart [115]. In addition to that, some scholars

have considered him the inventor of the method of dissection due to his anatomical studies on the eyeball and optic nerves, though several studies have highlighted the lack of evidence pointing towards a systematic use of dissections [92, 274].

Aside from the Croton medical school, other contemporary centers of medical education existed in Cyrene, Rhodes, Cnidos, and Cos [278, 430]. Among all of them, the Coan medical school was considered the most famous one due to the adherence of the distinguished physician *Hippocrates of Cos* (c.460 – c.370 BCE), who is often regarded as the *Father of Medicine* and one of the most impactful figures in medicine of all times. Hippocrates promoted medicine as a scientific discipline and emphasized the importance of a holistic approach towards both the prevention and the treatment of diseases, taking into account environmental causes, nutrition, as well as the overall lifestyle of the patient [241, 244]. Furthermore, a strong emphasis was given to the study of anatomy, though Hippocrates did not perform any dissections himself and held the conviction that anatomy can be learned sufficiently by observing the human body, resulting in many incorrect anatomical assumptions [327]. The most influential work on the teachings of Hippocratic medicine is the *Hippocratic Corpus*, a compilation of around 60 medical treatises directed towards both physicians and laymen alike. While authorship of the *Corpus* is often attributed to Hippocrates himself, it is generally believed that many different authors have contributed to the entire collection [78]. The Hippocratic Corpus is well known for its frequent references to *Humorism*, an Ancient Greek doctrine which defined disease as an imbalance between four bodily humors (black bile, yellow bile, phlegm, and blood) and which became an accepted standard for medical education until the Renaissance [132, 207]. Additionally, the *Corpus* contained the Hippocratic Oath, an ethical code of conduct taken by students upon starting their medical education which is still recited in modified form today [104, 277]. The Oath heavily stressed the traditional apprenticeship model as the predominant method of medical education [277]. In addition to learning the practice of medicine through observation and experience, the texts of the Hippocratic Corpus constitute the birth of Greek medical literature and frequently served as theoretical study material for medical students, though the overall anatomical knowledge was still very limited [116].

The Dawn of Dissection as a Scientific Discipline

In the centuries after Hippocrates, the study of anatomy was intensified in Ancient Greece, beginning with the execution of systematic dissections. The first important figure in this context was the influential philosopher and polymath *Aristotle* (384 – 322 BCE). He was a student at the Platonic Academy in Athens, where he spent 20 years of his life before serving as a teacher for Alexander the Great and founding his own school at the Lyceum—a temple dedicated to Apollo Lyceus—in which research on many subjects was conducted, including medicine and anatomy [98]. In addition to his profound influence on Western philosophy, Aristotle’s zoological research focused intensively on the study of living organisms and distinguished more than 500 different species of mammals, birds, fish, reptiles, amphibians, insects, and many other invertebrates [52, 132, 276]. While he also frequently referred to human anatomy and provided both a correct description of many different organs as well as a precise topographic terminology, Aristotle admitted that he often generalized from his knowledge of animals when he drew conclusions about human anatomy and thus laid the foundation for the scientific discipline of comparative anatomy [93, 100]. Aristotle’s anatomical investigations, described in detail in the books *Parts of Animals* and *History of Animals*, were not only based on extensive empirical observations, but he was the very first to systematically perform both dissections

and vivisections of animals [52, 98, 327]. Therefore, Aristotle's empirical studies on biology led to enormous contributions in the field of anatomy and his animal dissections formed the breeding ground for later Ancient Greek anatomists to carry out human dissections.

In Hellenistic Egypt around the first half of the third century BCE, *Herophilus of Chalcedon* (335 – 280 BCE)—often considered the *Father of Human Anatomy*—and his younger contemporary *Erasistratus of Ceos* (c.304 – c.250 BCE) became first and paradoxically last to ancient physicians who performed systematic dissections of human cadavers and potentially even vivisections of condemned criminals [114, 477]. The city of Alexandria—founded by Alexander the Great in 322 BCE and established by the Ptolemaic Kingdom as the cultural and scientific capital of the Western world—served as the setting for their groundbreaking anatomical studies. However, the exact circumstances as to why the practice of human dissection was authorized during their lifetime for a period of about 30 – 40 years and why it suddenly disappeared again for almost 1800 years are still highly controversial in the literature [99, 477, 495]. In terms of anatomical contributions, the chief work of Herophilus revolved around the nervous, reproductive, and digestive system, while Erasistratus is best known for his studies on the cardiovascular system, specifically the heart [27, 114, 275, 477, 478]. Unfortunately, all of their works are entirely lost and their findings can only be reconstructed from the writings of later anatomists. In connection with the Alexandrian Library, Herophilus founded the famous medical school of Alexandria, at which both he and later Erasistratus taught [417]. The Alexandria Medical School served as a melting pot between Greek and Egyptian medical knowledge and gradually replaced the former ancient Greek medical schools such as those at Cos and Cnidos as the main center of excellence for medical education [402, 405]. In contrast to the traditional master-apprentice relationship, medical studies at the Alexandria School—alongside a considerable practical aspect—were characterized by an increasingly professional supervision, which progressively turned into a more professorial and theoretical model of medical education with a larger number of students supervised by fewer professors, similar to today's lecture-based education [132, 253, 348]. Additionally, this university-like atmosphere stimulated a non-professional type of medical education which was often sought by polymathic scholars as part of their scientific or philosophic activity and not for the purpose of professional practice. Thanks to the extensive anatomical studies by means of systematic human dissections of both Herophilus and Erasistratus, anatomy became an accepted part of the medical education at the Alexandria School of Medicine, though there is no mention that medical students actively engaged in such dissections as part of their education [116].

From Medical Sectarianism to Galenism

The centuries following the great anatomical advances by Herophilus and Erasistratus were marked by contradictory philosophies of medical education and practice [116]. There were three main medical sects with different scientific-theoretical orientations, which dominated the Greek and Roman medical landscape: *Rationalism*, *Empiricism*, and *Methodism*. The Rationalists, sometimes also referred to as *Dogmatists* in the literature, did not form a homogeneous *school* in the precise sense that could be identified with a particular theory. Instead, they were a group of doctors who shared a methodological attitude but could diverge in their theoretical orientations and doctrines [72, 252]. The Rationalists were primarily interested in acquiring theoretical knowledge to identify and explain the underlying causes of disease on the basis of reasoning [72]. Both Herophilus and Erasistratus with their systematic human dissections were followers of the Rationalist movement. Shortly after their anatomical studies,

they were challenged by the Empiricist school of medicine, a more unified group compared to Rationalism, which was established by *Philinus of Cos* (fl. 3rd century BCE), paradoxically a former pupil of Herophilus. Empiricism rejected all speculation of the unobservable and concentrated on medical knowledge that could be put into practice, not on theoretical explanations or knowledge about hidden causes [116, 253]. Consequently, Empiricists condemned the study of anatomy by dissection as inappropriate and unnecessary and instead held the conviction that observations—whether made by themselves or by others—are of paramount importance to both their practice and training program. While original and independent medical literature was generally neglected, they considered famous physicians from the past, in particular Hippocrates, as nearly infallible. As a result, they encouraged a tendency towards repeated medical commentaries, with education and teaching mainly through medical textbooks. [253]. The third influential medical sect that emerged in Rome at the beginning of the Christian Era under the influence of *Asclepiades of Bithynia* and his disciples were the Methodists. Their movement was characterized by a strictly anti-scientific view of both medicine and education and rejected any teaching aimed at studying the theoretical aspects of medicine, including anatomy [116]. Driven by the exponentially growing population in Rome and the resulting shortage of physicians, the Methodists sought to attract as many people as possible to study medicine and to teach them as quickly as possible, leading to a slow decline in the professionalism of Roman doctors in general [253]. All three opposing medical sects produced differently trained physicians who had varying opinions about the importance of anatomy during both teaching and practice, leaving the overall medical education landscape in a very inhomogeneous state. The 2nd century CE eventually marked the end of medical sectarianism in Greco-Roman medicine, when Galen—arguably the most influential physician and anatomist of classical antiquity—published his unifying theories, often simply referred to as *Galenism*, which led to the victory of Rationalism and the decline of both Empiricism and Methodism [116].

Galen of Pergamon (129 – c.200/c.216 CE) was an outstanding Greek physician and philosopher whose anatomical research made an enormous contribution to the understanding of human anatomy and uniquely shaped medical education, in particular the teaching of anatomy, until the 16th century [349]. Following an elaborate education in philosophy and his medical studies in both Pergamon and later Alexandria, Galen primarily practiced in Rome as court and gladiator physician and engaged in regular clinical practice [99, 116]. In terms of medical contributions, he summarized and systematized the works of his predecessors in a great number of medical treatises. He refined and advanced the theory of Humorism as the foundation of health and disease and developed many early surgical techniques [350, 437, 463]. Since human dissection was strictly forbidden throughout the Roman Empire, Galen relied on extensive animal preparation during his anatomical studies, which unfortunately led to a considerable number of errors when he transferred this knowledge to human anatomy. With regard to his personality, Galen enjoyed a high reputation in Roman society thanks to his rhetoric, although his writings were consistently marked by self-praise and polemics against other contemporary anatomists [346, 347]. During numerous public dissections and vivisections, he showcased his anatomical knowledge and skills to the public [476]. Overall, his medical and anatomical theories conveyed the impression that there was hardly anything left to learn. As a result, little medical research was conducted in the years and centuries after Galen. His theories were universally acknowledged as a complete and closed system and it was considered almost heretical to question his conclusions, such that medical progress

stagnated for more than 1000 years [248, 346]. With regard to his impact on anatomy teaching and medical education in general, it is paradoxical that Galen championed both the apprenticeship model and animal dissections compared to the study of books, but on the other hand considered the old Hippocratic books almost infallible and even wrote an unsurpassed number of medical books and commentaries himself, albeit none specifically for medical education [116, 253]. Therefore, Galen unwittingly fostered the victory of theoretical book study as the most practical and comfortable modality of learning for medical students, something that he would have passionately argued against [253].

Legacy of Greco-Roman Medical Education

Medical education in classical antiquity, largely shaped by the master-disciple teaching paradigm, evolved over time from a purely oral instruction with a strong practical component to a more theoretical practice including philosophical aspects, and later to a genuine learning from books, lectures, and practical instructions, before transforming into an undesirable, purely theoretical book study in the years after Galen. Anatomy entered the field of medicine and medical education under controversial discussions with the advent of dissections, mainly of animals and for a short time in Alexandria also of humans. Although Greco-Roman medical education remained heterogeneous and did not produce a standardized teaching model for the medical profession, it brought forth a number of novel aspects that would remain influential for a long time to come [253]. The decline of the Western Roman Empire in the 5th century CE also brought a decline in the Greek medical tradition as a whole and the study of Galen and other Greek anatomists almost disappeared completely. Only a slight portion of the Ancient Greek accomplishments in medicine were translated into Latin and a large body of medical knowledge remained unavailable for scholars in early medieval Western Europe [428]. By contrast, Galen's writings almost completely persisted throughout the Greek-speaking Eastern Roman Empire (Byzantium), where a number of scholars and physicians—laudably referred to as the medical refrigerators of antiquity—published summaries and encyclopedias of Galen's works, which formed the basis of anatomy teaching in Alexandria until the 6th century CE [346, 428].

2.1.3 Medieval Europe & Islamic Golden Age

During the *Dark Ages*, which lasted in Europe until the 10th century, progress in anatomy and its education was made exclusively in the Islamic world, with Europe falling back on magico-religious approaches to medicine and anatomy. At the beginning of the High Middle Ages there was a renewed interest in anatomy in Europe, culminating in the founding of the first universities and medical faculties in Europe. Anatomy education at this time was characterized by the triumphant advance of textbooks, which were to remain an essential source of learning until modern times.

The Influence of Christianization on Medical Education

The Early and High Middle Ages were largely marked by the rise and continuous spread of Christianity in Western Europe after it became the official Roman state religion under *Constantine* in 380 CE. The transformation from classical Greek to medieval Christian civilization brought with it an increasing shift from rational to religious medicine, although the

former was never completely abandoned and secular physicians—often condemned, mocked, and badly reputed—continued to practice side by side with clerical ones [428]. Similar to the Asclepieia from Ancient Greece, monasteries formed the new centers for both spiritual and physical religious healing. These monasteries also served as ecclesiastical institutions of medical education which gradually replaced the old system of public medical schools and dominated medical education from about 500 to 1000 CE [290]. In addition to handbooks on pharmacy, herbs, and general medicine, medical books by Greek scholars such as Galen were copied by monks in small quantities and were used during medical practice to treat the sick and the poor. The focus was on the treatment of diseases, not on gaining knowledge about the underlying causes. Therefore, human anatomy, along with other branches of medicine, including physiology and pathology, were largely considered irrelevant—similar to all other types of information about the natural world [428]. Disease and other evils were often interpreted as divine retaliation, which had to be patiently accepted as a spiritual test in which the healing of the soul was considered more important than the healing of the body. Overall, medical education in the Early and High Middle Ages was closely linked to the Christian religion and was carried out either in monasteries as a largely theoretical book study, or as an apprentice training with a strong focus on practical medicine by secular physicians [290].

Medical Education in the Islamic World

While anatomical knowledge completely stagnated in Medieval Europe, more important developments took place in the Muslim civilizations during the Islamic Golden Age starting from the 8th century. The voluminous writings from classical antiquity, including many works of Hippocrates, Aristotle, and Galen, were translated into Arabic [482]. Islamic scholars adopted these theories and from the 9th century onwards began to build on and supplement them with original contributions [428]. Although human dissections were disavowed by Muslim physicians for general cultural and specific religious prohibitions, liberal interpretations of the Quran allowed animal preparation and discussions concerning the structure and function of the human body to take place [327, 406, 482]. As a result, several renowned Muslim scholars made discoveries that provided considerable anatomical insights. *Muhammad ibn Zakariyya al-Razi* (Latinized *Rhazes*, 865 – 925 CE) was among the earliest influential Islamic physicians and a prominent medical teacher whose books on medicine, in particular his *Comprehensive Book on Medicine*, greatly influenced medical education and practice in the Latin west [421, 461]. Arguably the most important Islamic anatomist was *Ibn Sina* (Latinized *Avicenna*, 980 – 1037 CE), who was the author of the famous *Canon of Medicine*, an encyclopedia on medicine based largely but not exclusively on Galen's teachings [421]. The *Canon* contained an organized summary of the entire medical and anatomical knowledge of the time and was used until the 18th century in Europe as a medical textbook. Other famous Islamic scholars include *Ibn Al-Nafis* (1213 – 1288 CE), who partially explained pulmonary circulation, *Ibn Al-Haytham* (Latinized as *Alhazen*, c.965 – c.1040), who provided new insights into optics, and later *Mansur ibn Ilyas* (fl. 14th and 15th century CE), who is considered to have published the very first color atlas of the human body [126, 482]. It was thanks to these Islamic scholars and their written encyclopedic writings that many works of classical antiquity have been preserved and that Arabic medicine influenced the medieval West in the Late Middle Ages and in the Renaissance. Throughout the entire Islamic Golden Age, medical education took various forms. Large amounts of money were spent on the construction of hospitals (also known as *Bimaristans*) and dedicated medical schools, which both served as teaching facilities where medicine was studied and practiced [482]. Among the first was the

Academy of Gondishapur, which in the 6th and 7th centuries served as the most important medical teaching center of the Arab world [421, 468, 482]. Later, Baghdad developed into an intellectual center for science, medicine, philosophy, and education and in 918 CE housed one of the earliest Arab teaching hospitals [482]. In addition to disciplines such as pharmacology, therapeutics, and pathology, the medical curriculum also included anatomy, which was taught through lectures, illustrations, and ape dissections [320]. Apart from teaching in hospitals and specialized medical faculties, some students continued to be trained under the supervision and care of family members or renowned physicians in a master-apprentice model [104]. Another important medical contribution in this period was the formal licensing of physicians following successful oral and practical examinations, which was first introduced in 931 CE [320, 418]. Eventually, the Islamic civilization declined again as the modern development of medicine returned to Europe. However, the preservation and further development of medical knowledge by Islamic scientists was of lasting importance.

Formalized Anatomy Teaching & Revival of Human Dissection

During the High Middle Ages, Europe experienced a revived interest in medicine and anatomy. The earliest medieval center for medical practice and education was established in Southern Italy in the city of Salerno during the 9th century. The *Salernitan* School of medicine rose to prominence in the following centuries, when a plethora of Arabic medical literature—both translations of ancient Greek texts as well as original Arabic contributions—arrived in Salerno and were translated into Latin, most prominently by the Carthaginian physician *Constantine the African* (fl. 11th century) [444, 482]. Over the course of the twelfth century, a formalized academic curriculum with a strong focus on human anatomy gradually developed in Salerno for the first time in medieval Europe [14]. The curriculum was comprised of anatomical demonstrations, animal dissections, as well as theoretical book study [106, 146]. Following the example of Salerno, formalized medical education spread throughout Europe and in the 13th century found its way into the newly founded universities of Bologna, Paris, Montpellier, Oxford, Padua, and many others. Two edicts of *Frederick II* (the Holy Roman Emperor) from 1231 and 1240 CE defined formal guidelines for the study of medicine, which should include both theoretical and practical aspects, whereby the study of medicine is preceded by three years of logic [290]. Furthermore, they mandated that a human body should be dissected for the purpose of anatomical studies once every five years and attendance was mandatory for everybody who was aiming at practicing medicine or surgery [327, 365].

By the end of the 13th century, the University of Bologna took a pioneering role in the revival of human dissection for the purpose of anatomy teaching. It is assumed that cadaver dissections were initially carried out in support of forensic investigations in the form of autopsies, as the University of Bologna was first established as a pure law school [76, 386]. Later on, human dissections were performed to assist surgeons in the study of anatomy, before finally serving as a novel teaching tool for pure anatomical studies [290]. The first officially approved and publicly accessible human dissection since the times of Herophilus and Erasistratus in Alexandria was carried out in 1315 CE by the famous Bolognese professor of anatomy *Mondino de Luzzi* (c.1270 – 1326 CE)—often referred to as the *Restorer of Anatomy* [156]. Only one year later he wrote the *Anathomia*, a practical manual for the execution of dissections, which historically was the very first—and for the next 200 years the most popular—textbook entirely devoted to anatomy [386]. During all medieval dissections, textbooks such as the *Anathomia* were recited by an anatomy professor (*Lector*), who sat on a high, elevated chair and oversaw

a surgeon (*Sector*) and a demonstrator (*Ostensor*) who respectively performed the dissection and pointed out the anatomical structures to be dissected. Over the course of the 14th century, such cadaveric dissections became increasingly common and were introduced in several other universities across Europe. However, the primary goal was to confirm and reiterate Galen's theories rather than discover new anatomical knowledge through personal observations. Despite these shortcomings, Mondino de Luzzi's work influenced the way anatomy (and especially dissection) was taught at many European universities for a long time [327].

After systematic human dissections were reintroduced as a means of teaching anatomy, several other medieval anatomists who followed de Luzzi published commentaries or additions to his work. *Guido da Vigevano* (1280 – 1349 CE), purportedly a student of de Luzzi, published a treatise on dissection which for the first time contained illustrations that were used for teaching anatomy to medical students [155, 386]. Vigevano's drawings precede the representations of *Henri de Mondeville* (1260 – 1320 CE) in Montpellier, who included 13 miniature anatomical illustrations in a work on surgery [327]. Since anatomical knowledge was still largely based on Galen's theories, these medieval illustrations of anatomy were mostly rudimentary and unrealistic [166]. Nevertheless, they paved the way for the woodcut illustrations by *Jacopo Berengario da Carpi* (c.1460 — c.1530 CE) and later the creation of more artistic drawings by both *Leonardo da Vinci* (1452 – 1519)—whose anatomical drawings were way ahead of its time, but only became known in the 19th century—and *Michelangelo Buonarroti* (1475 – 1564) at the beginning of the Renaissance. Furthermore, they marked the beginning of a new anatomy teaching paradigm that is still highly relevant for medical students today, as anatomical illustrations became increasingly popular in the following centuries—especially thanks to the invention of book printing and the proliferation of published medical texts [155, 353]. An excellent survey on the history of anatomical illustrations is provided in [37].

2.1.4 European Renaissance & Modern History

The European Renaissance (between the 14th and 17th centuries) was the age of rediscovery, revival, and the flourishing of art, culture, and science. The period was characterized by a humanistic world view that strongly emphasized the individuality and creative power of man and in many areas called for a return back to the original sources (Latin: *ad fontes*), i.e. a renewed study of the original Greek and Latin texts. In the context of anatomy, the expression *ad fontes* meant an intensified study of the human body through cadaver dissection, and it was during the Renaissance that dissection became the mainstay of anatomy education. In the centuries of the early modern period, interest in anatomy increased dramatically, but it was not until the 19th century that anatomy education began to resemble contemporary education with the introduction of modern university courses and curricula.

The Era of Andreas Vesalius

In the 16th century, anatomy education experienced the most important paradigm shift since the teaching of Galen with the foundation of modern human anatomy as an academic discipline and the establishment of cadaveric dissection as an essential tool for anatomy education by *Andreas Vesalius*, a Flemish anatomist who is considered as the *Father of Modern Human Anatomy* (1514 – 1564 CE). Despite the strong resistance of many renowned anatomists, including his own teachers, he was the first to vigorously question Galen's theories and later to

scientifically correct them by carrying out human dissections himself, combining the traditional roles of lector, ostensor, and sector in a single person [511]. His practical hands-on approach to anatomy teaching as professor for both anatomy and surgery at the university of Padua was focused on understanding the anatomy at hand rather than confirming existing theories [327]. In 1543 CE, he published his masterpiece, the book *De Humani Corporis Fabrica* (*On the Fabric of the Human Body*), which proved to be a key milestone in the history of human anatomy and one of the most impactful books on anatomy ever written. On the title page he is depicted dissecting a human corpse in an overcrowded anatomical theater alongside Hippocrates, Aristotle, and Galen, his pose suggesting that he is pointing out and correcting the mistakes of these famous ancient scholars. The *Fabrica* not only corrected many—albeit not all—anatomical errors from Galen and others, but also contained very vivid and realistic drawings of anatomical specimens in different poses and in various stages of the dissection process. This combination of novel anatomical knowledge with descriptive illustrations was initially regarded as blasphemous and heavily criticized by anatomists all over Europe, but later caused the paradigm shift from purely theoretical studies towards the addition of direct practical observations and experiences by means of dissections. Although Vesalius held the conviction that in order to learn anatomy, one has to perform human dissections himself, his teaching practices were still largely passive and the majority of students simply observed his dissections—although there are isolated reports of students who describe their practical dissection experiences.

The Rise of Anatomy in the Modern Period

In the years after Vesalius, cadaver dissection and anatomy in general experienced an increase in popularity not only within the scientific landscape of European universities, but also among the general public. This development led to the establishment of permanent anatomical theaters in Padua (1594 CE), Leiden (1597 CE), Bologna (1649 CE), Paris (1694 CE), and many other European cities in the 17th and 18th centuries [245, 246]. Many important anatomists contributed to the existing body of anatomical knowledge, including the famous discovery of blood circulation by English physician *William Harvey* in 1628 CE [389]. Furthermore, completely new academic disciplines such as pathology, histology, and embryology emerged, often times driven by technological advances such as the microscope. From an educational point of view, anatomy textbooks evolved with revolutionary power during this time, both for research and for pedagogical purposes [327]. Existing books by Galen and Avicenna were increasingly replaced by contemporary ones containing novel findings and discoveries. Illustrations within these anatomy books also evolved. Whereas in the past their main purpose was to communicate anatomical research results, their focus shifted towards a teaching incentive and abstracted from complexity for didactic purposes [155].

All over Europe, the increased interest in anatomy was accompanied by a lack of cadavers available for dissection, and there was no way of preserving the cadavers for more than a few days to counteract natural decomposition [76]. The steadily increasing demand for cadavers, combined with only a few voluntary body donations, led to unethical ways to obtain cadavers such as grave robbery, increased hanging of criminals, and even so-called *anatomy murders* [393]. These malpractices continued until laws were passed throughout Europe regulating the use of cadavers for anatomical dissections [156]. Additionally, new demonstration media developed in the form of anatomical wax models (ceroplastics)—first described by *Gaetano Zumbo* (1656 – 1701 CE) at the end of the 17th century—or specimens preserved in glass jars

suspended in either formaldehyde or other liquids [358, 381]. These anatomical specimens often found their way into anatomical museums such as the famous *La Specola* in Florence as well as into private collections, most prominently the one of *John Hunter* (1728 – 1793 CE), which also served as a study aid for students of the private anatomy school founded by his brother *William Hunter* (1718 – 1783 CE) [327].

The Development of the Modern Medical School

Private anatomy schools, such as the Hunterian one, flourished alongside hospital-based courses and were abundant throughout Europe [309]. They primarily served the purpose of educating practically trained medical practitioners and barber-surgeons, with a strong focus on anatomical concepts and hands-on experiences [327, 384]. In 1748 CE, William Hunter introduced what became known as the *Paris manner of dissection*, which specified that medical students should perform anatomical dissections themselves rather than learning anatomy through demonstrations alone, thus advancing an important pillar of anatomy teaching from the Renaissance [154]. From that point on, anatomy training steadily moved away from the passive *observation-and-demonstration* didactics in favor of acquiring anatomy knowledge through practical dissection [327]. The Hunterian model of anatomy education spread to the United States, where *William Shippen* (1736 – 1808 CE) started the first North American medical school at the College of Philadelphia in 1765 CE and made anatomy the foundation of his medical teaching [188]. During the 19th century, anatomy education and medical training in general became increasingly standardized around the world, leading to the decline of private schools and a shift towards formal, university-based medical training. State authorities such as the American Medical Association in the United States and the General Medical Council in the United Kingdom were established, responsible both for quality assurance measures and the formulation of recommendations and guidelines for medical education [188, 327]. Driven by a series of educational reforms, today's modern medical curricula worldwide have evolved through an evolutionary process in which anatomy is taught as an essential component through a combination of cadaver dissections, lectures, and in recent years an increasing number of additional teaching paradigms [469].

2.1.5 Anatomy Education in the 20th and 21st Century

During the 20th century, both medicine in general and anatomy became increasingly specialized. Technological innovations such as the electron microscope or the discovery of medical imaging enabled new types of anatomical research and led to great advances in the understanding of the organs and structures of the human body. These advances were also reflected in the educational landscape of anatomy. Whereas in the past, anatomical learning consisted primarily of a triangle between didactic lectures, practical dissections, and the study of anatomy textbooks, at the end of the 20th and the beginning of the 21st century a series of novel teaching resources were introduced which transformed the anatomy educational landscape into the multifaceted environment that exists today.

The Path Towards Modern Anatomy Education

Nowadays, anatomy students have a wide range of learning tools at their disposal, more than ever before in the history of anatomy education. The teaching modalities from the previously

mentioned triangle of anatomy education, consisting of lectures, dissections and textbooks, have been increasingly professionalized and supplemented by new approaches that have emerged as a result of technological development. For example, anatomy textbooks and atlases (such as the famous *Gray's Anatomy*) are still an indispensable tool for anatomy education—albeit no longer as dissection aids or research monographs—but as purely didactic resources with advanced illustrations and drawings [155]. The introduction of medical imaging, strongly influenced by the discovery of X-rays by *Wilhelm Röntgen* in 1895 CE, the development of computed tomography (CT) and magnetic resonance imaging (MRI), and the use of ultrasound as a diagnostic tool, made it possible for the first time to obtain an in-vivo visualization of human anatomy and led to the field of clinical radiology which is increasingly integrated into anatomy curricula. Wax models were first replaced by hard plastic models and more recently by organ models from the 3D printer, which are even able to use rubber-like materials to convey the texture and tactile feel of the organ they are supposed to model. In the late 20th century, computer-based learning resources became abundant, ranging from standalone desktop applications to web-based e-learning platforms and smartphone or tablet applications. Alongside interactive materials, they often comprise educational videos and 3D simulations to convey anatomical concepts. Recently, both Virtual Reality (VR) and Augmented Reality (AR) have been introduced and employed successfully as additional teaching modalities in the context of anatomy education. This plethora of educational resources has paved the way for anatomy learning to become more and more personalized. Medical students do not form a homogeneous group and the learning preferences can vary greatly among individual students. Consequently, students can choose from a variety of different teaching resources to obtain the best possible anatomy education.

The Role of Dissection in Modern Anatomy Education

While many anatomists welcome the recent availability of new anatomy teaching paradigms as adjuncts to cadaveric dissection, others have used this technological change for advocating that dissection is an old-fashioned technique which is inappropriate for adequately teaching anatomy in the 21st century [36, 119, 308, 390]. This excessive reliance on new technologies has triggered an ongoing debate between *modernists* and *traditionalists*. While the former group believes that new teaching and learning modalities should gradually replace cadaver dissection, the latter one argues that dissection remains the undisputed gold standard for anatomy education [249]. According to the traditionalists view, the use of novel teaching aids—often denounced as *digital body surrogates*—risks a return to the pre-Vesalian period, where animal surrogates replaced the human body [327]. They correctly criticize that the amount of time devoted to gross anatomy and dissection has continuously diminished in the last decades [117, 469]. A number of medical schools cannot afford the costs associated with maintaining dissection labs and have replaced cadaver dissections in favor of prosections, plastinated specimens, or even virtual dissection tables [143, 391, 445]. While all of these techniques have greatly improved in recent times and all have their individual benefits, many studies continue to be published highlighting the importance of hands-on practical experience obtained during cadaver dissections [133]. It is noteworthy that also medical students have frequently opined that dissection is the most effective method for learning anatomy, arguing that the practical hands-on experience provides an unmatched level of understanding [328]. Considering that the dissection of cadavers by students is the culmination of the millennia-old history of anatomy education, it should not be abandoned lightly in favor of new, largely untried educational methods, even in a modern curriculum.

The Relevance of Historical Developments for the Future of Anatomy Education

So what can history teach us about the future of anatomy education? This section demonstrated that anatomical sciences have always been at the core of medical education and that since ancient times a sound understanding of the structure and function of the human body has been an essential prerequisite for the medical profession. From a pedagogical point of view, the education of anatomy has been subject to continuous change in every epoch—especially driven by the constant increase in anatomical knowledge and the associated changes in training methods—, starting with informal education within a master-apprentice relationship from ancient times to dissection by the master and observation by the apprentice, supplemented by anatomy textbooks. Only recently, anatomy education became an increasingly multimodal learning experience with students actively participating in dissection and other forms of learning. Nowadays, numerous medical faculties promote this self-directed learning paradigm through integrated and problem-based curricula that combine other disciplines such as histology or radiology within anatomy education to deepen the level of understanding and to adapt to the changing needs among diverse groups of medical students.

Another important insight that can be derived from the history of anatomy education is that there has always been resistance when novel teaching paradigms have challenged the existing status quo. Today, many fear that the anatomy education landscape is in danger of losing traditionally established teaching methods such as cadaver dissections—which in their long history have proven their pedagogical value—in favor of new teaching paradigms that recently evolved in the wake of technological progress. Against this background, history teaches us that despite several *revolutionary* advances, anatomy education evolved *evolutionary*. With Vesalius, cadaver dissection became an indispensable part of anatomical learning and rewrote the thousand-year-old theories of the ancient Greek scholars, which were mainly taught with the help of anatomy textbooks. However, such atlases—albeit with corrected contents—remained an important learning modality for students until today. Later, the students themselves performed cadaver dissections instead of just observing an experienced anatomist, however, such passive dissections still exist today in the form of prosections. In a similar fashion, today’s multimedia approaches to anatomy education, including AR and VR, offer exciting new possibilities that were not possible before. However, they should go hand in hand with the traditional ones such that both categories can benefit from each other to evolve jointly. Particularly intriguing are approaches that combine two teaching modalities to get the best of both worlds.

The validation of novel teaching concepts constitutes another very important factor. In today’s rapidly developing times, new technologies continuously shape the anatomy education landscape and are proposed at an ever increasing rate. Therefore, it is necessary to carefully evaluate their benefits and to find the most relevant and appropriate application scenarios before they are widely integrated into the anatomy curriculum. Only validation can ensure that certain aspects of anatomy training are substantially improved by such novel methods, hence it should be given high priority.

2.2 Augmented Reality

Since its origins in the late 1960s, Augmented Reality (AR) has evolved from an emerging technology to a widely known tool that nowadays has found its way into many different areas of everyday life—particularly in response to the massive investments made by major technology companies in recent years. AR provides the ability to visualize and interact with complex information, making it an ideal instrument for various application domains, including the educational field. Considering that the contributions of this thesis revolve around the application of novel AR solutions within the context of anatomy education, this section provides an overview of AR, starting with its definition and a differentiation of AR from similar concepts. Furthermore, the underlying technologies that AR is comprised of are thoroughly discussed, and it will become apparent that all components of an AR system need to work nicely together to create a compelling AR experience that users want to experience.

2.2.1 Definition & Taxonomy

One of the most widely accepted definitions of Augmented Reality (AR) is given by Ron Azuma in a survey paper from 1997 [13]. According to him, AR is defined as a technology that satisfies three essential requirements: 1) both real and virtual content is combined; 2) users can interact with the content in real-time; and 3) the content is registered in 3D. From these three properties inherent to every AR system, Azuma derived the main goal of AR, which is *"...to enhance the user's perception of the real world by incorporating 3-dimensional virtual information into the scene, that appears to coexist in the same space as the real world"*. From Azuma's definition, also the technical requirements of an AR system can be derived, which involve a display to combine real and virtual imagery, a computer system to generate interactive graphics which the user can interact with in real time, a tracking system to correctly superimpose the virtual content with real-world objects, and a spatial registration component, such that computer-generated augmentations remain registered to the referenced objects in the real environment [43, 409]. In section 2.2.3 of this thesis, these technologies as well as additional elements required for AR systems are examined in detail. While AR is generally associated with visual overlays only, it is noteworthy that Azuma's definition is deliberately broad and also includes AR systems that provide an auditory, haptic, or even olfactory and gustatory experiences in its scope—though potentially very difficult to realize. Furthermore, the definition does not impose any restrictions as to the type of technology used, e.g. for a particular output device.

Another means of defining AR is to distinguish it from similar technologies such as Virtual Reality (VR). While most of the underlying technologies are identical in both AR and VR, the latter places the user in a completely computer-generated environment and the view of the real world is entirely replaced by the virtual world. Such VR systems aim to completely immerse the user in the virtual experience and entirely suppress the real world. In contrast, AR systems are specifically designed to enhance the perception of reality in a non-immersive way such that virtual content appears to become part of the real world. The space between reality and virtual reality is called Mixed Reality (MR). Within this space, both real and virtual elements can be combined to varying degrees. The term MR is attributed to Paul Milgrim and

Fumio Kishino, who first used it in their famous Reality-Virtuality (RV) Continuum [319]. MR is used as an umbrella term to describe the various ways in which real and virtual elements can be merged between the real environment on the one hand and a completely virtual environment on the other hand. A representation of their RV continuum is depicted in Figure 2.1. According to this taxonomy, Augmented Virtuality (AV) is located towards the right end (virtual environment) of the continuum, with most of the user's view replaced by virtual elements, although a view of the real world is still available to some extent. AR on the other hand contains primarily real elements, but with some additional virtual ones, and is therefore closer to the real end of the continuum.

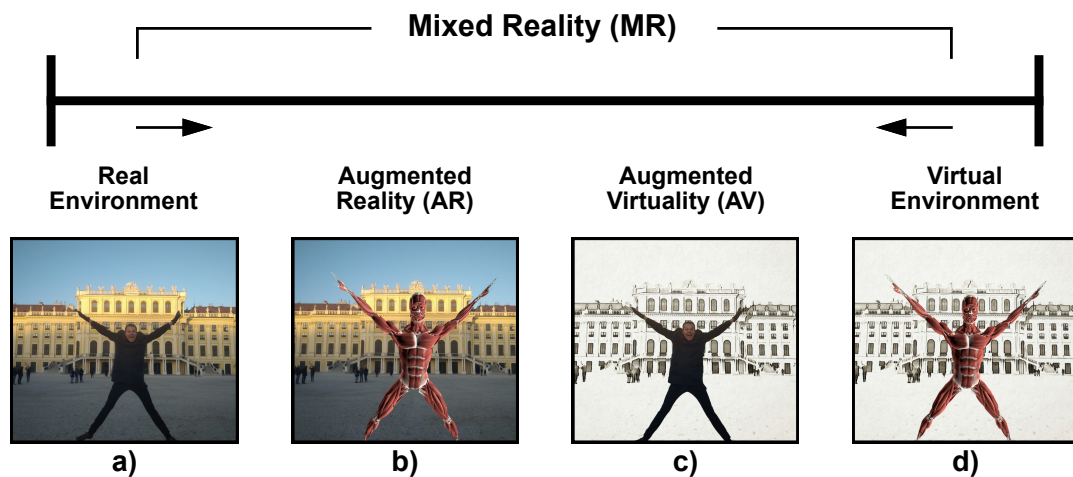


Fig. 2.1. The Reality-Virtuality (RV) Continuum according to Milgram and Kishino [319]. a) Photograph of the Vienna palace with a real person in front; b) AR view of the scene, with the real person replaced by a virtual anatomy model; c) in AV, the real person is depicted in front of a virtual representation of the palace; d) completely virtual environment, with the virtual anatomy model depicted in front of the virtual representation of the palace.

Several other taxonomies have been proposed in the literature, most notably the Reality, Virtuality, Mediality continuum by Steve Mann [293, 294]. Mediated Reality provides a more general framework that incorporates the RV continuum of Milgram and Kishino, and also includes an axis for mediality, i.e. the amount of modification applied to reality or virtuality.

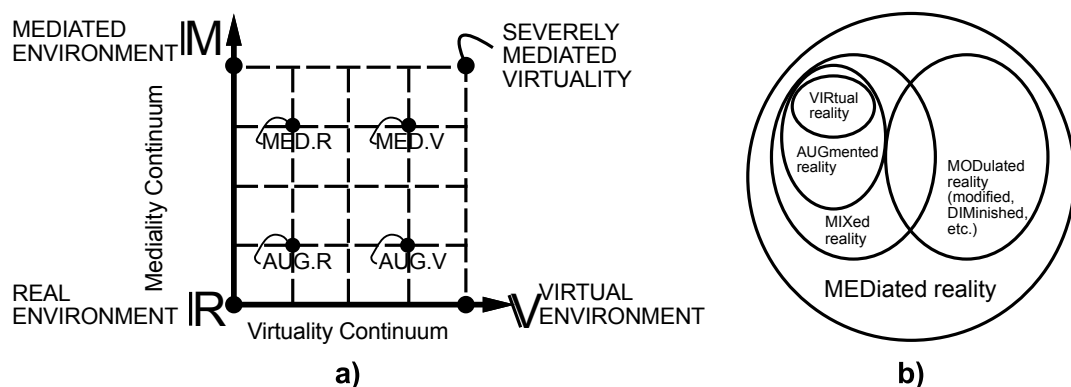


Fig. 2.2. Mann's Mediated Reality framework [293, 294]. a) Taxonomy of Reality, Virtuality, and Mediality. The continuum across the virtuality axis contains both AR and AV. On the mediality axis, modifications of both reality and virtuality can be incorporated. b) Overview of the mediated reality framework, which incorporates a potential modulation of either reality or virtuality in addition to the RV continuum.

A less established and significantly underrepresented taxonomy is the Mixed Fantasy Framework originally proposed by Christopher Stapleton in 2001 [432, 434]. The taxonomy builds upon the RV continuum of Milgram and Kishino, but includes the imagination of the user as a third important reality. The sweet spot for MR applications is therefore at the center of his Mixed Fantasy Framework, incorporating both the technical aspects as well as the user's imaginative contributions. Originally developed for MR applications in the field of entertainment, Stapleton particularly points out its applicability for educational systems [433]. The inclusion of ways to spark and capture the user's imagination offers significant added value to the learning of complex content, as it creates a more personal and engaging experience that ultimately aims to improve the overall knowledge acquisition and retention rates.

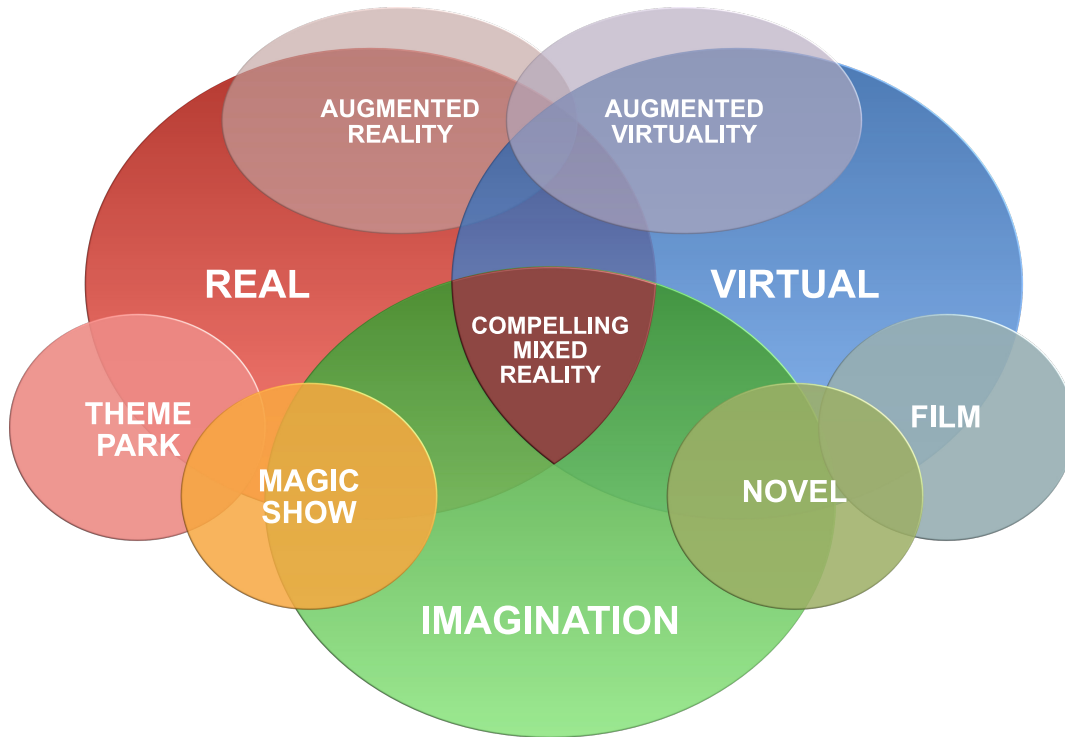


Fig. 2.3. Stapleton's Mixed Fantasy Framework [434]. While the upper part corresponds to the RV continuum of Milgram and Kishino, the taxonomy incorporates the user's imagination as a third component. According to this taxonomy, compelling MR applications not only contain real and virtual elements, but also incorporate the imaginative component into the system.

In summary, the first definition of AR that is still highly relevant today goes back to Azuma. Though it can help to specify the technology required to provide an AR experience, additional taxonomies such as the ones presented previously are required to fully understand the potential of AR in a broader context. After this short introductory section on AR, the following section will provide a brief overview of the history of AR and show that researchers even many years before Azuma have started to explore its potential.

2.2.2 A Brief History of Augmented Reality

The breakthrough of Augmented Reality (AR) started in the 1990's, when Thomas Caudell and David Mizell, two researchers at Boeing, first coined the term *Augmented Reality* to describe a system for guiding factory workers during the process of aircraft manufacturing [459]. Even before that, the earliest AR systems were developed by Ivan Sutherland and Thomas A. Furness III starting as early as 1968. Sutherland proposed the very first Head-Mounted Display (HMD), a ceiling mounted system called the *Sword of Damocles*, which employed both a mechanical and an ultrasonic tracker to locate the position of the head in space and was able to generate wireframe images of simple virtual objects that could be seen through semi-transparent mirrors. [447]. Around the same time, Furness developed a series of early AR systems related to military applications, specifically for aircraft targeting systems, where complex flight information from the cockpit was visualized by means of an infrared tracking system in a head-mounted AR helmet system. Despite the low computational capabilities available at the time, the techniques employed in these early AR systems were similar to the ones used in today's much more advanced systems. In the 1990's, several influential research papers on AR were published, such as the *KARMA* system by Feiner et al., which incorporated knowledge-based AR for repair and maintenance tasks [139], the first applications of AR to the medical domain by Bajura et al. [17], State et al. [435], Fuchs et al. [145], and Navab et al. [335], the first mobile AR system for outdoor usage by Feiner et al. [138], Rekimoto and Nagao's *NaviCam* as the first tethered hand-held AR display [385], or Schmalstieg's *Studierstube* as the first collaborative AR system [411]. Around 2000, Kato and Billinghurst developed the *ARToolKit* library for real-time tracking of square markers based on computer vision [228]. In the following years, hand-held devices became increasingly powerful. Wagner and Schmalstieg presented the first hand-held AR application running autonomously on a personal digital assistant (PDA), a precursor to today's smartphones [480]. The first actual mobile phone based AR application was demonstrated one year later by Mohring and Bimber in 2004 [324]. These developments led to millions of people having, for the first time, a technology in their pockets that would enable them to experience AR. This trend was further strengthened by the introduction of the first iPhone in 2007 and the first Android phone in 2008, which for the first time combined powerful processors, 3D graphics, and a variety of sensors with platforms that allowed developers to leverage all these technologies to create powerful mobile AR applications.

Within the last 15 years, the AR industry has experienced a massive growth with large technology companies heavily investing in AR. 2014 saw the introduction of the *Google Glass*, which despite its limited success demonstrated the potential of wearable AR. A few years later, Microsoft entered the playing ground of AR when they revealed the first iteration of the *HoloLens*. Additionally, several other companies such as Magic Leap, DAQRI, Epson, ODG, Vuzix, or North all have released AR displays applicable for both business or consumer scenarios. Equally important to the advances in hardware are the rapidly evolving software platforms such as PTC's *Vuforia*, which allow developers to create AR applications more easily than ever before. Recently, the introduction of software frameworks for both iOS (*ARKit*) and Android (*ARCore*), which include even complex algorithms for person tracking and occlusion handling based on machine learning techniques, has led to a wave of mobile AR applications and made AR ubiquitous. According to industry analysts, the AR market will grow from \$10.8 billion in 2019 to \$72.7 billion by 2024 due to increasing investment by large corporations.

This brief summary of the history of AR serves to demonstrate that the technology has been around since quite some time. A very elaborate historical overview was presented by Billinghurst et al. [43]. In their survey paper, the history of AR is divided into four phases: 1) *Experimentation* phase (Pre-80's), where early concepts and the required technologies for AR were defined; 2) *Basic Research* phase (1980's – mid-90's), where research into enabling technologies such as tracking, displays, and input devices was crucial; 3) *Tools & Applications* phase (1990's – 2007), during which early applications were developed and novel concepts for interaction and usability were defined; and 4) *Commercial Application* phase (2007 – present day), which is characterized by the widespread availability of AR in a number of different application domains. From its origins, AR has thus developed over the last 50 years into a technology with broad commercial acceptance, which is expected to gain even more momentum in the near future.

2.2.3 Enabling Technologies

Regardless of whether designed for the entertainment industry, educational projects, medicine, or other application domains, there are a number of enabling technologies that any AR system must incorporate to meet Azuma's working definition of AR. Although their importance may vary across different areas, the basic building blocks of an AR system are invariably identical. While entire books could certainly be written on any of the topics covered in this section, the following presents a concise overview of the main components that characterize an AR system. Particular emphasis will be placed on the technologies that are particularly relevant for the two AR solutions presented within this thesis for the topic of anatomy education.

Tracking

In the context of AR, tracking refers to the continuous measurement of the pose (position and orientation) of an entity. Such an entity can be anything from a printed marker to a 3D object or even a human body. Knowledge of an entity's pose in an AR scene with respect to the user enables the registration of virtual objects with this real-world entity. Therefore, the goal of tracking is to meet Azuma's third requirement for AR systems, namely that virtual content is *registered in 3D* such that it appears to be anchored as part of the real world. Tracking is closely correlated with two other technologies, one of them being registration and the other being calibration. The former refers to the alignment of coordinate systems between real and virtual objects. Calibration on the other hand constitutes an important prerequisite for registration, which involves the computation of local coordinate systems for all components of an AR system and the transformations between them. While static registration can be achieved using calibration, dynamic registration requires tracking. Accurate registration of virtual objects with physical objects from the real world using tracking technologies is one of the most important goals of AR systems. Depending on the specific requirements of an AR application, different tracking technologies may be employed. In the following, an overview of available tracking systems will be presented according to a classification by Schmalstieg and Höllerer, who distinguish between stationary tracking systems, mobile tracking systems using non-visual sensors, as well as optical tracking systems [409].

Stationary Tracking Systems In the early days of AR, stationary tracking technologies such as mechanical tracking, which requires a physical connection between the tracked entity and a fixed reference point, or acoustic tracking which is based on emitting and sensing ultrasonic waves to track the pose of an entity, were widely used [447]. However, these techniques only play a very negligible role today. Electromagnetic tracking is another form of stationary tracking which is based on measuring the pose of a receiver that is equipped with three orthogonal coils within an alternating magnetic field generated by a transmitter. Such electromagnetic tracking systems have been used effectively in several AR systems, especially during the 1990's [17, 459]. While they provide a very high update rate and are invariant to occlusions, inherent disadvantages include the limited working volume and their susceptibility to interference from ferromagnetic materials or other electromagnetic disturbances in the vicinity. In today's AR systems, electromagnetic tracking approaches are rarely used, with one noteworthy exception resulting from the trend to use mobile electromagnetic tracking approaches for measuring the position and orientation of hand-held controllers in 3D, such as the recently proposed *Aura* system or the Magic Leap controller [492].

Non-Visual Mobile Tracking Systems Previously discussed stationary tracking systems all severely limit the size of the AR environment in which the user can experience virtual content. Mobile sensors, which are ubiquitous in today's modern smartphones and tablets, are another means of tracking on a larger scale—particularly for outdoor AR applications. The most common (non-visual) sensors falling into this category are Global Positioning System (GPS) sensors, wireless networking signal strength sensors for WiFi or Bluetooth, and Inertial Measurement Unit (IMU) sensors. GPS tracking is based on satellites continuously transmitting their position and time to earth as coded radio signals. A receiver can calculate the distance to all these satellites by measuring the time required for the radio waves to travel to the receiver. Based on this information, its position on earth can be determined. Multiple AR systems—especially for outdoor AR—that use GPS tracking have been presented in the past [138, 407, 457]. While several techniques to improve measurement accuracy exist, GPS tracking is limited to positional tracking within the range of a few meters. Another positional tracking technology involves measuring the signal strength of wireless networks such as WiFi or Bluetooth, which can be used effectively for indoor AR scenarios, but requires additional equipment in the form of WiFi access points or Bluetooth beacons. While the achievable accuracy depends on the density of access points deployed to form the wireless network, it is generally superior to GPS for both indoor and outdoor scenarios [194, 366]. The third main type of non-visual mobile tracking systems is inertial tracking based on IMU sensors such as magnetometers, gyroscopes, and linear accelerometers that can be used to determine the velocity of a tracked object as well as its relative orientation in space. While inertial tracking sensors provide a very high update rate and can be used in any environment without additional equipment, their main limitation is drift and consequently measurement degradation of both orientation and position over time. All tracking technologies discussed above generally do not achieve sufficient accuracy for high quality registration of virtual content in AR. Therefore, they are often combined with other tracking techniques in hybrid approaches that fuse data from multiple sensors to improve the overall accuracy of the system, most prominently with optical tracking approaches based on computer vision techniques, which will be discussed in the next paragraph.

Optical Tracking In optical tracking, the images from digital cameras are analyzed by means of sophisticated computer vision algorithms and employed for tracking the 3D pose of an entity in the scene. Thanks to hardware miniaturization and advances in computing power in recent years, such digital cameras are now an indispensable component of mobile devices and AR head-mounted displays (HMD). As a result, optical tracking has become the most important approach to accurately register virtual content with the real world in AR applications. The first important distinction in optical tracking relates to the type of light that is captured by the camera sensor and therefore used for tracking. The simplest form of optical tracking uses passive sensors, i.e. regular video cameras that capture *natural light* in the visible spectrum, which is emitted either from the sun or from artificial light sources and captured by a charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) chip in the camera after being reflected by objects in the environment [409]. In contrast, the second type of light that can be used for optical tracking is *infrared light*. Infrared tracking employs an infrared light source to actively illuminate the scene and a camera with an infrared filter to measure the amount of infrared light that is reflected from the scene. Since infrared light is invisible to the human eye, this illumination is not perceived by the user of the tracking system. Although more complex sensors than for optical tracking are required, infrared tracking is invariant to lighting conditions and therefore not susceptible to changes in illumination. Therefore, active illumination with infrared light forms the basis of depth cameras, which can extract accurate depth information to capture the environment in 3D. While this can also be achieved with passive 3D sensors based on natural light using passive stereo matching, photogrammetry, structure-from-motion, or even learning-based depth prediction techniques, these approaches are generally slower and less accurate than techniques based on infrared light and, as previously discussed, require sufficient illumination of the environment. In recent times, several depth sensors have been developed that enable 3D sensing based on infrared light. As such sensors are also employed in the AR solutions developed within this thesis, it is necessary to take a closer look at how depth information can be obtained using such techniques.

According to a recently published white paper by Wagner, depth cameras can be classified based on whether depth is measured directly or indirectly [518]. Direct depth measurements are based on the time of flight (ToF) principle, while indirect depth measurements rely on stereo matching techniques that determine depth by calculating disparities between matching key points in the images of two parallel viewpoints. Both active and passive stereo (AS & PS) as well as structured light (SL) fall into the category of stereo-based solutions. In the case of AS and PS, two infrared cameras form the stereo system that represents the two viewpoints. As with all stereo-matching techniques, the accuracy of the depth measurements depends primarily on the density of visually distinguishable features. Any texture—whether natural or artificial—significantly improves the resulting depth estimates. In AS, such an artificial texture (e.g. in the form of a random dot pattern) is projected onto the environment with an infrared projector in such a way that, unlike with PS, texture-less surfaces can be effectively matched. Prominent examples of AS sensors include the Intel RealSense D-series and Occipital’s Structure Core depth sensor. In SL, on the other hand, the stereo system is comprised of one camera and an infrared projector that also projects a known pattern whose features need to be detected in the camera view. Depth cameras based on SL can achieve high quality measurements up to several meters of distance, but generally require a larger baseline to achieve this. The most prominent example of an SL camera is the first iteration of

the Kinect sensor, which was introduced by Microsoft in 2010 as an accessory for the Xbox 360 game console. In contrast to the previously discussed techniques that employ stereo matching algorithms for indirect depth measurement, ToF cameras can directly calculate 3D distances by determining the time it takes for an emitted infrared light signal traveling with the speed of light to reach the sensor again. However, this technology requires extremely accurate mechanisms to measure time differences with sub-nanosecond timing and is therefore only used in expensive light detection and ranging (LIDAR) sensors [518]. Instead of measuring time differences directly, consumer ToF cameras extract depth information by illuminating the scene with a modulated infrared light source and calculating the phase shift between the illumination and the reflection [269]. One of the main advantages of ToF cameras is their small form factor, as the infrared light source and the camera can be positioned very closely together and no baseline is required. Additionally, the calculations necessary to compute the depth information from the phase differences are computationally less expensive than stereo matching. ToF cameras were integrated in both the second iteration of Microsoft Kinect for Xbox One as well as the recently released Azure Kinect. In addition, they are an essential component within today's most popular HMD's such as the Microsoft HoloLens 1 & 2 and the Magic Leap One. In summary, Figure 2.4 once again provides an overview of all the depth measurement technologies described above. In practice, the depth sensor is almost always combined with a conventional video camera into a single device, a so-called RGB-D camera. Especially for AR, such RGB-D cameras are very appealing, as they provide both color images of the scene as well as geometric information that can be used to obtain a 3D reconstruction of the scene using simultaneous localization and mapping (SLAM) techniques [409]. Besides environmental scanning, two other important applications of depth cameras that play an important role for many AR applications are gesture recognition and human motion tracking, which will be discussed in detail within the paragraph on user input and interaction.

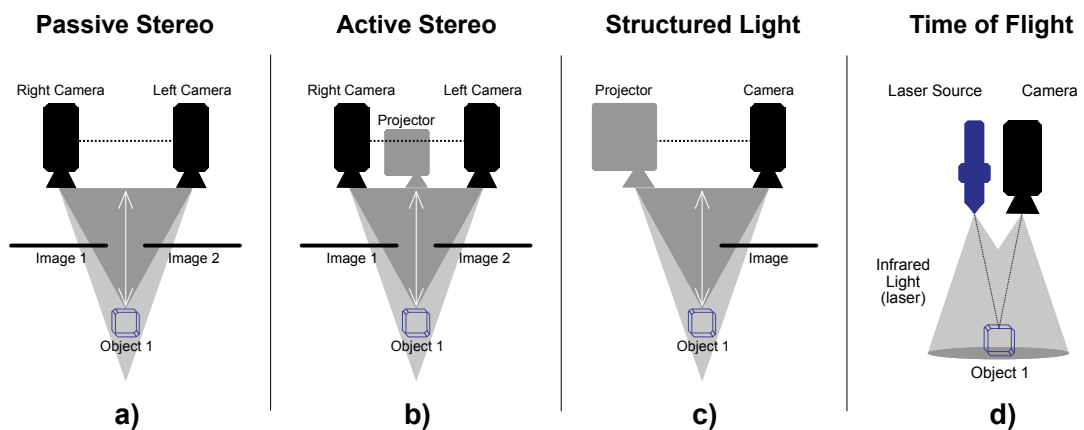


Fig. 2.4. Schematic overview of today's most important depth sensing technologies as used in many consumer RGB-D cameras, according to Wagner [518]. While passive stereo (a), active stereo (b), and structured light (c) are all based on stereo matching techniques to indirectly measure depth, time of flight (d) is the only technology that directly can measure depth (though in practice phase shifts are measured instead of time differences).

In addition to distinguishing whether natural or infrared light is used for tracking, another important difference in optical tracking relates to the type of features tracked by the system, which can be either natural or artificial. In the latter case, the tracking algorithm uses image processing and computer vision techniques on the camera stream to identify artificially designed fiducial markers that are attached to the target entity which is subject to tracking.

These markers have to be easily identifiable and are encoded in a way such that every marker can be uniquely determined. A variety of both circular and square markers has been proposed in the past, including the well known ARToolKit markers or QR codes [228]. While such markers are commonly used for tracking in regular video camera streams, another popular marker design that is often used with infrared illumination uses small spheres, coated in a specific retro-reflective material, that are rigidly attached to the tracking device. These spheres reflect a large part of the infrared light and are therefore easily visible in the image of the infrared camera. Such a setup is referred to as passive optical tracking. The counterpart, active optical tracking, is characterized by infrared light emitting diodes that are attached to the tracking target. However, this technology requires every diode to be wired, which is often times impractical. The major disadvantage of marker-based tracking is the modification of the real environment through the placement of such markers on the tracking targets. Natural feature tracking approaches offer an alternative by relying exclusively on characteristics in the natural environment. A large number of key points such as corners, edges, or intersections of lines, which are unique in their environment, are identified using image recognition algorithms and subsequently matched with the features of the object to be tracked. Various feature detectors have been proposed in the literature, including the well known Scale Invariant Feature Transform (SIFT), Speeded Up Robust Features (SURF), or Binary Robust Independent Elementary Features (BRIEF). Today, thanks to the recent advances in computational power and algorithms, deep learning based methods using convolutional neural networks (CNN) have become increasingly popular for learning these features implicitly. Therefore, interest point detection can be performed with CNNs as well. While real-time performance is still very challenging, such techniques are increasingly employed in the context of vision-based tracking of natural features. Compared to marker-based tracking, the identification of natural features requires higher computational effort as well as sufficient image contrast and a large number of clearly identifiable features, such that tracking textureless objects can be a challenge. A strong requirement for all optical tracking techniques is constant line of sight to the tracking target. In cases where this cannot be ensured, previously discussed options such as electromagnetic tracking, mechanical tracking, or hybrid approaches should be considered.

Display

AR applications, in accordance with the first requirement of Azuma's definition of AR, must combine both real and virtual imagery. To achieve this goal, a display is required to present the composited information to the user. In this section, an overview about different display technologies is provided, with a focus on those that are employed for the two AR solutions presented in this thesis. For this purpose, a taxonomy introduced by Bimber and Raskar will be used that categorize AR displays based on where the display is situated between the eyes of the user and the physical world into either head-attached, hand-held, or spatial displays [45]. A second classification by Billingham et al. distinguishes between AR displays based on how the combination of real and virtual imagery is achieved, namely either by using video see-through (VST), optical see-through (OST), or projector-based AR displays. For all three categories of Bimber and Raskar, these three different modes of combining real and virtual imagery of Billingham et al. can be applied. While displays are generally associated with purely visual AR, they can also exist for non-visual sensory modalities such as audio, touch or even smell and taste. However, since the contributions presented in this thesis deal exclusively with visual AR, a detailed discussion of non-visual AR displays is not included.

Head-Attached Displays The first category of AR displays according to Bimber and Raskar are displays that are worn on the user's head. The main representative of this category are Head-Mounted Displays (HMDs), which present virtual images directly in front of the user's eyes. The size of such HMDs has decreased dramatically in recent decades, from helmet-sized HMDs to lightweight AR glasses such as the Microsoft HoloLens, which also feature additional sensors such as depth cameras or IMUs. Two fundamental types of HMDs exist, which differ in the way virtual and real images are combined: video see-through (VST) and optical see-through (OST) displays. A comparison of the two is depicted in Figure 2.5. In the first case, a video camera system is used to capture the real world. Generally, two video cameras form a stereo system that is positioned in front of the screen and essentially replaces the eyes of the user. Classical video mixing techniques can be employed to blend virtual content with the camera view of the real world and the composited image is finally displayed on a standard display panel, similar to VR. A significant advantage of VST displays is related to this blending of real and virtual content. In VST, every individual pixel can be controlled to accurately define how real and virtual content is combined. Additionally, the hardware setup does not require complex optical elements as the main components are a pair of regular video cameras and a display. Most of the drawbacks of VST AR displays stem from the fact that the user does not have a direct view of the real world, but instead observes it through a pair of cameras. Generally, this results in lower resolution compared to seeing the scene directly, increased latency, and perceptual shortcomings due to the viewpoint displacement. Notable examples of recent VST HMDs which combine the benefits of VST with low latency and high resolution displays are the Lynx R1 and the Varjo XR-1.

The second main type of AR HMDs are OST displays, which combine real and virtual images by means of optical elements—essentially half-silvered mirrors—which are partially reflective and partially transmissive. While the light responsible for creating the virtual images is reflected into the user's eye, light coming from the real world can simply pass through the optics. As a result, users of OST AR displays can observe the real world with their own eyes. OST displays can be categorized based on the type of optics that is used to fuse real and virtual content. Most commonly, waveguides are used as optical elements. Light coming from a microdisplay is inserted into the waveguide at a certain point (in-coupling), reflected several times within the waveguide along a pre-defined optical path by means of total internal reflection, and finally exits the waveguide at another point towards the eye (out-coupling). While waveguides allow for very flat HMD designs, there are a number of difficulties in terms of optical efficiency and image quality. Popular examples of HMDs based on waveguides are the Microsoft HoloLens and the Magic Leap One. The most popular alternative to waveguides are free-space systems with arbitrarily shaped optical elements. Generally, curved combiners are used, which directly reflect light from the microdisplay into the eye. Therefore, free-space systems—such as the Meta2 from Meta View—are more complex to design than waveguides and usually have a larger form factor, but optically they are much simpler than waveguides and can produce higher image quality. A common shortcoming for all OST AR displays is that virtual content is displayed by adding additional light on top of light coming from the real world. In contrast to VST displays, it is not possible to darken the real world and to display black pixels. Furthermore, there is a large number of other important design parameters of OST displays that carefully have to be optimized and tuned. In many cases, it is relatively easy to improve one parameter at the expense of others, such that trade-offs between different parameters are required. Examples include the Field of View (FoV), eye box size, eye relief,

optical efficiency, brightness, transparency, and the overall size and form factor of the HMD. An extensive overview about this dilemma discussing in detail why making good OST AR displays is so difficult was recently presented by Wagner et al. [519].

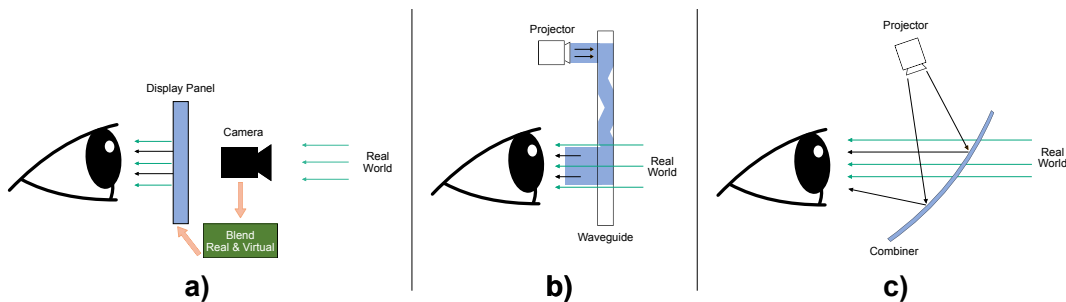


Fig. 2.5. Schematic overview of the most important types of HMDs. a) Video See-Through (VST) AR display. The images of two stereo video cameras capturing the real world are shown on a regular display panel. Virtual content can be added using classical video-mixing techniques; b) Optical See-Through (OST) AR display based on a waveguide as an optical combiner, which redirects light coming from a projector into the eye; c) Free-Space OST AR display, which uses a curved optical combiner to reflect light from the projector directly into the eye.

Besides HMDs, two other types of head-attached displays are retinal displays and head-mounted projectors. While the latter project virtual content onto retro-reflective surfaces in front of the user, retinal displays create virtual images by focusing a narrow bundle of collimated light rays into the pupil to be projected onto the retina using a low-power laser [215]. These displays can provide very bright virtual images with high contrast and potentially a large field of view. One prominent HMD that uses retinal projection is the second iteration of the Microsoft HoloLens, which employs a laser scanned by a microelectromechanical mirror (MEMS mirror) to create a narrow light ray bundle. Therefore, the differences between HMDs and retinal displays can be blurred and retinal projection might be employed by an HMD.

Hand-held Displays Hand-held AR displays form the second category of Bimber and Raskar's taxonomy [45]. Thanks to the rapid development of smartphone and tablet devices, hand-held AR displays have become the most prominent platform for AR today. The combination of real and virtual content is achieved in a similar way to VST-HMDs, with a back-facing video camera digitizing the real world and the user seeing the composited AR view on the display of the device. Recently, modern smartphones also integrate depth cameras, which allow AR applications to address the occlusion problem to integrate virtual objects into the scene at the correct depth. While regular hand-held AR displays generally show an AR view from the perspective of the device (i.e. camera), attempts have been made to show a view from the user's perspective by tracking the position of the user's eyes relative to the display [19]. Furthermore, hand-held devices using OST technology have been proposed in the past as standalone devices [47, 439], or even as an addition to smart watches [490]. However, smartphones and tablets are still the most important category of hand-held AR displays because they combine all necessary components of an AR system in a single device that is conveniently available to the users. The main limitation, on the other hand, is that the device must be held at arm's length, which can lead to arm fatigue and does not allow ambidextrous actions to be performed.

Spatial Displays The third and last category of Bimber and Raskar's taxonomy of AR displays are spatial displays, which differ from head-attached and hand-held displays in separating the display from the body and integrating it as a stationary part of the environment [45]. Similar to the previous two categories, real and virtual imagery can be combined using spatial displays either by means of VST, OST, or projector-based techniques. In the case of VST, such AR systems use regular monitors or television screens to present the AR view to the user. The simplest form of such a screen-based VST display is a desktop monitor that presents the video stream of a webcam. Alternatively, a laptop with an integrated webcam can be used. Another important VST spatial display configuration that is also employed for one of the AR-based anatomy learning solutions proposed in this thesis are *virtual mirrors*. In such a setup, the user stands in front of a large screen that displays the video stream from a camera mounted on top of the screen and pointing towards the user, giving the impression of looking into a digital mirror. Virtual mirrors are commonly used for AR applications which track the movements of the user in front of the system and overlay virtual content on top of the digital mirror representation shown on the screen. A well known example for such a virtual mirror application are virtual try-on's, which can augment the image of the user with virtual models of clothes or eye-wear.

In contrast to VST virtual mirrors, it is also possible to construct an OST virtual mirror by placing a semi-transparent mirror in front of a flat screen. In this case, users directly observe their mirror image such that a video camera is only required for tracking the user, not for displaying its video stream. Other OST spatial display configurations have been used to create half mirror workbenches, which enable close interaction with virtual objects using beam splitters to generate images that are aligned within the physical environment [48, 165, 376], or a virtual showcase, which employs a pyramid or cone shaped beam splitter in combination with active shutter glasses to combine the reflection of a screen such that the virtual image is reflected towards the user [49].

The third type of spatial displays use projectors to seamlessly overlay virtual content in the form of artificial textures, shading, or even animated content directly onto the surface of physical objects to create spatial AR applications [46, 382, 383]. Various scenarios are possible for both static and dynamic projection mapping, the latter requiring the tracking of the object whose surface is to be modified. In many cases, projection-based spatial displays use a projector that is mounted on a ceiling or wall to overlay virtual images onto flat surfaces or physical objects. However, also the human body can serve as a projection surface [192, 339], even in combination with an OST virtual mirror system [397]. Several parameters are important for projection-based spatial displays to work properly, including the surface material and brightness of the environment. Furthermore, projectors require accurate calibration each time the environment or the distance to the projection surface changes.

Overall, spatial displays represent an important class of AR applications. While they are less mobile and immersive compared to both head-attached and hand-held displays due to the remote viewing constraint, they are generally very cost effective, requiring only standard hardware components and PC equipment. Virtual mirrors are a particularly important class of spatial displays that can be used in VST, OST, and even projection-based settings. Figure 2.6 depicts all three of these virtual mirror configurations.

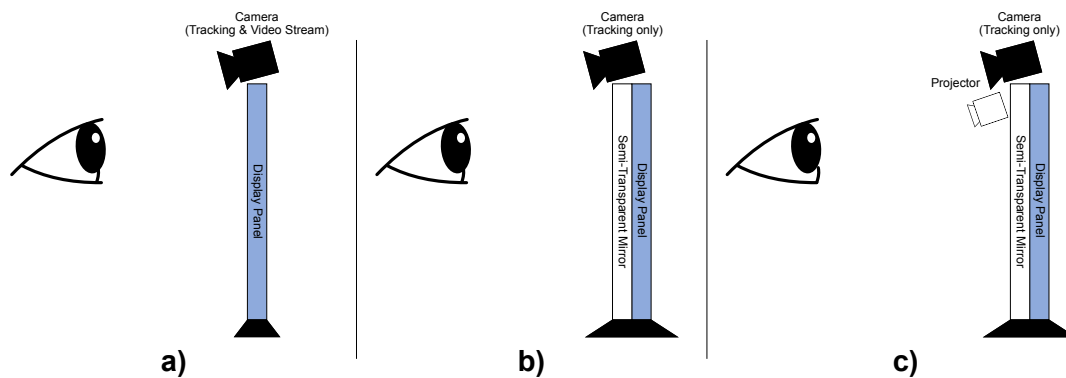


Fig. 2.6. Different spatial display configurations of virtual mirrors. a) Video See-Through (VST) setup, in which a camera is used both to track the user and to display the video stream as a digital mirror image on the screen; b) Optical See-Through (OST) setup, which places a semi-transparent mirror in front of the screen, such that users can see their true mirror image. The camera is only used for tracking purposes; c) OST virtual mirror combined with a projector. While the camera is again used only for tracking the user, the projector can overlay virtual content dynamically onto the user. In this case, the screen is merely used for displaying a user interface.

User Input & Interaction

Revisiting Azuma's definition of AR one more time, an AR system not only needs to precisely register virtual content with the real world and provide a suitable display for presenting the combination of real and virtual imagery in a composited AR view, but also provide an intuitive user interface (UI) and possibilities for the user to interact with virtual objects in the AR scene. This is a crucial factor and substantially determines whether an AR system is accepted by the user or not. Often times, however, insufficient relevance is placed upon the development of a user-friendly UI. The classical human-computer interaction concept of WIMP (windows, icons, menus, pointer) traditionally has been the dominating desktop UI metaphor. However, conventional devices such as an ordinary mouse and keyboard only allow input with 2 degrees of freedom (DOF) and are not designed for interactive AR experiences that allow the user to interact freely with virtual objects in 3D space (i.e. 6DOF). Therefore, more advanced input methods and interaction technologies specifically tailored for AR systems are required. In this section, a short overview of the most relevant interaction paradigms will be presented.

Augmented Browsing & Magic Lenses If an AR system does not allow direct user input but only serves to obtain additional information about the real world, e.g. to view virtual annotations registered with the environment, the interaction style is called *augmented browsing*. While interaction is limited to the most basic tasks of viewing and visualizing the AR scene, augmented browsers can provide very powerful AR experiences by simply providing the user with an additional stream of information, especially in AR navigation systems. In the case of HMD-based AR, users can simply move their head around to interact with the system and change their view of the AR scene. For hand-held AR displays on the other hand, the user can see relevant information by pointing the device towards the object of interest, such that the display can be seen as a physical *magic lens*, which enables the user to see an augmented version of the real environment. Magic lenses can also be achieved using HMDs or spatial displays, in which cases the lens is represented by some sort of tracked object.

Tangible AR Interfaces In most AR applications it is not sufficient to merely view and navigate an AR scene, but in many cases the experience only becomes meaningful when interaction with virtual objects is possible. Tangible User Interfaces (TUI) are one of the most important classes of human-computer interaction paradigms and allow users to employ physical objects as a medium to control the behavior of an application [204]. Using the concept of a TUI, any physical object in the environment can be converted into an input device for AR applications. For systems that use a TUI for superimposed virtual information on top of this tracked physical object, Kato and Billinghurst have introduced the concept of tangible AR (TAR) [44, 229]. A necessary prerequisite for tangible AR is the tracking of the physical object, which can be achieved using the techniques discussed in the previous section on *Tracking*. In the past, fiducial markers combined with marker-based tracking have been a popular configuration for tangible AR, where one or more markers were attached to a physical object to enable 6DOF tracking [141, 158, 377, 410]. More recent developments are moving in the direction of using complex objects and deformable surfaces instead of rigid objects as input for interaction in AR [218]. One specific group of TUIs are haptic interfaces, which can add haptic feedback for virtual objects in an AR scene. While haptic devices can be a valuable addition in certain AR scenarios, their main drawback is the limited working volume and that haptic feedback is generally only provided for a single point [409]. Overall, tangible AR interfaces provide an intriguing method for intuitive and convenient user interaction in AR by seamlessly fusing virtual content with physical objects from the real world and making the virtual objects tangible. However, requiring such a physical object can be cumbersome, especially in HMD-based or hand-held AR applications where the user might require both hands to be free.

Natural User Interfaces In contrast to TUIs, Natural User Interfaces (NUI) do not require a physical object as a proxy for interaction, but the system input is performed by means of natural and easy to learn modalities. NUIs seek to leverage interaction metaphors that users are familiar with from their everyday interaction with real-world objects, and to transfer them to the digital world. Therefore, the main characteristic of these interfaces is their intuitiveness. Perhaps the most abundant type of NUI are touch interfaces, that employ capacitive sensing to detect when a user touches a surface. Today's advanced touchscreens as used in smartphones and tablet devices not only enable multi-touch input recognition, but can also provide haptic feedback to notify the user when touch input is successful. For this reason, hand-held AR displays almost exclusively use touch input as the predominant interaction paradigm for controlling the AR experience. Another group of AR applications that can be effectively used with touch input are virtual touch screens that are projected onto arbitrary surfaces such as a desk [370]. Instead of flat surfaces, recent approaches even explore the use of certain body parts as surfaces for touch input, in which the user could for example dial a phone number directly on the palm of his hand [174, 404].

Aside from touch, another very important category of NUIs that is commonly used for AR applications relies on gesture-based interaction. The accurate detection of gestures requires the continuous tracking of the user's body in 3D space. Depending on the application and the desired modes of interaction, either the entire body or only certain regions of interest such as the head or the hands are tracked, the latter being particularly important for gesture recognition. Body tracking—also known as human pose estimation—can be facilitated if only a certain number of body joints are tracked, which are generally the counterparts of the joints found in the real human body and define a skeletal hierarchy of the user. Hence, it is also

commonly referred to as *skeletal tracking*. Knowledge about the position and orientation of the individual body joints in 3D space is sufficient to understand even complex skeletal configurations and thus enables the recognition of both static and dynamic gestures and other types of body-based user input. Various approaches to body tracking are available, including sensors or even whole-body motion tracking suits worn by the user, glove-like devices specifically designed for hand tracking, and purely image-based methods that solely rely on the input of either a single or multiple cameras. For the latter category, computer vision techniques, especially methods that rely on convolutional neural networks (CNN), are used to identify the individual body joints in the camera images. A steadily increasing body of research works has been published by the computer vision community on both 2D and 3D human pose estimation. Approaches can be classified based on whether they first detect individual persons in the image before inferring their joint positions (top-down) or localize the body joints of all persons first and link them to individuals in the following step (bottom-up). Further categorizations distinguish between methods that do or do not employ a model of the human body (generative vs. discriminative), methods that calculate body joint coordinates directly from the input image or via intermediate representations such as heatmaps (regression-based vs. detection-based), and methods that use end-to-end networks to map the input image to human poses or those that use multiple stages and supervision (one-stage vs. multi-stage) [84]. All of these different methods can either rely on images from an RGB camera or from a depth camera (see previous section on *Tracking*). RGB-based methods have recently gained a lot of popularity, with state-of-the-art methods being able to perform multi-person human pose estimation using a single RGB camera in real time [314]. Commercial devices such as the Azure Kinect by Microsoft on the other hand generally rely on the infrared images of the depth camera for body tracking. To increase robustness, a common pattern is to increase the size of the training data set with synthetically generated images, which can be accurately labeled and fed into the network [9]. In addition to full-body human pose estimation, a large number of works has focused exclusively on hand pose estimation, again either from RGB [329] or depth images [330]. Hand tracking can be considered a special case of skeleton tracking, wherein the hand is comprised of more than 20 hand and finger joints. Several AR applications have been presented, which use hand tracking and gesture-based user interaction paradigms, including *HandyAR* by Lee and Höllerer [265], in which virtual objects could be attached to the hand for both inspection and manipulation, Microsoft *HoloDesk* by Hilliges et al. [189], which employed hand tracking for interacting with virtual objects in an OST AR workbench, as well as *WeARHand* by Ha et al. [170], which could detect mid-air hand gestures for selecting and manipulating virtual 3D objects. Fully articulated hand tracking can be particularly valuable for AR applications as it enables very precise and natural manipulation of virtual objects and is therefore an essential component of state-of-the-art HMDs such as the second iteration of the Microsoft HoloLens and the Magic Leap One. However, a common drawback of gesture-based user interaction, especially for extended interaction times, is arm fatigue, as the hand must always be held within arm's reach, which can be tiring after a while. To recap the previous discussion on skeleton and hand tracking, Figure 2.7 depicts a typical joint hierarchy for both a full body and a hand model, as well as an exemplary depth image with superimposed skeleton tracking information.

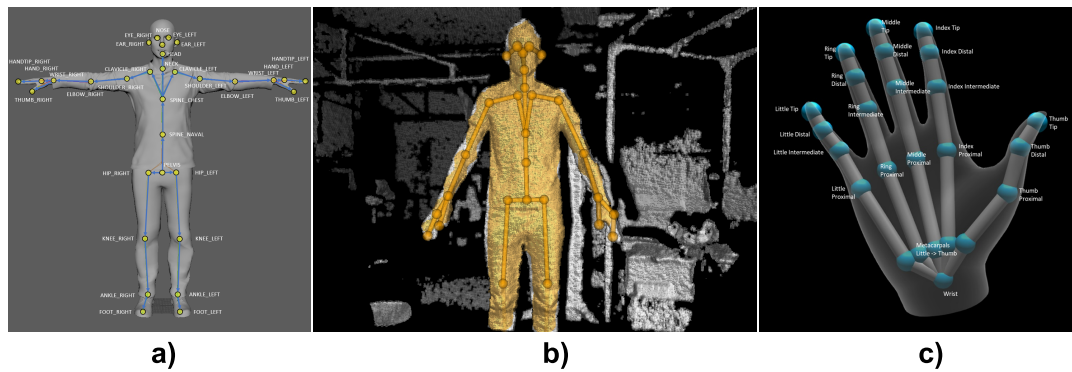


Fig. 2.7. Examples of skeleton and hand tracking. a) Joint hierarchy from the skeleton tracking model as employed by the Microsoft Azure Kinect; b) Skeleton tracking information overlaid on top of the image of a depth camera; c) Articulated hand model as employed by the Microsoft HoloLens 2.

Another form of NUI, which is particularly relevant for HMD-based AR systems, uses a person's point of gaze as an input modality to control the user interface. Enabled by real-time eye tracking from tiny infrared cameras integrated into the HMD, the gaze direction can be computed. Gaze-based interaction enables very fast and effortless user input, as our eyes can move from one focus point to another almost instantly and with little conscious effort. However, accurately tracking the user's gaze is still very challenging—especially if the user is wearing regular prescription glasses—and requires user-specific calibration. In addition, unconscious eye movements and the difficulty in recognizing the user's intention to select something (the so-called *Midas Touch* problem) must be taken into account, e.g. by activating a UI element only after the user's gaze has dwelt on it for some time. Therefore, gaze-based interaction is often combined with other forms of NUIs such as speech commands to form multimodal interaction methods. For example, a target could be selected by simply looking at it while confirmation is performed by a voice command. Instead of tracking the user's gaze, a simpler alternative is to determine the precise position and orientation of an HMD in the environment by means of positional tracking capabilities (e.g. by fusing IMU data with vision-based tracking information) and use the viewing direction of the user as input, similar to the cursor in HoloLens 1.

In addition to the previously discussed forms of NUIs, more exotic ones exist, that will not be discussed in detail but can potentially be used effectively in specific AR applications. These include additional sensors such as the *Myo* armband which measures the user's muscle activity [1], millimeter-wave radar sensors such as *Soli* [270], or even brain-computer interfaces that enable user interaction solely by measuring the brain's activity [422].

Collaborative User Interfaces Another form of user interfaces that rapidly evolved over the course of the last years are collaborative user interfaces, which enable multiple users to perform tasks collaboratively and engage in a shared experience [286]. AR offers unique opportunities for collaboration, both for scenarios where multiple users are in a shared, co-located AR space as well as for remote AR telepresence scenarios, in which users do not share the same location [41]. One specific application for the former case of co-located AR collaboration are interactive learning environments, in which students can engage in a shared learning experience and either annotate tracked physical objects with virtual information or purely work with virtual content that is registered in the environment [230, 231, 369].

Depending on the application, it can be relevant to visualize the viewing direction of users to the other collaborators. Several approaches have been proposed in the past, including a simple line rendered from the eye of a user in the viewing direction [242], a viewing frustum [323], or the exact gaze point by means of eye tracking [343]. In remote tele-collaboration scenarios, information needs to be shared explicitly between the collaborators. Application-wise, remote expert scenarios are a prime example of remote AR collaboration, where a local user performs a task with the help of a remote expert. Video sharing, potentially with additional virtual content overlaid on top of the stream, presents the most basic form of remote collaboration. More advanced systems reconstruct the 3D environment of the local user using depth cameras and share this geometric reconstruction with the remote expert, which can then choose the desired viewpoint arbitrarily [152, 153, 291]. Similar to co-located AR, several works have explored how previously discussed interaction methods such as gaze, gestures, or viewing direction can be shared in remote tele-collaboration AR applications [371, 373, 485]. Overall, AR can be used effectively in both types of AR collaboration scenarios and presents an intriguing method for enabling shared experiences.

Rendering & Visualization

The previous sections have surveyed the most important technologies that, according to Azuma's definition of AR, every AR system needs to incorporate. Another essential component implicit in Azuma's first requirement for fusing both real and virtual content is the rendering and visualization of virtual content, which aims to achieve visual coherence to seamlessly integrate virtual objects into the real environment. Rendering is concerned with employing 3D computer graphics techniques to generate a 2D image from a 3D scene. The most common form of rendering in AR is surface rendering, where 3D models of virtual objects are rendered as polygonal surface meshes and passed through the so called *programmable graphics pipeline*, which applies a set of coordinate transformations until the 3D model is projected onto the 2D screen. Additionally, it is possible to apply textures and materials to achieve a realistic rendering of the virtual objects. There are a variety of challenges specific to rendering and visualization in the context of AR. Creating realistic lighting and shadow effects in AR applications that correspond to the lighting of the real environment has been a topic of intense research in the past and can significantly improve the overall believability of the AR scene [243, 247, 292]. Two other important aspects that are particularly relevant for the AR solutions presented in this thesis are occlusion and perceptual visualization techniques, which are discussed in more detail below.

Occlusion The term occlusion generally refers to objects that block other objects located behind them from a particular viewpoint. Proper occlusion is essential for an immersive AR experience and requires virtual objects to be displayed only when there are no physical objects between them and the camera. Merely rendering virtual objects on top of the video background of an AR camera without correctly handling occlusions results in incorrect depth ordering, which prevents the 3D position of a virtual object from being correctly conveyed. In the real world, objects are no longer visible once they are completely occluded. The same thing is expected of virtual objects in a plausible AR application. In terms of perception, occlusion is the strongest depth cue, because no matter how ambiguous the situation might be, close objects cannot be occluded by distant objects [120]. In order to solve the occlusion problem in AR, one approach is to use a depth camera as discussed in the previous section

on *Tracking* to obtain a depth map of the scene, which allows to calculate when real objects occlude virtual ones. However, dedicated hardware is required that might not be available in certain scenarios, e.g. hand-held AR. Alternatively, vision-based methods that purely rely on RGB camera input exist, ranging from model-based object tracking and detection algorithms [455] to approaches that achieve occlusion-aware AR by computing a dense depth map based on a dense SLAM reconstruction and optical flow [196].

Perceptual Visualization AR visualization techniques can be employed to provide users with an intuitive understanding of virtual content that is available within the AR scene. In the previous section on occlusion, virtual objects could either fully occlude real objects or vice versa. More complex scenarios arise when artificial see-through effects should be achieved, in which virtual objects can be viewed through real-world objects to reveal hidden information—a technique known as X-ray visualization [403]. The main challenge for creating such synthetic views of hidden virtual objects is misleading depth perception. Naive approaches such as rendering the virtual object on top of the real one results in the well-known *floating effect*, which does not adequately convey the spatial and semantic relationship between visible and hidden object [224]. Similarly, rendering the virtual object semitransparent does not provide satisfactory results either [71]. The lack of correct depth perception has been recognized as a major challenge for AR visualization and remains a topic of intense research since decades [12]. The human brain uses several cues to establish a perception of depth. An extensive overview of these depth cues was provided by Drascic and Milgram [120]. Several visualization techniques for achieving a better depth perception in AR have been proposed. One of the earliest solution approaches used a *virtual window* technique to create the impression of looking inside the real object and seeing the virtual objects behind this window [39, 144, 424]. Such virtual windows are representatives of a particularly important category of perceptual visualizations known as *Focus + Context* (F+C) techniques, which draw attention to a portion of the data (*focus*) while at the same time the overall spatial relationship of neighboring information (*context*) is preserved [223]. Modulation between the focus and context regions can be achieved in several ways, such as cut-aways, exploded views, or ghosting techniques. F+C techniques have been successfully employed in several AR systems, many of them from the domain of medicine, to visualize internal anatomical structures [38, 222, 267]. In the same way, advanced perceptual visualization techniques form an essential component of the AR *Magic Mirror* platform presented in this thesis to create the impression that users can virtually view inside their own body.

Evaluation

Apart from the technical requirements discussed in the previous sections, the success of an AR application depends crucially on whether it is correctly evaluated by its end users. Formal user studies within realistic scenarios represent the ultimate challenge for an AR application and constitute a precondition for widespread adoption. Considering the fact that comprehensive evaluation studies of the two AR solutions proposed in this thesis form a substantial portion to the overall contribution, this section will provide a brief overview of the most important aspects of AR evaluation studies. The most relevant resources in this context are a series of surveys that have systematically reviewed a large number of AR papers and examined how AR systems can be evaluated [16, 109, 122, 426, 449]. While a general trend towards more formal user studies can be observed over the last decades, the overall percentage of AR papers

that do not provide detailed evaluation studies still remains very large. Several reasons for this shortage of AR evaluation studies have been identified, including a lack of knowledge about how to properly evaluate AR experiences, a poor understanding of the importance of user studies, and the almost infinite amount of possibilities for designing the actual study, which generally needs to be tailored to the AR application of interest [109, 122, 426, 449]. The following section will take a closer look at the different study types and examine which methods can be considered when designing a comprehensive AR evaluation study.

Types of Evaluation Studies In the earliest survey paper on this topic, Swan and Gabbard categorize AR evaluation studies based on the underlying phenomenon that is subject to evaluation [449]. They differentiate between low-level perceptual and cognitive aspects, task performance and interaction techniques, as well as collaborative aspects of AR. Subsequent surveys by Dünser et al. [122] and Bai and Blackwell [16] have used a similar approach and expanded this categorization with additional aspects. The first type of evaluation study according to Swan and Gabbard investigates whether virtual content is perceived as part of the real world and which perceptual cues are employed to distinguish between real and virtual imagery. Important representatives of this category are evaluation studies on size, distance, and depth judgments of virtual objects in AR [102, 129, 130, 273, 450]. An elaborate overview of a wide range of perceptual challenges occurring in AR is provided by Kruijff et al. [250]. Overall, perceptually-correct overlay of virtual content in AR remains a difficult task and additional evaluation studies on various of these challenges are required. Aside from perception and cognition studies, evaluating the task performance of a user with a specific AR application presents the second main type of user evaluations. Examples of this category are very diverse and range from evaluating novel interaction and user input techniques [29, 170, 372, 412, 452] to studies that investigate very specific phenomena such as improving spatial ability using an educational AR system for geometry learning [123] or improving procedural assembly tasks in industrial AR [179]. The evaluation of collaborative AR interfaces presents the third important category of experimental studies according to Swan and Gabbard [449]. While fewer papers have presented evaluation studies on collaboration in AR compared to the previous two categories, examples exist for both face-to-face AR collaboration [180] as well as remote collaboration [82, 227].

Types of Evaluation Methods Besides categorizing evaluation studies according to the underlying phenomenon that is investigated, Dünser et al. group evaluation studies according to the method used to evaluate the AR system [122]. Five important methods are listed. The two most commonly employed methods are objective and subjective measurements. The former includes measures that produce reliable and repeatable numbers that can potentially be analyzed automatically such as task completion time, accuracy / error rates, test scores, or the offset of an object in a positioning task. Subjective measurements on the other hand rely on the subjective judgment of users and include qualitative questionnaires, surveys, user ratings and rankings, as well as quantitative judgments of parameters such as the depth or distance of a virtual object. Besides objective and subjective measurements, additional evaluation methods listed by Dünser et al. include qualitative analysis and usability evaluation techniques [122]. While qualitative analyses evaluate data gathered from both structured and unstructured user observations, interviews, and behavioral analyses (speech, gestures, or non-verbal behavior), usability evaluations include heuristic and expert evaluation, as well as techniques such as Wizard of Oz. Lastly, informal evaluation methods based on informal user

observations and feedback exist. In many cases, experimental user studies employ not a single evaluation method, but a combination of several of the previously presented measures.

Aside from these very generic evaluation methods, additional measures exist that are often times specific to the application domain and the type of AR system that is evaluated. In the context of educational AR systems, it is also important to evaluate the impact of novel learning applications and the feasibility of incorporating them into the classrooms. A recent systematic review by da Silva et al. provides an overview of the various aspects which are important when evaluation AR systems for education [426]. Important measures include quantitative learning outcome or cognitive skills, as well as aspects such as spatial ability and knowledge retention rates, which are highly difficult to evaluate in short-term user studies.

2.3 Related Work & State of the Art

Learning about the human anatomy, as briefly described in the introductory section, is a complex endeavor for which a variety of different teaching methodologies exist today. Section 2.1 provided a historical perspective and summarized more extensively how the anatomy teaching landscape evolved to the present day. The previous section (2.2) then presented a basic overview of AR—in conjunction with its key enabling technologies—, which has great potential for considerably transforming the anatomy education landscape and which is employed in the two solutions presented in this thesis. Novel technologies such as AR have been recognized as an effective avenue for presenting 3D anatomical content to students with the goal of improving medical education environments in a large body of previously published research. This section will provide an exhaustive overview of such previous work and delineate the current state of the art in anatomy education research. After briefly discussing works on VR, the rest of this section will focus exclusively on other AR systems that have been proposed in the past. For the latter part, previous research works are categorized based on how AR content can be experienced by users, either with hand-held, head-attached or spatial displays. This is the same categorization, proposed by Bimber and Raskar, that has already been employed in the previous section to describe various AR display technologies [45].

2.3.1 Virtual Reality

VR systems completely immerse all senses of the user in a simulated virtual world, which generally aims to imitate properties of the real world. Several VR systems, both commercially available products such as *3D Organon Anatomy* (Medis Media, Queensland, Australia) and academic prototypes have been developed with the aim of improving anatomy education. Many of the early and highly-cited academic works in this area, though claiming to use VR, were merely computer-based systems in which virtual 3D models could be seen and interacted with using traditional mouse and keyboard input [151, 225, 268, 340, 414]. However, according to the previous definition, these are not considered true VR systems that fully immerse the user in the virtual environment.

More recently, a multitude of systems that employ HMDs to create VR experiences have been developed in the context of anatomy teaching [379]. Codd et al. developed a VR system for

learning the musculoskeletal anatomy of the human forearm and presented an evaluation study in which students studying with the proposed VR system scored higher in a knowledge assessment test than a group of students studying with traditional learning paradigms such as dissection and textbooks [91]. Similar results were presented by Falah et al., who showed a real-time 3D representation of the heart in an interactive VR environment that supported self-directed learning by students [136]. Additionally, they noted that studying with the VR system saves time for both students and lecturers and claimed that the system is an effective tool for improving medical education. Another recent VR system for cardiac anatomy was presented by Maresky et al., who found that students that worked with the system during a 30-minute learning session performed better in a knowledge test than a control group given only anatomy textbooks [296]. A large study with nursing students was published by Fairen et al., where a total of ten virtual 3D models representing different anatomical structures were available for self-directed learning in a VR system [135]. Students appreciated the interactivity of the system and mentioned that VR learning provides a valuable experience that meets their expectations. Two systems for cranial anatomy were developed by Izard et al. [206] and Pohlandt et al. [375]. The former allowed students to learn about the different bones and foramina that make up the cranium and listed qualitative opinions from a user study of their system. In contrast, Pohlandt et al. designed an immersive VR puzzle where students actively assemble the bones of the skull to learn names and spatial relations. During a pilot study, the system was found to provide a valuable extension to traditional teaching methods. Similarly, Mason et al. designed a fully immersive VR system for assembling an entire human skeleton [300]. In a user study, students were asked to complete this task as quickly as possible and with the fewest errors. During a knowledge assessment test, students that studied with the VR system achieved higher test scores compared to a group that only learned with self-written notes. Interestingly, the authors also studied long term effects of their system and found that students from the VR group achieved significantly better grades in the final module examination, suggesting that VR has the potential to improve retention rates. Two studies by Seo et al. investigated the potential of VR systems for learning canine anatomy [415, 416]. In the first study, they presented *Anatomy Builder VR*, a system employing the HTC Vive as HMD for assembling pelvic limb bones in VR. In a follow-up study, the same authors explored the effects of embodied learning of musculoskeletal structures in VR. The participants were equipped with motion trackers, allowing them to learn the basics of biomechanics and muscle movement by moving their own bodies with the goal of obtaining an increased spatial ability. Another interesting VR system was developed by Marks et al., who found that learning about the human nasal cavity in VR offers useful advantages for students in terms of engagement, improved understanding, as well as retention rates [297]. Recently, Moro et al. compared two consumer-grade VR headsets, the desktop-based Oculus Rift and the mobile-based Gear VR, with a regular desktop application for learning spine anatomy [326]. While no significant differences in test scores were found, the overall attitude of students towards VR systems was very positive. Students experienced higher adverse health effects such as nausea and blurred vision with the mobile-based Gear VR system compared to the Oculus Rift, suggesting that desktop-based VR—though more expensive than mobile-based VR, where the power of smartphones is used both as a computing and display device—is still superior due to more powerful compute capabilities. Only very recently, untethered consumer VR devices such as the Oculus Quest (Facebook, Menlo Park, CA) start to emerge that remove the need for an additional workstation while simultaneously being significantly more powerful than mobile-based VR.

Overall, important benefits of using VR for anatomy education include an increased motivation of students for the topics of interest [77, 91, 438], better spatial understanding [77, 258, 375, 416], a more active and engaging learning experience through various interaction paradigms [297, 325], as well as increased levels of curiosity that correspond with students spending more time with VR systems compared to traditional 2D methods [89]. Another advantage of VR systems lies in their ability to enable collaborative learning of anatomy, either in the form of co-located or remote collaboration [42]. However, only few studies have explored this research path and investigated the potential of collaborative VR systems in anatomy education. Among the few available papers on this topic is the previously mentioned study by Fairen et al., which compared two VR systems, a VR powerwall and a VR cave, for learning anatomy in small groups of nursing students [135]. One student led the learning session by interacting with virtual anatomical structures shown in the VR system, while a group of other co-located students could easily follow the explanations. The approach provided a promising first step towards collaborative anatomy learning in VR, however, the system was restricted to only one active user. In another recently conducted study, the use of the low-cost Google Cardboard VR was investigated, which allowed multiple students to investigate and manipulate the same 3D virtual organ models in a shared anatomy learning environment [301]. Among the main limitations of the system were motion sickness and eye fatigue, which are two common issues with VR systems, together with hardware problems. Despite the remaining challenges, VR has the potential to improve anatomy learning environments, and future studies should focus on both the collaborative aspect and the effectiveness of immersive and interactive forms of VR [256].

2.3.2 Augmented Reality

In contrast to VR, AR applications aim to enhance the perception of the real world by incorporating virtual content in real-time that appears to coexist in the same space [12, 13]. While a large body of research has explored the applicability of AR in various areas of education, this section will focus on AR systems specifically developed for the purpose of learning and teaching anatomy. In the following literature review, existing AR systems are categorized according to the way the combination of real and virtual imagery is displayed to the user, ranging from hand-held AR systems to those using spatial and head-attached displays.

Hand-Held Displays

AR systems based on hand-held displays overlay virtual content onto the live camera stream of a mobile device such as a smartphone or tablet. The ubiquity of such mobile devices and the combination of computing power, display, and interaction technology in a single device have made hand-held AR systems very popular in the past. With the recent introduction of advanced AR software frameworks for both iOS (ARKit from Apple Inc., Cupertino, CA) and Android devices (ARCore from Google LLC, Mountain View, CA), mobile AR is now more important than ever and its importance is growing rapidly.

Several hand-held AR systems have been proposed for various areas of anatomy education in the past. In 2012, von Jan et al. developed *mARble*, a mobile AR system which used the camera of the iPhone to detect skin-attached markers based on which virtual content

as well as additional multimedia content was superimposed [475]. Students described the learning experience as more enjoyable, interesting, and effective compared to traditional book learning. In another work, Jamali et al. presented a prototype mobile AR system called *HuMAR* for learning the human skeletal structure [213]. A hand-held tablet device in combination with the Vuforia AR toolkit was used for superimposing virtual bone models of the lower appendicular skeleton onto 2D printed markers. In a pilot study with 30 undergraduate participants, the authors found that students were satisfied with the usability and overall features of the system, which in turn could have a positive impact on their learning process. Furthermore, students mentioned an increased motivation for the topics of interest when learning with the *HuMAR* hand-held AR system. Similarly, Rodrigues et al. used Vuforia marker detection for overlaying virtual bones of the hand onto the user's actual hand [392]. More recent systems were proposed by Kurniawan et al. [255] and Khalid et al. [234] for general purpose anatomy learning, as well as by Dixit et al. for the anatomy of the pelvis [112]. Jain et al. introduced a tablet-based AR system for learning spatial anatomy by means of displaying virtual 3D surface models derived from CT scans [212]. The application was found to provide a valuable supplement which traditional anatomy instruction can benefit from. In a recent study, Henssen et al. presented *GreyMapp-AR*, a tablet-based system for learning neuroanatomy [181]. In a study involving 31 medical students, questions about the cross-sectional anatomy of deep brain structures were answered more accurately by students who learned with 2D cross-sections than by students who learned only with the *GreyMapp-AR* system. However, the AR system resulted in students experiencing less cognitive load during the exam. In accordance with other previously mentioned studies, the AR system was considered to be a valuable addition to more traditional learning methods. Both the AR system by Jain et al. and the *GreyMapp-AR* system by Henssen et al. are depicted in Figure 2.8. A very popular subcategory of hand-held AR systems are *Magic Anatomy Books*, which integrate virtual content into the book for providing the viewer with additional information. Küçük et al. developed such a Magic Book for neuroanatomy, which allowed students to experience anatomical models of the brain and skull directly within the textbook [251]. In an experimental study, the authors found that the mobile AR system decreased cognitive load by making abstract information more graspable to the students. Furthermore, the learning experience was considered more engaging and satisfying compared to traditional book learning. Similar Magic Book applications were demonstrated by Westwood et al., who presented the *Gunner Goggles* system for integrating multimedia content in the form of videos and 3D models into an anatomy textbook [491], as well as by Juanes et al., who enriched an anatomy atlas with explanatory videos, annotated 3D models, as well as medical image data [221]. More recently, Moro et al. published a comparative study that investigated the benefits of a mobile AR system in comparison to a VR system for anatomy learning [325]. While no significant differences in terms of learning outcome were measured, the study results showed that AR can be used as an effective supplement for existing teaching modalities while at the same time increasing the motivation and engagement of students. Similar results in terms of increased motivation, fun, and engagement were found by Birt et al., who compared a tablet-based AR system to a VR system for both learning neuroanatomy as well as acquiring procedural knowledge during laryngoscopies [51].

Overall, previous studies have highlighted the potential benefits of using hand-held AR applications in the context of anatomy learning environments. One of the main advantages is that most people already own the devices (i.e. smartphone or tablet), which are required to

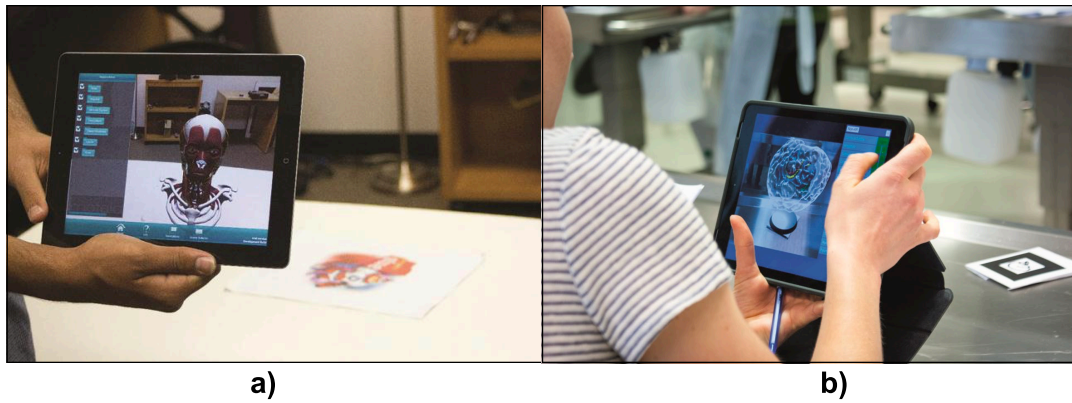


Fig. 2.8. Two exemplary AR systems based on hand-held displays. a) AR system by Jain et al., which employs a tablet device and marker-based tracking to display virtual models of both the skull and the facial muscles, which are reconstructed from a CT volume. [212]; b) *GreyMapp-AR* system by Henssen et al., which also uses marker tracking in combination with a tablet to facilitate the study of neuroanatomy [181].

experience this technology, and carry them around in their pockets. Therefore, mobile AR is readily accessible, inexpensive, and does not require any additional specialized equipment, which is the case for VR. However, hand-held mobile AR solutions also come with several disadvantages. The mobile device needs to be carried around by the user and pointed towards points of interest in the scene. As a result, interaction possibilities are restricted and hands-free working is not possible. Additionally screen sizes are limited and cannot compete with the field of view offered by AR systems that are based on spatial or head-mounted displays.

Spatial Displays

The second main category of AR systems according to Bimber and Raskar are those that employ spatial displays to present AR content to the user [45]. Section 2.2 has shown that several different forms of such AR systems based on spatial displays exist, which vary depending on how real and virtual images are combined. The most common and relevant type are screen-based systems based on the video see-through principle, which display the view of a video camera that is altered with additional virtual content by means of classical video-mixing techniques on a regular monitor. In its simplest form, such screen-based AR systems therefore require only a camera, a computer to run the the AR application, as well as a display device.

Several screen-based AR systems have been proposed in the literature for the purpose of supporting anatomy education. One of the earliest applications was developed by Chien et al., who developed an interactive AR system for learning the anatomy of the skull, which was based on a regular consumer webcam mounted onto a computer monitor [88]. Virtual 3D models of the skull were superimposed on rectangular markers detected in the webcam video stream. A comparative user study was conducted with two groups, one studying with the AR application and another one using regular anatomy atlases for learning. Thomas et al. presented the *BARETA* (Bangor Augmented Reality Education Tool for Anatomy) system, which could be used to study the human ventricular system in AR [460]. Instead of marker-based tracking, *BARETA* employed a magnetic tracker with two sensors and electronics units. A user study with 34 first-year medical students was performed to determine the usefulness and usability of the AR learning system. Participants stated that the system was suitable for understanding the shape and topography of the ventricular system and they enjoyed the novel

learning experience, though difficulties with camera positioning and the magnetic tracker were mentioned. Another desktop-based AR system was introduced by Yeom, who combined AR with haptics to learn about human abdominal anatomy [501]. In a small evaluation study with 23 students and one teacher, the author found a positive overall attitude towards the system, with a high degree of usability and ease of use. Another combination of desktop-based AR with haptics was presented by Saenz et al. who developed the *FlexAR* system for hands-on learning of kinetic anatomy [399]. The user of the system could manipulate a physical anatomy model of the arm with AR markers attached. Virtual muscles can then be examined on the screen, while the haptic interface enabled students to better understand flexion and extension of muscles. In 2015, Ferrer-Torregrosa et al. introduced *ARBOOK*, an AR Magic Book that was comprised of a video camera mounted on a desktop monitor in combination with marker tracking for studying descriptive anatomy of the lower limb [140]. Similar to the magic books discussed in the previous section on hand-held AR systems, *ARBOOK* was able to enrich the information available on a 2D printout with additional 3D anatomical content. A total of 211 students were recruited for a user study. Participants from the experimental group achieved significantly higher scores in a knowledge assessment test than students studying solely with anatomical textbooks. Additionally, students from the AR group experienced higher levels of motivation. As a result, the authors state that *ARBOOK* is a useful supplement for regular anatomy learning.

A particularly important category of screen-based AR systems in the context of anatomy learning are virtual mirrors, which enable users to see anatomical models superimposed on their own bodies. The first of these systems was introduced by Blum et al. in 2012 under the codename *mirracle* [54]. The system employed a Microsoft Kinect for tracking the pose of the user in front of the system and provided an in-situ visualization of static anatomical models directly on the body of the user, therefore enabling users to interactively explore the human anatomy in relation to their own body. Furthermore, the *mirracle* system featured a natural user interface which could be controlled with gesture input. Meng et al. expanded the system with a more accurate overlay of virtual anatomy models by employing anatomical landmarks within a registration procedure [316]. In a follow-up work, both the precision as well as the applicability of their personalized AR system for the purpose of anatomy learning were evaluated [289]. The accuracy was found to be sufficient for teaching purposes and students highlighted the educational value of the system. Additionally, an interactive AR Bone Puzzle game was implemented based on a modified version of this system [436]. Similar screen-based AR systems have been proposed by several other groups. Bauer et al. employed an identical setup to overlay a user-specific model of internal anatomy onto the user of their system in real-time [25, 26]. A calibration step is used to measure the bone lengths of the user and thus to achieve a very accurate overlay. Similar systems were introduced by Manrique et al. for muscle learning [295] and by Lao et al. for studying the cardiovascular system [259]. All screen-based AR systems presented above employ a large monitor or TV screen as the display device and overlay 3D anatomy models onto a live camera stream. In contrast, *Augmented Studio*, proposed by Hoang et al., directly projected virtual imagery onto the user's body [192]. In a pilot study, the authors demonstrated the usability of their system and highlighted the more engaging learning and teaching experience for both students and teachers. Examples of three screen-based AR systems are depicted in Figure 2.9.

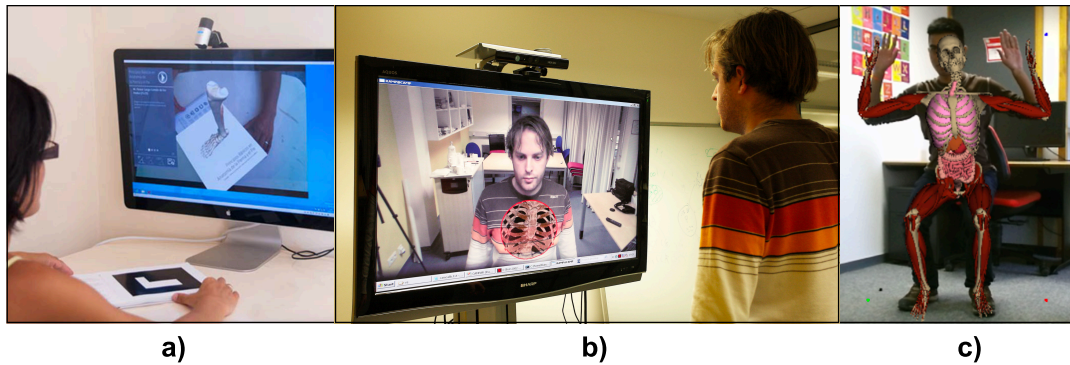


Fig. 2.9. Three exemplary screen-based AR systems. a) The desktop AR system *ARBOOK* by Ferrer-Torregrosa et al. [140]; b) the *mirracle* system by Blum et al. [54], which tracks the user in front of the system and provides an in-situ visualization of anatomy models; c) virtual mirror application by Bauer et al. [26], which employs a similar setup as the *mirracle* system and focuses on accurate anatomical overlays.

The main advantage of AR systems that employ spatial displays is their cost effectiveness due to the use of standard hardware components such as regular video cameras and TVs or monitors as display devices. In contrast to hand-held AR systems, spatial displays are stationary in the environment. Therefore, users can employ both hands for interacting with the system by means of gesture input. Additionally, they offer a larger FoV than hand-held AR systems, which generally corresponds to the FoV of the camera. Common disadvantages include—similar to hand-held AR systems—the limited and only indirect user interaction as well as the fact that such systems merely provide a remote viewing rather than a see-through metaphor. Furthermore, multi-user collaboration can be challenging due to the limited interaction space.

Head-Attached Displays

Besides hand-held and spatial displays, Bimber and Raskar list head-attached displays as the third important category of AR systems [45]. As discussed in section 2.2, the most common form of such head-attached displays are HMDs—either OST or VST—which present virtual imagery directly in front of the user’s eyes. In recent years, this category became very prominent due to technological advances and the introduction of several HMDs, most notably the Microsoft HoloLens 1 + 2 (Microsoft, Redmond, WA) and the Magic Leap One (Magic Leap, Plantation, FL). Today, a series of additional companies are developing their own HMD, such that the market of HMD-based AR is expected to grow significantly over the next decade.

These recent technological advances have led to a series of works that evaluated the potential of such HMD-based AR systems in various disciplines, including anatomy education. One of the earliest research paper was published in 2018 by Hanna et al. [172]. The authors developed an AR application based on the Microsoft HoloLens for anatomical pathology, which enabled the user to see virtual annotations, gross and microscopic pathology specimens, as well as slide images during autopsies. While no formal user study was performed, the AR system allowed the intuitive display and manipulation of data relevant to digital pathology. Michalski et al. proposed a HoloLens AR application for learning cardiac anatomy that includes 3D animations of the heart as well as virtual electrocardiography for specific disorders [317]. The system employed marker tracking using the Vuforia AR toolkit and allowed students to

manipulate the virtual heart models via gesture input. Holman et al. developed an interactive AR lecture using the Microsoft HoloLens for neuroanatomy instruction [195]. The students were able to manipulate virtual 3D models of brain structures that were reconstructed from MRI images and view their respective 2D counterparts. The pedagogical efficacy was evaluated in undergraduate students by means of a knowledge assessment test in which students who learned with the HoloLens AR application performed better than students who were taught with traditional teaching methods. In another publication, Zorzal et al. presented *Anatomy Studio*, an AR application combining both an HMD (Meta 2) and a tablet device that can be used to perform virtual dissections and to observe virtual cryosections [506]. During a pilot study with ten participants, the authors demonstrated that *Anatomy Studio* can be used effectively by pairs of users for the task of reconstructing various anatomical structures from cryosections. Zhang et al. explored the benefits of AR to improve the learning experience and memory recall in general human anatomy and physiology [505]. Within a user study with 22 undergraduate students, the authors found that results of a knowledge assessment test were superior for the group of students learning with a traditional projector-based power point presentation than with their HoloLens-based AR application. However, the students in the HoloLens group were significantly more satisfied with the learning experience. A randomized controlled trial assessing the efficacy of an HMD-based AR application for learning about musculoskeletal anatomy was published by Stojanivska et al. [440]. In a user study with a total of 64 medical students, the authors found that the anatomy of the musculoskeletal system can be learned just as effectively in AR as in traditional cadaver dissection. Furthermore, less curricular time was required to achieve these results. In addition to these scientific contributions, several commercial HMD-based AR applications for anatomy learning have been introduced, including *HoloHuman* by Pearson (Pearson PLC, London, UK) and *Complete Anatomy* by 3D4Medical (3D4Medical, Dublin, Ireland) for the HoloLens as well as *Medivis* (Medivis, Inc., Brooklyn, NY) for the Magic Leap One. *HoloHuman* was evaluated in a recent study by Zafar and Zacher, who assessed the potential of the application for learning head and neck anatomy compared to traditional cadaver learning [504]. In a user study with 88 second-year dental students, questionnaire results prior and after a learning session with the AR application revealed that *HoloHuman* provides additional value to the students in terms of understanding of 3D anatomy, though the majority stated that AR should only serve as an adjunct tool and not replace traditional cadaver training.

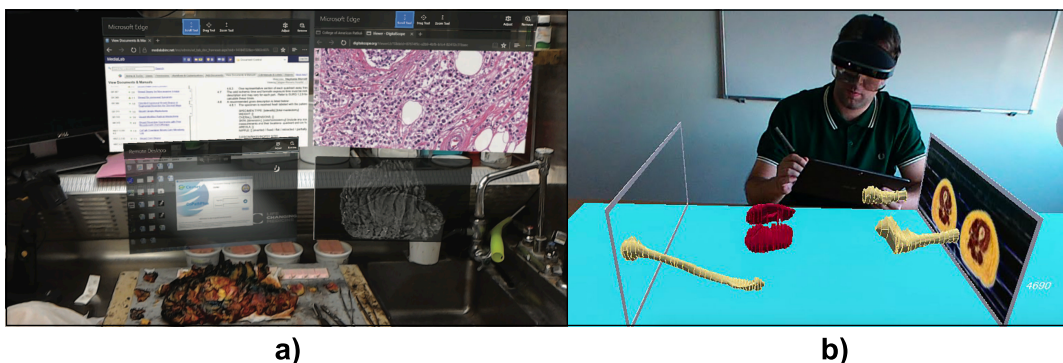


Fig. 2.10. Two exemplary head-attached AR systems using Head-Mounted Display (HMDs). a) AR system by Hanna et al. for learning anatomical pathology [172]; b) *Anatomy Studio* by Zorzal et al., which allows users to reconstruct anatomical structures from cryosections [506].

HMD-based AR applications offer a series of advantages compared to previously discussed systems that employ either hand-held or spatial displays. HMDs allow the user to freely move around in the environment while simultaneously enabling hands-free working, thus not restricting interaction possibilities. However, state-of-the-art HMDs are generally very expensive and still suffer from various technical challenges that were discussed in section 2.2.

2.4 Summary

The study of human anatomy has a centuries-long history, which has ultimately led to a heterogeneous and diverse learning environment with a range of different educational methods that medical students today have at their disposal. This historical perspective given in section 2.1 of this chapter also introduced the debates between *traditionalists* and *modernists*, who have opposing views towards the introduction of new digital anatomy learning paradigms. However, there is a general consensus that anatomy should be taught in a multifaceted manner and that developing novel educational solutions for student-centered and self-directed anatomy learning is desirable.

Augmented Reality (AR) with its numerous benefits over many traditional anatomy learning modalities has the potential to become an integral building block of the future educational environment in human gross anatomy and presents the basic underlying technology of the novel AR solutions introduced in this thesis. Therefore, section 2.2 presented a general overview of AR, including various taxonomies and definitions, followed by a short review of its history and a thorough discussion of the most important enabling technologies. With regard to the latter, various aspects of tracking, AR displays, user input and interaction paradigms, AR visualizations, and evaluation strategies were covered.

Lastly, section 2.3 provided a comprehensive summary of related work and current state of the art in anatomy education, focused on novel systems based on Mixed Reality (MR). This literature review included systems based purely on Virtual Reality (VR) as well as a larger part on newly proposed AR anatomy learning systems. Especially works that are based on HMDs are still fairly recent and only started to gain significant impact in the area of education with the introduction of devices such as the HoloLens or Magic Leap. Mobile, hand-held AR systems started to emerge with strong force since the introduction of smartphones and tablet devices, while AR systems based on spatial displays have been around since the 1990's, but recently gained popularity with advances in body tracking and gesture detection research.

The following chapters will introduce two novel AR anatomy learning solutions that constitute the major contributions of this thesis: the AR *Magic Mirror* platform (chapter 3) and the *VesARlius* application (chapter 4). Equipped with the theoretical and technical background information obtained in this chapter, both the novelty and the educational value of these new AR solutions for learning anatomy will be more readily comprehensible.

The Magic Mirror Anatomy Learning Platform

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The AR *Magic Mirror* anatomy learning platform presents the first major contribution of this thesis. The system falls into the category of screen-based virtual mirror systems and allows users to obtain knowledge about human gross anatomy in relation to their own body. Highly detailed virtual 3D models of anatomical organs and structures are superimposed onto the digital mirror image of the user and follow his or her movements in real-time. Furthermore, the platform can be used to register arbitrary medical section images from CT or MRI onto the user for interactive analysis of this data via a natural user interface. At the beginning of this chapter, the main technical aspects of the AR *Magic Mirror* platform are presented. Section 3.1 starts with a general overview of the most important concepts, including both the hardware setup and the software framework employed. Subsequently, section 3.2 introduces the real-time animation component of the system, which presents one of the major novelties compared to previous developments. Following these technical aspects of the system, section 3.3 presents the results of a perceptual investigation concerning the differences between *Reversing Magic Mirrors* and *Non-Reversing Magic Mirrors* as two particular types of *Magic Mirror* designs. Finally, section 3.4 outlines another major contribution of this work, which is the evaluation of the AR *Magic Mirror* platform and the integration of the system into the medical curriculum.

3.1 Magic Mirror Concept & Overview

The AR *Magic Mirror* is an interactive learning platform for human gross anatomy. The basic design of the system is based on the *mirror metaphor*: when the user stands in front of the *Magic Mirror*, an augmented version of his or her digital mirror image can be seen. The fundamental goal of employing this mirror metaphor within the *Magic Mirror* is putting the user at the center of an engaging and personalized learning experience. Users can interact with virtual anatomy models that are superimposed *in-situ* onto their digital mirror image to study complex anatomical concepts in relation to their own body. Learning about the human anatomy on the basis of one's own body is a very natural way of acquiring knowledge, which becomes particularly apparent when looking at the system in analogy to a real-world physical mirror. Mirrors are an essential part of our daily lives. We look into them every morning while we brush our teeth, shave, or put make-up on. We use mirrors to constantly check and monitor our appearance, whether it is our physical condition or the way we dress. Therefore, looking into a mirror is a very personal experience that we have made hundreds and thousands of times. The AR *Magic Mirror* platform leverages these previous experiences to create a learning environment that feels natural to the user and requires no prior practice or knowledge of the system: engaging with the system is as easy as stepping in front of it. However, the *Magic Mirror* goes several steps further than regular mirrors. While the live stream of a video camera—shown on a display device—represents the digital mirror image of the user, advanced perceptual visualization techniques enable users to virtually see internal anatomical structures that are aimed at resembling their real counterparts. This way, the AR *Magic Mirror* platform provides a virtual view *inside* the body.

3.1.1 Evolution of the Magic Mirror System

The original idea for the *Magic Mirror* was developed in 2012 by Blum et al. [54]. Their *miracle* system, previously discussed in section 2.3, was developed primarily for showcasing the possibilities of AR in combination with body tracking and not for advanced educational purposes. Meng et al. extended the initial prototype and integrated a novel registration technique for more accurate overlays of static virtual anatomy models and presented a number of serious gaming applications for high-level educational activities [316]. In this thesis, the AR *Magic Mirror* platform was re-implemented from the ground up to provide an interactive and personalized anatomy learning tool for medical students. The novel *Magic Mirror* platform represents a great leap forward compared to the previously proposed prototypes, both in terms of significant technical improvements and in terms of contributions to the evaluation of the system. Thus, the *Magic Mirror* system has gone through an evolutionary process that started as a purely technology-oriented prototype and has been further developed within the framework of this thesis to a highly personalized pedagogical learning platform for anatomy teaching. Figure 3.1 depicts this evolution and highlights the differences between the systems by Blum et al., Meng et al., and the platform proposed in this thesis.

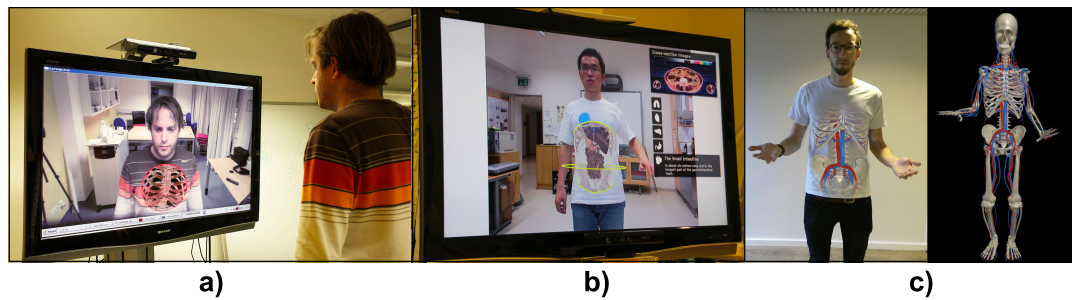


Fig. 3.1. Evolution of the *Magic Mirror* (former *mirracle*) AR system. a) With *mirracle*, Blum et al. presented the original idea for the system; b) *Magic Mirror* system by Meng et al. [316], which built upon *mirracle* by improving the overlay accuracy and added new features for displaying 3D organ models and medical image data; c) The AR *Magic Mirror* platform presented in this thesis, which presents significant advancements and novelties compared to the systems by Blum et al. and Meng et al., especially in terms of dynamic animations, perceptual visualization, as well as evaluation and curriculum integration.

3.1.2 Hardware Configuration

In addition to a regular PC that is required to run the software, the two major hardware components of the AR *Magic Mirror* anatomy learning platform, in accordance with the VST virtual mirror setup in Figure 2.6, are a *camera* and a *display device*. The camera is responsible for both body tracking as well as capturing a live video stream of the user, who is standing in front of the display. While a regular RGB camera is sufficient for the latter, tracking the pose of the user generally requires a depth camera, as discussed in section 2.2. Though RGB-based methods for body tracking are increasingly presented in the literature recently, they still suffer from several challenges such as depth ambiguities and require an enormous amount of compute power. Therefore, the AR *Magic Mirror* platform presented in this thesis features a camera that combines both an RGB sensor for capturing the digital mirror image of the user as well as a ToF-based depth sensor for body tracking in a single housing. For the most part of the development process, the Microsoft Kinect v2 served this purpose, though recently the new Azure Kinect replaced the previous version of the Kinect as it offers more precise and accurate skeleton tracking algorithms based on Deep Learning. In terms of the display device, every conventional desktop monitor, TV screen, or even projector can be employed, though bigger screen sizes make the learning experience more engaging. In principle, all required hardware components can be combined in a laptop, assuming it is powerful enough to perform RGB-based body tracking or contains a depth sensor. More recently, even mobile devices such as smartphones and tablets increasingly feature depth sensors, such that the AR *Magic Mirror* platform could potentially run even on these devices. However, for the purpose of the contributions in this thesis, the AR *Magic Mirror* platform was always comprised of a VST virtual mirror setup featuring a regular PC, a Kinect sensor, and a display device.

3.1.3 Software Framework

The software framework of the AR *Magic Mirror* platform consists of three custom built, independent libraries that are combined in the final application to provide a modular design and facilitate both scalability and extensibility. The entire framework is written in C++ and OpenGL, which enables real-time performance with very low latency to support fast user

movements in front of the system. One of these libraries is the *NarVisLib*, a cross-platform visualization library for the quick and easy creation of prototypes of modern C++ and OpenGL applications, which serves as the foundation of the entire *Magic Mirror* framework. In addition to OpenGL window and input handling, the library contains functionalities for importing 3D models and provides a set of shaders for the realistic rendering of these models. The second library that forms an essential part of the *AR Magic Mirror* platform is *KinectLib*, which—as the name suggests—is responsible for interfacing with the Microsoft Kinect sensor. The library abstracts from the actual sensor type and is compatible with both Kinect v2 and the recently introduced Azure Kinect. Besides the functionality to access raw frame data such as the color image from the RGB camera or the depth map from the IR sensor, the library also provides skeleton tracking data in the form of 3D joint positions for up to 6 persons. The third and last library is *NuiLib*, which contains a set of functionalities for natural user interaction, particularly for gesture detection. These three libraries—*NarVisLib*, *KinectLib*, and *NuiLib*—form the basic building blocks of the *AR Magic Mirror* platform and facilitate the implementation of more complex software components, which are crucial for the overall user experience of the system. In the following paragraphs, these essential software components will be explained in detail.

User Interface As discussed in the introductory section of this chapter, the *AR Magic Mirror* platform is based on the mirror metaphor, which allows users to see a digital mirror image of themselves, augmented by virtual anatomy models. The main element of the user interface is therefore the *AR View* that presents the user's digital mirror image, i.e. the live video stream from the Kinect RGB camera. Virtual models of the human anatomy are then superimposed based on the skeletal tracking information from the Kinect depth camera to create the impression of looking inside the body. A key requirement for medical students to genuinely benefit from the *AR Magic Mirror* platform is that these human anatomy models must contain a high degree of realism and include all relevant anatomical structures, including very fine arteries, veins and nerves. For this reason, highly detailed, manually created 3D anatomy models from the company *Plasticboy* (Plasticboy Pictures CC., Cape Town, South Africa) were purchased. The full body anatomy package includes both male and female models and covers all major organ systems of the human body. Furthermore, high-resolution textures (including diffuse, normal, specular reflection, and shadow maps) are provided for every anatomy model, which allows for a very realistic rendering of these structures. Figure 3.2 depicts an overview of the virtual human anatomy models available within the *AR Magic Mirror* platform.

The aforementioned *AR View*, though representing the main focus area that largely shapes the user experience of the entire *Magic Mirror*, comprises only one half of the user interface. The other half can be used to display additional information to the user, most importantly a detailed view onto the entire human anatomy model or medical section images from Computed Tomography (CT) or Magnetic Resonance Imaging (MRI). Therefore, the user interface of the *AR Magic Mirror* platform is modeled as a split-screen view, containing the *AR View* on the left side and the view for additional information on the right side of the display. Figure 3.3 shows a side-by-side comparison between two common user interface configurations of the *AR Magic Mirror* platform: *AR View* + virtual human anatomy model and *AR View* + medical section images. While the former configuration, in particular the real-time dynamic animation of the virtual human anatomy model based on skeleton tracking data, will be discussed extensively in section 3.2, an overview of the visualization of medical section images as additional information will be provided in the following.

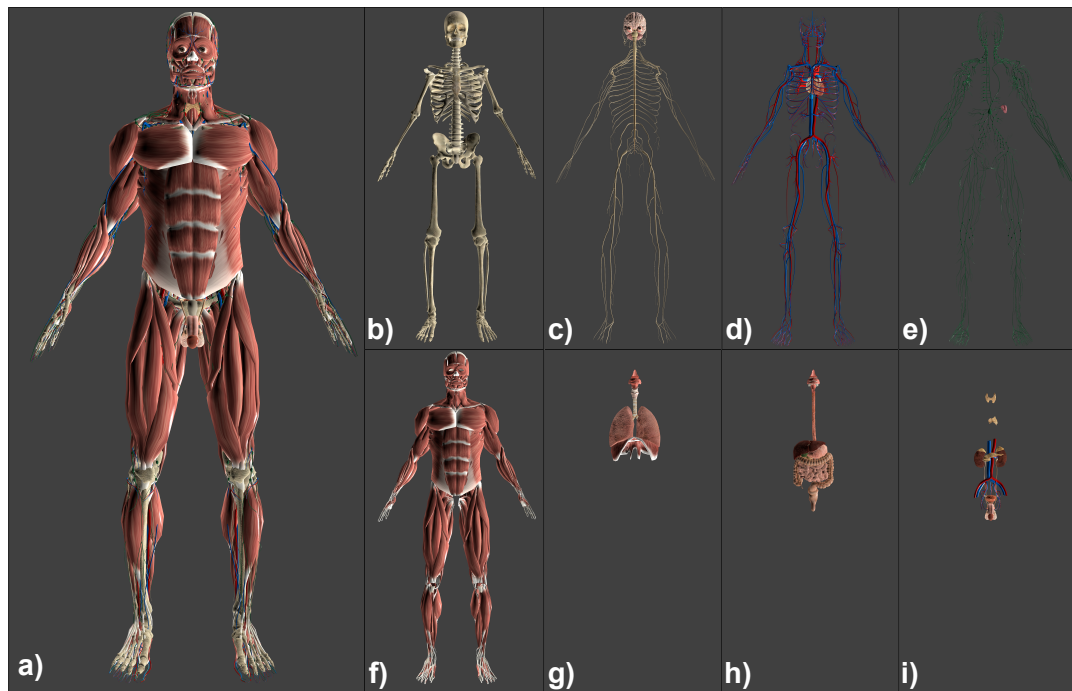


Fig. 3.2. Overview of the virtual human anatomy model that forms an essential part of the AR *Magic Mirror* platform. Although this figure only includes models for a male body, the female counterpart is included within the AR *Magic Mirror* platform as well. a) combination of all body systems available in the human anatomy model; b-i) individual body systems, with b) skeleton system, c) nervous system, d) circulatory system, e) lymphatic system, f) muscular system, g) respiratory system, h) digestive system, i) reproductive system.

Medical Section Images In today's digitized healthcare domain, the skills to interpret medical section images from CT or MRI have become more important than ever before. Furthermore, several studies have shown that integrating medical imaging into preclinical anatomy education increases students' understanding of both radiology and gross anatomy [161, 182]. The AR *Magic Mirror* platform offers the possibility to load the raw contents of arbitrary DICOM data sets and display the corresponding section images as part of the user interface. In the case of CT data, this allows to dynamically change the *windowing* (i.e. the level and the width) to obtain the desired contrast for a specific range of Hounsfield units. Alternatively, a set of common windows such as for the lungs, bones, or soft tissue are pre-defined. From an educational point of view, one of the most important prerequisites for successfully extracting relevant knowledge from medical section images is the possibility to assign annotations to specific anatomical structures within these images. In Figure 3.3b, such an annotated CT slice is depicted. In this context, finding an optimal positioning of multiple, variable-sized image annotations is important, since all relevant parts of the corresponding image should be easily comprehensible. For this purpose, a semi-automatic tool for calculating an optimal arrangement of 2D image annotations was developed. The only manual input consists of clicking on the desired anatomical structure (anchor point) within the image and providing a corresponding label. Subsequently, both the position of the label as well as a thin line connecting both the label and the anchor point are automatically calculated. Three important criteria need to be fulfilled for an optimal positioning: 1) labels must not overlap with the image; 2) labels must not overlap with other labels; and 3) no line crossings are allowed. Furthermore, the distance between labels should be sufficiently large. To avoid the overlapping of labels

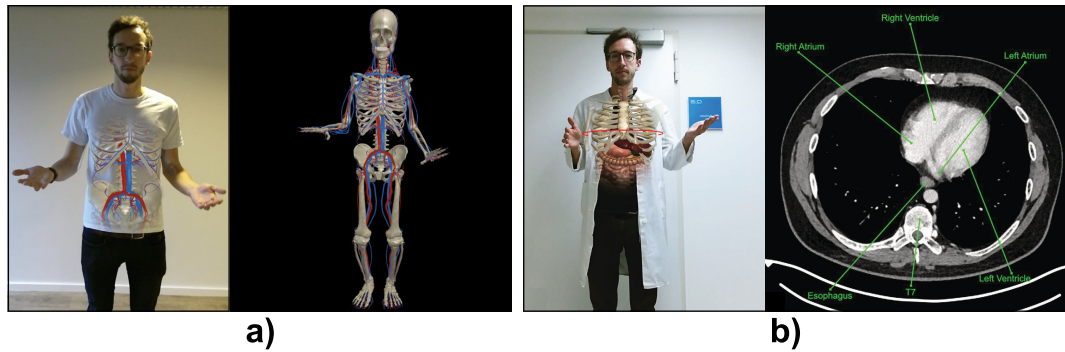


Fig. 3.3. User Interface of the AR *Magic Mirror* platform, comprised of a split-screen view with an AR View on the left and a view for additional information on the right. Two common configurations are depicted: a) AR View + virtual human anatomy model; b) AR View + medical section image from CT volume.

with the image, the first step of the algorithm is to add a certain percentage of padding to all sides of the image. Subsequently, a rectangle is defined, measuring the size of the original image plus half the padding size. As a third step, the centroid of all anchor points within the image is calculated. Starting from this centroid, a certain number of equidistant rays are emitted, whereby the intersection points of these rays with the previously defined rectangle determine a certain number of candidate positions for the labels. Lastly, for each anchor point, the closest available candidate position is calculated and assigned if its label does not cause an overlapping with another label from a previously assigned anchor point. Lastly, for each pair of lines, their corresponding line equations are determined and in the case of a crossing, their label positions are switched. An overview of the algorithm is shown in Figure 3.4.

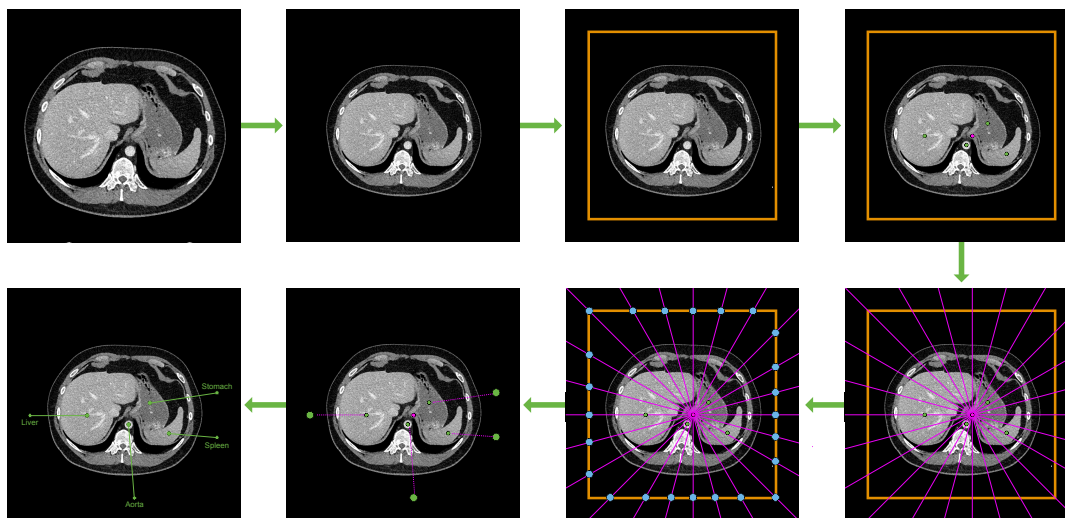


Fig. 3.4. Pipeline overview for the semi-automatic annotation algorithm. Starting from an original input image, the subsequent steps add a padding, calculate a rectangle within the padding area, calculate the centroid of all anchor points, propagate equidistant rays from the centroid towards the edges of the image, calculate the intersection points between the rays and the previously defined rectangle as candidate label positions, determine the closest candidate position for each annotation, and finally render the lines between anchor points and corresponding label position. Note that in this example, no swapping between labels due to line intersections occurs.

Once the medical section images are annotated, they can be integrated into the AR *Magic Mirror* platform. A crucial step for enabling an interactive and personalized learning experience

is the registration of that image data to the individual person standing in front of the system. This registration is performed semi-automatically by defining a set of landmarks—similar to the work of Meng et al. [316]—within the image volume and subsequently matching these landmarks with the corresponding 3D joint positions from the skeleton tracking to obtain an accurate registration. Predestined landmarks include the shoulder and hip joints as well as particular sections of the spine. After successful registration, the user has the ability to interactively explore the section images. A red circle indicates at what height the currently displayed section image is. Scrolling through the volume can be accomplished with dedicated input gestures, which are discussed in detail in the following paragraph.

User Input & Interaction The nature of the *AR Magic Mirror* platform, which places the user in front of a large, stationary display, makes natural user interaction based on hand tracking and gesture input the most obvious choice for interacting with the system. For each frame, the skeletal tracking information derived from the depth image of the Kinect by means of machine learning techniques contains accurate 3D positions of several body joints, including those of the left and right hand. Based on this information, more complex gestures performed by the user can be derived. Within the *AR View*, virtual human anatomy models are superimposed onto the user's body. In order to create the impression of virtually looking inside the body, anatomy models are only visible through a small, *virtual window*, which is depicted in both *AR Views* in Figure 3.3 and described in more detail in the upcoming paragraph. Therefore, one of the most essential user interactions available in the *AR Magic Mirror* platform is to position this virtual window such that it points to the area of interest. To make this as intuitive as possible, the position of the virtual window is controlled by the position of the left hand. In the most basic scenario, the positioning of the virtual window is restricted to the longitudinal axis of the body. In this case, the virtual window is centered on the user's body, while its height corresponds to the position of the left hand and can be controlled by moving it up and down. In case the virtual window should also be relocated laterally, it is possible to control its center directly by the position of the left hand—possibly with a fixed offset. Figure 3.5a and 3.5b schematically depict both of these cases.

Another important type of user interaction is controlling what types of human anatomy models are visible in the *AR View* and possibly also in the view for additional information. While various configurations are feasible, the most common approach within the *AR Magic Mirror* platform is to first determine which of the 8 body systems (see Figure 3.2) should be visible and then to display all anatomical structures belonging to this organ system. To allow the user to select the desired organ system as intuitively as possible, the area between the neck joint and the hip joint is divided into 8 distinct sections with each body system assigned to one of these sections. The actual selection then depends on the height of the user's right hand, i.e. by moving the right hand up and down, different body systems can be selected. Figure 3.5c shows this partitioning into the 8 different sections. Three distinct selection modes are available within the *AR Magic Mirror* platform: 1) *INDIVIDUAL*, which only shows the body system corresponding to the currently selected section; 2) *SKELETON-BASE*, which always shows the skeleton in addition to the body system corresponding to the currently selected section to provide more contextual information; and 3) *ADDITIVE*, which shows all body systems starting from the one corresponding to the bottom-most section up to the one corresponding to the currently selected section. Depending on the specific educational question, users have the possibility to choose the most appropriate selection mode.

In case the user interface of the *AR Magic Mirror* platform is configured to display medical section images in the view for additional information, the previously described interaction with the right hand is overloaded. In addition to selecting different organ systems in the *AR View*, the height of the right hand now also controls which section image is displayed. By moving the right hand up and down, the user can interactively explore the volume and scroll through the individual section images. A red circle within the *AR View* indicates the height of the currently selected section image (see Figure 3.5d).

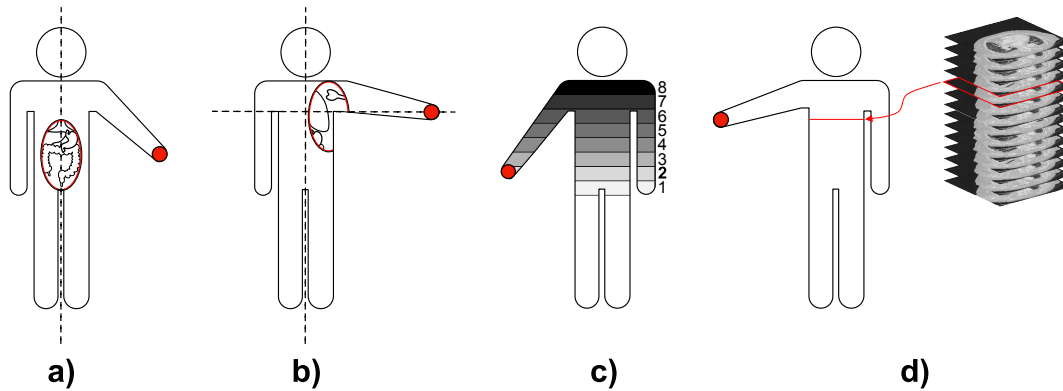


Fig. 3.5. Overview of the different user interactions that are based on the position of the left and right hand. a) positioning of virtual window with the left hand, restricted to the longitudinal axis; b) positioning of virtual window with the left hand, both longitudinally and laterally; c) partitioning of the area between the neck and the hip into 8 distinct sections, with each section corresponding to one of the 8 body systems that contain all virtual anatomy models that belong to this system. Selection is based on the height of the right hand; d) user interaction with medical section images. The height of the right hand controls which section image is displayed, with a red line indicating its position in relation to the user's body.

All previously described user interactions were solely dependent on the position of the user's left and right hand. Additional interactions that allow users to control more advanced functionalities of the user interface can be enabled by recognizing mid-air gestures using machine learning techniques. A few static hand states such as an open or closed hand (i.e. a fist) can already be recognized out of the box by the Kinect skeletal tracking algorithm. Within the *AR Magic Mirror* platform, these static hand states are used for two different user interactions: resizing the virtual window and—assuming that the appropriate user interface configuration is active—navigating the virtual human anatomy model. The former is achieved by opening both hands simultaneously and moving them either away from each other to enlarge the virtual window, or closer together to reduce the window size. Similarly, closing both hands simultaneously allows the user to reposition the virtual camera that is used to render the virtual model of the human anatomy (see figure 3.3a) to obtain a close-up view of certain anatomical structures. Upon triggering the interaction, the user can translate the virtual camera along all three major axes by moving both hands accordingly. Furthermore, it is possible to change the virtual camera's yaw by rotating both hands on an imaginary circle defined by the two points corresponding to the initial 3D hand positions. In addition to these built-in hand states, more sophisticated gestures require dynamic tracking of hand positions over time or more advanced gesture detection techniques based on machine learning. The *AR Magic Mirror* platform can detect the following mid-air hand gestures: one, two, and three fingers, as well as right hand swipes from right to left and top to bottom. In case medical section images are shown, the former gestures are used to switch between transversal (one

finger), sagittal (two fingers), and frontal slices (three fingers). Swiping from top to bottom, in the case of CT section images, changes the windowing, i.e. the level and width, to adapt the contrast. Lastly, a right-to-left swipe switches between the two different user interface configurations, namely *AR View* + virtual human anatomy model and *AR View* + medical section images.

Perceptual In-Situ Visualization One of the most important characteristics of the *AR Magic Mirror* platform is the ability to superimpose virtual models of the human anatomy directly onto the user's body, creating the illusion of looking *inside* the body and seeing one's own internal organs. Achieving such a realistic looking *in-situ* visualization in AR is a challenging task due to misleading depth perception. Naively superimposing virtual anatomy models onto the user without considering perceptual aspects does not produce convincing visualization results, as virtual objects appear to *float* on top of the user. An example of such a naive overlay is depicted in Figure 3.6a and has been employed by similar AR virtual mirror systems, such as the ones from Bauer et al. [25, 26] (see Figure 2.9c). To address this problem, the original *mirracle* system by Blum et al. already implemented a perceptual visualization technique in the form of a *virtual window* for improving depth perception such that virtual anatomy models could only be seen through an elliptic focus region [54]. The *AR Magic Mirror* platform developed within the course of this thesis follows a very similar approach, though the implementation of the virtual window has a slightly different strategy. Both types of virtual windows can be achieved programmatically by using a masking operation. The mask takes the form of a texture that contains an ellipse with varying transparency values. While Blum et al.'s transparency mask is binary, with values of 1 inside the ellipse and values of 0 outside the ellipse, resulting in a sharp cut-off at the boundaries, the *AR Magic Mirror* platform uses a more advanced transparency mask that includes a transparency gradient whereby transparency values gradually decrease from 1 in the center to 0 at the boundaries of the ellipse, resulting in a softer transparency fall-off. These two types of virtual windows are compared in Figure 3.6b and 3.6c. The perceptual AR in-situ visualization forms an essential component of the overall application, which significantly contributes to the learning experience with the *AR Magic Mirror* platform being perceived as personalized and engaging.

Implicit User Calibration In order to fit the virtual human anatomy models as accurately as possible to the proportions of the user of the *AR Magic Mirror* platform, a calibration procedure is required. All previous virtual mirror systems, including the ones by Blum et al. [54], Meng et al. [316], and Bauer et al. [25, 26], employed an explicit calibration to measure the user's body proportions, which required the user to hold a specific pose (generally a T-pose) for a certain amount of time before interaction with the system was possible. In contrast, the *AR Magic Mirror* platform presented in this thesis allows the user to engage with the system immediately upon stepping in front of it by calculating the user calibration implicitly. This can be accomplished by continuously measuring a number of *scaling regions* over a specified time frame and calculating a confidence level for each of these regions. Once the highest confidence level for each body scaling region is reached, the implicit user calibration is complete and the size of all virtual human anatomy models should accurately reflect those of the user's real counterparts. Within the *AR Magic Mirror* platform, a total of seven different body scaling regions are defined. This includes scales for the legs, hips, arms, torso, shoulder, and head in both width and height. Figure 3.7a depicts a schematic overview of all seven scaling regions. While an even more fine-grained scaling with additional scaling regions can be defined (e.g.

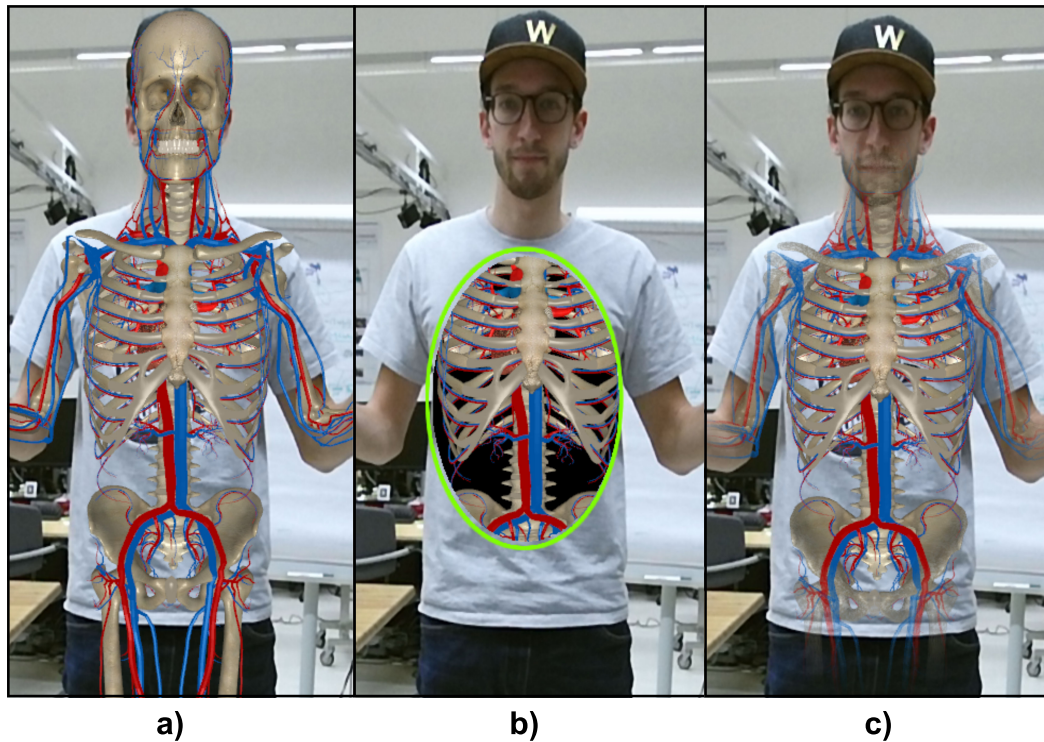
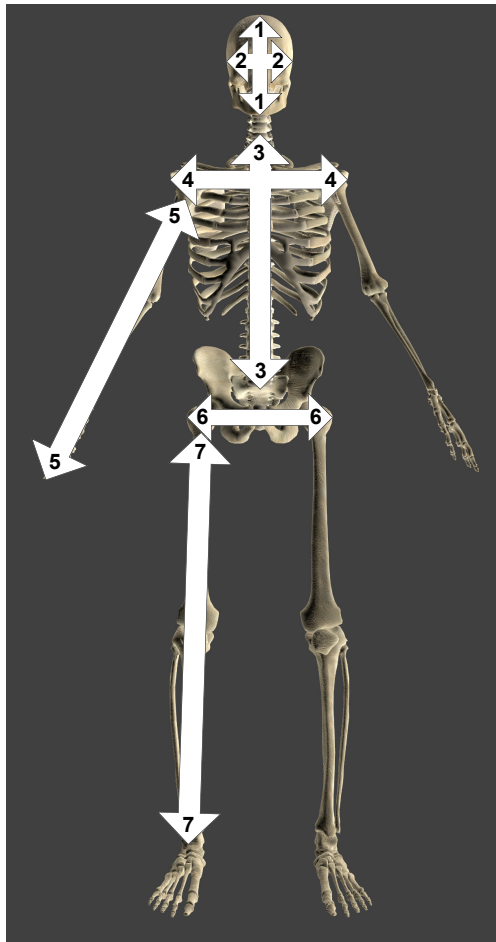


Fig. 3.6. Comparison of different strategies for visualizing virtual human anatomy models on top of the user's body. a) naive AR overlay of anatomy models, resulting in misleading depth perception and the well known *floating* effect; b) AR in-situ visualization using a virtual window, similar to that employed within Blum et al.'s *mirracle* system [54]. Virtual anatomy models can only be seen through an elliptic focus region; c) advanced AR in-situ visualization proposed in this thesis, featuring a virtual window that follows a transparency gradient.

multiple scaling regions for the spine or individual scaling regions for the upper and lower arm and leg), these seven scaling regions provide a sufficiently accurate overlay for a large number of users with different body proportions, including both male and female users, from very thin to more corpulent individuals, and even children.

The actual scale value for each of the seven different scaling regions is determined with respect to the underlying 3D joint positions of the user. For example, the *Shoulder* scale is defined as the Euclidean distance between the left and right shoulder joint. Similarly, the *Torso* scale is calculated on the basis of the neck joint and base joint of the spine, the *Arm* scale on the basis of the shoulder and wrist joints, the *Hip* scale on the basis of the left and right hip joints, and the *Leg* scale on the basis of the hip and foot joints. Lastly, the width and height of the head are estimated by fitting an ellipse to the user's face and using the size of the two axes as the respective head scale. Once all these seven scale values are estimated, a confidence level is calculated for each body scaling region according to the procedure *SetBodyRegionScale* outlined in Figure 3.7b. The procedure is performed once in each frame for every body scaling region. As soon as a user steps in front of the AR *Magic Mirror*, a certain number of initial scale measurements are collected for all body scaling regions over a series of frames. All scale measurements of subsequent frames are then compared with all previously collected scales and added to the list of scales if they fall within a specific range around the current mean scale of that region. Once the number of required scale measurements has been recorded, the

mean scale is set to the final scale of this body region. Recalculating the scale of a particular body scaling region is performed in case a certain number of measurements fall outside of the range around the mean scale. This way, even if the initial scale measurements of the user were inaccurate (e.g. if the user engages with the system from the side or if certain body joints are initially occluded), the scaling algorithm continuously tries to determine the optimal scale for all body scaling regions. The entire user calibration procedure is performed every time the *primary user* changes. As the AR *Magic Mirror* platform can track up to six users simultaneously, the primary user is always determined as the one closest to the depth sensor.



a)

Algorithm 1 Computation of the scaling confidence for a particular body scale region.

```

1: procedure SETBODYREGIONSCALE
2:   Input:
3:    $R \leftarrow$  body scale region
4:    $s \leftarrow$  current scale of body scale region  $R$ 
5:    $S \leftarrow$  list of all previous scales or  $R$ 
6:    $cc \leftarrow$  correction counter
7:    $mc \leftarrow$  maximum number of corrections
8:    $rs \leftarrow$  required number of scales
9:    $rsp \leftarrow$  required scales percentage
10:   $dp \leftarrow$  deviation percentage
11:  Output:
12:   $C \leftarrow$  scaling confidence for body scale region  $R$ 
13:  Algorithm:
14:     $ms \leftarrow$  mean of  $S$ 
15:     $r \leftarrow$  range
16:    if  $S.size() < \frac{rs}{100}rsp$  then
17:       $S \leftarrow$  append  $s$ 
18:    else
19:       $r \leftarrow \frac{ms}{100}dp$ 
20:      if  $s > m - r$  AND  $s < m + r$  then
21:         $cc \leftarrow 0$ 
22:         $S \leftarrow$  append  $s$ 
23:        if  $S.size() < \frac{rs}{2}$  then
24:           $C \leftarrow$  ScalingConfidence-Mid
25:          if  $S.size() == rs$  then
26:             $C \leftarrow$  ScalingConfidence-High
27:        else
28:           $cc \leftarrow cc + 1$ 
29:          if  $cc > mc$  then
30:             $S \leftarrow clear()$ 
31:             $S \leftarrow$  append  $s$ 
32:             $S \leftarrow$  ScalingConfidence-Low

```

b)

Fig. 3.7. Overview of the implicit user calibration employed within the AR *Magic Mirror* platform. a) schematic illustration of the seven body scaling regions: *HeadHeight* (1), *HeadWidth* (2), *Torso* (3), *Shoulder* (4), *Arm* (5), *Hip* (6), and *Leg* (7); b) outline of the algorithm to calculate the scaling confidence for a given body scaling region.

3.2 Real-Time Skeletal Animation

The previous section presented a general overview of the AR *Magic Mirror* platform, including a brief explanation of the mirror metaphor as the underlying conceptual framework of the system, an overview of the hardware configuration, as well as key aspects of the software framework, encompassing the user interface, a module for displaying medical section images, user interaction and input, advanced perceptual in-situ visualization, and finally the implicit user calibration. While previous *Magic Mirror* systems by Blum et al. [54] and Meng et al. [316] conceptually consisted of similar components—albeit software-wise on a more rudimentary level—the major shortcoming of these systems was that only *static* information about the human anatomy, either in the form of volume renderings from CT scans or virtual 3D models, could be superimposed. One could argue that the educational value of seeing an in-situ AR visualization of such static anatomical content is rather limited for a medical student who is supposed to study every single detail about the human body during undergraduate anatomy studies. Therefore it is clearly not sufficient to display virtual human anatomy models only *statically*. Coming back to the paradigm of the mirror metaphor: a truly personalized and engaging AR *Magic Mirror* experience can only be achieved when the system behaves like a true virtual mirror. First and foremost, this requires that all of the user's movements are transferred onto the virtual anatomy model such that it moves accordingly—a technique known as real-time skeletal animation. This way, a *dynamic* animation of virtual 3D models, especially of the user's extremities and head, can be achieved. The integration of real-time skeletal animation for 3D anatomy models is one of the most important characteristics that really sets the AR *Magic Mirror* platform apart from the previous systems of Blum et al. [54] and Meng et al. [316]. Thus, the AR *Magic Mirror* offers medical students a unique learning experience that cannot be achieved with other modalities: personalized and interactive AR-based learning of dynamic anatomical content with respect to their own bodies.

Real-time skeletal animation consists of three main stages. Starting from a given 3D model that is provided as a surface mesh, a *character rig* is created that defines a hierarchical tree of interconnected bones and provides the basic data structure required for the animation. In the subsequent *skinning* phase, this character rig is bound to the 3D model, defining which parts of the surface mesh are controlled by which parts of the rig. Finally, based on the real-time joint information from the skeletal tracking algorithm, the individual bones of the character rig are transformed to match the current pose of the user. In the following sections, these different steps of skeletal animation are presented in detail.

3.2.1 Rigging

The goal of skeletal animation within the AR *Magic Mirror* platform is to deform the 3D human anatomy models according to the current pose of the user in real time. This technique is also referred to as *Avateering* as the 3D anatomy models serve as a virtual avatar whose movement is controlled by that of the user. The first step in this process is known as *Rigging*, which involves embedding a hierarchy of virtual bones known as a *character rig* or *skeleton* into the anatomy model. Since all 3D models in the AR *Magic Mirror* platform are grouped according to the body system they belong to, and since each of these body systems must be

individually controllable, a character rig is defined only once before being copied to each of the eight different body systems. This character rig is ultimately responsible for driving the deformation of the anatomy models. While a number of techniques exist to create such a character rig automatically, these approaches generally require the 3D models to adhere to a certain mesh topology and do not work for very specific models such as those contained in the AR *Magic Mirror* platform, e.g. the nervous, circulatory, or lymphatic system that merely consist of a very thin and complex network of structures [18, 96]. Therefore, rigging is typically performed manually within a 3D modeling software such as Blender (Blender Foundation, Amsterdam, Netherlands) or Maya (Autodesk, San Raphael, USA). The optimal arrangement of virtual bones in the character rig strongly depends on the underlying 3D model. A common misconception is that skeletal animation can only be applied to models that resemble a humanoid character. However, this animation technique can be employed to deform objects of any shape, simply by defining a set of virtual bones. For humanoid characters, including the 3D anatomy models in the AR *Magic Mirror* platform, the virtual bones of the character rig are typically defined in close correspondence with their real counterparts in the human body. While the rig can potentially contain a virtual equivalent for each individual real bone, a much coarser set of virtual bones is generally preferred to reduce the complexity of animating the underlying 3D model. Figure 3.8 depicts the character rig that is employed for all eight body systems within the AR *Magic Mirror* platform. It is comprised of three bones for both the arms (upper arm, forearm, hand) and legs (thigh, lower leg, foot), one for the head, as well as two bones for the spine.

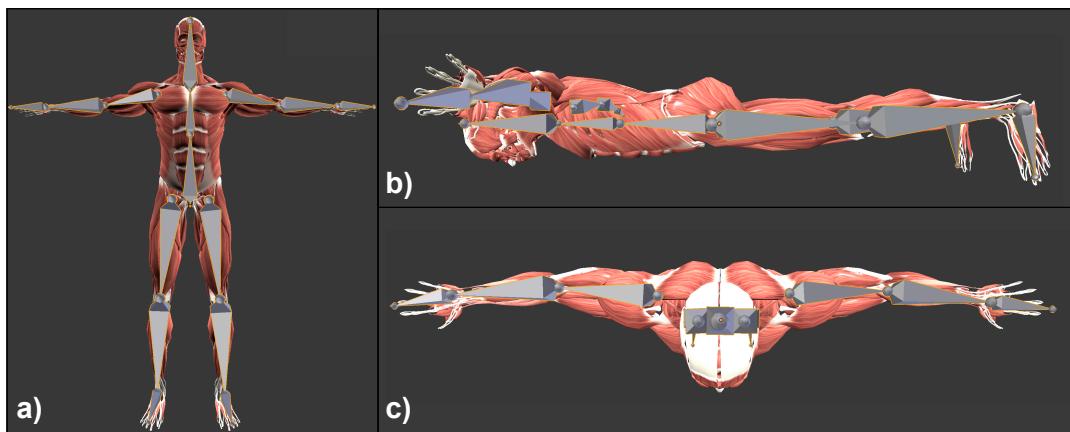


Fig. 3.8. Illustration of the character rig that is used to deform the underlying anatomy models within the AR *Magic Mirror* platform. The rig consist of 15 joints in total (excluding the root bone). While only the muscular system is depicted in this figure, this same rig is used for animating all other virtual anatomy body systems. Three orthographic views onto the virtual anatomy are shown: a) frontal view; b) side view; and c) top view.

As mentioned above, the virtual bones of the character rig used for skeletal animation generally form a hierarchical tree structure, with each bone representing a node within this hierarchy. Starting from the so-called *root* bone, a parent-child relationship is created that reflects the bone structure of the rig. This way, every virtual bone in the hierarchy has a parent bone, with the exception of the root bone. Additionally, each bone is associated with a 3D transformation that includes the bone's position, orientation, and scale. By arranging the virtual bones within a tree structure, the animation of the anatomical 3D models is facilitated considerably since it can be performed by simply processing chains of such bone transformations. The

final transformation of any child bone can be calculated by multiplying the transformation of its parent bone with its own transformation. Consequently, whenever a parent bone is transformed, the same transformation is applied to all its children. However, when a child bone is transformed, the parent bone is not affected. This behavior directly corresponds to real-world body movements. For example, when we move our hands, our fingers are expected to move along with it, but we can move our fingers independently of our hands. This specific type of skeletal animation, in which a complete set of bone configurations identifies a unique pose of the rig, is known as *Forward Kinematic Animation*. In contrast, *Inverse Kinematic Animation* determines the orientation of all virtual bones given a specific pose of the rig. While both forward and inverse kinematics can be combined in skeletal animation, the AR *Magic Mirror* platform solely relies on using the former to accurately match the pose of the 3D anatomy models with that of the user.

3.2.2 Skinning

Once the character rig is created, the second stage of real-time skeletal animation consists of connecting the visual representation of the underlying 3D anatomy models to the virtual bones of the rig—a process known as *Skinning*. In other words, the 3D anatomy model is bound to the virtual bones of the character rig such that transformations of these virtual bones drive the deformation of the model. The complexity of skinning arises from the fact that each virtual bone should only influence the deformation of those particular parts of the model that lie within its surrounding, i.e. rotating the forearm bone should only deform the parts of the model that make up the forearm. If the rotation of the forearm would also affect the model's shoulder, the deformation would obviously not be accurate. Skinning is therefore essential to ensure both correct movements of the appropriate parts of the model as well as accurate deformations. To achieve this, each virtual bone of the character rig is assigned to a group of vertices which the mesh of the 3D model is comprised of. Skinning now involves calculating how the transformations of each virtual bone affect the position of the mesh vertices. While the majority of vertices are typically controlled only by a single virtual bone, vertices around joint positions can be associated with multiple bones. In this scenario, each bone has a particular influence on the transformation of these vertices, which is known as the *vertex weight* or the *blend weight*. If for instance a vertex is located exactly between two virtual bones, it is reasonable to assign each bone a weight of 0.5 since it is expected that the two bones have an equal influence on the transformation of this vertex. Defining these vertex weights is an essential prerequisite for the skinning algorithm. Therefore, prior to discussing the actual skinning algorithm, the procedure of *weight painting* and how it can be performed for the 3D anatomy models employed within the AR *Magic Mirror* platform will be discussed in more detail in the following paragraph.

Weight Painting

The goal of weight painting is to determine the influence that each virtual bone of the character rig has on the individual vertices of the mesh. For each vertex, a list of weights is assigned, which contains the individual influences of all contributing virtual bones. Typically, most vertices of a mesh are associated with only one vertex weight of a particular bone, i.e. the transformation of this vertex is completely controlled by the transformation of the associated bone. However, especially for vertices near joints, multiple virtual bones can influence the

transformation of a vertex. Similar to rigging, several techniques have been proposed for automatically calculating these vertex weights given a mesh of a 3D model and its underlying character rig [209, 210, 487]. In addition, most software programs for 3D modeling such as Blender or Maya contain basic techniques for the same purpose. In most cases, however, these algorithms only serve as an initial starting point. Especially for complex 3D models such as those contained in the *AR Magic Mirror* platform, these initial estimates for the vertex weights need to be optimized via manual weight painting. Figure 3.9 depicts the results of the weight painting stage for the muscular model employed within the *AR Magic Mirror* platform. To eliminate the need to paint every single muscle individually, the model is subdivided into six main parts: head, torso, the two arms, and the two legs. For each of these parts, the influences of all virtual bones that contribute to the final deformation can be seen.

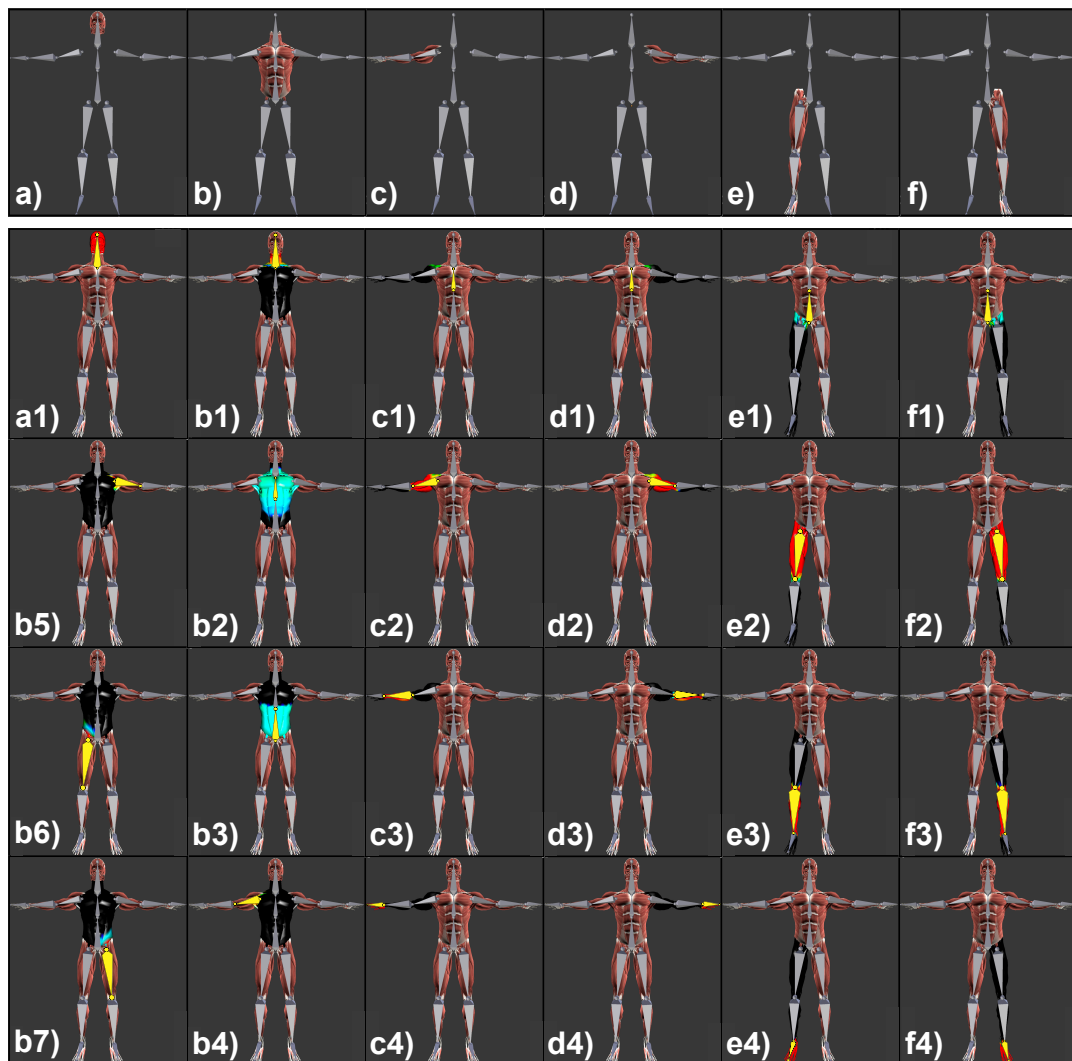


Fig. 3.9. Results of the weight painting process for the 3D muscle anatomy model. The top row illustrates the six different meshes into which the model was divided: a) head; b) torso; c) right arm; d) left arm; e) right leg; and f) left leg. For each of these six meshes, the bottom rows depict which virtual bones of the character rig contribute to the deformation of its vertices. a1) for the head mesh, only a single virtual bone controls the transformation of its vertices. b1 – b7) a total of seven bones influence the transformation of the vertices that make up the torso. For all four extremity meshes, the transformation of its vertices is influenced by four virtual bones: c1 – c4) right arm; d1 – d4) left arm; e1 – e4) right leg; and f1 – f4) left leg.

Linear Blend Skinning

For a given 3D model, the previous sections discussed how to obtain both a character rig of virtual bones and the weights that determine the influence of these bones on the individual vertices of the model. The actual skinning algorithm now takes this information as input and calculates how the transformation of the virtual bones affects the vertices of the model. While various skinning algorithms have been proposed over the last few decades, the de facto standard used within game engines such as Unity or Unreal and which also constitutes the default deformation method in the AR *Magic Mirror* platform is known as *Linear Blend Skinning* (LBS) [232]. For LBS, we assume a 3D model given by the vertices $\mathbf{v}_1, \dots, \mathbf{v}_n \in \mathbb{R}^3$, a list of virtual bone transformations $\mathbf{T}_1, \dots, \mathbf{T}_m \in \mathbb{R}^{3 \times 4}$, as well as the vertex weights $w_{i,j}$, that for each vertex \mathbf{v}_i are given by $w_{i,1}, \dots, w_{i,m} \in \mathbb{R}$ and satisfy $w_{i,j} > 0$ and $\sum_{j=1}^m w_{i,j} = 1$. The deformed vertex positions \mathbf{v}'_i can then be computed as a linear combination of virtual bone transformation matrices \mathbf{T}_j via the following formula:

$$\mathbf{v}'_i = \sum_{j=1}^m w_{i,j} \mathbf{T}_j \mathbf{v}_i = \left(\sum_{j=1}^m w_{i,j} \mathbf{T}_j \right) \mathbf{v}_i \quad (3.1)$$

One of the main advantages of LBS is that it can be implemented very efficiently as a shader program to run on the GPU, thus making it very attractive for real-time interactive applications. Artifacts such as loss of volume can occur with LBS in case the bone transformations differ significantly in their rotational component. While alternative skinning approaches such as dual quaternion skinning [233], implicit skinning [470], or physics-based techniques [239] generally exhibit fewer or these artifacts, they tend to be more computationally expensive. Therefore, LBS represents a good compromise between deformation quality and computational efficiency, which makes it the ideal skinning algorithm to be employed within the AR *Magic Mirror* platform.

3.2.3 Real-Time Animation

The last step in achieving real-time skeletal animation in the AR *Magic Mirror* platform is to calculate the transformation matrices for all virtual bones in the character rig based on the Kinect skeleton tracking information. Instead of providing these transformations directly, the Kinect body tracking algorithm estimates the 3D position and orientation of several body joints from which the bone transformations can be derived, given that every bone can be represented by two distinct joints. Therefore, the Kinect body tracking effectively serves as the engine for the real-time skeletal animation. In the case of occluding body parts, joint estimates may contain a significant portion of error. The AR *Magic Mirror* platform integrates two approaches to minimize these effects: rotational smoothing and physical joint constraints. The former simply averages the rotational component of the bone transformations over a series of frames to yield smoother body motion. Additionally, physical joint constraints limit the range of motion for specific body joints to mitigate implausible bone transformations due to measurement errors. In conclusion, the real-time skeletal animation within the AR *Magic Mirror* platform, which involves realistic deformation of the 3D models of human anatomy based on the user's movements, is one of the key features of the system and plays a crucial role in making the learning experience with the AR *Magic Mirror* interactive and personalized.

3.3 Reversing vs. Non-Reversing Magic Mirrors

The work presented in this section is an extended version of parts of two papers presented at the conferences IEEE VR 2017 [60] and ISMAR 2017 [59]. The content is reproduced with the permission of all authors, ©IEEE.

“*The AR Magic Mirror is a great tool for personalized anatomy learning, but shouldn't all anatomy models be reversed?*”

— **Prof. Dr. Wolfgang Böcker, Head of the Clinic for General, Trauma and Reconstructive Surgery, LMU**

In the previous sections, the most essential technical features of the *AR Magic Mirror* platform have been presented. Throughout the course of this section, a very intriguing perceptual question will be examined, which arises directly from the fact that the mirror metaphor forms the basic design principle of the *AR Magic Mirror*. On one particular occasion in 2017, the system was demonstrated to Prof. Dr. Wolfgang Böcker, head of the Clinic for General, Trauma and Reconstructive Surgery at the University Hospital of the LMU Munich, who mentioned the above quote, stating that all virtual anatomy models should be reversed from left to right. Otherwise, the anatomy would reflect a so called *Situs Inversus*, a rare congenital positional anomaly that is characterized by a lateral or mirror image arrangement of organs and vessels in the human body. In subsequent demonstrations to LMU medical students, similar observations were made and students mentioned that organs such as the liver and the stomach would appear on the wrong side of the body.

These statements initiated a more in-depth investigation of the perceptual challenge of lateral anatomy inversion within the *AR Magic Mirror* platform. In particular, we studied the differences between a *Reversing Magic Mirror* (RMM) and a *Non-Reversing Magic Mirror* (NRMM): similar to real, physical mirrors, left and right appear to be reversed in an RMM, i.e. lifting the left hand in front of a real mirror or an RMM corresponds to the mirror image lifting the right hand. In images generated by an NRMM, however, this apparent inversion does not occur, i.e. in accordance with the previous example, the mirror image will also lift the left hand. Figure 3.10 shows a side-by-side comparison of these two types of *Magic Mirror* setups. Since in medicine left and right are always defined with respect to the patient's point of view, medical students are not used to looking at mirrored anatomy. As a result, the *AR Magic Mirror* platform presents an unfamiliar view to its users: a virtually augmented gallbladder, for instance, located on the right side of the human abdomen, is displayed by an RMM on the left side of a user's digital mirror image. An NRMM, however, would display the gallbladder more intuitively on the right side of the user's digital mirror image

The following subsections therefore examine the question of whether an RMM or NRMM is more appropriate for the purpose of interactive AR anatomy learning with the *Magic Mirror* platform. After a general discussion of mirror perception and a comparison of the perceptual differences between both types of *Magic Mirror* systems, a detailed description of an empirical user study conducted to answer the above question is presented. Lastly, the underlying psychological effects and the implications of using an NRMM on user perception, anatomy knowledge transfer, and interaction are discussed.



Fig. 3.10. "Spot the difference!" Comparison between a *Reversing Magic Mirror* (RMM) and a *Non-Reversing Magic Mirror* (NRMM). a) Similar to a real, physical mirror, left and right appear to be reversed in an RMM. Whereas the person in front of the system raises the left hand, the digital mirror image displayed on the TV screen raises the right hand; b) In the case of an NRMM, lateral inversion does not occur and the digital mirror image raises the left hand.

3.3.1 General Mirror Perception

"Mirror, mirror on the wall...". Throughout history, people have always been fascinated by surfaces in which they could see a reflection of themselves. From the first ancient obsidian fragments, polished metals, and wealth-reflecting status objects of kings and aristocrats to the nowadays ubiquitous everyday item - mirrors have undergone a remarkable evolution accompanied by a profound impact on religion, sciences, and arts [315, 364]. Many legends have sprung around mirrors and they are still subject to countless myths, superstitions, and rituals around the world. According to one of those, mirrors are "*portals to another world or dimension*". On first thought, this might sound like a quote from a science-fiction story. However, Bertamini argues that mirrors are in fact a window into a completely virtual world [31]. According to him, everything we see inside a mirror is completely virtual, which in a sense makes a mirror the perfect VR system. Our brain is tricked into thinking that people or objects we see in a mirror physically exist. Due to this phenomenon, mirrors have been the subject of intensive research in the fields of psychology and human perception.

The Illusion of Explanatory Depth

Illusion of explanatory depth is a common phenomenon occurring in many different areas of our daily life [394]. People have the tendency to overestimate their knowledge of certain procedures or objects, as demonstrated by Lawson et al. on the example of bicycles [260]. The same principle of illusion of explanatory depth holds true for mirrors as well. Even though we gaze into mirrors multiple times a day, most of us do not have an in-depth understanding of what exactly happens on the surface of a mirror. Bertamini and Parks have shown during experiments that people failed to accurately judge the size of their enantiomorph's (mirror image) face, especially with varying distance from the mirror [32]. In another study, Lawson and Bertamini provide evidence that people generally expect to see their own mirror image earlier when approaching a covered mirror from the side [261]. Closely related to this research is the so called *Venus Effect* [33, 34]. In paintings such as *The Robeky Venus* by Velázquez, it occurs if both a mirror and an actor looking into the mirror are present, with the reflection

in the mirror not corresponding to the view of the actor but the view of the observer of the painting. Most people describe such paintings as if the actor is looking at the reflection in the mirror. All these misperceptions manifest the simultaneous simplicity and complexity of mirrors.

Lateral Inversion

One particular mystery related to mirrors that has been a controversial topic for decades is the question of *why mirrors reverse left and right, but not up and down?* [97, 160, 453, 454]. Mathematically, mirrors reverse across the axis perpendicular to their surface, resulting in front and back being reversed, similar to a glove being turned over. However, Ittelson et al. demonstrated that the reversal is observed along the axis of the greatest perceived symmetry [205]. As a result of the bilateral symmetry of the human body, this axis coincides with the left-right axis. According to Takano, the most important factor as to why left and right appear to be reversed in a mirror is a phenomenon called *viewpoint reversal*, which states that people standing in front of a mirror judge left and right based on their viewpoint [454]. In order to judge left and right in the mirror image, people also assume the viewpoint of the mirror image. Geometrically, the mental process to assume the viewpoint of your mirror image is equivalent to a translation and a subsequent rotation by 180°. Therefore, people are inclined to assume that their mirror image is formed by a rotation around the vertical (up-down) axis, i.e. by walking around the mirror to become the virtual self [31, 33]. However, the resulting image is not how a regular mirror image looks like, but exactly resembles the image produced by a non-reversing mirror. Such non-reversing mirrors show the *true mirror image* of a person and can be built physically by placing two mirrors perpendicular to each other to form two sides of an equilateral triangle [488], or as proposed more recently, by combining a multitude of tiny mirrors to form a curved surface, which directs incoming light rays back to the observers eye such that the image is horizontally flipped [187]. Implementing a digital, non-reversing mirror is as simple as rearranging the columns of a digital camera image from left to right. Therefore, a regular RMM can be converted into an NRMM by flipping the Kinect RGB camera stream along the vertical axis.

Left-Right Confusion

Lateral inversion in mirror images is closely related to the general topic of left-right confusion. For the majority of people it is a matter of course to distinguish correctly between left and right. However, a considerable portion of the population lacks this supposedly inherent ability [351, 441, 497]. Several neuropsychological factors, including visuospatial processing, memory and sensory information [351], as well as brain hemispheric asymmetry [191], appear to contribute to the discrimination process. Left-right confusion generally has a negligible impact on our daily lives, such as a late arrival after a wrong turn by car. However, laterality errors in the medical field have the potential to harm the patient and lead to disastrous results, e.g. in the case of wrong-sided interventions or wrong-sided diagnosis and therapy [321, 514, 413]. One particularly important factor that contributes to the left-right confusion in medicine is that left and right are always defined in relation to the patient's viewpoint, such that the doctor's right is the patient's left. Traditional anatomy learning resources such as textbook illustrations take this into account by consistently presenting a third-person view onto the anatomy of someone else. Similarly, when performing a patient examination or conducting an operation, physicians always perform a mental rotation by exchanging their own left and right

with the patient's left and right. Gormley et al. examined the left-right discrimination abilities of medical students and observed greater difficulty among female students and those students who intended to become general practitioners or psychiatrists [157]. Other studies by Thomas et al. and McKinley et al. revealed that the left-right confusion tended to be higher in cases involving additional mental rotation [458] or various forms of distraction [307]. In all these studies, it is argued that medical professionals should be trained to be aware of left-right confusion as early as in their undergraduate studies.

Considering the lateral inversion property of mirrors and the general importance to correctly discriminate between left and right within the medical domain, two intriguing perceptual questions arise: is a *Non-Reversing Magic Mirror* (NRMM) the more natural choice for the task of AR anatomy learning, and does the use of a regular, *Reversing Magic Mirror* (RMM) even carry the risk of teaching anatomy incorrectly? In order to find an answer to these questions, an empirical user study was conducted, which will be presented in the following subsection.

3.3.2 Empirical User Study

For the purpose of understanding the perceptual differences between an RMM and an NRMM, and to determine whether the latter—as the concept that offers medical students a more familiar view of 3D anatomy—is better suited for personalized AR anatomy learning, we conducted an empirical user study during which medical students were asked to distinguish between anatomically correct and anatomically incorrect placement of virtual organs for both scenarios. After completing a series of pre-tests, participants were introduced to both the RMM and NRMM concepts through a basic interaction game. During the main part of the user study, five different virtual organs were superimposed onto the bodies of the participants for both the NRMM and RMM visualization, either on the anatomically correct side of the body or on the opposite one. Figure 3.11 contains screenshots of the overlays that participants would see during the user study. In the following subsections, the specifics of the empirical user study will be presented, including a brief discussion of the experimental platform and study participants, followed by a detailed description of the study design, hypotheses, as well as the study task and procedure. Lastly, the results obtained during our user study will be presented. Without disclosing too many of the study results beforehand, it will be shown that medical students performed better at identifying anatomically correct placement of virtual organs in an NRMM setting. Interestingly, there were also considerable differences in performance depending on the seniority of medical students. Additionally, interaction proved to be significantly more difficult in the NRMM compared to a regular RMM.

Experimental Platform

Throughout the course of the empirical user study, a slimmed-down version of the AR *Magic Mirror* platform was used. While the hardware configuration was identical, consisting of a Microsoft Kinect v2 mounted on a large display device at a height of two meters facing downwards, some of the aforementioned software features such as the advanced AR in-situ visualization and the gesture-based user interaction, were excluded from the system. Instead, the five aforementioned virtual organ models were superimposed one by one onto the digital mirror image of the user by means of a very naive superimposition, see Figure 3.11. The purpose of using such a reduced version of the AR *Magic Mirror* platform during the user

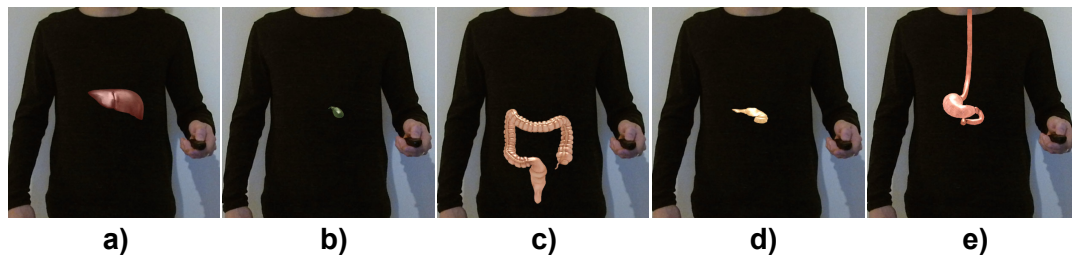


Fig. 3.11. Image sections of screenshots showing all five different organs that were virtually superimposed onto the bodies of the participants during the NRMM vs. RMM organ identification study. a) the *liver*, which is located primarily on the right side of the abdomen; b) the *gallbladder*, which is located in the upper right corner of the abdomen; c) the *colon*, with the appendix and the ascending section on the left side of the abdomen; d) the *pancreas*, whose tail is pointing towards the left side of the body; and e) the *stomach*, whose greater curvature lies on the left side of the body. In all cases, the participant is lifting the right hand while standing in front of the system. As the digital mirror image is lifting the left hand, all views illustrate anatomically correct RMM overlays.

study was to allow participants to fully concentrate on the location of these virtual organs. During the experiments, participants were asked to determine for both the RMM and NRMM condition whether or not a virtual organ was displayed on the anatomically correct side of the body. A Logitech R400 presenter was employed to record the choices of the participants. While pressing the left button on the presenter corresponded to the decision that a virtual organ is superimposed on the anatomically correct side, pressing the right button corresponded to an anatomically incorrect placement. A third button on the bottom of the Logitech presenter was programmed to switch to the next condition during the experiments, such that the entire experimental procedure was controlled by the participant.

Participants

Twenty-five medical students were recruited to participate in the user study. In order to determine whether they possessed the necessary anatomical knowledge to properly identify correct organ placement, a preliminary anatomy test was administered, which will be presented in more detail in the following subsection. Five participants failed this pre-test, which led to their exclusion from the user study, leaving a total of twenty participants (10M, 10F). Half of the participants were considered as juniors and the other half as seniors, with the criterion whether they had passed their written medical examination or not. Juniors had an average experience of 3.2 ± 1.76 semesters, compared to 9.6 ± 2.04 semesters of experience for the seniors. The average age of the participants was 26.4 ± 3.1 years and all participants were right handed.

Task & Procedure

The empirical user study was divided into three distinct parts. In the first part, the participants had to complete a series of paper-based pre-tests, including the aforementioned anatomy knowledge test as well as a mental rotation and a left-right discrimination test. Secondly, an interaction game had to be played, which introduced the participants to the differences between an RMM and an NRMM. Subsequently, the main part of the user study, the RMM vs. NRMM organ identification study, was conducted. All three parts are discussed in the following paragraphs. Figure 3.12 provides an overview of these individual parts of the user study.

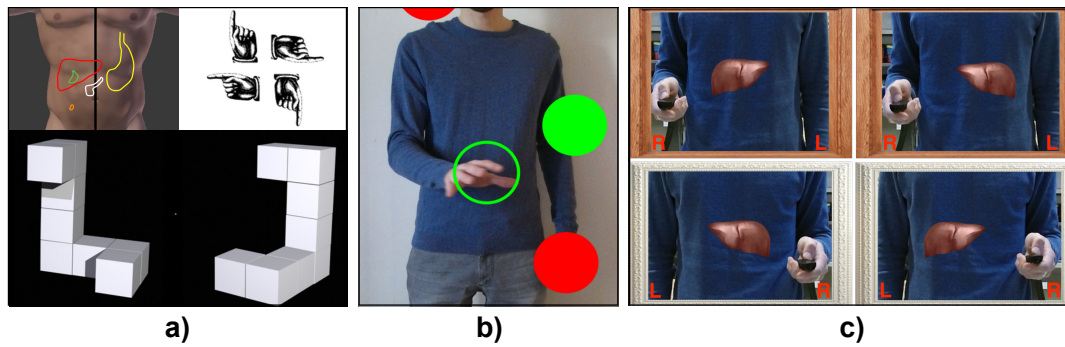


Fig. 3.12. Overview of the three different parts of the user study: a) Illustration of all three paper-based pre-tests. In the anatomy knowledge pre-test (top left), all five different organs had to be outlined on the correct side of the image to ensure sufficient anatomy knowledge (liver (*red*), stomach (*yellow*), pancreas (*white*), gallbladder (*green*), and appendix (*orange*)). During the mental rotation pre-test, participants had to decide whether block stimuli (bottom) were identical or mirrored. Lastly, a left-right discrimination pre-test was conducted, where users had to read in which direction hand stimuli (top right) are pointing; b) Participant during interaction game. The dominant hand, indicated by a non-solid green circle, is tracked. Solid green circles *falling* from the top have to be caught, while solid red circles should be avoided. The participant in front of the system is lifting the right hand. As the mirror image is also lifting the right hand, an NRMM condition is depicted; c) Comparison of the four different conditions during the RMM vs. NRMM organ identification study: *NRMM-NF* (top left), *NRMM-F* (top right), *RMM-F* (bottom left), and *RMM-NF* (bottom right). The participant is lifting the right hand to choose whether the presented augmentation is anatomically correct, which is the case for the two *non-flipped (NF)* conditions in the left column. To depict the difference between an NRMM and an RMM, the NRMM conditions are surrounded by a window frame, as an NRMM can be thought of as a see-through window. RMM conditions are surrounded by a mirror frame. Note: these surrounding frames were not shown to participants during the user study.

Pre-test I: Anatomy Knowledge During the first pre-test the participants were asked to outline the location of five different organs in an illustration of a frontal view of a person’s abdomen, see Figure 3.12a (top left). The organs of interest corresponded to those that were virtually augmented during the main part of the experiment, namely the *liver*, *gallbladder*, *colon*, *pancreas*, and *stomach*. Instead of the entire colon, only the appendix had to be outlined which is located in the lower right quadrant of the abdomen. All five organs have a distinct laterality within the human body and are therefore well suited for studying the perceptual differences between an RMM and an NRMM setting. Only those participants who were able to correctly outline all five organs were considered for the rest of the user study. Though all students were familiar with frontal view anatomy illustrations from textbooks and potentially patient examinations, five students failed to pass the anatomy knowledge pre-test and were thus excluded from the study. In all five cases, the pancreas was drawn incorrectly with the head pointing to the wrong side.

Pre-test II: Mental Rotation A second pre-test was conducted to assess the mental rotation ability of the participants. Mental rotation (MR) is the ability to imagine how a certain stimulus would look like when rotated. MR is a key factor of spatial reasoning and has been shown to be positively correlated to success in anatomy learning [164]. During the MR pre-test, we presented the participants with a total of 10 pairs of 3-dimensional Shepard and Metzler-like block stimulus images, which were proposed by Ganis and Kievit [149, 420]. Each stimulus consisted of 7 to 11 cubes composed of 4 different arms and contained computer generated shading and foreshortening depth cues. An example of such a block stimuli is shown in the bottom of Figure 3.12a. The participants had one minute to decide whether the 10 pairs of

block stimuli were equal or mirrored to each other, with the second form being rotated by either 0°, 50°, 100°, or 150° with respect to the first form.

Pre-test III: Left-Right Discrimination During the third and final pre-test we compared the left-right discriminatory ability of the participants. As could be seen previously, there is a considerable portion of the population that has difficulties with correctly discriminating between left and right, and that this ability is particularly important within the medical field. Similar to a study presented by Brandt and Mackavay [66], participants were presented with stimuli of hands pointing in different directions [509]. Figure 3.12a (top right) shows four exemplary hand stimuli. In the first part of this pre-test, we used a 5 × 5 grid of hands, with the index finger always pointing either up or down. The participants were asked to read aloud as accurately and as quickly as possible in which direction the corresponding hands were pointing. In the second part of the pre-test, an identical task had to be performed, this time with all hands pointing either to the left or to the right. The difference in task completion time during these two experiments was used as a metric for the participants' left-right discrimination ability.

AR Interaction Game For the purpose of familiarizing participants with the RMM and NRMM designs, which were used during the main part of the user study, and to compare the interaction performance for both conditions, we developed a simple AR interaction game. Solid green and red colored circles were superimposed onto the RGB video stream of the Kinect. All circles were spawned at the top of the color image and *fell* towards the bottom of it. Another non-solid green circle was displayed at the 2D screen coordinates of the user's dominant hand, with the circle constantly following the movements of this hand. The objective of the interaction game consisted in catching a total of 20 green circles while simultaneously avoiding all red ones. Two parameters were varied during the experiment: The time it took for the next circle to spawn decreased after every 5 green circles by 0.5 s, starting from 3.0 s. Similarly, the time it took for circles to fall from top to bottom was decreased by the same amount after every 5 green circles, starting from 3.5 s. Both the number of green circles and red circles caught were recorded. The experiment was conducted in two runs: in the first run the participants performed the experiment for a regular RMM visualization. Subsequently, the visualization was switched to an NRMM design and the task was repeated. Figure 3.12b shows an image section of a screenshot during the interaction game. After successful completion of the AR interaction game, the participants were aware of the differences between an RMM and an NRMM design, whose perceptual differences were subject to investigation during the following organ identification study.

RMM vs. NRMM Organ Identification Study During the last and most important part of the empirical user study, the ability of participants to identify correct placement of virtually augmented organs for both RMM and NRMM setups was investigated. During the course of the experiment, five virtual organs (*liver, gallbladder, colon, pancreas, and stomach*) were augmented one by one onto the participant's digital mirror image, either on the anatomically correct side of the body or on the opposite side. Thus, a total of four different conditions were traversed: 1) *NRMM-NF* (Non-Reversing Magic Mirror, Organ Non-Flipped), 2) *NRMM-F* (Non-Reversing Magic Mirror, Organ Flipped), 3) *RMM-NF* (Reversing Magic Mirror, Organ Non-Flipped), and 4) *RMM-F* (Reversing Magic Mirror, Organ Flipped).

The two conditions for which the virtual organ was non-flipped (*NF*) corresponded to the anatomically correct placements. Figure 3.12c depicts an AR view of all four different conditions. After each time a participant provided an answer for a certain condition using the hand-held Logitech presenter, a black screen was displayed and the participant was asked to proceed to the next condition by pressing another button on the presenter. Only then did the camera image become visible again. This design choice was made to avoid too obvious changes between the RMM and NRMM conditions. Though we asked the participants to provide an answer as quickly as possible, priority was placed on correct answers. By not allowing participants to engage in a prior training session, training effects are eliminated from the study. The main objective of this part of the empirical user study was to investigate whether an NRMM offers perceptual advantages over the traditional RMM design and whether these in turn result in an increased overall rate of correct answers.

Design

There were three independent variables for the organ identification part of the user study. The type of virtual organ augmented onto the digital mirror image of the participant had five levels corresponding to the five organs of interest in Figure 3.11. Virtual organs could be either displayed on the anatomically correct side of the body (non-flipped) or on the opposite one (flipped), corresponding to two levels. The third independent variable controlled which AR *Magic Mirror* design was used: either a regular RMM or an NRMM. Consequently, the experiment had a $5 \times 2 \times 2$ within-subjects design. A balanced Latin square matrix was employed for randomizing these conditions across all study participants [493].

Hypotheses

Prior to designing the empirical user study, the following five hypotheses were formulated that were subject to an extensive statistical evaluation:

- H1.** The overall percentage of correctly identified virtual organs is higher for the NRMM conditions in comparison to the regular RMM conditions.
- H2.** The average decision time (in seconds) is smaller for the NRMM conditions compared to the RMM conditions.
- H3.** The percentage of correctly identified virtual organs for the RMM conditions is higher for less experienced participants.
- H4.** Participants with higher mental rotation or left-right discrimination ability perform better for the RMM conditions.
- H5.** During the interaction game, the total amount of errors (missed green circles, hit red circles) is significantly higher for the NRMM compared to the RMM.

Furthermore, we expect the vast majority of participants to qualitatively prefer the NRMM conditions and to quickly establish the link between these views and the familiar patient examination and textbook view.

Results

In this section, a detailed analysis of the results obtained during the empirical user study will be presented. An overview of the findings for the main part of the study, the organ identification experiment, is summarized both in Table 3.1 and in Figure 3.13. Overall, participants achieved significantly higher percentages of correct answers for the two NRMM conditions compared to both RMM conditions ($F_{1,78} = 10.8, p < 0.01, \eta^2 = 0.12$). The highest percentage of correct answers was achieved using the *NRMM-NF* condition ($98.00\% \pm 6.16\%$), followed by the *NRMM-F* condition ($90.00\% \pm 10.26\%$), the *RMM-NF* condition ($85.00\% \pm 15.73\%$), and lastly the *RMM-F* condition ($79.00\% \pm 25.53\%$).

Tab. 3.1. Comparison of the mean percentages of correct answers and decision times among all 20 participants during the organ identification study. Results are depicted for the four individual conditions individually as well as combined for the two NRMM and RMM conditions. The two NRMM conditions show a higher overall average of correct answers with slightly lower decision times compared to the RMM conditions.

| Conditions | Correct Answers | | Decision Times | |
|---|-----------------|-------------|----------------|-------------|
| | Mean μ | SD σ | Mean μ | SD σ |
| (NRMM-NF) Non-Reversing Magic Mirror, Organs Non-Flipped | 98.00% | 6.16% | 5.06 s | 2.78 s |
| (NRMM-F) Non-Reversing Magic Mirror, Organs Flipped | 90.00% | 10.26% | 4.59 s | 1.82 s |
| (RMM-NF) Reversing Magic Mirror, Organs Non-Flipped | 85.00% | 15.73% | 5.32 s | 3.53 s |
| (RMM-F) Reversing Magic Mirror, Organs Flipped | 79.00% | 25.53% | 5.97 s | 3.97 s |
| (NRMM) Non-Reversing Magic Mirror Combined | 94.00% | 5.99% | 4.83 s | 2.17 s |
| (RMM) Reversing Magic Mirror Combined | 82.00% | 18.24% | 5.64 s | 3.62 s |

In order to examine whether the seniority level of participants affected the percentage of correctly identified organs during the experiment, all participants were divided into two groups: to the first group—in the following referred to as the *junior group*—those medical students were assigned who had not yet participated in the preliminary medical examination. Consequently, all other medical students formed the *senior group*. The two groups were balanced and each contained a total of 10 participants. For correct organ identification percentages, we observed an interesting difference between juniors and seniors. While no significant differences were recorded for the NRMM conditions, juniors scored significantly better than seniors in the RMM conditions ($F_{1,38} = 8.67, p < 0.01, \eta^2 = 0.19$), see Figure 3.13.

In terms of average mean times, participants were slightly faster in the two NRMM conditions (*NRMM-NF*: 5.06 ± 2.78 s, *NRMM-F*: 4.59 ± 1.82 s) compared to the RMM conditions (*RMM-NF*: 5.32 ± 3.53 s, *RMM-F*: 5.97 ± 3.97 s), see Table 3.1. As decision times varied considerably between the participants, the differences were not statistically significant, as revealed by an analysis of variances ($F_{1,78} = 1.37, n.s$).

Comparing the average percentage of correct answers for each of the five different organs among all participants revealed the following results: in the NRMM conditions, all five organs had comparably high identification results (liver 100.0%, colon 95%, gallbladder 92.5%, pancreas 92.5%, and stomach 90.0%). Overall, results for the RMM conditions were worse: the stomach was detected correctly in only 60.0% of the cases, followed by the pancreas (82.5%), liver (87.5%), colon (90.0%), and gallbladder (90.0%).

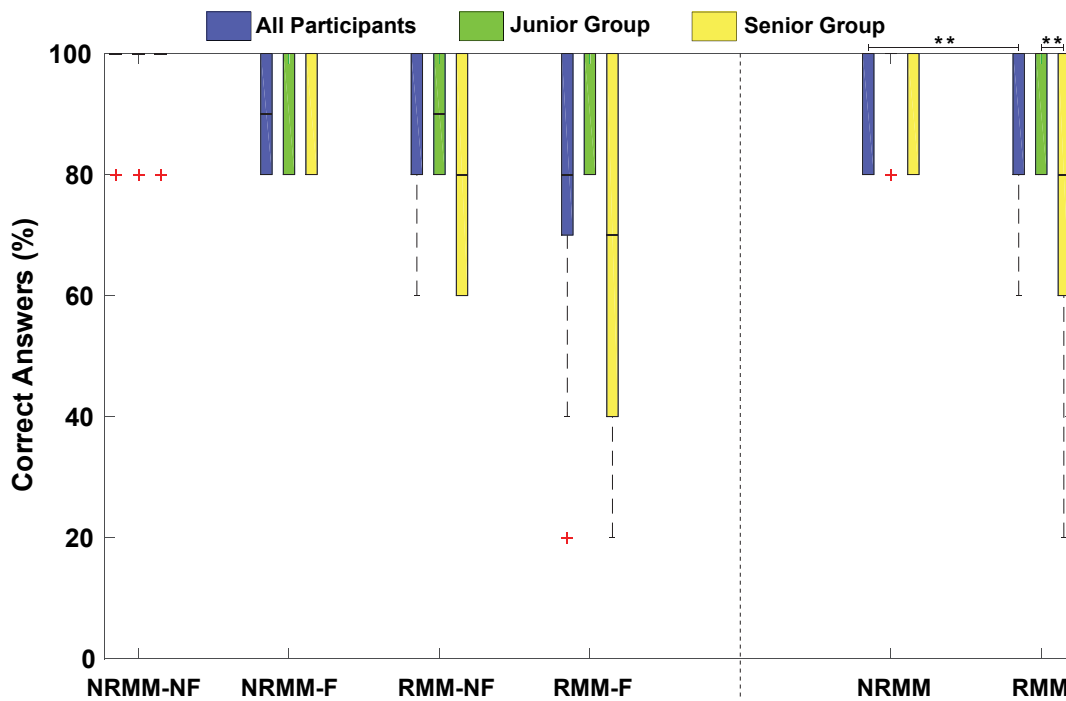


Fig. 3.13. Combined results for the organ identification experiment. Participants were asked to identify correct placement of virtual organs in four different *Magic Mirror* views, denoted on the x-axis. Junior medical students performed significantly better for the RMM conditions compared to the group of senior medical students. Combined results for both NRMM and RMM conditions are shown on the right.

For evaluating the results of the interaction game, the total error count in both conditions was defined as the sum of missed green circles and hit red circles. For the RMM case, a mean error of 1.7 ± 1.26 was measured, compared to 5.0 ± 1.59 for the NRMM case. These differences were statistically significant at the $p < 0.001$ level, ($F_{1,38} = 52.92, p < 0.001, \eta^2 = 0.58$).

Lastly, the results of the two paper-based pre-tests were evaluated. In the mental rotation (MR) pre-test, participants achieved a mean percentage of correct answers of $85.0 \pm 11.47\%$. In the left-right discrimination (LRD) pre-test, an average time difference of 4.36 ± 2.05 s between the up-down and the left-right condition was measured. Correlations between the results of these two pre-tests and the participants' performance during the interaction game and organ identification study were calculated using Spearman's rank correlation coefficients. Pearson's correlation is sensitive to outliers as well as skewness, hence we used non-parametric metrics to report correlations. A moderate correlation was observed for MR score and LRD score, with the latter defined as the time difference between up-down and left-right discrimination tasks ($r_s = -0.46, n = 20, p < .05$). Secondly, we found a moderate correlation between LRD score and RMM error count during the interaction game ($r_s = 0.56, n = 20, p < .05$). However, no such correlation could be found for LRD score and the NRMM error count ($r_s = 0.39, n = 20, ns$). Additionally, MR score was not strongly correlated to error counts during the interaction game.

After the user study, post-experimental interviews were conducted with all participants. Only two male, junior students did not express a preference for either the NRMM or RMM view. They stated that both designs are equally well suited for learning anatomy. All other participants expressed strong preference for the NRMM view, stating that it is the more natural choice for an AR anatomy learning system and resembles a more familiar view of the anatomy.

3.3.3 Discussion & Study Implications

The previous section presented a detailed overview of the empirical user study comparing a regular *Reversing Magic Mirror* (RMM) to a *Non-Reversing Magic Mirror* (NRMM) for the purpose of AR anatomy learning. Since medical students are more familiar with the view of an NRMM from other anatomy learning modalities such as textbooks, the implications of an NRMM design on the learning ability of medical students, the underlying psychological effects, and possible consequences on the perception and interaction of users were investigated. During the user study it was found that participants generally identified the correct organ locations significantly better under NRMM conditions—showing their *true* digital mirror image—than under RMM conditions, which confirms our previously defined hypothesis **H1**. As expected, however, participants achieved significantly better results during the interaction game under the RMM condition, also confirming hypothesis **H5**. On the one hand, these results demonstrate the applicability of an NRMM system for AR anatomy learning, while on the other hand, user interaction with NRMM systems remains a challenge. A comparatively high standard deviation was observed in the RMM conditions. This could be attributed to the design of the experiment, which allowed only two different decisions: either the placement of the virtual organ is anatomically correct or not. Further repetitions of the experiment could have led to lower standard deviations.

Another interesting finding was related to the seniority of medical students. More experienced students (seniors) more often provided incorrect answers under RMM conditions than students with less experience (juniors), confirming hypothesis **H3**. One possible explanation for this trend is the *mere-exposure effect* [73, 322], a psychological phenomenon in which a person develops a strong preference for a particular stimulus through continuous exposure, as can be observed when learning anatomy from textbooks. More experienced medical students have been continuously exposed to the concept of exchanging their own left and right with the patient's left and right, either through textbook illustrations, patient examinations, or even surgical procedures. However, since junior medical students achieved comparable percentages of correct answers in both NRMM and RMM conditions, it is intriguing to discuss the long-term effects of learning anatomy with an RMM. One possible outcome could be an improved left-right discrimination ability due to the continuous study of NRMM and RMM views, that could also have a positive effect on mental rotation ability. However, the exact opposite may also be the case, as medical students may be confused when they see conflicting views in different learning resources (i.e. textbook vs. RMM). An RMM could even carry the risk of learning anatomy with wrong laterality. Prior to integrating such solutions into the medical curriculum, the risk of such negative outcomes should therefore be eliminated. Alternatively, students should be made fully aware of the working principle of an RMM in advance of a learning session.

The decision times between the RMM and NRMM conditions did not differ significantly, such that hypothesis **H2** has to be rejected. Most of the participants first tried to understand whether an RMM or NRMM condition was currently indicated, e.g. by lifting the hands or touching their body, and only then continued to reason about whether virtual organs were displayed on the anatomically correct side of the body or not. This also explains the high variance of the measured decision times. Although moderate correlations between the mental rotation and the left-right discrimination scores of the participants were found, no

significant correlations between these pre-test scores and the results of the organ identification study could be observed. Therefore, not enough evidence to support hypothesis **H4** could be found. However, the weak, non-significant correlation between the mental rotation score and the total error rate during the organ identification study should be further investigated. Another interesting perceptual difference between RMM and NRMM designs is user perception. One senior female participant stated that she imagined her digital mirror image for NRMM conditions to be detached from herself. Instead, she imagined it was a patient standing in front of her. A user-centered, personalized AR overlay is more specific to RMM designs. It would therefore be attractive to investigate in a future study whether users of an NRMM design perceive their digital mirror image as themselves or as decoupled, also in the case of a third person observer, e.g. during collaborative anatomy learning sessions.

Although NRMM designs seem to be better suited for the task of AR anatomy learning, it remains unclear how users should interact with these systems. Naturally, people have great difficulty interacting in reversed coordinate frames [176, 186]. One possible approach is to decouple the interaction from the displayed image, e.g. by displaying a cursor that is controlled as if the system were operating in RMM mode. This will create a discrepancy between the displayed image of the user on the screen and the cursor, but could allow efficient user input. Another possibility would be to switch between NRMM and RMM mode depending on the current task to be performed. During interaction, e.g. selecting the currently displayed body system, the system would operate in RMM mode, and once the system is displayed, it would then switch to NRMM mode.

All these aspects demonstrate that the decision whether an RMM or NRMM design should be used for AR anatomy learning is not self-evident. The empirical user study presented in this section showed that both designs have particular benefits and shortcomings. Previously acquired domain knowledge and lateral significance, as in the case of anatomy learning, as well as the mere-exposure effect can be a strong argument in favor of an NRMM design. However, challenges with user interaction and user perception could be factors justifying an RMM design. Looking back at the quote introducing this chapter, it has become apparent that while the mirror metaphor of the *AR Magic Mirror* platform provides the basis for creating a personalized and intuitive user experience, it can also be the source of confusion, as left and right in medicine are always defined with respect to the patient's point of view. Therefore, it becomes essential to correctly introduce users to the underlying working principle of the system—both in the case of an RMM or NRMM. As a direct consequence of the results of this empirical user study on RMM and NRMM designs, an introductory learning sequence was developed to teach first-time users the underlying principles and operational concepts of the *AR Magic Mirror* platform. This introductory learning sequence played a crucial role during the evaluation of the *AR Magic Mirror* platform and its integration into the medical curriculum at the Ludwig-Maximilians University (LMU) in Munich, which will be presented in the following section.

3.4 Evaluation & Curriculum Integration

The work presented in this section is an extended version of parts of two papers published in the journals *Annals of Anatomy* in 2018 [254] and in *Anatomical Sciences Education* in 2019 [61]. The content is reproduced with the permission of all authors, ©Elsevier for [254] and ©American Association of Anatomists for [61].

The ultimate goal of the *AR Magic Mirror* platform is to serve as an additional teaching modality that can be effectively used by medical students for the purpose of interactive and personalized anatomy learning. While previous sections have highlighted both the technical and perceptual aspects of the platform that are essential to ensure a rich overall user experience, this section will focus on the evaluation of the *AR Magic Mirror* and its integration into the undergraduate medical curriculum. The introductory chapter of this thesis described the current anatomy learning landscape, which consists of a rich variety of educational resources that are available at the students' disposal. In the section on the historical background of anatomy education, it was shown that although new learning modalities started to emerge more rapidly in recent decades, traditional ones such as anatomy textbooks, didactic lectures, and cadaver dissections have formed the foundation of anatomy education for hundreds of years. Novel educational resources such as the *AR Magic Mirror* platform therefore must be compared to such established learning resources in order to prove their educational value. However, as was demonstrated in the section on related work, whereas many prototype systems have been proposed in the literature, none of these systems has been evaluated during large-scale user studies comprising a sufficiently large number of students and taking place over a long period of time under realistic learning conditions. Also for the *AR Magic Mirror* platform—despite its history stretching back almost 10 years—such extensive evaluations have not been performed yet. Previous studies were limited to evaluating individual components and sub-modules of the system with a limited number of participants and a pure focus on qualitative feedback [288, 289]. Within this thesis, the *AR Magic Mirror* platform was integrated thoroughly into a realistic curricular setting for the first time and evaluated by a large number of medical students, such that representative educational conclusions could be established. The results obtained during these studies, which took place over a total period of three years at the Ludwig-Maximilians University (LMU) in Munich, represent a significant portion of the overall contributions to this thesis. A total of three evaluation studies were performed that are described in the following sections. Within a large-scale pilot study with 880 first-year medical students, early qualitative feedback towards the *AR Magic Mirror* platform was obtained. Following an iterative improvement and optimization process of the system, another large-scale study with 749 medical students was conducted that demonstrated the potential of the novel AR platform for serving as an additional learning modality for human gross anatomy. Lastly, the *AR Magic Mirror* platform was integrated into an elective course, during which 72 medical students intensively worked with it for an extended period of time. Within this study, the quantitative learning effect provided by the system in comparison to both traditional anatomy learning resources as well as commercially available products was measured. Over the course of the following sections, it will become evident that the *AR Magic Mirror* platform is perceived by medical students not only qualitatively as a valuable educational resource, but also offers quantitative advantages in terms of learning outcomes and 3-dimensional understanding of anatomical structures and their relations within the human body.

3.4.1 Pilot Study

In order to develop an AR *Magic Mirror* that is tailored to the specific needs of medical students during anatomy learning, it is crucial to obtain feedback from the end users of the system at a very early stage of the development process. For this reason, an early prototype of the AR *Magic Mirror* platform was integrated into a human gross anatomy course at the LMU Munich, which extended over a period of two semesters in 2016 / 2017. A pilot study was conducted to find out whether the system could be used effectively as an additive teaching tool for integrated anatomy and radiology learning. A total of 880 first-year medical students worked with the system in groups of about 12 persons during a specially designed tutorial, in which they had the opportunity to interactively examine radiological images in different anatomical section planes. Subsequently, each participant was asked to assess the value of the system by completing a Likert-scale questionnaire. The following subsections provide a detailed overview of this pilot study, including a brief description of the AR *Magic Mirror* prototype that was employed during the study, the curricular setting in which the study was conducted, as well as the results of the survey. The findings clearly confirm that the AR *Magic Mirror* is indeed a valuable teaching resource that enables interactive and student-centered anatomy learning and has the potential to be vertically integrated into the medical curriculum.

AR Magic Mirror Prototype

The early-stage prototype of the AR *Magic Mirror*, which was used throughout the pilot study, contained only a basic subset of features of the platform described in sections 3.1 and 3.2, and due to its early stage of development was more comparable to the earlier system by Meng et al. [316]. Nevertheless, the basic features of the AR *Magic Mirror* platform were incorporated, including medical section images, gesture-based user interaction, and user-specific overlay of 3D anatomy models. In terms of section images, both a CT volume of the thorax and abdomen as well as high-resolution photographs of cryosections from the *Visible Human Project* were available [2]. Although not providing a perfect match between real anatomy and medical section images, it provides a good approximation and encourages the student to discover the sectional anatomy in relation to their own body. User interaction was limited to scrolling interactively through the different section images by moving the right hand up and down, analogously to the gesture interaction described in section 3.1. Also the available anatomy model was only a slimmed down version of the complete 3D model of the human body and consisted only of the skeleton, which in addition was only statically overlaid on the current user, without the real time skeletal animation described in section 3.2.

Curricular Framework

To better understand the relevance and implications of this pilot study, it is important to first understand the curricular framework that the prototype of the AR *Magic Mirror* was integrated into. The LMU Munich has one of the 37 accredited German medical faculties (as of February 2020) and follows a split curriculum, characterized by the teaching of preclinical courses in the first two years, followed by clinical disciplines, including radiology, in the next three years. As a consequence of this division, there is a time gap between anatomical education and other clinical disciplines such as radiology, which in the meantime leads to a decreasing knowledge of anatomical foundations. As part of a gross anatomy course in the first two semesters, medical students attend a dissection course that enables them to familiarize themselves with

the structures of the human body through hands-on dissection, but there is no opportunity to directly compare these structures and organs with relevant clinical section images. Therefore, the prototype of the *AR Magic Mirror* was integrated as a novel tool into this gross anatomy course to alleviate this discrepancy and to combine anatomical knowledge with clinically relevant information.

Gross Anatomy Course

A total of 880 first-year medical students attended the gross anatomy course in 2015 / 2016 over a period of two semesters. To investigate whether the *AR Magic Mirror* prototype is a valuable addition to the course, a tutorial was designed which each of the students completed. At the beginning of the tutorial the system was presented to groups of about 12 students. Senior medical students who had already completed their anatomical training and had previously received extensive training on the *AR Magic Mirror* served as instructors during the tutorial. After all participants got acquainted with the general control and the functionalities of the system, they were given the opportunity to work with the system individually in a self-directed learning session. A set of learning objectives in the form of predefined questions was provided as a guide to help students during the tutorial. These included, for instance, identifying the internal structures of the heart and the course of the aorta in different sectional planes. To obtain comparable results, all students were asked the same questions throughout the pilot study. Each tutorial session was split into two parts. In the first part, half of the group worked with the *AR Magic Mirror* prototype, while the other half studied with worksheets that represented a more traditional approach to anatomy learning. These worksheets presented radiological and clinically based cases such as coronary angiography or chest CT scans with easily identifiable pathologies such as pericardial effusion or pneumothorax. After successfully completing the first part of the tutorial, students exchanged groups such that everyone could work with both the worksheets and the *AR Magic Mirror* prototype.

Survey

At the end of the tutorial, all participants were asked to complete an anonymous survey containing five explicit statements about the *AR Magic Mirror* prototype, which had to be answered on a five-point Likert-scale. Possible choices were "strongly agree", "agree", "neutral", "disagree", and "strongly disagree". In addition, participants were asked to rate the entire tutorial by school grades from A to F. As the main objective of the study was to investigate whether or not the *AR Magic Mirror* prototype can be effectively integrated into anatomy education, we also asked students for their qualitative feedback on the system and on potential improvement suggestions as well as criticism. The survey was not compulsory and students could choose whether or not to participate.

Results

This section presents a detailed analysis of the results obtained during the survey. From the 880 first-year medical students who attended the gross anatomy course, a total of 748 students evaluated the *AR Magic Mirror* prototype by completing the anonymous questionnaire (85.00% response rate). Figure 3.14 summarizes the results from the five explicit statements of the Likert-scale questionnaire. Overall, the students rated the experience with the *AR Magic Mirror* very positively and appreciated the addition of the tool to the gross anatomy course.

The majority of students reported that the system increased the motivational aspect of anatomy learning (14.5% strongly agreed, 43.5% agreed). Compared to learning medical section images using traditional textbooks, the AR *Magic Mirror* showed great potential and was considered beneficial by most students (22.7% strongly agree, 46.4% agree). Concerning the ability of the system to provide a good first contact to medical section images, students were undecided. While the largest percentage of students strongly agreed with the statement (30.5%), there was still a significant percentage who strongly disagreed with it (14.2%). The median choice, however, was "agree". One of the main advantages of the AR *Magic Mirror* prototype compared to previously proposed multimedia educational tools is its interactive component. This was appreciated by the students and was reflected in the results of the survey. A total percentage of 82.4% agreed with the statement that the system stimulates active learning (34.9% strongly agreed, 47.5% agreed). Interestingly, the AR *Magic Mirror* prototype was perceived to greatly improve the general 3-dimensional understanding of human anatomy for almost all students (93.4%) with a medium choice of "strongly agree". Since the gross anatomy course was spread over two semesters, the anatomical knowledge acquired by the students increased steadily, and students did not have the same amount of knowledge when they completed the AR *Magic Mirror* tutorial. To account for this fact, it is not enough to evaluate all the surveys together, as shown in figure 3.14, but also to split the evaluation into two separate parts and compare the surveys of students who completed the tutorial in the first half of the course with those from the second half. In general, all students rated the five explicit statements about the benefits of the AR *Magic Mirror* prototype higher in the second half of the course. Especially the motivational aspect improved notably over time. While the system increased the motivation to learn anatomy for 54% of the students in the first half of the dissection course, the percentage increased to 62% for the students taking the survey in the second half.

In addition to the five explicit statements, the participants were asked to state the advantages and disadvantages of the AR *Magic Mirror* prototype as well as possible suggestions for improvement and points of criticism in the free-form feedback area of the survey. The most frequently cited advantage ($n = 107$) was that the 3-dimensional understanding of anatomy is improved by the ability to switch between different section planes (horizontal, sagittal, vertical). In addition, interactively scrolling through the different section images allowed the students to better understand the course of certain anatomical structures ($n = 66$). Further advantages of the AR *Magic Mirror* compared to traditional textbooks were that the system was found to be better suited for introducing section images to the medical students ($n = 39$), that the topography of the organs is more easily recognizable ($n = 38$), that the system provides a more interactive way of obtaining anatomical information ($n = 35$), and that active learning is encouraged ($n = 12$). Moreover, the AR *Magic Mirror* was considered by some students as a good tool to deepen the already acquired knowledge of human gross anatomy ($n = 7$). The most frequently mentioned criticism was that the current prototype of the AR *Magic Mirror* had temporary software bugs ($n = 62$). In addition, students would have appreciated section images of the head and limbs ($n = 53$), male and female data sets ($n = 31$), larger and higher resolution section images ($n = 43$) along with a better UI design ($n = 24$), an option to freeze the currently selected section image ($n = 47$), additional annotations of structures ($n = 41$), and a visual aid to display the current height of a given section image ($n = 27$). Lastly, students were asked to submit a final rating of the entire tutorial based on school grades. Results showed that more than 80% of students rated the tutorial as excellent ($A = 32.6\%$) or good ($B = 47.9\%$), while less than 5% rated it as poor ($D = 3.2\%$) or unacceptable ($F = 1.1\%$).

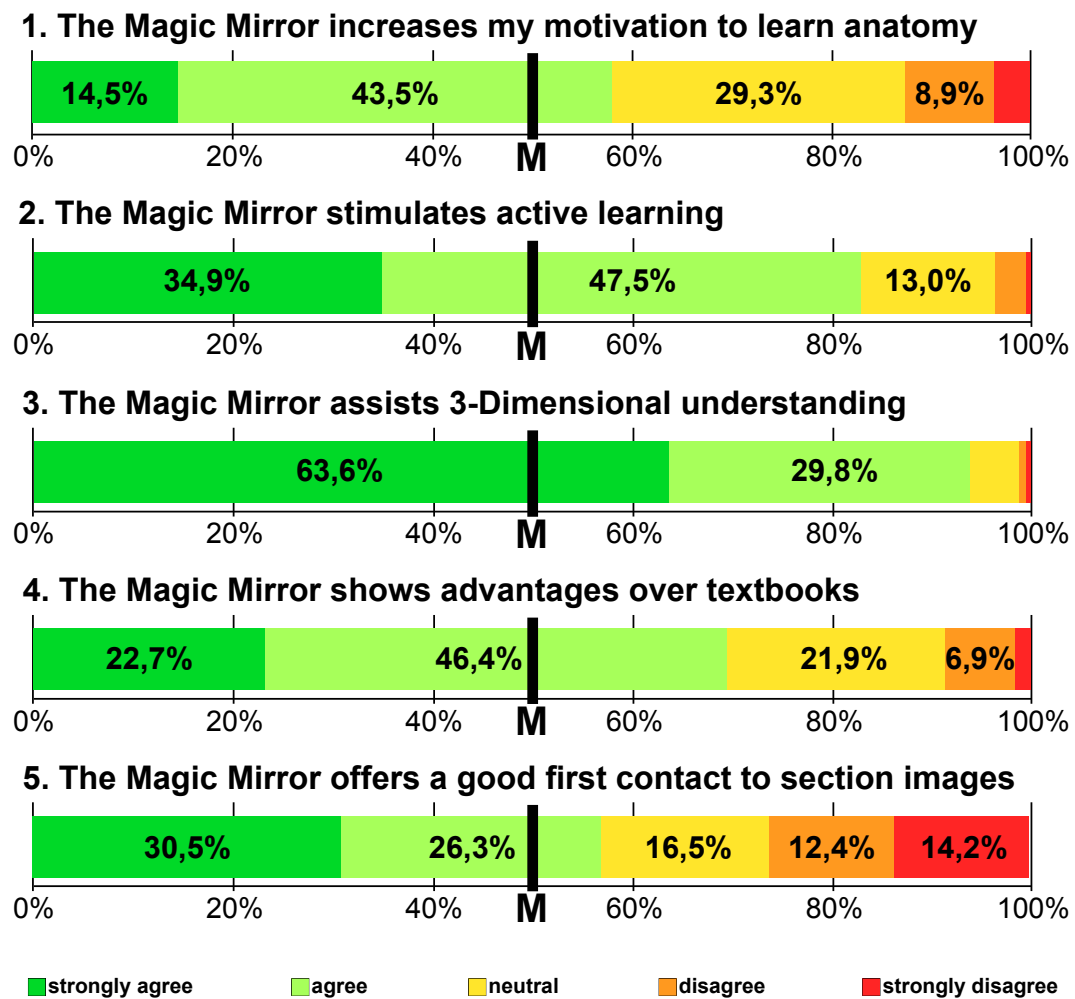


Fig. 3.14. Survey results of the pilot study in which 748 first-year medical students evaluated an AR *Magic Mirror* prototype. The survey contained five questions (1–5) that had to be scored on a five-level Likert scale. The available options were "strongly agree," "agree," "neutral," "disagree," and "strongly disagree." The percentages of the respective answers are given. Percentages below 5% are omitted. The median answer is given as M.

Discussion & Study Implications

Overall, the evaluation results of the pilot study confirmed the initial hypothesis that the AR *Magic Mirror* has the potential to serve as a valuable anatomy learning resource for students within the undergraduate medical curriculum. By integrating an early prototype of the system into a gross anatomy course, it was possible to obtain early feedback from a large number of medical students. The qualitative results of the study strongly suggest that the AR *Magic Mirror* improves the motivation of students to learn anatomy and promotes active learning that allows students to transfer previously acquired knowledge to clinically relevant subjects. The study results also showed that with increasing anatomical knowledge, the motivation of students to work with the AR *Magic Mirror* system increased, indicating that not only undergraduate medical students can benefit from the system, but also senior students in advanced stages of their studies who mainly focus on clinical content. Unlike traditional anatomy learning modalities and other AR anatomy learning systems, the specific design of the AR *Magic Mirror* platform—based on the *mirror metaphor*—allows students to learn both anatomical and radiological content interactively in relation to their own bodies. The results

of the pilot survey confirm that the ability of students to interactively explore anatomical models and medical section images in a clinically relevant context with AR on their own bodies is one of the main advantages of the system, which also validates the general concept of the AR *Magic Mirror*. Interestingly, almost all students consistently mentioned that working with the AR *Magic Mirror* prototype leads to an improved 3-dimensional understanding of anatomical structures. This particular benefit is unique to the AR *Magic Mirror* and presumably contributed to the fact that the system was generally perceived as advantageous over regular anatomy textbooks. Combined with the overall positive attitude of medical students towards the system, this improved spatial understanding of anatomy is one of the key findings of the pilot study.

In addition to the positive aspects described above, the survey results also revealed important suggestions for improving the AR *Magic Mirror* platform. Most of these were of a technical nature, such as making the overall system more stable and adding additional content and functionality. This early feedback on the technical aspects of the system was essential and directly influenced the development of future iterations of the platform.

3.4.2 Gross Anatomy Course Study

The pilot study described in the previous section represented the first large-scale evaluation of the AR *Magic Mirror* within a realistic curricular environment. The survey results obtained during the study confirmed the hypothesis that the system can be used effectively as a supplementary tool within human gross anatomy courses and that it offers specific advantages in the context of anatomy learning. Despite this overall positive feedback, there were certain limitations to the study, as only an early prototype of the AR *Magic Mirror* was tested and the survey was a relatively short, informal questionnaire of medical students. Furthermore, the prototype was only evaluated against traditional textbook learning, while other technological teaching modalities were ignored. Novel educational resources such as the AR *Magic Mirror* platform, however, must be compared with both established learning resources as well as state-of-the-art multimedia resources to demonstrate their pedagogical value. While textbooks certainly belong to the former category, a number of novel multimedia resources have been introduced in recent years. Hence, to confirm the results of the pilot study and to investigate how AR anatomy learning with the *Magic Mirror* platform compares to state-of-the-art multimedia resources, a follow-up study was designed in which the system was again integrated into the two-semester gross anatomy course at the LMU Munich that was attended by 749 first-year medical students in 2016 / 2017. Compared to the pilot study, a greatly enhanced implementation of the AR *Magic Mirror* platform was employed, which incorporated all the technological features that were presented in sections 3.1 and 3.2, including advanced gesture interaction, real-time skeletal animation, all virtual 3D models of the human body for both male and female, and additional content for integrated radiology learning. Throughout the gross anatomy course, medical students worked with both the AR *Magic Mirror* platform and the *Anatmage*, a virtual dissection table for combined learning in anatomy and radiology, during specially designed tutorial sessions that covered a variety of anatomical topics and accompanied the regular lectures and dissection course. After each tutorial session, an evaluation survey was administered to the students and a statistical analysis of the results was performed. The following sections present a detailed overview of this follow-up study.

Integrated Gross Anatomy & Radiology Learning

The objective of the present study was to compare the performance of the AR *Magic Mirror* platform with the virtual dissection table *Anatamage*—a state-of-the-art teaching modality for integrated learning in anatomy and radiology—and to measure whether the two systems offer advantages over learning with traditional atlases. The importance of integrating clinically relevant content in the form of radiology into gross anatomy courses has been recognized as an effective approach to achieve early exposure to medical images while simultaneously increasing students' motivation and understanding of both radiology and gross anatomy alike [161, 318, 331, 333, 367, 419]. Increased educational activities are therefore needed that take advantage of recent developments for teaching both disciplines jointly. In the past, various integration approaches have been proposed for the combined teaching of gross anatomy and radiology, including traditional lectures on interventional radiology [108], cross-sectional images on nearby monitors or hand-held devices during dissection courses [285, 331], peer-to-peer interactions with free medical image viewer software [494], E-learning platforms [94, 105, 302, 401], and virtual dissection tables [101, 356, 357]. All recommendations strongly advocate active learning and suggest a paradigm shift towards multimodal teaching environments [133, 368, 427, 445].

The Anatamage Table

A particularly successful commercial product for integrated anatomy and radiology education is the virtual dissection table *Anatamage* (Anatamage Inc., San Jose, California). *Anatamage* tables have previously been integrated into gross anatomy courses, with studies showing not only a positive overall perception of the system but also a positive influence on the learning outcome of students [70, 90, 103, 127, 201], even suggesting the system as a potential substitute for cadaver dissection courses [6, 147, 148] and for radiological training [101, 356, 357]. *Anatamage* is operated by touch input and allows the user to interactively control a life-size, realistic visualization of the human 3D anatomy. Similar to the AR *Magic Mirror*, various medical section images can be displayed and quickly examined by scrolling through the slices with the *Anatamage* touch-table interface. All three cross-sectional planes can be visualized, including annotations for some anatomical structures. The system offers pre-loaded medical image volumes including CT, MRI, and photographic images of cryosections. It is also possible to upload image volumes from real patients and display them on the large LCD screen. Compared to the inexpensive AR *Magic Mirror* platform (approx. 1.000,00 €), the cost of the *Anatamage* table is much higher (80.000,00 €), as it combines two high-resolution, life-size touchscreen displays and a computer in one housing. Figure 3.15 depicts two groups of students interacting with both the AR *Magic Mirror* platform and the *Anatamage* virtual dissection table in a laboratory environment during the gross anatomy course study.

Curricular Environment & Tutorial Sessions

The general framework of the gross anatomy course at the LMU Munich is divided into a theoretical component, consisting of traditional anatomy lectures (90 hours), and a practical laboratory component, which includes a compulsory dissection course (72 hours). The latter is divided into five different parts with the following anatomical topics: 1) Thorax & Neck; 2) Musculoskeletal System - Part I; 3) Head; 4) Musculoskeletal System - Part II; and 5) Abdomen & Pelvis. Typically, a total of 36 medical students dissect a single cadaver over the entire period of the dissection course in smaller groups of 12 people. For the purpose of comparing the AR



Fig. 3.15. Comparison of the two technologies that were compared during the gross anatomy course study. Two groups of first-year medical students are working in a laboratory environment with a) AR *Magic Mirror* system, and b) the *Anatomage* virtual dissection table.

Magic Mirror platform and the *Anatomage* virtual dissection table with regard to their potential for serving as complementary teaching resources for the integrated teaching of anatomy and radiology, both systems were evaluated in five specially designed tutorial sessions as part of the practical component of the gross anatomy course, which covered a period of two semesters in 2016 / 2017. The contents of the tutorial sessions were closely related to the topics covered within the five different parts of the dissection course, such that students could transfer their previously acquired theoretical and dissection-based anatomical knowledge into clinically relevant applications. Each tutorial was designed to reflect a specific clinical case. Starting with an introductory video explaining the working principle and functionalities of the AR *Magic Mirror* platform, as well as a short overview of the *Anatomage*, students were asked to locate relevant anatomical structures using both systems. For this purpose, both the AR *Magic Mirror* and the *Anatomage* were configured to display annotated medical section images of a CT volume and high-resolution photographs of cryosections to facilitate this knowledge transfer. Exactly the same section images and annotations were integrated within both systems in order to obtain comparable data. In addition to the medical section images, the *Anatomage* contained a complete virtual model of the human anatomy, which was segmented from a CT volume. Similarly, the AR *Magic Mirror* platform included virtual anatomy models that were specifically adapted to match the topic of the tutorial session. Students had the ability to show, hide, and select individual structures and view corresponding annotations. Figure 3.16 shows an overview of the anatomy models that were integrated into the tutorial sessions.

Following the introduction to both the AR *Magic Mirror* and the *Anatomage*, there was time to work freely with the two systems in order to evaluate their benefits and to interactively explore the relevant information of the various clinical contents with each system. Current research on best practice for integrated education in anatomy and radiology suggests that small group learning is the preferred method for both students and residents [368]. Thus,

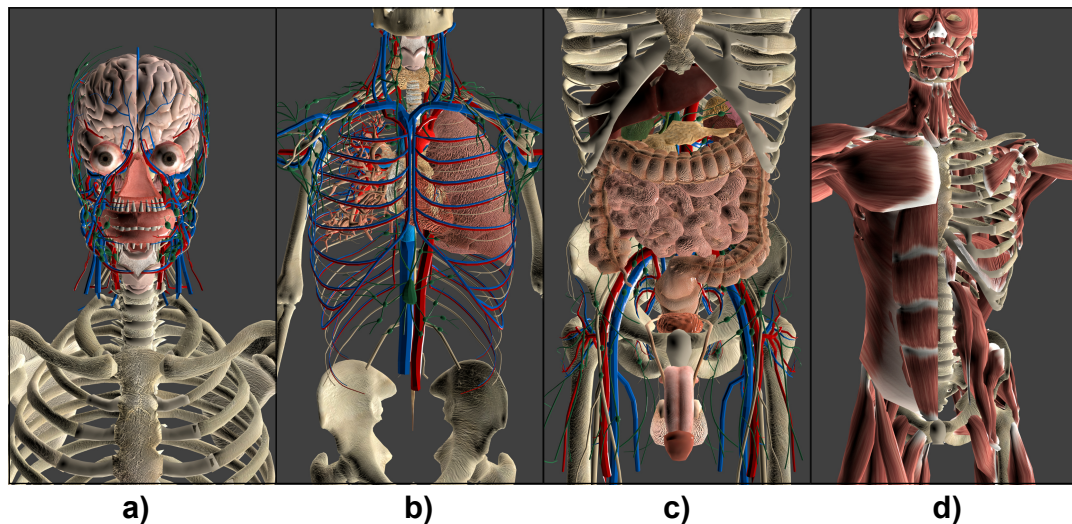


Fig. 3.16. Comparison of the virtual human anatomy models used within the AR *Magic Mirror* platform during the tutorial sessions of the gross anatomy course. For each tutorial session, a specific subset of 3D models was assembled and specially adapted to guide the medical students during the learning experience. The 3D models are shown for a) the *Head* tutorial, b) the *Thorax & Neck* tutorial, c) the *Abdomen & Pelvis* tutorial, and d) both tutorials on the *Musculoskeletal System*. In the latter, outer layers of muscle from the left side of the body are removed to indicate that deeper layers of muscle were also studied.

students attended the tutorial sessions in the same groups in which they conducted the cadaver dissection course, i.e. groups of 12 students evenly distributed across the AR *Magic Mirror* and the *Anatomage*. These small group sizes also ensured that each individual student had a quality interaction time with both systems during the tutorials. After the students had worked with the two systems for one hour, they changed groups and worked with the other system for an additional hour, resulting in a total duration of the tutorial of two hours. Each student participated in one tutorial session over the entire period of the gross anatomy course. All tutorials were conducted and supervised by senior medical students who had already completed their anatomical training, were well acquainted with the use of both systems, and participated in an introductory seminar to ensure that all tutors provided the same level of guidance during the tutorials.

Evaluation Survey

In accordance with the previously conducted pilot study, the subjective attitude of medical students towards both the AR *Magic Mirror* platform and the *Anatomage* and their potential to serve as a supplementary teaching resource for integrated gross anatomy and radiology learning was assessed by means of an evaluation survey at the end of the tutorial session. The survey was designed by medical education experts from LMU Munich and, compared to the survey from the pilot study, was more extensive, containing 22 explicit statements concerning the usability and benefits of both systems. All statements were tailored to provide clear and unambiguous information about the systems' capabilities. A visual analogue scale (VAS) was used to rate each statement, from 0 (*strongly disagree*) to 20 (*strongly agree*), and users gave their rating to each statement once for the AR *Magic Mirror* platform (11 statements) and once for the *Anatomage* platform (11 statements). All questionnaires were filled out anonymously and it was the student's free decision to participate. A total of 749 first-year medical students participated in the tutorial sessions during the gross anatomy course in the winter semester

2016 / 2017 ($n = 481$, 161 male, 320 female) and in the summer semester 2017 ($n = 268$, 105 male, 163 female). The mean age of participants was 21.0 ± 4.0 years, ranging from 18 to a maximum of 35 years. All medical students received no financial compensation for participating in the study. Regarding the study hypotheses, it was assumed that the AR *Magic Mirror* and the *Anatomage* were both perceived as valuable additions to the gross anatomy course. To confirm the results of the pilot study, it was also expected that the AR *Magic Mirror* would provide unique benefits to students, particularly in terms of improved 3-dimensional understanding, as section images are presented in direct relation to the user's body.

Results

The results of the VAS survey data obtained during the gross anatomy course are summarized in Table 3.2. Students signaled their approval to 22 explicit statements ($S1 - S22$) concerning the usability and additional teaching value of both the AR *Magic Mirror* platform and the *Anatomage* on a 20-point VAS. The AR *Magic Mirror* platform achieved comparable values to *Anatomage* with slightly higher ratings for the latter in almost all statements. Both systems were found to offer comparable benefits to dissection courses ($S5 - S6$, $F_{1,1496} = 3.29$, $p = 0.07$, ns) and greatly enhance them ($S3 - S4$), with significantly higher scores for the *Anatomage* ($F_{1,1496} = 32.96$, $p < 0.001$, $\eta^2 = 0.02$). However, both systems were considered not suitable for replacing dissection courses completely ($S1 - S2$, $F_{1,1496} = 35.31$, $p < 0.001$, $\eta^2 = 0.02$). The AR *Magic Mirror* platform was considered significantly more intuitive to work with than the *Anatomage* ($S7 - S8$, $F_{1,1496} = 26.90$, $p < 0.001$, $\eta^2 = 0.02$), and both systems received good scores in terms of engineering quality ($S9 - S10$, $F_{1,1496} = 23.58$, $p < 0.001$, $\eta^2 = 0.02$). While the *Anatomage* was found to be the significantly superior tool for a first contact to anatomy ($S11 - S12$, $F_{1,1496} = 214.86$, $p < 0.001$, $\eta^2 = 0.13$), the vast majority of students could imagine working with both of the systems on their own ($S13 - S14$), again with significantly higher scores for *Anatomage* ($F_{1,1496} = 18.19$, $p < 0.001$, $\eta^2 = 0.01$). Comparatively good results were achieved in terms of the improvement of the students' subjectively assessed spatial understanding ($S15 - S16$, $F_{1,1496} = 3.16$, $p = 0.08$, ns) as well as their anatomical knowledge ($S19 - S20$, $F_{1,1496} = 3.59$, $p = 0.06$, ns). Significantly higher scores were obtained for the *Anatomage* with respect to its potential for increasing anatomical knowledge ($S17 - S18$, $F_{1,1496} = 21.83$, $p < 0.001$, $\eta^2 = 0.01$). In terms of advantages of the two systems over traditional textbooks ($S21 - S22$), the *Anatomage* achieved significantly higher scores compared to the AR *Magic Mirror* platform ($F_{1,1496} = 48.80$, $p < 0.001$, $\eta^2 = 0.03$).

Discussion

The results of the present survey clearly demonstrate the potential of both the AR *Magic Mirror* platform and the *Anatomage* virtual dissection table as additional teaching resources for integrated learning in anatomy and radiology. Both systems were perceived by first-year medical students as valuable additions to the gross anatomy course. While the *Anatomage*, as a state-of-the-art commercial product, received slightly higher scores in most of the survey statements, the learning experience with the AR *Magic Mirror* platform proved to be particularly intuitive. Most importantly, the survey results confirmed the findings of the previously conducted pilot study, in which the advantages of the AR *Magic Mirror* in the context of AR anatomy learning were commonly recognized. In particular, medical students again found that the system enhances their 3-dimensional understanding of anatomical structures and

Tab. 3.2. Summary of the survey results from the gross anatomy course study. Medical students signaled their agreement with 22 explicit statements (*S1 - S22*), 11 of which referred to the AR *Magic Mirror* and the other half to the *Anatomage*. Ratings were given on a Visual Analogue Scale (VAS) with 20 points. For each statement, the mean score and standard deviation are provided. Additionally, significant differences are highlighted, included effect sizes.

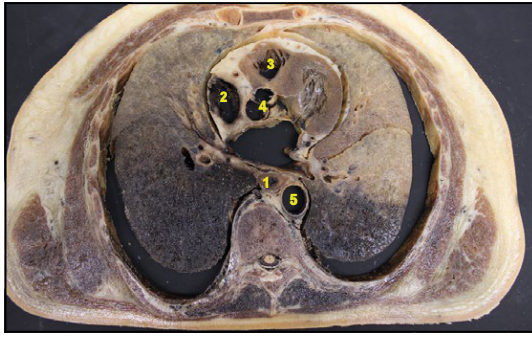
| Survey Statements | VAS ^a |
|---|---|
| | Gross Anatomy Course (n = 749) Mean (± SD) ^b |
| ^a Visual Analogue Scale (0 - 20): 0 = completely disagree, 20 = completely agree ^b Standard Deviation ^{s, m, l} Effect Sizes: s = small ($\eta^2 < 0.02$), m = medium ($\eta^2 > 0.13$), l = large ($\eta^2 > 0.26$) | |
| 1. The AR Magic Mirror is able to fully replace dissection courses | 3.85 (± 4.28) |
| 2. Anatomage is able to fully replace dissection courses | 5.32 (± 5.23)]*** - s |
| 3. The AR Magic Mirror is a good enhancement for dissection courses | 13.93 (± 5.33) |
| 4. Anatomage is a good enhancement for dissection courses | 15.46 (± 4.95)]*** - s |
| 5. The AR Magic Mirror offers no benefits to dissection courses | 7.36 (± 5.56) |
| 6. Anatomage offers no benefits to dissection courses | 6.84 (± 5.44) |
| 7. The AR Magic Mirror is intuitive to work with | 14.18 (± 4.71) |
| 8. Anatomage is intuitive to work with | 12.89 (± 4.90)]*** - s |
| 9. The AR Magic Mirror seems to be well-engineered | 12.20 (± 4.64) |
| 10. Anatomage seems to be well-engineered | 13.37 (± 4.73)]*** - s |
| 11. The AR Magic Mirror provides a good first contact to anatomy | 11.52 (± 3.67) |
| 12. Anatomage provides a good first contact to anatomy | 14.84 (± 5.22)]*** - m |
| 13. I can imagine working with the AR Magic Mirror myself | 14.95 (± 5.21) |
| 14. I can imagine working with the Anatomage myself | 16.00 (± 4.60)]*** - s |
| 15. The AR Magic Mirror enhances my 3-dimensional understanding | 14.36 (± 4.96) |
| 16. Anatomage enhances my 3-dimensional understanding | 14.81 (± 4.80) |
| 17. The AR Magic Mirror can be beneficial for increasing anatomical knowledge | 13.60 (± 4.84) |
| 18. Anatomage can be beneficial for increasing anatomical knowledge | 14.74 (± 4.59)]*** - s |
| 19. Using the AR Magic Mirror increased my personal anatomical knowledge | 11.58 (± 5.21) |
| 20. Using Anatomage increased my personal anatomical knowledge | 12.09 (± 5.29) |
| 21. The AR Magic Mirror offers advantages over traditional atlases / textbooks | 11.13 (± 4.91) |
| 22. Anatomage offers advantages over traditional atlases / textbooks | 12.89 (± 4.86)]*** - s |

their relationships within the human body. As mentioned above, the tutorial sessions were attended by small groups of up to 12 students, one half of which worked with the AR *Magic Mirror* platform, while the other half worked with the *Anatomage* platform, before eventually switching groups after one hour of group learning. Considering the fact that six students shared one device during the tutorial session and that each student only attended one of these sessions, the total interaction time per student with both systems was limited to about 10 minutes. Due to these time constraints, the main purpose of the tutorial sessions was a direct transfer of knowledge and it was difficult to generate new knowledge through extended interaction with the systems. Despite these limitations, all previously defined hypotheses about the benefits of the AR *Magic Mirror* platform were confirmed by the present gross anatomy course study, which therefore represented an important step towards the full validation of the system and its integration into the medical curriculum.

3.4.3 Elective Anatomy & Radiology Course Study

During the two previous studies the *AR Magic Mirror* platform was integrated into the gross anatomy course at the LMU Munich and was evaluated with a total of 1629 medical students in their first year. The system was compared to both traditional textbook learning and the *Anatmage* virtual dissection table as an example of a state-of-the-art commercial product that is widely used in many universities around the world for integrated anatomy and radiology learning. Both studies found that the *AR Magic Mirror* platform was a valuable addition to the course and that the system could be effectively used for interactive, self-directed anatomy learning, improving students' motivation and 3-dimensional understanding of human anatomy. While the results of these two studies clearly demonstrated that the deployment of the *AR Magic Mirror* platform in the context of anatomy learning is not only feasible, but also has the potential to improve certain aspects of the current anatomy learning experience, there were two major limitations of the studies. First, the time spent on the *AR Magic Mirror* platform was limited both during the pilot study and during the gross anatomy course study. Naturally, the question arises whether the good overall study results are due to a *new technology bias* and the majority of medical students using an AR system for the very first time, or whether the students' perception of the system and the advantages it offers increases as they spend more time on self-directed learning with the system. In addition, both evaluations were based on qualitative surveys in which students expressed their subjective opinions about the different learning modalities. For novel anatomy teaching resources such as the *AR Magic Mirror* platform, however, it is essential to prove their pedagogical value compared to well-established teaching aids not only in qualitative surveys, but it also must be measured quantitatively. For medical students, one of the most important quantitative metrics for measuring this pedagogical value is learning outcome. Consequently, the second question that arises is whether learning anatomy with the *AR Magic Mirror* leads to an increased learning outcome, and whether this increase is significantly higher than with other learning resources. Another intriguing question that emerged during the evaluation of the gross anatomy course study was whether there are differences in learning outcome between students and whether there is a specific group of students that particularly benefits from learning with the *AR Magic Mirror* platform.

In order to answer all these questions, a third user study was designed, which was conducted as part of an elective course on anatomy and radiology. During the elective course, which took place over an entire weekend, the participants were assigned to three groups and underwent a self-directed learning session using either the *AR Magic Mirror* platform, the *Anatmage*, or traditional radiology atlases. Two multiple choice tests, before and after the learning session, were evaluated to measure the quantitative learning effect in all three groups. In addition, a mental rotation test was administered to the students prior to the learning session to investigate whether students with better spatial ability could benefit more from the *AR Magic Mirror* platform. Taking into account the results of the previous two studies, it was hypothesized that all three learning modalities offer a comparable transfer of knowledge and that both the *AR Magic Mirror* platform and the *Anatmage* are considered valuable resources for integrated anatomy and radiology learning. Furthermore, it was expected that the *AR Magic Mirror* platform would provide unique benefits to students, particularly in terms of improved 3-dimensional understanding, since the section images are presented in direct relation to the user's body. The following section provides a detailed overview of the study design and the insights gained during this third evaluation study.



Choose the right answer

- A) Number 1 supplies air into the lungs.
- B) Number 2 is the first part of the pulmonary trunk.
- C) Normally, number 3 contains oxygen-rich blood.
- D) Number 4 separates the left ventricle from the aorta.**
- E) The blood in structure 5 is low in oxygen.

Fig. 3.17. Example multiple-choice question from the anatomy pre-test. Specific anatomical structures are highlighted with numbers from 1 – 5. From the five potential answers (A – E), only one was correct (D).

Participants

A total of 72 first-year medical students were recruited for the elective anatomy and radiology course. All students had previously completed the gross anatomy course and were therefore already familiar with both the AR *Magic Mirror* platform and the *Anatomege*. The mean age of the participants was 21.36 ± 3.40 years (23 male and 49 female students), ranging from 18 to a maximum of 31 years. As with the gross anatomy course, all students participated voluntarily in the elective course and received no financial compensation.

Pre-test I: Anatomy Knowledge

At the beginning of the elective course, students were asked to take an unannounced exam with 20 multiple choice questions that were similar to the anatomy part of the first main German medical exam. All questions from this anatomy pre-test counted equally, resulting in a maximum of 20 points to be achieved. While all questions were related to topographical anatomy, the questions could either be formulated with text sentences only (text questions) or refer to radiological or section images (image questions). All questions consisted either of statements, for which the correctness had to be evaluated, or of positive and negative statements, of which only one was correct. Figure 3.17 illustrates an example of a question aimed at understanding the topographic anatomy of the thorax. The questions of the pre-test were categorized into the well-known learning taxonomy of Bloom [53]. The test contained questions from two taxonomic levels of difficulty, which were equally divided into *Knowledge* (10 questions) and *Comprehension* (10 questions). In the former, students should be able to recall, recognize, and retrieve relevant knowledge from memory. The latter means that students should be able to construct meanings from oral, written, and graphic messages through interpreting, illustrating, summarizing, interfering, comparing, and explaining. The reliability of the anatomy pre-test was validated using Cronbach's alpha, which yielded an acceptable value of $\alpha = 0.77$. Students had 30 minutes to answer all questions and there were five multiple choice options to answer. Since all students had just completed their anatomical training in the gross anatomy course, the questions were designed to be quite challenging in order to avoid systemic bias.

Pre-test II: Mental Rotation

In addition to the anatomy knowledge pre-test, the participants performed a web-based mental rotation test (MRT) for assessing their mental rotation ability. The test was very similar to the

one performed during the user study on *Reversing* and *Non-Reversing Magic Mirror* designs, (see section 3.3.2). A subset of 15 pairs of freely available 3D Shepard and Metzler-like block stimuli images proposed by Ganis and Kievit were randomly selected from the 48 available stimuli and presented to the participants [149, 420]. Each stimulus consisted of a combination of 7 to 11 computer-generated cubes with four arms pointing in different directions. Figure 3.12a depicts an example of such a block stimuli. The participants had one minute to decide whether the 15 pairs of block stimuli were identical or mirror-images of each other. In each test pair an example image is presented next to the second shape, which is rotated by either 0°, 50°, 100°, or 150° with respect to the first shape.

Participant Sorting

Based on the results of the anatomy knowledge pre-test as well as the MRT results, the participants were divided into three comparable groups for the subsequent self-directed learning session. All three groups were balanced with 24 participants each: 1) *AR Magic Mirror* platform (7 male, 17 female, mean age 21.52 ± 4.38); 2) *Anatomage* (9 male, 15 female, mean age 21.36 ± 2.61); and 3) *Theory* (learning with atlases, 7 male, 17 female, mean age 21.19 ± 2.94). A manual sorting and group assignment of the participants was performed to ensure that the average pre-test and MRT results as well as the standard deviation were as close as possible in all three groups (see first columns in Tables 3.3 and 3.4). Finally, all participants received their personal pre-test results and it was announced that there would be another anatomy knowledge exam at the end of the self-directed group learning session.

Group Learning Phase

The participants gathered for the self-directed group learning sessions in spatially separate rooms in which the various media were prepared: the first room with two *AR Magic Mirror* systems, the second with two *Anatomage* tables, and the third room with a sufficient number of anatomical and radiological atlases [338, 362]. Prior to the learning session, all groups were informed that the present tutors would only provide technical or operational support. Therefore, group learning was entirely self-directed with no additional assistance from the tutors, and students were only allowed to use the teaching medium from their respective group. On the basis of the content covered in the anatomy knowledge pre-test, a number of main topics were defined on which the students were to concentrate during the 3-hour self-guided group learning session. Topics included the anatomical relationships of the abdominal region, the anatomy of the heart, and the topography of the thorax. These objectives, which concern broader anatomical regions, were chosen in favor of explicit learning statements, such as the identification of specific structures, in order to avoid a knowledge bias in the subsequent anatomy post-test.

Post-Test: Anatomy Knowledge

Following the self-directed group learning session on the specified topics and a break of 30 minutes, the anatomical knowledge of the participants was again evaluated with a final knowledge test. This test had the same structure as the pre-test, with the exception that all questions were either entirely different or at least significantly modified to avoid a memory bias. Similar to the pre-test, the questions were selected from the same two levels of Bloom's taxonomy, with one more question (11) from the slightly more demanding *Comprehension* domain and one question less (9) from the *Knowledge* domain [53]. The reliability of the

anatomy post-test was good, again verified by Cronbach's Alpha ($\alpha = 0.82$). Neither the anatomy knowledge pre-test nor the post-test were relevant for the official grading of students, and the final score was calculated as the number of correctly answered questions in each test.

Extended Learning Session & Survey

The anatomy knowledge post-test described above marked the end of the first day of the elective anatomy and radiology course. On the second day an extended learning session was conducted in which the students worked with the other two systems that they had not worked with during the group learning session on the first day. In this way, all students worked with all three media for at least 3 hours. The extended learning session was required to compare the subjective perceptions of all 72 medical students regarding the effectiveness and added value of both the AR *Magic Mirror* platform and the *Anatomage* compared to traditional anatomy learning with atlases and textbooks. At the end of the second day, students were asked to complete a final evaluation survey to assess the quality of all three teaching aids for integrated anatomy and radiology learning. The survey was identical to the one conducted during the gross anatomy course.

Results

The statistical evaluation of test results was performed using a univariate analysis of variance (ANOVA) with repeated measures in conjunction with Tukey's post-hoc tests to identify significant differences between the three different groups (AR *Magic Mirror* platform, *Anatomage*, and Atlas-based *Theory*). The statistical package SPSS, version 24.0 (IBM Corp., Armonk, NY) was used for this analysis.

Pre- vs. Post-test Scores Overall, participants achieved higher scores in the anatomy knowledge post-test compared to the pre-test in all three study groups. For all participants combined, the scores for the pre-test were $48.87 \pm 13.17\%$, while score for the post-test increased to $56.77 \pm 17.17\%$. These differences were significant at the $p < 0.001$ level ($F_{1,148} = 13.56, \eta^2 = 0.08$). Similar observations were made when looking at the three groups individually. In both the AR *Magic Mirror* group and the *Theory* group, students achieved significantly higher scores during the post-test (AR *Magic Mirror*: $F_{1,48} = 4.34, p < 0.05, \eta^2 = 0.08$; *Theory*: $F_{1,48} = 5.08, p < 0.05, \eta^2 = 0.10$). However, the test score differences were not significant for participants in the *Anatomage* group ($F_{1,48} = 3.97, p = 0.52, ns$). A detailed summary of all anatomy knowledge test results is given in Table 3.3. In order to get an even deeper insight into the test results of the individual groups, an additional evaluation was carried out in which the test scores were examined separately with regard to the two different types of questions that were asked during the tests. As mentioned above, the questions in the pre- and post-test were of two types: the first type of questions (image questions) referred to a given medical section image, while the second type of questions (text questions) merely consisted of a statement without an associated section image, aimed at a general understanding of anatomy. The results show that the overall increase in post-test scores is largely due to a better performance on image questions in all three groups. For the AR *Magic Mirror*, test scores for the image questions increased significantly from $29.60 \pm 18.37\%$ to $64.89 \pm 19.69\%$ ($F_{1,48} = 42.94, p < 0.001, \eta^2 = 0.47$). For students in the *Anatomage* group, there was also a significant increase from $28.80 \pm 21.66\%$ to $59.11 \pm 14.60\%$

($F_{1,48} = 33.65, p < 0.001, \eta^2 = 0.41$), while for the *Theory* group, image question scores increased from $30.40 \pm 14.28\%$ to $59.11 \pm 16.89\%$ ($F_{1,48} = 42.13, p < 0.001, \eta^2 = 0.47$). For the text questions, students achieved slightly lower scores in the post-test in both the *AR Magic Mirror* group ($54.13 \pm 15.43\%$ compared to $48.00 \pm 17.32\%$) as well as the *Anatontage* group ($54.40 \pm 17.18\%$ compared to $51.60 \pm 18.18\%$), while a slight increase could be observed for the *Theory* group ($57.33 \pm 16.67\%$ compared to $59.20 \pm 21.39\%$). However, none of these differences were statistically significant. Figure 3.18 illustrates the pre- and post-test results both for the total number of students and for the three groups individually, respectively for all test questions combined and separately for the two different types of test questions.

Tab. 3.3. Summary of the pre- and post test scores of the elective anatomy & radiology course. Percentages of correct answers are provided for all participants combined and for each of the three groups individually, as well as for the two types of test questions (image-based and text-based) and for all questions combined.

| Conditions | | Pre-Test | | | Post-Test | | |
|---|----|---------------------------|-----------------------------|----------------------------|---------------------------|-----------------------------|----------------------------|
| Number of questions Standard Deviation | n | All Questions (m = 20) | Image Questions (m = 10) | Text Questions (m = 10) | All Questions (m = 20) | Image Questions (m = 10) | Text Questions (m = 10) |
| | | Mean % (± SD) | Mean % (± SD) | Mean % (± SD) | Mean % (± SD) | Mean % (± SD) | Mean % (± SD) |
| Magic Mirror | 24 | 48.00 (± 13.07) | 29.60 (± 18.37) | 54.13 (± 15.43) | 56.00 (± 14.08) | 64.89 (± 19.69) | 48.00 (± 17.32) |
| Anatontage | 24 | 48.00 (± 14.22) | 28.80 (± 21.66) | 54.40 (± 17.18) | 55.16 (± 10.97) | 59.11 (± 14.60) | 51.60 (± 18.18) |
| Theory | 24 | 50.60 (± 12.53) | 30.40 (± 14.28) | 57.33 (± 16.67) | 59.16 (± 14.28) | 59.11 (± 16.89) | 59.20 (± 21.39) |
| All Participants | 72 | 48.87 (± 13.17) | 29.60 (± 18.12) | 55.29 (± 16.28) | 56.77 (± 13.13) | 61.04 (± 17.17) | 52.93 (± 19.37) |

Mental Rotation Test Analysis In accordance with the participant sorting, the 24 medical students in each of the three groups not only had similar test results in the pre-test, but also comparable mental rotation skills (*AR Magic Mirror* platform: $71.80 \pm 22.74\%$; *Anatontage*: $71.88 \pm 20.16\%$; and *Theory*: $71.68 \pm 20.71\%$). For the purpose of analyzing the influence of the participants' mental rotation ability on the improvement percentages between pre- and post-tests, a median split was performed at 70%, separating the students into subgroups with high and low MRT scores, see Table 3.4. For the subgroup *MRT-High* the following average MRT scores were obtained: *AR Magic Mirror* platform ($91.54 \pm 7.38\%$); *Anatontage* ($87.07 \pm 10.28\%$); and *Theory* ($87.21 \pm 9.66\%$). In the *MRT-Low* subgroup, the average MRT scores were $50.42 \pm 10.48\%$ for the *AR Magic Mirror*, $52.55 \pm 10.19\%$ for the *Anatontage*, and $51.92 \pm 11.84\%$ for the *Theory* group. The two subgroups (*MRT-High* and *MRT-Low*) were balanced for all three learning modalities and each contained 12 participants. Regarding the improvement percentage between pre- and post-test scores, an interesting difference was observed between these two subgroups. In the *Theory* group, students with a high MRT score improved significantly more in the post-test than students with a low MRT score ($13.00 \pm 10.93\%$ vs. $3.46 \pm 10.49\%$, $F_{1,23} = 6.29, p < 0.05, \eta^2 = 0.21$). The opposite effect was observed for the *Anatontage* group in which students with a low MRT score achieved higher improvement percentages than students with a high MRT score ($2.85 \pm 15.79\%$ vs. $10.91 \pm 14.40\%$), although the results in this case were not significant ($F_{1,23}=1.6, p = 0.22, ns$). For the *AR Magic Mirror*, students achieved roughly the same improvement regardless of their MRT scores ($7.89 \pm 14.07\%$ vs. $7.49 \pm 13.56\%$, $F_{1,23} = 0.001, p = 0.97, ns$).

Survey At the end of the elective course, all students were asked to fill out the same survey that had previously been conducted during the one-year gross anatomy course for comparing the additional value of both the *AR Magic Mirror* platform and the *Anatontage*,

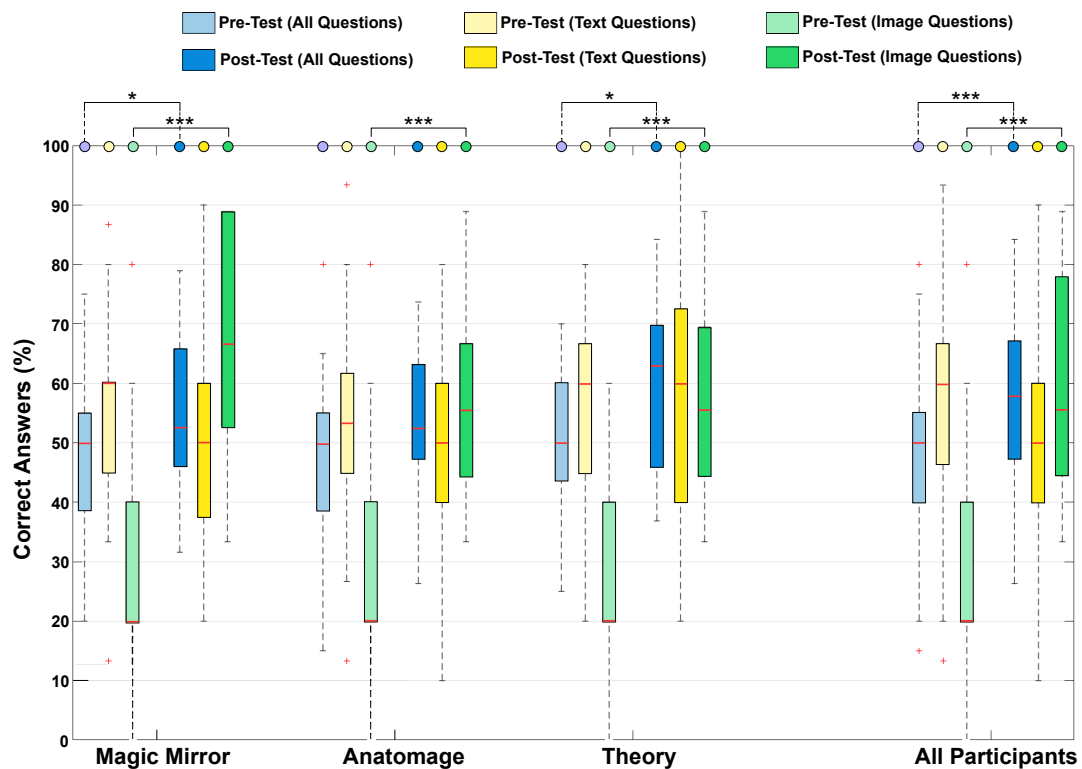


Fig. 3.18. Graphical overview of the percentages of correct answers achieved by students during both the pre- and post-test. Questions could be classified either as image or text questions. Results are presented for each of the three groups (AR *Magic Mirror* platform, *Anatomage*, and *Theory*) individually as well as combined. Significant differences are indicated as * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$).

see section 3.4.2. An overview of the results from all 72 students attending the elective course is depicted in the second column of Table 3.5. For comparison, the results of the gross anatomy course study are also shown in the first column. While the *Anatomage* received slightly better overall ratings in the first survey and seemed to be preferred by the students for self-directed learning in anatomy and radiology, the AR *Magic Mirror* surpassed the *Anatomage* in almost all statements in the second survey with regard to the student ratings. Similar to the previous survey, both systems were considered valuable additions for enhancing dissection courses ($S3 - S4: F_{1,142} = 0, p = 0.96, ns$; $S5 - S6: F_{1,142} = 0.27, p = 0.6, ns$), albeit not as a full replacement ($S1 - S2: F_{1,142} = 1.3, p = 0.25, ns$). The results for statements $S7 - S8$ demonstrate that the AR *Magic Mirror* platform has clear advantages over the *Anatomage* in terms of intuitiveness. For the AR *Magic Mirror* platform, VAS scores improved from 14.18 ± 4.71 in the gross anatomy course study to 16.29 ± 3.82 in the elective course study, while they dropped for *Anatomage* from 12.89 ± 4.90 to 10.97 ± 5.07 . The differences between AR *Magic Mirror* and *Anatomage* were significant at the $p = 0.001$ level ($F_{1,142} = 50.53, \eta^2 = 0.26$). In contrast to the gross anatomy course study, the AR *Magic Mirror* platform was considered to be the better-engineered tool ($S9 - S10$). However, the difference was not statistically significant ($F_{1,142} = 2.57, p = 0.11, ns$). While the *Anatomage* was considered a great tool for the first contact to anatomy in the first survey ($S11: 14.84 \pm 5.22$), these results could not be confirmed during the elective course study as a slight drop to 10.56 ± 6.33 was observed. Decreasing VAS scores (11.52 ± 3.67 to 9.68 ± 6.02) were also recorded for the AR *Magic Mirror* platform ($S12$). No significant differences were recorded for

Tab. 3.4. Mental Rotation Test (MRT) scores and improvement percentages between pre- and post-tests for the AR *Magic Mirror*, *Anatomage*, and *Theory* group. The results are reported both for the three groups as a whole and separately for the two subgroups with high and low MRT scores.

| Conditions | Entire Group (n = 24) | | MRT ^a - High (n = 12) | | MRT ^a - Low (n = 12) | |
|---------------------------------|----------------------------|----------------------------|----------------------------------|----------------------------|---------------------------------|----------------------------|
| | MRT ^a Score | Improvement | MRT ^a Score | Improvement | MRT ^a Score | Improvement |
| ^b Standard Deviation | Mean % (± SD) ^b | Mean % (± SD) ^b | Mean % (± SD) ^b | Mean % (± SD) ^b | Mean % (± SD) ^b | Mean % (± SD) ^b |
| Magic Mirror | 71.80 (± 22.74) | 8.00 (± 13.73) | 91.54 (± 7.38) | 7.89 (± 14.07) | 50.42 (± 10.48) | 7.49 (± 13.56) |
| Anatomage | 71.88 (± 20.16) | 7.16 (± 15.62) | 87.07 (± 10.28) | 2.85 (± 15.79) | 52.55 (± 10.19) | 10.91 (± 14.40) |
| Theory | 71.68 (± 20.71) | 8.58 (± 11.68) | 87.21 (± 9.66) | 13.00 (± 10.93) | 51.92 (± 11.84) | 3.46 (± 10.49) |

this statement ($F_{1,142} = 0.72, p = 0.4, ns$). In comparison to the gross anatomy course study, an even larger number of students could imagine working with the AR *Magic Mirror* platform during self-directed learning sessions after finishing the elective course ($S13: 14.95 \pm 5.21$ vs. 16.03 ± 4.98), while scores decreased for the *Anatomage* ($S14: 16.00 \pm 4.60$ vs. 14.32 ± 5.47). The VAS scores for the self-directed learning potential ($S13 - S14$) were significantly higher than those of *Anatomage* ($F_{1,142} = 5.06, p = 0.03, \eta^2 = 0.03$). Furthermore, the AR *Magic Mirror* platform was found to increase the 3-dimensional understanding ($S15 - S16$) and the personal knowledge about gross anatomy slightly more than *Anatomage* ($S15 - S20$). However, none of these differences were statistically significant ($S15 - S16: F_{1,142} = 0.71, p = 0.4, ns$; $S17 - S18: F_{1,142} = 0.04, p = 0.84, ns$; $S19 - S20: F_{1,142} = 0.4, p = 0.51, ns$). Lastly, VAS scores were almost identical in terms of the advantages that both systems offer over traditional atlases and textbooks ($S21 - S22: F_{1,142} = 0.1, p = 0.93, ns$).

Student Perceptions At the end of the survey, students had the opportunity to give written feedback in free text fields about their subjective perception of the use of both the AR *Magic Mirror* platform and the *Anatomage* during the elective course. A total of 57 students (79.17%) provided such feedback in addition to answering the 22 survey statements. Altogether, the written feedback was consistent with the overall study results. Both the AR *Magic Mirror* ($n = 13$) and the *Anatomage* ($n = 11$) were considered great tools for increasing the 3-dimensional understanding of topographic anatomy. Additionally, both systems were found to "offer a better way of learning section images than textbooks", "improve the understanding of the relative position of organs in the body", and "increase spatial understanding". Furthermore, the two systems allowed to "quickly explore an entire 3D volume", "jump to certain structures much faster [than radiology atlases]", and "easily trace the course of vessels". A couple of students ($n = 5$) particularly appreciated the possibility of the AR *Magic Mirror* platform to "show anatomy on one's own body", which was found to "improve 3-dimensional understanding" and to "better understand at what height certain anatomical structures are located". Two other reasons why some students appreciated working with the AR *Magic Mirror* platform were the interactive user interface ($n = 9$) and the possibility for self-directed learning ($n = 7$). With regard to the first point, students appreciated "the very intuitive user interface and user interaction", "the concise and accurate gesture control", and "the simplicity of user interaction". On the subject of self-directed learning with the AR *Magic Mirror*, students could imagine "working with the system at home using a TV or laptop" and considered it "great for independent learning [of certain anatomical concepts] on their own". The *Anatomage* was well received by the students for its large display ($n = 6$), which was considered "great for providing a good overview of many different section images simultaneously", and for collaborative learning in small groups ($n = 6$),

Tab. 3.5. Survey results from medical students comparing the AR *Magic Mirror* platform and the *Anatamage* table in terms of their additional value in the context of integrated anatomy and radiology learning. For comparison, the first column again shows the results of the gross anatomy course study (see section 3.4.2), while the second column shows the results of the present elective course study. Significant differences are indicated as * ($p < 0.05$) and *** ($p < 0.001$).

| Survey Statements | VAS ^a | |
|--|-----------------------------------|-----------------------------|
| | Gross Anatomy Course (n = 749) | Elective Course (n = 72) |
| | Mean (± SD) ^b | Mean (± SD) ^b |
| 1. The AR Magic Mirror is able to fully replace dissection courses | 3.85 (± 4.28) | 3.95 (± 4.57) |
| 2. <i>Anatamage</i> is able to fully replace dissection courses | 5.32 (± 5.23)]****-s | 4.86 (± 4.80) |
| 3. The AR Magic Mirror is a good enhancement for dissection courses | 13.93 (± 5.33) | 14.56 (± 5.22) |
| 4. <i>Anatamage</i> is a good enhancement for dissection courses | 15.46 (± 4.95)]****-s | 14.51 (± 5.12) |
| 5. The AR Magic Mirror offers no benefits to dissection courses | 7.36 (± 5.56) | 6.29 (± 4.97) |
| 6. <i>Anatamage</i> offers no benefits to dissection courses | 6.84 (± 5.44) | 6.74 (± 5.30) |
| 7. The AR Magic Mirror is intuitive to work with | 14.18 (± 4.71) | 16.29 (± 3.82)]****-1 |
| 8. <i>Anatamage</i> is intuitive to work with | 12.89 (± 4.90)]****-s | 10.97 (± 5.07)]****-1 |
| 9. The AR Magic Mirror seems to be well-engineered | 12.20 (± 4.64) | 13.01 (± 4.19) |
| 10. <i>Anatamage</i> seems to be well-engineered | 13.37 (± 4.73)]****-s | 11.74 (± 5.31) |
| 11. The AR Magic Mirror provides a good first contact to anatomy | 11.52 (± 3.67)]****-m | 9.68 (± 6.02) |
| 12. <i>Anatamage</i> provides a good first contact to anatomy | 14.84 (± 5.22)]****-m | 10.56 (± 6.33) |
| 13. I can imagine working with the AR Magic Mirror myself | 14.95 (± 5.21) | 16.03 (± 4.98)]*-s |
| 14. I can imagine working with the <i>Anatamage</i> myself | 16.00 (± 4.60)]****-s | 14.32 (± 5.47)]*-s |
| 15. The AR Magic Mirror enhances my 3-dimensional understanding | 14.36 (± 4.96) | 15.32 (± 3.99) |
| 16. <i>Anatamage</i> enhances my 3-dimensional understanding | 14.81 (± 4.80) | 14.92 (± 4.52) |
| 17. The AR Magic Mirror can be beneficial for increasing anatomical knowledge | 13.60 (± 4.84) | 15.07 (± 4.44) |
| 18. <i>Anatamage</i> can be beneficial for increasing anatomical knowledge | 14.74 (± 4.59)]****-s | 14.72 (± 4.52) |
| 19. Using the AR Magic Mirror increased my personal anatomical knowledge | 11.58 (± 5.21) | 16.04 (± 3.70) |
| 20. Using <i>Anatamage</i> increased my personal anatomical knowledge | 12.09 (± 5.29) | 15.60 (± 4.69) |
| 21. The AR Magic Mirror offers advantages over traditional atlases / textbooks | 11.13 (± 4.91) | 12.50 (± 4.93) |
| 22. <i>Anatamage</i> offers advantages over traditional atlases / textbooks | 12.89 (± 4.86)]****-s | 12.57 (± 4.93) |

which "stimulated discussions on topographic anatomy [between students]". As for limitations, some students ($n = 3$) found the AR *Magic Mirror* platform "tiring during extended learning sessions" and missed a "multi-user mode" ($n = 2$). For the *Anatamage*, negative feedback mainly revolved around technical difficulties of the system, especially the "unresponsive touch display" ($n = 8$) and the "missing multi-touch capabilities" ($n = 3$). Despite the positive feedback of both systems regarding an improved 3-dimensional understanding, many students emphasized in their comments that neither system can replace a dissection course ($n = 18$), especially due to "the lack of haptics" ($n = 10$). Two students considered the two systems as "interesting toys" and "fun-to-play-with tools" that "cannot replace textbook learning". Other general comments were related to the overall feedback of the course ($n = 8$), which was found to have "increased the level of personal anatomy knowledge" and "offered a good repetition of topographic anatomy", as well as potential improvement suggestions for the two systems to "include pathologies" ($n = 4$), "display more annotations" ($n = 4$), and "include quiz-based learning" ($n = 2$).

Discussion

The purpose of the present study was once more to examine the advantages of the AR *Magic Mirror* platform in the context of integrated anatomy and radiology learning and to

quantitatively evaluate these advantages in comparison to other anatomy learning resources, specifically the *Anatontage* and traditional textbook learning. From the results of the user study, three main observations can be derived.

Firstly, the learning outcome in all three groups (*AR Magic Mirror*, *Anatontage* and *Theory*) was positive, since the students achieved higher test scores after attending a three-hour self-directed group learning session during the elective course. While this result was certainly expected for the *Theory* group, it also confirmed earlier studies which showed increased learning performance for the *Anatontage* group [6, 148]. Most importantly, for the first time a quantitative learning effect could be demonstrated for the *AR Magic Mirror* platform, confirming previous studies that had already qualitatively assessed the added value of the system. These results are particularly promising for the *AR Magic Mirror* platform, since both the *Anatontage* and traditional anatomy and radiology atlases are well-established learning modalities and new technologies such as the *AR Magic Mirror* platform have to prove their additional pedagogical value compared to existing ones—which this study has now succeeded in doing. At the same time, the positive results confirm recent studies that highlight the opportunities for interactive learning experiences, especially using AR and VR technology [3, 86, 110]. According to the obtained results of the elective course, interactive AR systems can indeed be successfully integrated into medical curricula and provide an effective additional teaching tool for integrated anatomy and radiology learning. In addition to the positive overall learning effect, which constitutes the most important finding from the present study, a more detailed analysis of the pre- and post-test results provides further insight into the specific benefits of all three learning modalities. Interestingly, no statistically significant differences in test scores were observed for text questions regarding the topographical anatomy. However, the test results improved significantly when images were available to support the topographical relationships between the structures that were the subject of the test questions. In consequence, the better overall performance in the post-test was mainly due to a significant improvement in the image questions for all three groups. The slight decrease in the number of correctly answered text questions for the *AR Magic Mirror* platform and the *Anatontage* groups, in conjunction with a slight increase in these questions for the *Theory* group, could be attributed to the additional textual information that traditional anatomy and radiology atlases provide regarding topographic relations. Whereas the first two systems were restricted to the display of annotated CT and cryosection images, students could read additional information accompanying the section images in the textbooks, thereby resulting in a potential increase in their anatomical knowledge. Another hypothesis which might explain the statistically insignificant differences in the text questions would be that knowledge of topographic anatomy is acquired far more effectively during the dissection course, which offers unique advantages that none of the three learning modalities can provide. Such an explanation would be consistent with the results of the survey and with the subjective perception of the students, confirming that both the *AR Magic Mirror* and the *Anatontage* are valuable additions to a gross anatomy course and enhance the overall learning experience, but are not able to completely replace a dissection course. The same certainly holds true for traditional textbook learning, although this was not explicitly analyzed during the survey. Despite the fact that all 72 students previously participated in the gross anatomy course and learned the basics of topographic anatomy both during lectures and in a dissection course, the results of the pre-test showed that the students had difficulties in answering the questions dealing with radiological section images, which indicates that establishing a link between

topographic anatomy and radiological images is difficult to achieve and requires dedicated teaching modalities. This observation is consistent with recently published studies advocating a more integrated radiology education in gross anatomy [113, 182]. Of the three learning modalities, the students achieved the highest improvements in correctly answered image questions in the AR *Magic Mirror* group, closely followed by the *Theory* and the *Anatomage* group. A probable explanation for this slight advantage of the AR *Magic Mirror* could be that radiological section images can be examined in relation to the user's body, which offers an egocentric spatial relationship compared to an object-centered one. This was highlighted by several participants in the free text feedback and outlined as one of the main advantages of the AR *Magic Mirror* platform over the other two modalities.

The second observation is related to the results of the survey. For the purpose of comparing the subjective perception of students towards the AR *Magic Mirror* platform during the elective course with that of the one-year gross anatomy course from the previous study (see section 3.4.2), the survey contained exactly the same 22 statements in both studies. While the *Anatomage* received slightly better ratings in almost all statement categories during the gross anatomy course study, the exact opposite was the case during the elective course study, where the AR *Magic Mirror* platform was superior to the *Anatomage* in all aspects. During the tutorial sessions of the former, the exposure time with the two systems was very limited, despite the fact that the learning session was organized in small groups and the tutors guaranteed that each student worked with both systems. The AR *Magic Mirror* was considered an interesting and entertaining tool compared to the *Anatomage* as an already well-established anatomy learning resource, but the immediate benefits and real-world applications for expanding students' knowledge of anatomy were less obvious. However, acceptance of the AR *Magic Mirror* increased greatly during the more extensive elective course, surpassing that of the *Anatomage* in almost all parts of the survey. A large number of students expressed their desire to work with the AR *Magic Mirror* platform by themselves and valued the intuitiveness of the system, suggesting that it is beneficial not only during dedicated learning sessions as part of the medical curriculum, but also as an additional teaching resource for self-directed learning. These differences in exposure time during the elective course and the gross anatomy course are presumably also the reason for the large discrepancy in the mean ratings for the survey statements *S19* and *S20* (*Using Magic Mirror / Anatomage increased my personal anatomical knowledge*) and the large standard deviation. Given the time restrictions during the gross anatomy course, the purpose of the tutorial sessions was to convey certain anatomical concepts to the students. During the elective course, on the other hand, students had the opportunity to explore the possibilities of both systems more freely, which facilitated not only the conveyance but also the generation of knowledge. Overall, the combination of both survey results and the students' subjective feedback demonstrates that both the AR *Magic Mirror* platform and the *Anatomage* provide valuable additions during integrated anatomy and radiology learning. These outcomes are consistent with current research that calls for complementary anatomy teaching modalities that do not aim to replace existing ones but to enable multimodal, self-directed learning [133, 368, 427, 445]. In particular, techniques such as AR have the potential to improve anatomy learning and are in growing demand by medical students. In most modern medical curricula, however, these novel learning tools are not yet included. The present study is therefore an important first step in this direction, providing for the first time a quantitative evaluation of such a novel AR platform, the *Magic Mirror*, and comparing its effectiveness and advantages with established anatomy learning modalities.

The third important observation concerns the correlation between the students' performance in the MRT test and the improvement percentage between pre- and post-test. Among the students with a low MRT score and a poor spatial reasoning ability, higher post-test scores were obtained in the groups working with the AR *Magic Mirror* and *Anatmage* compared to the students in the *Theory* group. These findings suggest that both systems enhance the understanding of 3-dimensional relationships of anatomical structures inside the human body, something that is difficult to achieve with 2D projections contained in regular atlases and textbooks, especially for students with a low mental rotation ability. Consequently, these findings not only confirm the results of the survey analysis and the qualitative feedback from the students, but also suggest that both the *Anatmage* and the AR *Magic Mirror* platform could help to promote the development of spatial reasoning skills in students with low mental rotation capability. It was previously reported that good spatial reasoning skills have a positive influence on anatomical learning [150, 479]. In a recent study, Sweeney et al. found a weak correlation between results in an anatomy knowledge test and students' spatial abilities [451]. Rizzolo and Stewart claim that the association between a dissection course and studying imaging modalities is particularly relevant for the development of spatial reasoning skills [390]. Consequently, additional studies on the impact of the AR *Magic Mirror* platform on the acquisition of spatial reasoning skills by medical students could be interesting, e.g. by introducing the system into the dissecting room and displaying radiological section images that directly correspond to the anatomy of the organ donor, similar to recent studies by Paech et al. [356, 357].

Overall, the present study demonstrated that the AR *Magic Mirror* platform has proven itself as an additional teaching modality during integrated anatomy and radiology training. The system increased the students' anatomical knowledge, improved the 3-dimensional understanding of anatomical structures, and offered significant advantages over state-of-the-art tools such as *Anatmage* and traditional textbook learning. Furthermore, the results indicate that especially those students with lower spatial reasoning skills can benefit from learning with novel technologies such as the AR *Magic Mirror* platform. As AR becomes increasingly popular in education [3, 15], it will be interesting to see if 3-dimensional tools like the AR *Magic Mirror* platform can make the transition from research projects to commonly used complementary learning tools for medical students around the world.

Limitations While the overall results of the elective course study are extremely promising, there were some limitations that need to be discussed in order to interpret the results of the study correctly. First, it was possible to provide identical section images for the students in both the AR *Magic Mirror* group and the *Anatmage* group, while the students in the *Theory* group had traditional anatomy and radiology atlases at their disposal containing additional information not available in the first two systems. However, all digital section images were manually labeled by medical experts according to the terminology in the radiology atlas, such that for all three groups all relevant information was available to answer the questions in both the pre- and post-test. Secondly, only a limited number of section images were available to students during the study. Pathologies were not part of the investigations, but could be a topic of interest for future research. Another limitation of the study was that cognitive load associated with the use of the AR *Magic Mirror* platform and the *Anatmage* was not specifically studied. Especially in AR-based education, novel systems should not overload the user with virtual information [499]. While measuring cognitive load could certainly be an

interesting topic for future research as well, none of the participants mentioned experiencing cognitive difficulties while working with the system. Finally, the present study was conducted at a single center and the number of students participating in the elective course was not particularly large compared to the two previous studies. Future studies across multiple centers should be conducted to re-validate and confirm the results of the present study and discover other potential applications for 3-dimensional tools such as the *AR Magic Mirror* platform in the medical curriculum.

3.5 Summary

In this chapter, an overview of the *AR Magic Mirror* platform as a revolutionary teaching resource for self-directed and personalized anatomy learning was presented. Following a brief outline of the conceptual framework of the system as well as its previous iterations by Blum et al. [54] and Meng et al. [316], the technical novelties, including real-time skeletal animation, improved interactive gesture control, and advanced perceptual in-situ visualization, were presented (see sections 3.1 and 3.2). In addition to these technical contributions, section 3.3 provided a detailed analysis of the perceptual differences between *Reversing* and *Non-Reversing Magic Mirrors* (RMM vs. NRMM) and their effects on user interaction and perception in the context of AR anatomy teaching. While the study revealed that previously acquired domain knowledge, lateral significance, and the mere-exposure effect can make an NRMM design the preferred configuration, an RMM design greatly facilitates interaction with the system and more closely reflects the mirror paradigm that forms the basic underlying principle of the *AR Magic Mirror* platform. Both the technical improvements and the study of the two different *Magic Mirror* designs paved the way for another major contribution of this thesis, the large-scale evaluations of the platform and its integration into the medical curriculum. During three user studies, the *AR Magic Mirror* platform was deployed for the first time in a realistic curricular environment and its additional value for serving as a complementary tool for both anatomy and radiology education was evaluated. Overall, a total of **1701** medical students worked with the *AR Magic Mirror* platform during specially designed tutorials or self-directed group learning sessions and validated the benefits of the system compared to both traditional textbook learning and the *Anatmage* as a state-of-the-art commercial product for integrated anatomy and radiology education. In all three studies, the *AR Magic Mirror* platform could prove its additional value and was found to offer unique benefits to medical students, particularly in terms of 3-dimensional understanding of anatomical structures. These benefits were not only measured qualitatively during surveys, but also a quantitative learning effect could be demonstrated for the first time.

Thanks to these very encouraging results, the *AR Magic Mirror* platform is nowadays fully integrated into the gross anatomy course at the LMU Munich and every first-year medical student attends a set of mandatory tutorial sessions, closely resembling those described in the second user study. Furthermore, additional studies are currently underway to investigate the long-term benefits of the system in terms of student learning outcome. These long-term studies are expected to further manifest the role of the *AR Magic Mirror* platform as a highly promising new resource for interactive, student-centered, and personalized anatomy learning.

The VesARlius Anatomy Learning Application

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The anatomy learning application *VesARlius* represents the second major contribution to this thesis. While the previously introduced AR *Magic Mirror* platform was a screen-based AR system that allowed users to study anatomy in relation to their own bodies, *VesARlius* is an AR anatomy learning application that leverages state-of-the-art Head-Mounted Display (HMD) technology to visualize virtual 3D models of anatomical structures and radiological section images. Besides the different approaches to displaying AR content, the major difference between the two solutions is that *VesARlius* allows a large number of co-located medical students to engage in collaborative, team-based anatomy learning sessions. Whereas the AR *Magic Mirror* platform is limited to only a single user interacting with the system at a time, *VesARlius* incorporates a number of different collaboration paradigms that allow multiple co-located students to explore the system's content in a collaborative and synchronized learning environment. At the beginning of this chapter, the technical aspects of the *VesARlius* application are presented (section 4.1). Similar to the AR *Magic Mirror* platform, *VesARlius* was evaluated within two user studies performed at LMU Munich in realistic curricular environments. The results of these evaluation studies are outlined in section 4.2. During both studies, the limited field of view (FoV) of the HMD was mentioned as one of the main limitations of the *VesARlius* application. Therefore, section 4.3 proposes a series of novel visualization approaches that are aimed at minimizing these FoV restrictions, which are inherent to all current state-of-the-art HMDs.

4.1 VesARlius Concept & Overview

In the section on the history of anatomy education at the beginning of this thesis we learned about *Andreas Vesalius*, a sixteenth-century Flemish anatomist—often referred to as the *Father of Modern Human Anatomy*—who initiated one of the most disruptive paradigm shifts in the history of anatomy by changing the educational emphasis from predominantly theoretical studies to practical, hands-on observations of the human body through cadaver dissections. In today's time, novel AR anatomy teaching resources, as seen in the previous chapter, have the potential to initiate another impactful paradigm shift, away from passive, teacher-centered, and delivery-based learning towards interactive, student-centered, and explorative learning that emphasizes the hands-on character of anatomy education. Just as traditional book study has remained one of the most important learning resources for medical students to this day and was not completely abandoned in favor of dissections in the centuries after *Vesalius*, the introduction of novel AR learning resources does not intend to completely replace established learning paradigms such as book study or lectures as the only learning medium suitable for all purposes and for all students. However, these traditional paradigms will be increasingly supplemented and enhanced by novel tools that leverage the potential of AR. The *VesARlius* anatomy learning application that was developed in this thesis and that received its name from the aforementioned *Andreas Vesalius* is one of these novel tools that allows students to study human gross anatomy interactively by means of AR. The application is specifically designed for the Microsoft HoloLens and leverages the power of HMD-based AR technology. Virtual models of 3D anatomy structures as well as radiological section images can be placed at arbitrary locations in the environment and viewed through the display of the HoloLens. In contrast to the *AR Magic Mirror* platform that can only be operated by a single user, *VesARlius* enables multiple co-located students to engage in a collaborative team-based learning environment. In medicine, peer-learning is a well established practice that is used effectively by many students. Collaborative AR systems for multiple co-located users offer the potential to combine the benefits of peer-learning and interactive AR learning environments. *VesARlius* as a novel AR anatomy learning application has been specifically designed for this purpose and employs a series of multi-user collaboration paradigms that enable large groups of co-located users (10+) to jointly study anatomy. Multi-user AR collaboration presents a unique setting with distinct challenges and requirements for user interaction and information sharing. The following subsections will therefore present a detailed overview of the technical features as well as the multi-user collaboration paradigms that are employed within the *VesARlius* application.

4.1.1 User Interface

The *VesARlius* application is specifically tailored for running on the Microsoft HoloLens and is implemented using *Unity3D* as the underlying game engine and the *Mixed Reality Toolkit* (MRTK), which provides a set of components and features to accelerate the development of cross-platform Mixed Reality applications in *Unity3D*. As soon as *VesARlius* is started on the HoloLens, the user is presented with the application's user interface (UI), which provides access to all important functions of the application. The UI, which can either be locked in a fixed position or follow the user's head rotation, is comprised of several components, which will be discussed in the next subsections. An overview of the UI can be seen in Figure 4.1.

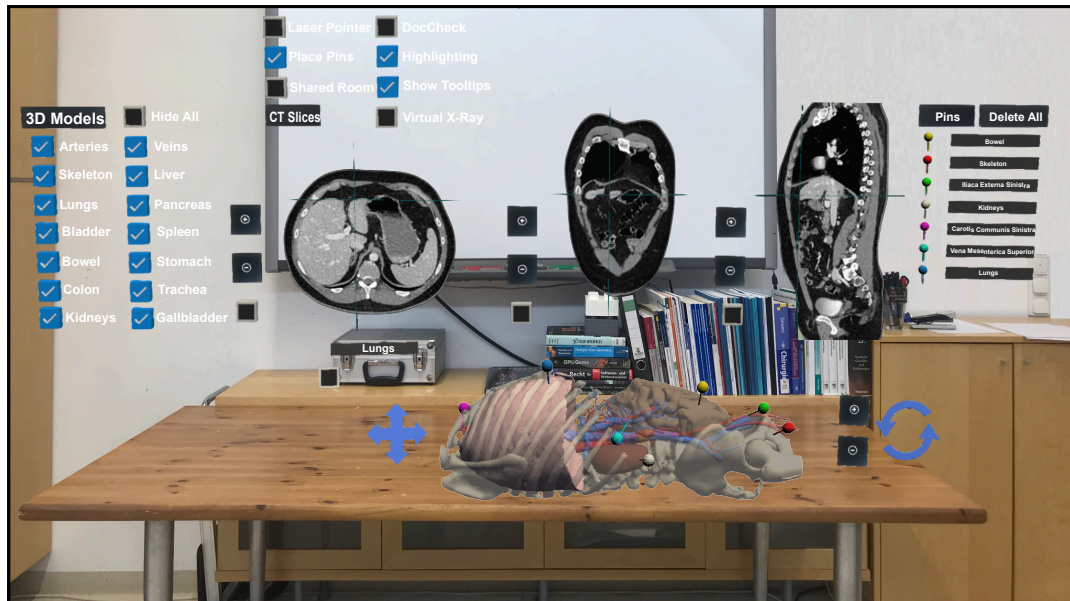


Fig. 4.1. Illustration of the different components that the *VesARlius* user interface (UI) is comprised of. The virtual 3D model shown in the bottom of the UI represents the core element of the *VesARlius* application. The model is reconstructed from the radiological section images in the center of the UI, such that there is a one-to-one correspondence between the two. A menu for showing and hiding individual anatomical structures in the 3D model is depicted on the left of the UI. Additional components of the UI include a menu for controlling several settings of the application at the top, as well as a pin menu that displays all currently active pins and the names of the corresponding structures on the right of the UI.

3D Virtual Anatomy View

The 3D virtual anatomy model not only constitutes the core component of the *VesARlius* UI, but also the most important element of the entire application. The user has the possibility to place the 3D model together with the other UI components at arbitrary positions in space. Repositioning can be done at any time by pressing the arrow symbol to the left of the model. This will cause the model to follow the user's head movement until the placement is confirmed and the model is locked in space again. Additionally, the two controls next to the rotation symbol at the right of the model enable the user to rotate the 3D model in both directions along the longitudinal axis. This allows the user to explore the model from both the front and the back. Since the position of the model is fixed in space, the user can freely choose the point of view onto the model by walking around or approaching it, allowing every detail of the model to be explored. One of the main differences between the 3D model that is employed within the *AR Magic Mirror* platform and the model that is available in the *VesARlius* application is that the latter is reconstructed from a CT volume. While *VesARlius* also provides the ability to display generic models that have been created using a 3D modeling software, a model reconstructed from CT data offers a number of distinct advantages that can be very useful for interactive and collaborative anatomy learning. These advantages will be discussed in detail in the following subsection. Manually reconstructing anatomical structures from CT data is a very time-consuming and tedious task. Therefore, a semi-automatic approach was chosen, in which a number of structures were segmented using the *ITK Snap* medical image segmentation toolkit (University of Pennsylvania, Philadelphia, USA). Both traditional threshold based segmentation as well as region growing approaches were used. Additionally, a manual refinement of the resulting segmentations was performed under the guidance of two experienced medical students from the Faculty of Medicine at LMU Munich. Figure 4.2 depicts

all anatomy structures that have been segmented using this process and that are available within the *VesARlius* application. Individual structures can be selected by the user by means of the HoloLens *Tap* gesture or by clicking onto the structure with the HoloLens pointer. Upon selection, the structure will be highlighted, i.e. all other structures of the 3D model will be rendered semi-transparent while the selected structure is fully opaque (see Figure 4.1, where the lungs are highlighted). Lastly, it is possible to show and hide individual structures within the 3D model using the menu on the left side of the *VesARlius* UI. For every structure, a checkbox indicates whether it is currently displayed or not. Additionally, there is a checkbox to show or hide all available anatomical structures.

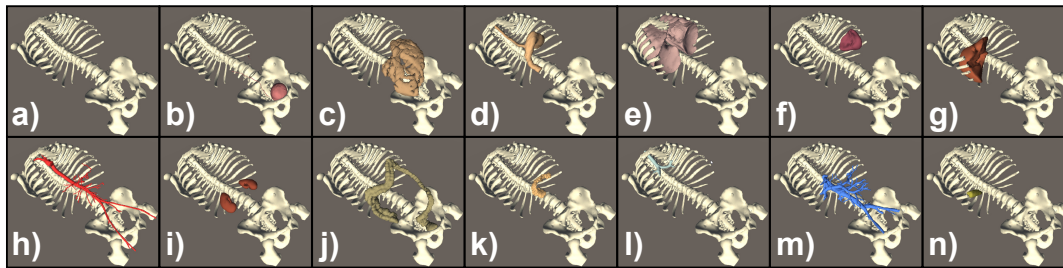


Fig. 4.2. Overview of the individual structures that the 3D anatomy model employed within the *VesARlius* application is comprised of. Each structure is shown in combination with the skeleton for better comprehension of the anatomical context. a) skeleton only; b) bladder and ureters; c) small intestine; d) stomach and esophagus; e) lungs; f) spleen; g) liver; h) arteries; i) kidneys; j) colon; k) pancreas; l) trachea (lower respiratory tract); m) veins; n) gallbladder. While both arteries and veins are shown as one structure, they consist of several individual arteries and veins that have been divided manually.

Medical Section Images

Aside from the 3D anatomy model, the medical section images constitute the second main component of the *VesARlius* UI. Similar to the AR *Magic Mirror* platform, arbitrary DICOM images can be integrated into the application. Three images corresponding to the three orthogonal section planes (transversal, sagittal, and frontal) are displayed directly above the 3D model, and the user can scroll through each of these images using small controls located to the left of the respective image. Additionally, it is possible to click on a specific point on one of the three section images, triggering a cross-hair to visually highlight the selected point. As this point not only represents a 2D pixel in the respective section image, but a voxel within the entire 3D volume, it is possible to calculate and highlight the corresponding points in the other two section images as well. This way the user has the possibility to select any pixel in one section image and see the corresponding pixels in the other two. This feature is very common in modern DICOM viewers and can be very helpful for medical students to better understand the spatial relationships of certain anatomical structures in the body. On top of that, one of the most important characteristics of the medical section images is the one-to-one correspondence with the 3D anatomy model. In the previous subsection it was explained that the virtual anatomy models are reconstructed directly from the CT volume. As a result of this, each vertex in the 3D model corresponds to a particular voxel within the CT volume. It is therefore possible to click on a specific vertex in the 3D model such that the corresponding voxel is highlighted in all three orthogonal image planes. While it is also possible to obtain a specific vertex by clicking on a point in one of the section images, it is likely that this vertex location will fall either inside a specific anatomical structure or on a point that does not belong to any of the segmented structures. The one-to-one correspondence is therefore bilateral in nature, but only the former direction provides a significant educational benefit. Another important

feature of the *VesARlius* application is that the medical section images can be directly placed into the 3D volume by activating a small check box below the controls that allow the user to scroll through the section image. By *grabbing* the image (either through the continuous use of the *Tap* gesture or by pressing the button on the HoloLens clicker) the user has the possibility to slide the section image through the entire 3D volume along the respective axis in order to interactively explore the course of certain anatomical structures. It is possible to activate either a single section image only or a combination of several section images. Figure 4.3 depicts an overview of these different configurations.

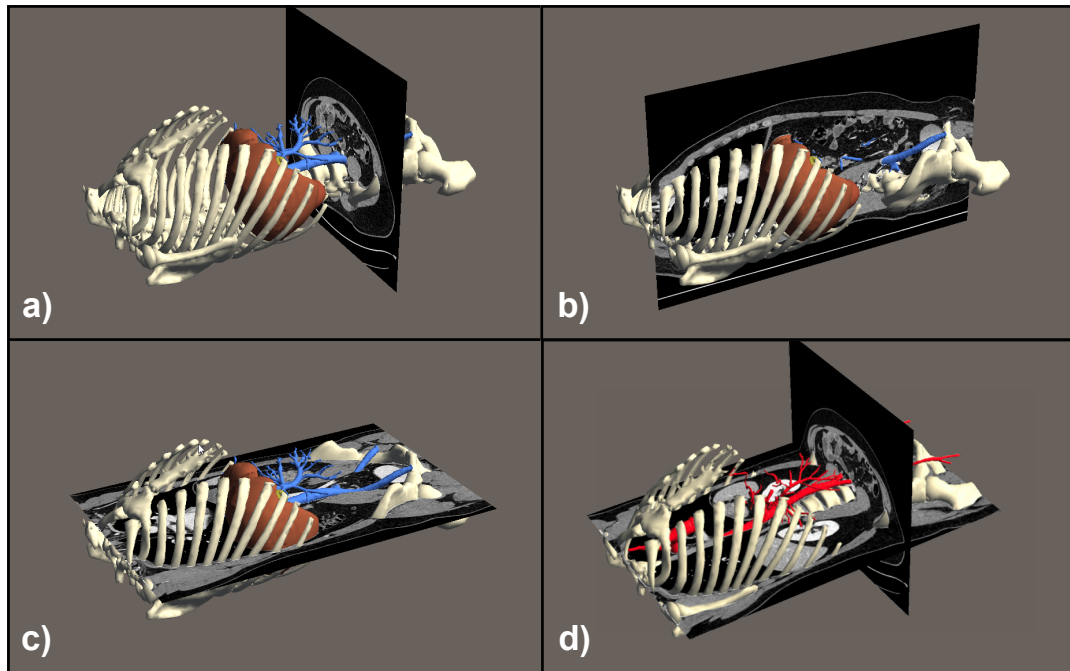


Fig. 4.3. Close-up views of the 3D model with medical section images placed directly inside the model. All section images are displayed exactly where they correspond to the 3D model such that students can obtain a better understanding of the CT images and the 3-dimensional relations between anatomical structures. a) transversal section image; b) sagittal section image; c) frontal section image; d) combination of transversal and frontal section images.

VesARlius Settings Menu

At the top of the UI, directly above the transversal CT slice, the *VesARlius* settings menu is located, allowing the user to enable or disable a number of settings that control specific functionalities of the application. All three settings in the left column of the menu (*Laser Pointer*, *Place Pins*, and *Shared Room*) are specific to the collaboration features of the *VesARlius* application and will be discussed extensively in the upcoming subsection (see Figure 4.1). Subsequently, a short overview of the remaining four settings in the right column of the menu will be presented.

DocCheck Information Instead of the three orthogonal section images, *VesARlius* offers the possibility to display entries from the well-known medical dictionary *DocCheck*, which provides textual information on a wide range of anatomical topics [508]. The application recognizes which structure is currently selected within the 3D model and automatically retrieves the correct *DocCheck* entry. Even cross-references to other dictionary entries are available. In this

way, *VesARlius* combines the benefits of an interactive AR learning experience with traditional information from anatomy textbooks. Figure 4.4 illustrates an example *DocCheck* entry of the liver.

The screenshot shows a 'Liver' entry from DocCheck. It is organized into several columns and sections:

- 1 Definition:** The liver is the central organ of the entire metabolism. The most important functions of this organ are:
 - Decomposition and excretion of substances
 - Production of essential proteins
 - Utilization of food components
- 2 Overview:** The liver is the largest digestive gland in the adult human body. It generates several blood proteins, antibodies and bile, and is the main detoxification organ. Almost all nutrients that are absorbed in the blood from the intestine initially arrive at the liver, and then based on requirement these are released into the blood or eliminated from the blood. Other functions of the liver are the storage of vitamins and the synthesis of initial products for hormone production.
- 3 Anatomy:** The liver of a human adult weighs approximately between 1400 and 1800 gm. It is a soft, fairly smooth structured organ that is situated in the right upper abdomen. The liver can be macroscopically subdivided into 4 different lobes:
 - Lobus hepatis dexter
 - Lobus hepatis sinister
 - Lobus quadratus hepatis
 - Lobus caudatus hepatis
- 4 Functions:** The liver is closely involved in the metabolism of glucose, fat and proteins. Glucose is absorbed from the intestinal blood supply and passes it on to the rest of the body in a controlled way. A surplus is stored as glycogen. In times of hunger, the stored substance is metabolized to glucose. The liver influences the blood sugar level through the control of hormones (e.g. insulin) and can keep it constant independent of the food supply. Insulin activates the "burning" of the sugar in the liver and checks the decomposition of fat.
 - 4.1 Overview:**
 - Glucose in the form of glycogen
 - Fat in the form of lipoproteins
 - Several vitamins and iron
 - Blood
 - Generation of proteins
 - Albumin
 - Fibrinogen
 - Fibrinogen
 - Generation of bile
 - Synthesis of cholesterol and bile acids
 - Decomposition and detoxification
 - Decomposition of hemoglobin resulting in bilirubin
 - Metabolism of ammonia into urea
 - Hormones
 - Medicaments
 - Defense function (germs from the GIT)
 - Hematopoiesis in the fetus up to the 7th month of pregnancy.
- 5 Liver enzymes:** In case of liver diseases, the blood test shows valuable evidences of the type and extent of the disease. Enzymes are needed in the liver like elsewhere in the body, to sustain its metabolic activities. In case of damage to the liver cells, these enzymes can be found in increased quantities in the blood serum. Based on the increase in the type of enzyme, one can infer the type of the disease. The magnitude of the enzyme increase corresponds to the extent of the damage to the liver cells. Cell damages can be caused by, among others, virus infections, alcohol, poisoning or tumors.

All enzymes in the liver cells can also be found in other body cells, like for instance in the heart and skeletal muscles.
- 6 Diagnostics:**
 - Anamnesis
 - Palpation
 - Inspection (skin marks, ascites and edema)
 - Laboratory diagnostics
 - Bilirubin (direct and indirect)
 - Bilirubin excretion in urine
 - GGT, SGPT, GGT, ALP, alkaline phosphatase
 - CHE, quick value and albumin
 - Hepatitis serology
 - Serum iron, serum ferritin, copper and Ceruloplasmin level
 - Imaging procedures
 - Ultrasonics
 - CT
 - NMR
 - ESCP
 - Liver biopsy
- 7 Important liver diseases:**
 - Fatty liver
 - Alcoholic hepatitis
 - Acute viral hepatitis A, B, C, D and E
 - Hepatitis with other viral diseases
 - Chronic hepatitis
 - Liver cirrhosis
 - Acute liver failure
 - Hepatic coma
 - Liver metastases
 - Hepatocellular carcinoma (HCC)
 - Liver abscesses

Tags: Digestion, Gastroenterology, Gland, Liver, Organ

Fig. 4.4. Exemplary *DocCheck* entry for the liver [508]. Instead of displaying the radiological section images, the user of the *VesARlius* application has the possibility to display information from the medical dictionary *DocCheck* for the currently selected organ.

Anatomical Structure Highlighting The second setting in the right column of the *VesARlius* settings menu controls whether anatomical structures within the 3D model are visually highlighted in case the user selects them. As mentioned previously, highlighted structures are rendered fully opaque while all other structures will be rendered semi-transparent. This functionality can be specifically helpful when multiple students collaboratively study smaller anatomical structures such as individual arteries and veins. Figure 4.5 shows a comparison between two close-up views of a 3D model. In Figure 4.5a the superior mesenteric artery is highlighted such that all other structures are rendered semi-transparent, whereas in Figure 4.5b no structure is highlighted.

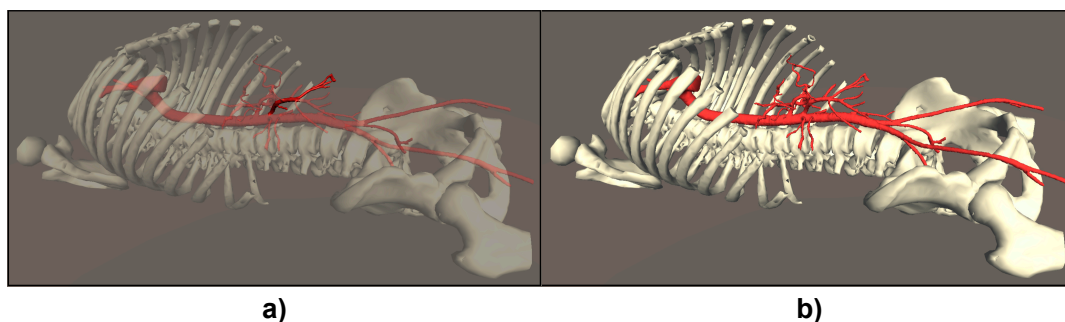


Fig. 4.5. Comparison of a 3D model with a) the superior mesenteric artery highlighted, and b) no anatomical structure highlighted. In the former case, the selected structure is rendered fully opaque while all other structures are semi-transparent.

Anatomy Tooltip Another feature of the *VesARlius* application that can be controlled via a menu setting is the anatomy tooltip. If the user selects a specific anatomical structure within the 3D model, a small tooltip below the transversal section image displays the name of this structure. Similarly, if the user selects a specific point in one of the three orthogonal section

images above the 3D anatomy model, the application evaluates whether the corresponding pixel belongs to one of the segmented anatomical structures and, if it does, displays the name of the structure in the tooltip. In the previous Figure 4.1 the lungs are highlighted and the anatomy tooltip below the transversal section image displays the associated text to the user.

Virtual X-Ray Module The last setting in the right column of the *VesARlius* settings menu is used to activate or deactivate the virtual X-ray module of the application. When enabled, all UI components except the 3D anatomy model are hidden and a virtual model of a mobile C-arm is displayed instead. The user has the ability to position the C-arm along the 3D anatomy model using a series of controls. Two virtual arrows drive the translation of the C-arm, while two sliders are used to rotate the arc of the C-arm in the vertical and horizontal directions. Once the user has successfully positioned the C-arm, it is possible to take a virtual X-ray image by tapping on a small virtual button. This virtual X-ray image resembles a digitally reconstructed radiograph (DRR) and is calculated from the CT volume using a technique known as ray casting. The simulated X-ray image is then displayed to the user next to the 3D anatomy model. Figure 4.6 illustrates a close-up view of the virtual X-ray module of the *VesARlius* application.

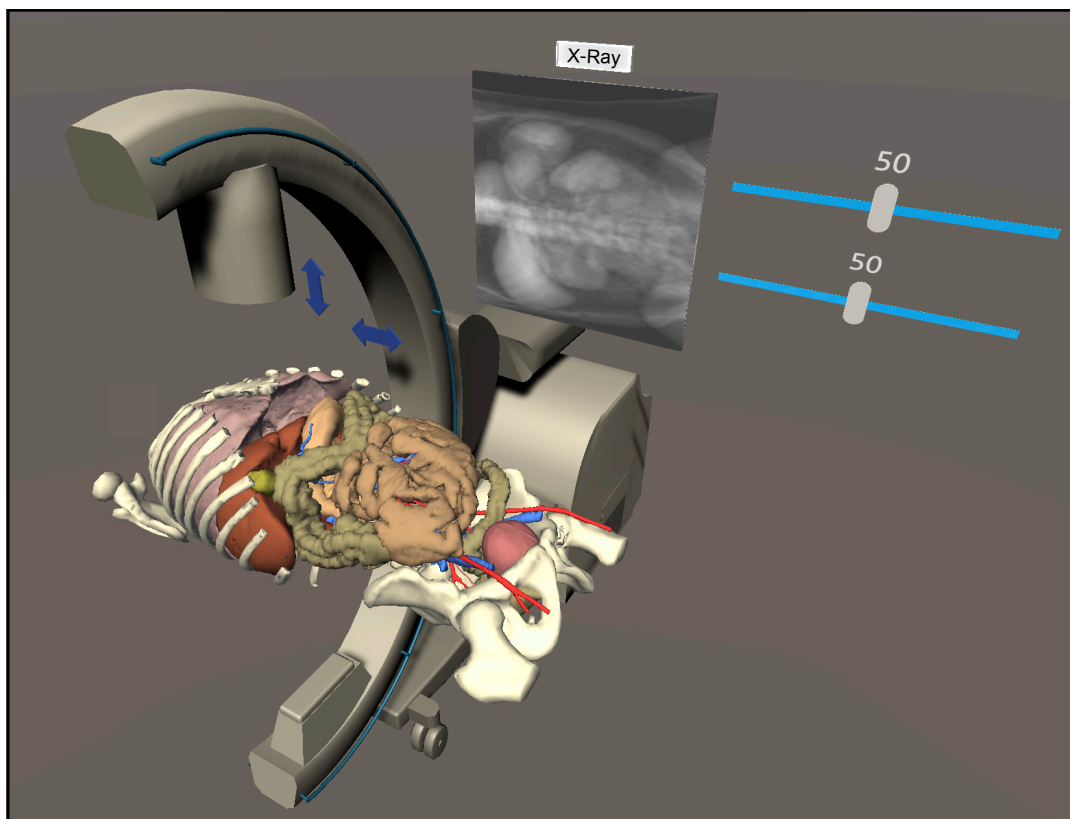


Fig. 4.6. Overview of the *VesARlius* virtual X-Ray module. The user can position a virtual model of a mobile C-arm and take virtual X-ray images, which represent digitally reconstructed radiographs (DRRs) and are calculated from the CT volume using ray casting. The resulting DRRs depend on where the X-ray source and the detector of the C-arm are positioned.

Pin Menu

Alongside the 3D anatomy model, radiological section images, and the *VesARlius* settings menu, the last remaining component of the UI is the pin menu to the right of the frontal CT image, see Figure 4.1. Since the placement of colored pins represents one of the paradigms in *VesARlius* for enabling collaboration between multiple co-located students, it will be discussed in more detail in the next subsection. The pin menu shows all pins that have been placed into the 3D model as well as the names of the anatomical structures in which the pins are placed. Additionally, the pin menu provides a button for deleting all currently placed pins. A close-up view of the pin menu is shown in Figure 4.7.

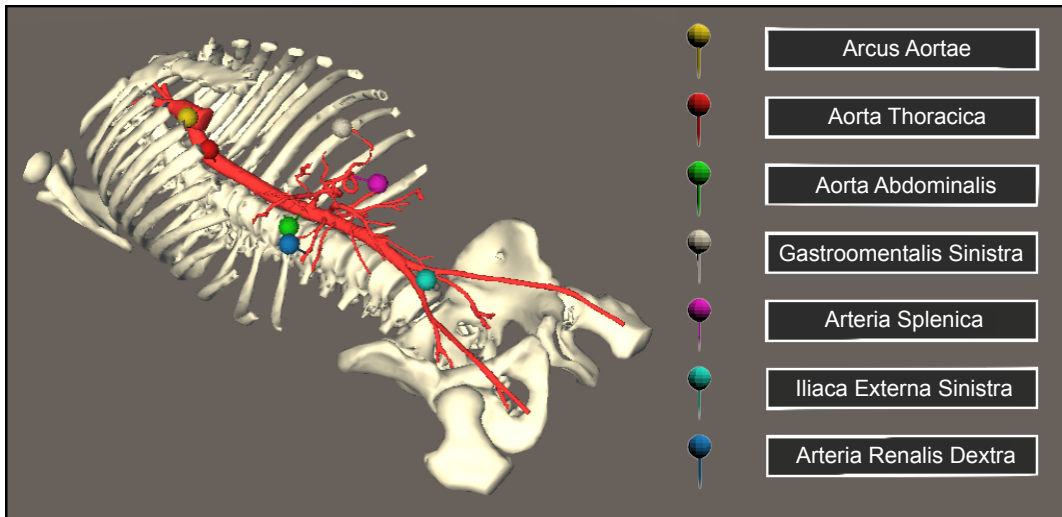


Fig. 4.7. Close-up view of the *VesARlius* pin menu which provides a summary of all pins currently placed in the 3D anatomy model and the names of the corresponding structures.

4.1.2 Collaboration Paradigms

Although the functionalities described in the previous subsection already make the *VesARlius* application a valuable resource for interactive, AR-based anatomy learning, the unique selling point of the application is that multiple co-located students can engage in a collaborative learning experience by sharing the content of the application across several devices. This allows multiple students, each of them wearing a HoloLens, to view and interact with the same 3D anatomy model by synchronizing the entire UI between them. As previously mentioned, the *VesARlius* application is implemented using the *Mixed Reality Toolkit* (MRTK), which provides a set of components and functionalities to facilitate the development of cross-platform Mixed Reality applications in *Unity3D*. One of these components is the *HoloLens Sharing Service* that forms the underlying basis for the collaboration paradigms discussed in this subsection. The *Sharing Service* allows multiple HoloLens devices to communicate with each other and remain seamlessly synchronized in real time. It consists of both a *Client* library, which allows applications to connect directly to the *Sharing Service*, as well as a server executable (the *Sharing Service* itself) that enables discovery and connecting individual clients. This infrastructure allows multiple students with a HoloLens to jointly collaborate with a fully synchronized version of the *VesARlius* application. Figure 4.8 shows four medical students jointly exploring the *VesARlius* anatomy model in such a collaborative learning environment. In addition to synchronizing the entire UI of the application, *VesARlius* provides

a set of collaboration paradigms that are particularly aimed at facilitating the collaboration between students in joint learning sessions. In the following, a detailed overview of all these collaboration paradigms is presented.



Fig. 4.8. Four medical students use the *VesARlius* application during a joint anatomy learning session. They work in a *Synchronized Room* such that the entire UI is identical for all students. *Colored Pins* are placed on the virtual 3D model to highlight different structures of interest. The CT images correspond to the position of the last placed pin. A dotted red line originating from the HoloLens of the left student indicates the *Virtual Laser Pointer* functionality. (Note: the dotted red line is only used for highlighting the gaze point and is not shown on the HoloLens).

Synchronized Rooms

The most important collaboration paradigm that allows multiple, co-located users to engage in an interactive and collaborative learning environment within the *VesARlius* application are *Synchronized Rooms*. For all users within the same room, the entire UI of the application is synchronized in real-time. This applies to all functionalities of the application, such as the rotation of the 3D model, the selection and highlighting of individual anatomical structures or image sections, and updates to the *VesARlius* settings menu. Each time a user performs a UI update, such as placing a colored pin on a specific anatomical structure, the information is propagated to all users in the same synchronized room and the pin appears to everyone. When the *VesARlius* application is launched, users are presented with a list of all currently active rooms. They have the choice of either entering one of these available rooms or opening a new one. Additionally, users are always free to leave the current room and join a new one using the *Share Room* checkbox in the left column of the *VesARlius* settings menu. Figure 4.8 shows a scene where a group of four students in a single synchronized room interacts with the *VesARlius* application.

Individual Content Placement

While all elements of the *VesARlius* UI are subject to the above room synchronization, users still have the ability to freely position their local copy of the application in the environment. As soon as the virtual arrow control located on the left side of the 3D anatomy model is selected, the entire UI will start following the user's head movement. The user can therefore reposition the UI by simply looking around until the placement is confirmed and the position of the UI is locked again in the environment. While this positional synchronization could easily be achieved using marker-tracking, it severely limits the number of users that can observe a specific virtual object from a given position. Especially when working in teams of co-located users or in restricted environments with limited space, students can thus position their individual copy such that they can comfortably move around without disturbing other users.

Virtual Laser Pointer

Another important paradigm for enabling multi-user collaboration in the *VesARlius* application is the *Virtual Laser Pointer*. This feature can be effectively used to direct the focus of other users to a particular object of interest or a specific element of the *VesARlius* UI. Similar to a real-world laser pointer, a small colored circle is displayed at the location where the viewing direction vector of the user who is currently controlling the laser pointer (i.e. the presenter) intersects with a virtual object. There can be one presenter for each synchronized room at a time, and all users can take over the virtual laser pointer from another user to facilitate communication between them. This can be achieved by enabling the corresponding checkbox in the *VesARlius* settings menu. Although all users could possibly be assigned a personal virtual laser pointer with a specific color at the same time, this would result in a confusing and convoluted UI as multiple colored dots would quickly change their position due to rapid changes in viewing directions. The virtual laser pointer functionality is shown in Figure 4.8 with the left student acting as the presenter when the laser pointer functionality is enabled.

Colored Pins

The last essential collaboration paradigm that has been integrated into the *VesARlius* application are *Colored Pins*. Compared to the virtual laser pointer discussed earlier, these pins can be helpful to achieve a more permanent emphasis of certain anatomical structures in the 3D model. Users can place colored pins by tapping on a specific location on the model, resulting in a new pin being placed on the nearest vertex and pointing in the direction of the corresponding vertex normal. A total of seven colored pins can be placed into the model, with each pin having a different color. The position of all pins is identical for all users within a synchronized room and each user has the ability to manipulate the pin locations. A list of all currently placed pins together with the name of the corresponding anatomical structure in which they are placed is part of the *VesARlius* UI. In Figure 4.8 several colored pins have been placed into the 3D model. An overview of the pin menu is shown in Figure 4.7, where the maximum number of seven colored pins have been placed on different arterial branches.

4.2 Evaluation & Curriculum Integration

The work presented in the first half of this section is an extended version of parts of two papers, one presented at the conference ISMAR 2019 [64] and the other one published in the journal *Anatomical Sciences Education* in 2020 [62]. The content is reproduced with the permission of all authors, ©IEEE for [64] and ©American Association of Anatomists for [62].

The technical features of the *VesARlius* application that were presented in the previous section allow multiple co-located students to jointly work with the system and engage in an interactive and collaborative AR anatomy learning environment. In order to determine the effectiveness of the *VesARlius* application as a complementary teaching resource during collaborative anatomy learning sessions, the system was embedded into the curricular framework of LMU Munich and evaluated with medical students within two user studies, similar to the evaluation of the *AR Magic Mirror* platform. The first study was conducted during a full-day gross anatomy seminar with 16 first-year medical students and focused not only on the overall benefits of the system in terms of quantitative learning outcome, but especially on the collaborative features of *VesARlius* for team-based learning of anatomy in small groups compared to traditional learning with textbooks and 3D models. In a follow-up study, which took place during an elective course with 20 medical students, the particular advantages of running *VesARlius* on an HMD were investigated. For this purpose a *CT-Test* module was developed and integrated into the *VesARlius* application. The students were given the task of correctly determining the position of a particular CT slice, with one half operating *VesARlius* on a conventional desktop PC, while the other half ran the application on the HoloLens. Although both studies had a relatively small number of participants, much less than the large-scale studies with the *AR Magic Mirror* platform, they nevertheless demonstrate the great potential of integrating novel collaborative AR systems that stimulate interactive and student-centered learning into a modern anatomy curriculum.

4.2.1 Gross Anatomy Seminar Study

The first evaluation of the *VesARlius* application, which investigated the potential of the system to enable interactive and collaborative anatomy learning in teams, was conducted as part of an experimental user study that took place during a full-day seminar on human gross anatomy. The differences in learning outcome between the experimental group studying anatomy with *VesARlius* and a control group studying with traditional anatomy textbooks and 3D models were quantified using two anatomy knowledge tests. Furthermore, a series of additional questionnaires as well as a survey was administered to the participants in order to determine the mental effort experienced while working with *VesARlius* and the students' subjective overall impressions of the application. In conjunction with previous research that introduced such novel AR systems into the medical curriculum, in particular the *AR Magic Mirror* platform, three hypotheses were formulated that were subject to investigation during the experimental user study: 1) the *VesARlius* application offers an equivalent or better learning outcome compared to traditional anatomy learning with textbooks and 3D models; 2) working with the *VesARlius* application improves the students' subjective 3D understanding

of topographic anatomy; and 3) the *VesARlius* application offers unique advantages in terms of the collaborative aspects of learning. In the following subsections, the individual parts of the experimental user study will be presented, followed by a detailed description of the study results and a discussion of the most important findings. Overall, the study design was almost identical to the one employed during the elective anatomy & radiology study, which was aimed at measuring the quantitative benefits in terms of learning outcome of the AR *Magic Mirror* platform. Figure 4.9 provides an overview of the underlying study design and contains all important stages of the experimental user study in chronological order.

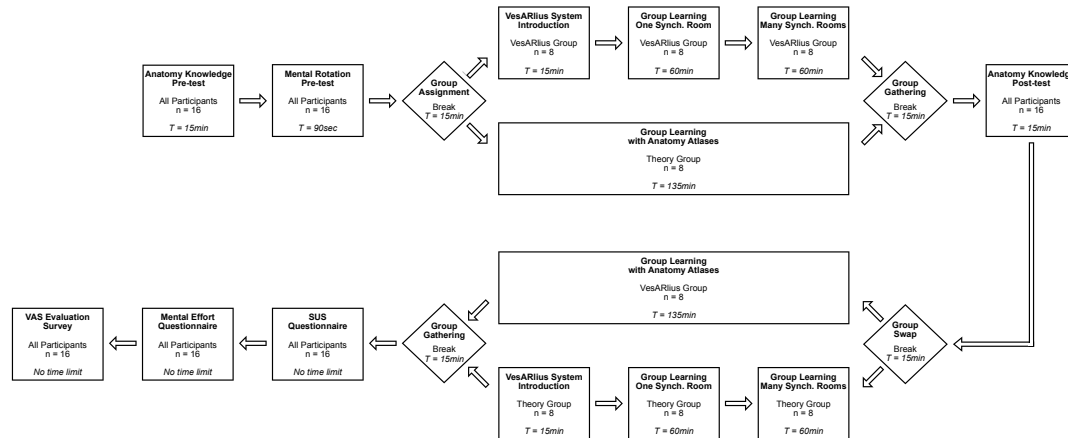


Fig. 4.9. Schematic overview of the study design with all stages of the experimental user study in chronological order. For each stage, the number of students (n) and the available time (T) are given.

Participants

Similar to all previous evaluation studies of the AR *Magic Mirror*, the present study of the *VesARlius* application was conducted at the Faculty of Medicine at the LMU Munich. Sixteen first-year medical students (11 women, 5 men) with an average age of 21.0 ± 2.9 years were recruited as participants. Prior to the study, all students had already completed the course on macroscopic anatomy, consisting of both a theoretical part with 90 hours of traditional lectures and a practical laboratory part including a compulsory dissection course. None of the students reported previous experience with the Microsoft HoloLens or other AR-HMDs, however, some of them had prior exposure to smartphone-based AR (2.31 ± 1.20) and computer games (3.44 ± 1.90), both of which were assessed on a 7-point Likert scale. The students all voluntarily took part in the user study and were paid a total of 80€ as financial compensation. In addition, all study data were recorded anonymously during the user study and written consent was obtained from each of the subjects. Most importantly, none of the students participated in any of the AR *Magic Mirror* evaluation studies described in section 3.4.

Pre-Tests: Anatomy Knowledge & Mental Rotation

Following a brief opening segment in which the general structure of the seminar was presented, the students were confronted with two unannounced paper-based pre-tests: 1) an anatomy knowledge test; and 2) a mental rotation test, both of which were similar in style to the tests used during the elective anatomy & radiology study from section 3.4.3. The former was co-designed by two anatomists responsible for the anatomy teaching curriculum at LMU Munich and consisted of 20 multiple choice questions (with 5 potential answers each) about topographic anatomy. Of these 100 possible answers, 71 came from the *Knowledge* domain of

Bloom et al., while the remaining 29 came from the *Understanding* domain [53]. An exemplary question from the anatomy knowledge pre-test is shown in Figure 4.10a.

The second pre-test was a mental rotation (MR) test to assess the students' spatial ability. Similar to the MR tests used within the AR *Magic Mirror* evaluation studies, students were shown image pairs of Shepard and Metzler-like block stimuli, and they had to identify identical block stimuli for each of the 20 questions [149, 420]. Two exemplary questions from the MR test are depicted in Figure 4.10b. Both pre-tests were conducted in a large auditorium with students spatially distributed to avoid copying answers from neighboring students, see Figure 4.11.

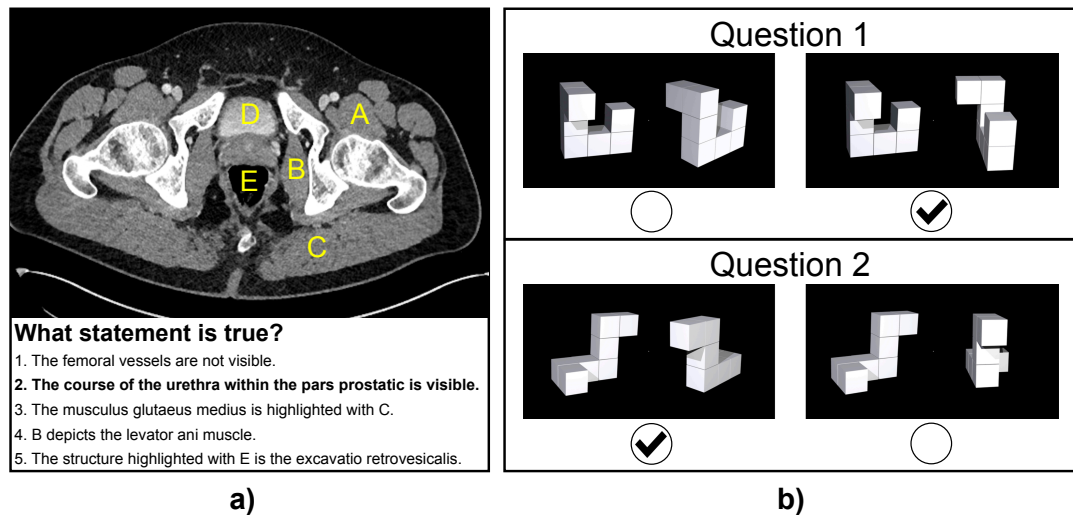


Fig. 4.10. Example questions from the two paper-based pre-tests, with the correct answers highlighted. a) multiple-choice question from the anatomy knowledge test; b) two questions from the mental rotation pre-test.



Fig. 4.11. All 16 first-year medical students during the two paper-based pre-tests in the auditorium.

Group Assignment

Based on the results of the two pre-tests, the students were manually assigned to either the experimental group (in which students worked with the *VesARlius* application on the HoloLens) or the control group (in which students worked with traditional anatomy textbooks and 3D models). Consequently, both groups consisted of eight students with comparable anatomy skills (*VesARlius*: $25.65 \pm 9.80\%$; *Theory*: $25.65 \pm 6.25\%$) and mental rotation skills (*VesARlius*: $41.90 \pm 20.35\%$; *Theory*: $41.90 \pm 27.90\%$). The students in the experimental group had an

average age of 21.4 ± 3.6 years (5 female, 3 male) compared to 20.6 ± 2.3 years (6 female, 2 male) in the control group.

Collaborative Group Learning Session

During the collaborative group learning session, which formed the main part of the present user study, the students from both groups were given a set of learning objectives derived from the contents of the pre-test focusing on the topography of the organs in the abdominal and pelvic regions. In particular, the students were asked to locate all organs on which questions were asked in the pre-test and to examine their vascularization. Additionally, the students had to review the relationship of the abdominal and pelvic structures to each other and their position (specifically their height) in the body. The learning objectives were intentionally set very broadly in order to avoid a knowledge bias in the post-test. Students in the experimental group worked with the *VesARlius* application on Microsoft HoloLens HMDs, while in the control group three different types of anatomy textbooks [118, 362, 462], two of each type, as well as three 3D organ models of a male torso, a male pelvis, and a female pelvis (SOMSO@MODELLE GmbH, Coburg, Germany) were distributed. The entire collaborative learning session in both groups was completely self-directed and the students had no additional help from an experienced anatomist or teacher who could answer specific questions. Figure 4.12 depicts both groups in their respective learning environment.

While students in the control group could choose to study in a large group or in subgroups for the entire duration of the collaborative learning session (135 min), the structure of the learning session in the experimental group was predetermined and comprised three different parts. As none of the students had previous experience with an AR-HMD, the first part of the session was a 15-minute tutorial to introduce all participants to the general use of the HoloLens as well as to the specific functionalities of the *VesARlius* application. By the end of the tutorial, all students were able to see their individual copy of the *VesARlius* application. In the second part of the learning session (60 min), all students were requested to work together in a single synchronized room where the entire state of the application was identical for everyone and all collaboration paradigms offered by the *VesARlius* application could be employed. For the third and final part of the learning session (another 60 min), students could either stay in the same synchronized room, open a new room with other students, or work with the application individually.



Fig. 4.12. Comparison of the two groups during the collaborative group learning session. a) students from the experimental group working with *VesARlius* on the HoloLens; b) students in the control group studying with anatomy textbooks and 3D models.

Anatomy Knowledge Post-Test

Following the collaborative group learning session and a short break of 15 minutes, all students gathered in the auditorium to take another anatomy knowledge test. To avoid a memory bias, none of the questions from the pre-test were repeated, although the general structure of the post-test was identical to that of the pre-test with 20 questions and 5 possible answers each. Furthermore, the learning taxonomy of Bloom et al. was used again to classify the response options. For the slightly more challenging post-test, only 64 possible answers came from the *Knowledge* domain, while 36 belonged to the *Understanding* domain. All questions in both the anatomy pre-test and the post-test counted equally and students could receive one point for each correct answer.

Extended Group Learning Session

After the anatomy knowledge post-test the students of both groups were exchanged for another collaborative group learning session in which students of the control group could also work with the *VesARlius* application and the students of the experimental group could compare their learning experiences with traditional anatomy learning using textbooks and 3D models. The structure of this extended group learning session was identical to the first one and allowed all students to work with both *VesARlius* and traditional anatomy learning modalities for at least 135 minutes. Throughout the extended group learning session, students were encouraged to reflect on whether their performance would have been better with the learning modality they had not worked with in the first learning session. Additionally, students should focus on the advantages and disadvantages of both resources.

Post-Experimental Survey Questionnaires

At the end of the user study, a set of post-experimental questionnaires was handed out to the students to collect their subjective feedback on the usability of the *VesARlius* application, the mental effort levels experienced during the user study, as well as their general opinion towards the application and its potential to complement existing anatomy learning paradigms.

System Usability Scale An industry standard *System Usability Scale (SUS)* questionnaire was used to subjectively assess the usability of the *VesARlius* application [68]. The SUS provides a convenient tool to assess the technical aspects of a generic system and comprises a 10-point questionnaire with five possible response options that range from "*strongly agree*" to "*strongly disagree*". The final SUS score that emerges from the questionnaire can be considered as a measure of the usability and maturity of the system. A SUS score above 68 is regarded as above average and a SUS score above 80.3 as in the top tenth of the percentile. In terms of school grades, a score of 68 would correspond to a C, while anything above 80.3 can be considered an A.

Mental Effort Test The second post-experimental questionnaire aimed at measuring the amount of mental effort invested while working with the *VesARlius* application. The students reported subjectively perceived mental effort based on a qualitative 9-point scale according to Paas [355]. A value of 1 corresponded to a "*very, very low mental effort level*" experienced when using the *VesARlius* application, while a value of 9 was associated with a "*very, very high mental effort level*".

Survey The third and final post-test was a comprehensive, paper-based evaluation survey with a total of 23 explicit statements on various aspects of *VesARlius*, including the students' personal attitude towards the application, its potential within the medical curriculum, and the advantages and disadvantages compared to other learning modalities. Students rated their agreement for each of the 23 statements on a visual analogue scale (VAS) from 0 (strongly disagree) to 20 (strongly agree). Each statement had a 15 cm long line on the questionnaire, divided into 20 steps, on which the students had to place a mark indicating their agreement with the statement. In addition to these 23 survey statements, there was a short questionnaire with three questions on the collaborative aspects of the *VesARlius* application, based on a 9-point Likert scale. Finally, the survey included a section for free text feedback, in which students could report both positive and negative aspects of the application and suggest possible improvements.

Results

Independent samples t-tests were carried out to identify significant differences between pre- and post-test results of the experimental (*VesARlius*) and the control group (*Theory*). All statistical analyses were performed using the SPSS version 24.0 statistical package (IBM Corp., Armonk, NY). The significance level was $p < 0.05$. In the following, all descriptive data are presented in the form of mean and standard deviation and effect sizes are reported using Cohen's d , where values below 0.2 are considered a small effect, values between 0.2 and 0.5 are considered a medium effect, and values above 0.8 are considered a large effect.

Anatomy Knowledge Pre-Test vs. Post-Test scores Compared to the pre-test, the students managed to achieve significantly higher scores in the anatomy knowledge post-test. For all 16 students combined, the percentage of correct answers improved from $25.65 \pm 7.95\%$ in the pre-test to $47.20 \pm 13.65\%$ in the post-test. These differences were statistically significant with a high effect size at the level of $p < 0.001$ ($t(30) = -5.46, p < 0.001$, Cohen's $d = 1.93$). Looking at both groups separately, students in the control group improved from $25.65 \pm 6.25\%$ to $43.75 \pm 12.15\%$, while similarly students in the experimental group improved from $25.65 \pm 9.80\%$ to $50.65 \pm 15.00\%$. In both cases these differences were statistically significant (*Theory*: $t(14) = -3.75, p = 0.002$, Cohen's $d = 1.87$; *VesARlius*: $t(14) = -3.95, p = 0.0015$, Cohen's $d = 1.97$). Although the average post-test scores were higher in the experimental group than in the control group, these differences were not statistically significant ($t(14) = -1.01, p = 0.33$, ns). Table 4.1 provides an overview of these results.

Tab. 4.1. Overview of the results from the anatomy knowledge pre- and post-tests administered to students during the experimental user study. The results are displayed for all students as well as separately for both groups.

| Conditions | Pre-Test | | Post-Test | | | |
|---------------------------------|---------------------------------|-------------------------------|---------------------------------|---------------------------------------|----------------------------|--------------------|
| | Anatomy Knowledge $n^a = 20$ | Mental Rotation $n^a = 20$ | Anatomy Knowledge $n^a = 20$ | System Usability Scale $n^a = 100$ | Mental Effort $n^a = 7$ | |
| ^b Standard Deviation | Mean% (\pm SD) | Mean% (\pm SD) | Mean% (\pm SD) | Mean (\pm SD) | Mean (\pm SD) | |
| VesARlius | 8 | 25.65 (\pm 9.80) | 41.90 (\pm 20.35) | 50.65 (\pm 15.00) | 83.63 (\pm 10.58) | 4.63 (\pm 2.67) |
| Theory | 8 | 25.65 (\pm 6.25) | 41.90 (\pm 27.90) | 43.75 (\pm 12.15) | 76.38 (\pm 16.49) | 5.63 (\pm 2.26) |
| All Participants | 16 | 25.65 (\pm 7.95) | 41.90 (\pm 23.60) | 47.20 (\pm 13.65) | 80.00 (\pm 13.90) | 5.13 (\pm 2.45) |

System Usability Scale The perceived usability of the *VesARlius* application was assessed by means of a SUS questionnaire. Overall, students were unanimously very positive about *VesARlius*, which was reflected in a high average SUS score of 80.00 ± 13.90 for all students combined. Interestingly, an examination of the SUS scores for the two groups individually revealed that the students in the experimental group provided slightly higher scores for the application than students in the control group. For the former, the average SUS score was 83.63 ± 10.58 compared to only 76.38 ± 16.49 in the control group, though these differences were not statistically significant ($t(14) = 1.05, p = 0.31, ns$).

Mental Effort For comparing the mental effort that students invested while working with the *VesARlius* application during the collaborative learning sessions, a 9-point scale of Paas was used [355]. Average mental effort levels for all students combined were relatively high at 5.13 ± 2.45 . Similar to the results of the SUS questionnaire, there were slight differences between the experimental and control groups. While these differences were not statistically significant ($t(14) = -0.81, p = 0.43, ns$), students in the former group invested slightly less mental effort (4.63 ± 2.67) compared to students in the latter group, who used the *VesARlius* application after the post-test and for whom an average mental effort level of 5.63 ± 2.26 was recorded.

Survey The qualitative evaluation survey consisted of three different parts: 1) the 23-statement questionnaire on the overall characteristics of *VesARlius*; 2) a short survey on the collaboration paradigms of the application; and 3) an optional section for free text feedback. Overall, the survey results indicate that the *VesARlius* application was generally perceived as a valuable tool for collaborative anatomy learning and as a great addition to existing modalities with very specific advantages.

The results from the first part of the survey, the 23-statement questionnaire, are summarized in Table 4.2. The first two statements ($S1 - S2$) of this questionnaire were concerned with the students' general opinion towards the importance of sectional anatomy. There was unanimous agreement among students in both the experimental and control groups that sectional anatomy is important to all types of physicians ($S1: 18.63 \pm 1.26$) and that it should be an integral part of the medical curriculum ($S2: 18.19 \pm 1.60$). The next four statements ($S3 - S6$) revolved around the relation between *VesARlius* and dissection courses. The application was found to provide specific benefits compared to dissection courses ($S5: 5.44 \pm 4.32$) and the majority of students agreed that *VesARlius* presents a valuable supplement ($S4: 16.25 \pm 4.54$), which should be integrated into the course ($S6: 1.56 \pm 0.96$). However, the application was found to be inadequate for replacing practical cadaver preparation ($S3: 1.56 \pm 0.96$). Mixed results were recorded for statements $S7 - S11$ in which *VesARlius* was compared with other established anatomy learning modalities. In general, students were not convinced that learning anatomy with *VesARlius* alone was sufficient ($S12: 15.13 \pm 5, 78$) and that the application can replace traditional anatomy textbooks ($S7: 8.38 \pm 6.04$) or 3D models ($S9: 9.00 \pm 5.76$). However, they felt that *VesARlius* provided some advantage over the former in the context of anatomy learning ($S8: 13.38 \pm 3.81$). Since all participating students had successfully completed the gross anatomy course and thus participated in the tutorial sessions with both the *Anatmage* and the *AR Magic Mirror* platform, it was also possible to compare the *VesARlius* application with these two modalities. According to students' feedback, *VesARlius* proved to be superior to both the *Anatmage* ($S11: 17.56 \pm 2.85$) and the *AR Magic Mirror* ($S10:$

17.06 ± 3.86). Statements *S13* – *S15* of the questionnaire examined the motivational aspects of *VesARlius*. The application was found to offer a fun way of collaborative anatomy learning (*S14*: 14.63 ± 4.47) and to have a positive effect on both motivation (*S13*: 13.19 ± 5.41) as well as on anatomy learning in general (*S15*: 12.88 ± 4.73). The next category of statements (*S16* – *S20*) was concerned with the students' personal opinion towards the application as well as its specific benefits. Regarding the question whether *VesARlius* is suitable as an introductory instrument for learning anatomy, both groups were undecided and of the opinion that a certain level of anatomical knowledge should be a prerequisite (*S20*: 11.63 ± 7.19). Concerning the acquisition of anatomical knowledge, the students felt that *VesARlius* could be effectively used to improve their learning success (*S17*: 17.63 ± 2.83) and to better understand certain anatomical concepts (*S16*: 14.81 ± 4.67). Overall, working with *VesARlius* during the collaborative group learning sessions was perceived to improve anatomical knowledge for the majority of students (*S19*: 15.25 ± 4.63). Interestingly, most students also reported that working with *VesARlius* improved their subjective 3D understanding of topographic anatomy (*S18*: 16.19 ± 4.29). The last three statements (*S21* – *S23*) investigated the maturity of the *VesARlius* application as well as its potential for self-directed anatomy learning in groups. The majority of students thought that the system is mature and well-thought out, although there is still room for improvements (*S21*: 12.88 ± 2.33). Most importantly, however, all students expressed a desire to spend more time with *VesARlius* (*S23*: 17.69 ± 3.13) and could imagine working regularly with the application in independent anatomy learning sessions (*S22*: 19.06 ± 1.80). Another noteworthy observation is the comparison of the approval rates with the 23 statements between the two groups. Interestingly, they were slightly higher within the experimental group in almost all cases, although significant differences were found for only two statements. This was the case for the question whether learning anatomy with *VesARlius* alone would be a great challenge (*S12*), for which students in the control group gave significantly higher scores than students in the experimental group (*Theory*: 18.25 ± 2.43; *VesARlius*: 12.00 ± 6.59; $t(-2.52), p = 0.02$, Cohen's $d = 1.26$), and for the question whether *VesARlius* awakened the students' interest in anatomy (*S16*), for which again students in the experimental group gave significantly higher scores (*Theory*: 10.64 ± 4.24; *VesARlius*: 15.13 ± 4.29; $t(14) = 2.22, p = 0.04$, Cohen's $d = 1.11$). A summary of all previous results can be found in Table 4.2.

The second part of the survey was a separate questionnaire on the collaborative paradigms of the *VesARlius* application that contained the following three questions: *Q1*: *I found the collaborative features of VesARlius useful*; *Q2*: *I think the collaborative features of VesARlius were sufficient*; and *Q3*: *I found the collaborative features of VesARlius disturbing and would rather learn on my own*. In summary, the collaborative functionalities were found to be useful (*Q1*: 5.63 ± 1.36) and not disturbing to the learning experience (*Q3*: 2.00 ± 1.37). Students also found that the available functionalities were sufficient to enable collaborative learning in teams of co-located students (*Q2*: 5.44 ± 1.32). While the Likert-scale ratings were slightly better in the experimental group, no statistically significant differences could be found.

In the third and last part of the survey, students had the opportunity to provide free text feedback both on the *VesARlius* application and on their experiences during the entire user study. In accordance with the previous reported results, all students greatly appreciated working with the application. From the collected responses three broader categories of student feedback could be deduced: 1) positive aspects and benefits; 2) problems and

Tab. 4.2. Results from the 23-statement questionnaire, listed both for all 16 participants combined as well as individually for the experimental (*VesARlius*) and control (*Theory*) group.

| Survey Statements | VAS ^c | | |
|---|--|---|--|
| | All Participants (n = 16) Mean (± SD) ^b | Theory (n = 8) Mean (± SD) ^b | VesARlius (n = 8) Mean (± SD) ^b |
| 1. Sectional anatomy is of decisive importance for the profession of physicians | 18.63 (± 1.26) | 18.75 (± 1.04) | 18.50 (± 1.51) |
| 2. Sectional anatomy should be an important part of the medical curriculum | 18.19 (± 1.60) | 18.38 (± 1.51) | 18.00 (± 1.77) |
| 3. I can imagine that VesARlius will eventually replace the dissection course | 1.56 (± 0.96) | 1.50 (± 0.76) | 1.63 (± 1.19) |
| 4. VesARlius is a very suitable supplement to the dissection course | 16.25 (± 4.54) | 16.50 (± 3.25) | 16.00 (± 5.78) |
| 5. VesARlius does not add any benefit in comparison to the dissection course | 5.44 (± 4.32) | 6.13 (± 4.32) | 4.75 (± 4.50) |
| 6. VesARlius should be integrated into the dissection course | 17.94 (± 2.93) | 17.38 (± 3.29) | 18.50 (± 2.62) |
| 7. I can imagine that anatomy learning with VesARlius can replace learning with atlases | 8.38 (± 6.04) | 7.00 (± 6.35) | 9.75 (± 5.80) |
| 8. VesARlius has great advantages over a textbook or atlas | 13.38 (± 3.81) | 11.75 (± 3.45) | 15.00 (± 3.63) |
| 9. I can imagine that anatomy learning with VesARlius can replace learning with 3D models | 9.00 (± 5.76) | 7.00 (± 6.09) | 11.00 (± 4.99) |
| 10. Anatomy learning with VesARlius is superior to learning with the Magic Mirror | 17.06 (± 3.86) | 16.00 (± 4.34) | 18.13 (± 3.23) |
| 11. Anatomy learning with VesARlius is superior to learning with the Anatomage table | 17.56 (± 2.85) | 16.63 (± 3.38) | 18.50 (± 2.00) |
| 12. Learning anatomy with VesARlius alone would be a great challenge for me | 15.13 (± 5.78) | 18.25 (± 2.43)^f | 12.00 (± 6.59)^f |
| 13. Working with VesARlius increases my motivation to learn anatomy | 13.19 (± 5.41) | 13.25 (± 3.73) | 13.13 (± 6.98) |
| 14. Anatomy learning with VesARlius is fun | 14.63 (± 4.47) | 13.38 (± 4.00) | 15.88 (± 4.82) |
| 15. Working with VesARlius has awakened my interest (even more than before) in anatomy | 12.88 (± 4.73) | 10.63 (± 4.24)^f | 15.13 (± 4.29)^f |
| 16. Learning with VesARlius increases my chances of success in understanding anatomy | 14.81 (± 4.67) | 12.50 (± 5.15) | 17.13 (± 2.85) |
| 17. I'm sure that the system can be used to my advantage and to improve my learning success | 17.63 (± 2.83) | 16.50 (± 3.16) | 18.75 (± 2.05) |
| 18. Working with the VesARlius system improves my 3-dimensional understanding | 16.19 (± 4.29) | 16.38 (± 2.72) | 16.00 (± 5.66) |
| 19. The exercise was profitable with regard to my anatomical knowledge | 15.25 (± 4.63) | 15.13 (± 4.73) | 15.38 (± 4.87) |
| 20. The VesARlius system is suitable as an introductory tool to anatomy | 11.63 (± 7.19) | 10.88 (± 7.45) | 12.38 (± 7.35) |
| 21. The VesARlius system seems mature and well thought out | 12.88 (± 2.33) | 13.13 (± 2.17) | 12.63 (± 2.62) |
| 22. I can imagine working independently with the VesARlius system | 19.06 (± 1.80) | 18.75 (± 2.19) | 19.38 (± 1.41) |
| 23. I would like to spend more time working with the VesARlius system | 17.69 (± 3.13) | 16.63 (± 3.93) | 18.85 (± 1.75) |

limitations; and 3) suggestions for improvement. Regarding the positive feedback, more than half of the students ($n = 9$) stated that *VesARlius* offers a much better visualization of anatomical structures than traditional textbooks and is particularly useful for learning the course of individual vessels ($n = 4$) and for gaining a better spatial understanding of both topographic anatomy ($n = 7$) and the relationship between certain structures ($n = 3$). Some students pointed out that *VesARlius* is a playful way of learning anatomy ($n = 4$) and leads to an increased motivation ($n = 2$). Furthermore, five students explicitly appreciated the collaborative features of *VesARlius*, which, as it turned out, "make the entire learning experience much more fruitful", "provide a [very effective] means of discussing anatomy together", and "provide a great opportunity to share knowledge with other students". Within the second feedback category on the problems and limitations of the *VesARlius* application, comments were mostly limited to technical shortcomings of the hardware (i.e. the Microsoft HoloLens) that was used during the user study. The total weight of the HMD was considered to be too high ($n = 5$), which caused pain to a few students as the device had to be worn for an extended period of time ($n = 4$). In addition, the small field of view (FoV) was described by six students as a major limitation. Almost half of the students explicitly emphasized that *VesARlius* cannot replace practical dissection courses ($n = 7$) because it "misses tactile feedback" and "does not provide [intuitive] gestures for manipulating and deforming virtual 3D organ models". Finally, two students noted that small structures such as certain arteries and veins are difficult to select with the existing HoloLens input methods. The students' comments on possible suggestions for improvement were consolidated in the third and final feedback category. A recurring theme was the inclusion of more content related to 3D anatomy models

such as muscles, male and female reproductive organs, and the heart ($n = 8$). In addition, several students requested additional CT and MRI volumes, including clinical cases ($n = 3$). Another feature request was related to the interaction of 3D models. Two students proposed a feature that would allow the user to "pick an organ and zoom [into it] to see fine grained annotations". Finally, some students ($n = 3$) mentioned that a "quiz module" could be a very valuable addition for "testing the acquired anatomical knowledge".

Discussion

In the present study, the potential of the *VesARlius* application for enabling collaborative AR anatomy learning was evaluated. The learning outcome was measured using a pre-test/post-test design and compared to traditional learning using textbooks and 3D models. Significant differences between the test results were found for both the experimental group (*VesARlius*) and the control group (*Theory*). While the post-test scores were slightly higher in the *VesARlius* group than in the *Theory* group, these differences were not statistically significant. Besides the anatomical knowledge tests, students also assessed the application's usability and the experienced mental effort when using *VesARlius*. In terms of usability, a high average SUS score of 80.00 ± 13.90 revealed that the application was generally very well perceived by the students. The level of mental effort tended towards the upper end of a 9-point Likert scale with an average score of 5.13 ± 2.45 . Finally, the subjective attitude towards the *VesARlius* application was assessed by means of a survey, which confirmed the positive results from the SUS questionnaire and highlighted that the majority of students could imagine using *VesARlius* as a complementary tool for anatomy learning. In the following, the most important results of this study are discussed in detail on the basis of the originally formulated hypotheses.

Learning Outcome The first hypothesis that was formulated stated that students learning with the *VesARlius* application have equivalent or better educational performance compared to students learning with traditional anatomy textbooks and 3D models. This hypothesis was partially confirmed by the study results, since post-test scores were higher in the experimental group and the survey results indicated clear advantages over traditional learning paradigms, although none of these differences were statistically significant. These positive results are consistent with a number of previously published works that demonstrated positive learning effects of AR systems when integrated into the medical curriculum [61, 88, 251]. Conversely, a recent study by Wainman et al. found that HoloLens-based AR is significantly inferior to 3D physical models in the context of learning pelvic anatomy [481]. In this study, participants were given 10 minutes to memorize 20 anatomical structures of the pelvis. In comparison to a control group that studied with 2D images of key views, a 70% accuracy increase was measured for the 3D model group while only a non-significant change of 2.5% was found for the AR group. Although considerably more time was given to students for interacting with the *VesARlius* AR application in the present study, and the study objectives were more complex than simply memorizing names of anatomical structures, additional studies are needed to better determine the specific benefits of AR in the context of gross anatomy learning. Furthermore, *VesARlius* contained a much larger number of features compared to the AR application employed within the study by Wainman et al., which could be another potential explanation for the inconsistent results. AR has unique advantages when introduced into educational environments, in particular with respect to student engagement, motivation or interactivity, and it should not be reduced to a mere tool for presenting digital information [40,

110]. These advantages are also reflected in the positive opinions of participating students about *VesARlius*—both in terms of subjective free-text feedback and qualitative survey results—and reinforce the growing demand for multimodal teaching opportunities for actuating the paradigm shift towards self-directed, student-centered, and explorative anatomy learning [3, 86, 110, 133, 368, 427, 445]. Both the high SUS score that *VesARlius* received as well as the students' subjective preference for *VesARlius* over comparable systems such as *Anatmage* and even the *AR Magic Mirror* platform further illustrates that the application has the potential to meet the above criteria and serve as a complementary teaching resource for collaborative anatomy education. However, the results of the mental effort questionnaire emphasized the need to minimize cognitive load, since it has been shown that high mental effort is associated with reduced motivation and learning outcome [85]. Interestingly, a general trend was observed that students in the experimental group provided slightly better scores for *VesARlius* in almost all relevant assessment criteria (higher SUS score, less mental effort, overall better survey scores). Conducting a third anatomy knowledge test after the second collaborative group learning session could potentially have led to more balanced results, as it would have allowed students in the control group to see the immediate effect of their learning session with *VesARlius* in terms of test results. However, this third knowledge test would have inflated the study protocol even further and possibly included a systematic bias due to lack of concentration after a full day of intensive study. Nevertheless, such studies could be a subject for future research.

Improved 3D Understanding The second hypothesis was about students' spatial ability and stated that learning with *VesARlius* increases the perceived 3D understanding of topographic anatomy. A growing number of medical students and educators are increasingly demanding interactive AR systems to improve the 3D understanding and the spatial ability of students [325, 466]. An interesting, bidirectional relationship between spatial ability and anatomy learning has been found in previous studies: spatial ability is predictive of performance in gross anatomy courses, and participation in gross anatomy courses increases students' spatial ability [150, 284, 479]. From the experimental results of this study, in particular survey statement *S18* (*Working with the VesARlius system improves my 3D understanding*), it appears that students actually perceive the application to improve their 3D understanding of the anatomical relationships, which confirms the above hypothesis. A solid 3D understanding was also very beneficial for numerous questions in the anatomy knowledge tests and the better overall results in the post-test may be attributed to an improved 3D understanding obtained within the collaborative group learning session with *VesARlius*. However, this assumption has to be tested in a follow-up study and is not substantiated by the results of the present study. Finally, it is possible that the extremely positive results for survey statement *S18* may have been influenced by the relatively low overall spatial ability of the students—as revealed by the mental rotation pre-test. The results could have been slightly different for a group of students with better spatial ability. Future work is therefore required to evaluate whether learning with the *VesARlius* application improves students' spatial ability, which could include continuous mental rotation tests over a longer period of time.

Collaborative Learning The third and final hypothesis was formulated to examine the particular benefits of the collaboration paradigms that the *VesARlius* application offers to the students in the context of anatomy learning. These collaboration paradigms distinguish the application from other academic or commercial anatomy learning resources and form the unique selling

point of *VesARlius*. Overall, students were very positive about the collaborative learning experience of *VesARlius* and recognized the collaborative paradigms as useful and sufficient for enabling team-based anatomy learning in both the survey questionnaires and the free text feedback. During the two group learning sessions, students working with the *VesARlius* application preferred to study within the same synchronized room and utilize all available collaboration paradigms. Of the 16 students, only five left the primary synchronized room, two of them studying together in another synchronized room and three students studying individually in a private room. In contrast, students from the control group that worked with traditional learning materials (i.e. anatomy textbooks and 3D models) were quick to split into smaller subgroups of 2–3 people and remained within these subgroups for most of the session. These observations strongly suggest that the *VesARlius* application stimulates active learning in team-based, collaborative anatomy learning environments. Although anatomy textbooks and 3D models are indispensable teaching resources for medical students that are essential to anatomy learning, these modalities do not offer the same advantages when it comes to interactive collaboration in larger teams. Previous applications of collaborative AR systems in other educational domains have found similar advantages in terms of increased motivation, interaction, and learning outcomes [298, 369, 503]. Therefore, the integration of collaborative AR systems like *VesARlius* into anatomy education is a very natural development to combine the advantages of these two worlds.

Despite the fact that collaborative, AR-based anatomy learning is associated with unique pedagogical advantages, supporting the above hypothesis, a number of educational challenges need to be considered when designing such collaborative AR systems. One of the most frequently documented challenge, both in general AR applications and in collaborative AR, is cognitive overload [83, 121, 369]. In the present study, the mental effort invested by students while working with the *VesARlius* application was explicitly measured with a mental effort test according to Paas [355]. The results of this test showed a tendency towards the upper end of a 9-point Likert scale, indicating a relatively high level of mental effort. Consequently, the design of an intuitive user interface is crucial in the development of collaborative AR systems in order to maximize the learning ability of students while minimizing the challenge of cognitive overload. Due to the high overall acceptance of the application and the very positive student feedback from the survey, the positive aspects of *VesARlius* seem to outweigh the rather high mental effort required to interact with the system. Nevertheless, additional investigations are needed to confirm this trend and to clearly establish in which scenarios high mental effort occurs.

Other persistent challenges mentioned by the students in the free text feedback mainly concern the hardware limitations of the HoloLens, especially the limited field of view and the rather bulky form factor. While these obstacles are currently a barrier for widespread adoption in preclinical anatomy courses, future generations of the hardware are expected to address these issues. Moreover, lower purchase costs (currently \$3,500,00 for the HoloLens) could even allow students to privately acquire these devices, making remote collaboration scenarios at home feasible.

In summary, despite the remaining challenges, the results of the present study represent an important first step towards a modern, multimodal gross anatomy curriculum complemented by novel AR-based resources that encourage interactive, student-centered, and collaborative

anatomy learning. A particular path for future research in this direction is the integration of such collaborative AR systems into a cadaver dissection course to provide students with additional information. HMD-based AR solutions such as *VesARlius* can offer immediate benefits in these types of scenarios, since dissections are generally performed in teams and several students must work together in a complex environment.

Limitations The present study exhibits some limitations that will be discussed in the following. Firstly, the number of participants was relatively low compared to the AR *Magic Mirror* evaluation studies, primarily as a consequence of the high equipment costs and the limited availability of the HoloLens. Procuring such a large number of devices required complex logistics, as the eight HoloLenses were supplied by different university departments. However, future evaluation studies should seek to incorporate more participants in order to verify the findings and to further investigate the assumptions that evolved from the present study results. A second limitation was related to the total time the students worked with *VesARlius* (two hours), which was much longer than a comparable study by Wainman et al. [481], but still rather short in relation to their total study time during the preclinical anatomy course. Nevertheless, pilot studies like the one presented in this section have the potential, despite limited interaction times, to gain very important insights into the future development of collaborative AR applications and to establish possible integration strategies into the medical curriculum. However, future studies with a larger number of participants and longer working hours with *VesARlius* will be necessary to establish the application as an integral part of the gross anatomy course. With regard to 3D understanding and spatial abilities, no mental rotation post-test was included in the study design, which could have shown better results, attributed to working with *VesARlius*. Due to the lack of such a test, a quantitative improvement in 3D understanding cannot be determined with certainty, but only qualitatively according to students' subjective self-assessment. Lastly, another limitation concerns the structure of the collaborative group learning session in the control group. Whereas in the experimental group the learning session consisted of an introduction to the *VesARlius* application and two parts in which the collaboration paradigms of *VesARlius* could be used, the students in the control group could decide during the whole time of the group learning session how the individual subgroups were formed. The provision of six textbooks and three anatomical models to the students indirectly stipulated smaller study groups. However, the formation of small subgroups of 2–3 students at the beginning of the learning session shows that the traditional textbook as a medium for anatomy learning is naturally limited to very few students working together, although it would have been interesting to see whether the initial learning in a large group would have led to different perceptions of group learning in *VesARlius*.

4.2.2 Elective Course Study

The pilot study presented in the previous section successfully evaluated the use of *VesARlius* in a realistic curricular environment with first-year medical students. Overall, AR-based anatomy learning with *VesARlius* was found to offer unique advantages over traditional learning resources, and the application was considered a valuable learning supplement, especially by providing the opportunity for interactive and collaborative learning. Unlike the AR *Magic Mirror* platform and other recently proposed novel systems for anatomy teaching, *VesARlius* runs on the Microsoft HoloLens and therefore uses an HMD to display virtual information

in combination with the real world. But is an HMD the best way to operate *VesARlius*, or do students benefit equally from the application when it runs on a conventional desktop computer? To answer this fundamental question, a small follow-up study was conducted as part of an elective course within the medical curriculum at the LMU Munich. Two groups (the experimental group running *VesARlius* on the HoloLens and the control group running it as a standalone application on a regular desktop PC) were formed and individually worked with *VesARlius* for a total of one hour. Following this learning session, students from all groups underwent a specially designed test during which 60 CT images had to be positioned at the correct location within the virtual 3D model (either while the skin of the model was shown or hidden). The students' test performance was determined by the distance of the placed CT images from their ground truth position. Two hypotheses were subject to investigation during the study: H1) Students in the experimental group generally perform better than students in the control group; and H2) Students in both groups achieve better test performance when the virtual skin is hidden.

CT-Test Module

The *VesARlius CT-Test* module was developed specifically for the task of evaluating the students' ability to correctly determine the position of a given (target) CT image within the 3D anatomy model during the elective course study. At the beginning of the test, the target CT image was presented next to the anatomy model. In addition, a semi-transparent plane with an acrylic glass material and the dimensions of the target CT image was visualized within the 3D model, similar to the regular functionality of *VesARlius* for displaying section images inside the model, see Figure 4.3. Depending on the nature of the target CT image, the acrylic glass plane was displayed either in the transversal, sagittal, or frontal plane. Repositioning of the plane could be performed in accordance with the regular *VesARlius* user interaction methods by selecting a specific location on the 3D model, by grasping the plane and sliding it along the model, or by using dedicated controls that would move the plane one step up or down (corresponding to a slice thickness of 2 mm). As a result of the one-to-one correspondence between the CT volume and the 3D anatomy model in *VesARlius*, the ground-truth position of every CT image within the model can be determined. The goal of the CT-Test was therefore to position the acrylic glass plane at the ground-truth position of the target CT image, with the offset from this ground-truth position corresponding to the error. Two conditions with varying difficulty levels were available for the test. In the first condition (*WithoutSkin*), all anatomical structures were visible (see Figure 4.13a). In the more challenging *WithSkin* condition, the virtual skin was reconstructed from the CT volume and displayed on top of the other anatomical 3D structures, preventing the internal organs from being visible (see Figures 4.13b, 4.13c, and 4.13d).

Participants

A total of twenty second-year medical students (12 female, 8 male) with a mean age of 20.2 ± 2.1 took part in the elective course. None of the students had participated in the first *VesARlius* evaluation study or had any prior experience with HMD-based AR. All students participated in the study voluntarily and received no financial compensation. In contrast to the previous evaluation study, the students were randomly assigned to either the experimental or the control group without any pre-tests.

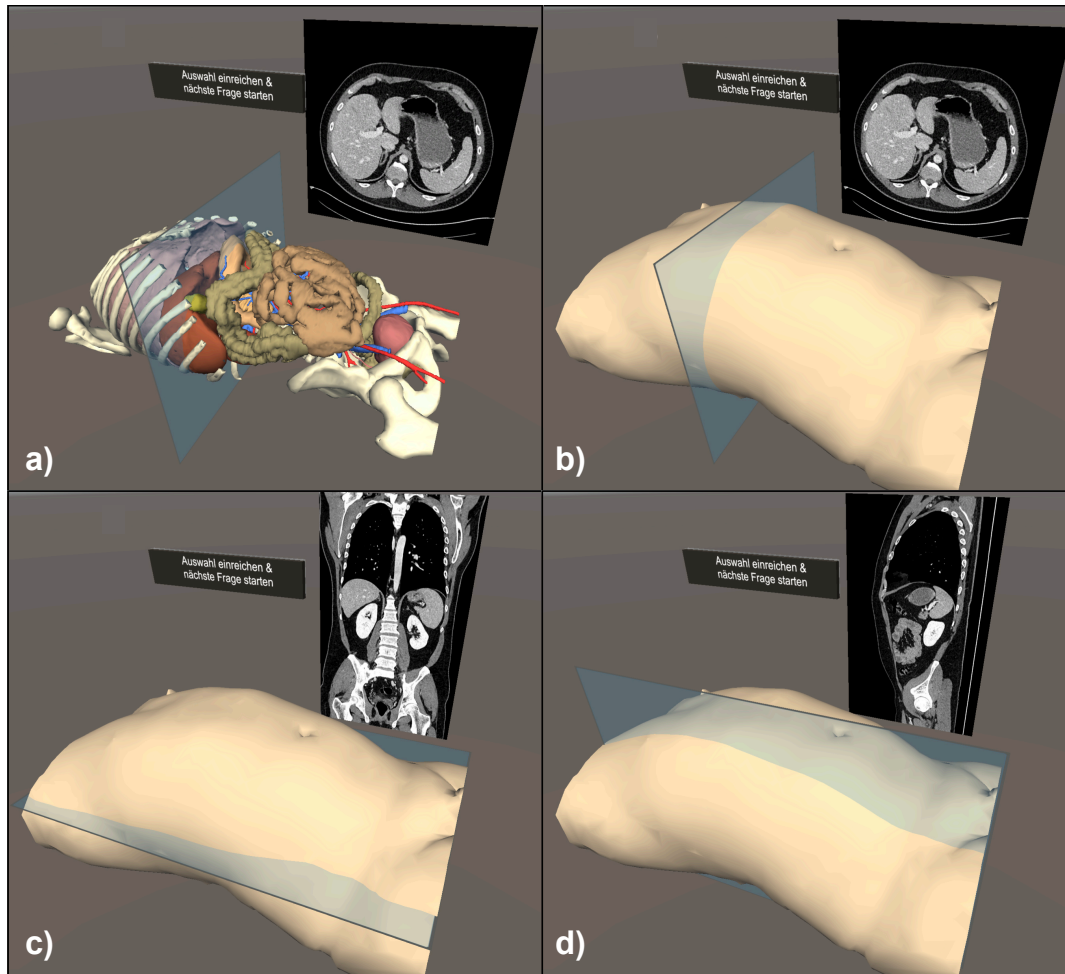


Fig. 4.13. Four close-up views of the *VesARlius* CT-Test module. a) the transversal target CT image must be positioned within the 3D model for the *WithoutSkin* condition, in which all anatomical structures except the skin are shown; b) identical task as in a), but for the *WithSkin* condition; c) frontal target CT image; d) sagittal target CT image. In all cases, a button is displayed to the left of the target CT image, allowing the user to confirm the placement of the acrylic glass plane and move to the next CT image.

Study Procedure

The entire elective course was divided into two different parts: 1) the learning phase, in which students in both the control and experimental groups worked individually with the *VesARlius* application either on the desktop PC or on the HoloLens; and 2) the test phase, in which students in both groups took the CT-Test. In the following, these two phases are described in more detail.

Learning Phase At the beginning of the study, the group assignments were announced and the students of the experimental and control groups went to separate rooms. Subsequently, the students of both groups received a short introduction to the *VesARlius* application and all available functionalities. In addition, the students of the experimental group working with *VesARlius* on the HoloLens were instructed in the use of the device. After this introduction, the students of both groups underwent a one-hour learning phase during which they studied a number of pre-defined anatomical topics with *VesARlius*. In particular, the students were asked to locate different anatomical structures such as specific arterial branches in both the

CT images and the 3D anatomy model. During the entire learning phase, all students worked with an individual copy of *VesARlius* and collaboration within synchronized rooms was not possible. At the end of the one-hour learning phase, all students gathered in an auditorium and the CT-Test module, which had been deactivated in the previous learning phase, was introduced. After this explanation, the students went back to the group rooms and started the test.

Test Phase Upon starting the CT-Test, the students were immediately presented with the first target CT image for which the position within the 3D model had to be determined. The placement of the acrylic glass plane had to be confirmed by pressing a button next to the target CT image, prompting the next target CT image to be displayed. During the entire CT-Test, the position of 60 target CT images had to be determined. Of these 60 CT images, half of them had to be placed under the *WithoutSkin* condition such that students could see all internal organs and the skeleton, while the other half had to be placed under the more demanding *WithSkin* condition. Moreover, the 60 CT images were taken in equal parts from the three orthogonal sectional planes, with 20 transversal, sagittal, and frontal section images each. All 60 CT images were manually selected for inclusion in the test by an experienced anatomist from the Faculty of Medicine at the LMU Munich and were displayed to the student in a randomized order. No time limit was imposed during the test, allowing the students to take as much time as they needed to determine the position of each target CT image.

Results

Similar to the *VesARlius* evaluation study from the previous section, independent samples t-tests were used to detect significant differences between the CT-Test results of the two groups. Furthermore, the significance level was set to $p < 0.05$ and Cohen's d was employed as a measure of effect size. For all statistical analyses, the statistical package SPSS version 24.0 was used (IBM Corp., Armonk, NY).

Since the goal of the CT-Test was to determine the ground-truth position of a CT target image within the virtual 3D anatomy model, the only performance metric was the offset between the estimated position and this ground-truth position (measured in mm). Overall, the students in the experimental group working with *VesARlius* on the HoloLens achieved better test results than the students in the control group. The average error in the former was 29.33 ± 27.71 mm compared to 34.61 ± 20.64 mm in the control group. While these differences were considerable, they were not statistically significant ($t(1198) = 1.89, p = 0.059, ns$).

When comparing the test results for the two different conditions corresponding to the two CT-Test difficulty levels (*WithSkin* vs. *WithoutSkin*), significantly better test results were obtained for the *WithoutSkin* condition. For all students of both groups combined, the average error for the *WithSkin* condition was 37.61 ± 24.92 mm in comparison to only 26.34 ± 24.15 mm for the *WithoutSkin* condition. These differences were statistically significant ($t(1198) = 4.06, p = 0.005$, Cohen's d = 0.23). Similar observations could be made if the two groups were considered separately. Students in the control group achieved a lower average error for the *WithoutSkin* condition (27.26 ± 27.72 mm) compared to the *WithSkin* condition (41.97 ± 26.41 mm), with the differences being statistically significant at the $p < 0.05$ level ($t(598) = 3.83, p = 0.014$, Cohen's d = 0.31). Similar results were measured in the experimental

group, where students had an average error of $33.24 \pm 33.92\text{mm}$ for the *WithSkin* condition compared to $25.42 \pm 29.33\text{mm}$ for the *WithoutSkin* condition. Again, these differences were statistically significant ($t(598) = 1.95, p = 0.05$, Cohen's $d = 0.16$). Lastly, comparing the test results for the two conditions between the groups, mixed results were found. Students in the experimental group achieved significantly better test results for the *WithSkin* condition than students in the control group (Control: $41.97 \pm 26.41\text{mm}$; Experimental: $33.24 \pm 33.92\text{mm}$; $t(598) = 2.09, p = 0.037$, Cohen's $d = 0.17$). For the *WithoutSkin* condition, results were again better for students in the experimental group, though not statistically significant (Control: $27.26 \pm 27.72\text{mm}$; Experimental: $25.42 \pm 29.33\text{mm}$; $t(598) = 0.51, p = 0.61$, ns). A graphical summary of all previous results can be found in Figure 4.14.

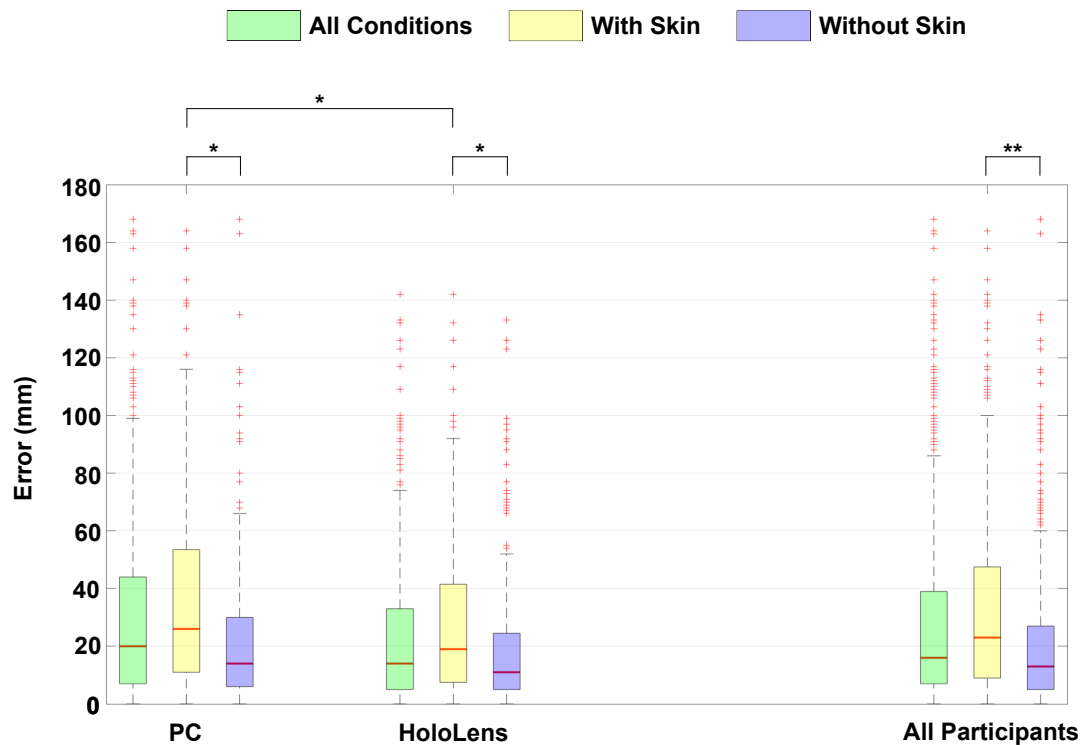


Fig. 4.14. Overview of the results of the CT-Tests. The average error for the two conditions *WithSkin* and *WithoutSkin* is shown both for the control group (PC) and the experimental group (HoloLens) individually and for all students combined (All Participants).

Discussion

In contrast to the first *VesARlius* evaluation study during the gross anatomy seminar, the present study did not focus on the general advantages of the application in terms of learning outcome and collaboration paradigms, but rather sought to investigate whether the HoloLens as a medium for presenting the contents of *VesARlius* offers significant advantages over a standalone application running on a regular desktop computer. Two main observations may be inferred from the results of the user study.

Firstly, the test performance was generally better within the experimental group running *VesARlius* on the HoloLens. Due to the fact that the test results for the *WithSkin* condition differed significantly between the two groups, but not for the *WithoutSkin* condition and also not for the two combined, the originally formulated first hypothesis ("Students in the

experimental group generally perform better than students in the control group") can only be partially confirmed. Nevertheless, the test results show a strong trend that the HoloLens is indeed the better medium for operating the *VesARlius* application. One noteworthy observation related to test performance in both groups is the very high standard deviation and the relatively large number of outliers (i.e. large errors in determining the ground-truth position of a target CT slice) that occurred in both groups and for both conditions. A likely explanation could be that determining the exact position of a target CT image within the 3D anatomy model is indeed a rather challenging task, especially for second-year students who all completed the gross anatomy course but who had little exposure to clinical topics and thus to medical imaging modalities in general. Examining in which cases these outliers predominantly occur and whether there are differences between the three orthogonal section planes could be an interesting topic for future research. Due to the bilateral symmetry of the human body, determining the ground-truth position of sagittal CT images could be much more challenging than transversal and frontal CT images, and laterality errors might even have been the source of the large standard deviation and the vast number of outliers in the present study.

The second observation concerns the inferior test performance for the *WithSkin* condition and relates directly to the second hypothesis ("*Students in both groups achieve better test performance when the virtual skin is hidden.*"). Both for all participants combined and within the two individual groups the performance was significantly better in the *WithoutSkin* condition compared to the *WithSkin* condition, confirming the above hypothesis. Due to the fact that internal structures, in particular anatomical landmarks on the skeleton and on large organs, were concealed by the virtual skin for the *WithSkin* condition, the task of determining the ground-truth position of a target CT image was considerably more challenging. Overall, the *WithSkin* condition required a high degree of spatially understanding the topographic location of many different anatomical structures. Considering the results of the first evaluation study, which found that learning with the *VesARlius* application improves the subjectively assessed 3D understanding of the students, an interesting topic for a follow-up study would be to assess whether students with a high spatial ability perform significantly better on the CT-Test than others with a lower spatial ability. In addition, a comparative study between *VesARlius* and the AR *Magic Mirror* platform would be very intriguing, evaluating the CT-Test performance on both platforms and exploring the potential benefits of the in-situ visualization of medical section images provided by the latter.

4.3 Out-of-View Object Visualization

The work presented in this section is an extended version of parts of two papers presented at the conferences ISMAR 2018 [63] and ISMAR 2019 [58]. The content is reproduced with the permission of all authors, ©IEEE.

VesARlius, as an HMD-based AR application, was developed to enable collaborative anatomy learning on the Microsoft HoloLens. The evaluation study presented in section 4.2.2 demonstrated that running *VesARlius* on the Microsoft HoloLens as a display medium exhibits distinct advantages over operating it as a standalone application on a regular desktop computer. However, the HoloLens, like all other state-of-the-art HMDs, is far from perfect and suffers from a series of limitations with regard to both hardware and software. In the post-experimental

survey of the first and more extensive *VesARlius* evaluation study (see section 4.2.1), several shortcomings of the application were identified by students, which in fact were hardware-related limitations of the HoloLens. One particular limitation that was repeatedly mentioned by the students was that depending on the position of the user, certain parts of the user interface could not be visible due to the limited field of view (FoV) of the HoloLens. While future HMD generations will certainly improve on the FoV, building an HMD with a large FoV while simultaneously providing good specifications for all other important design parameters (e.g. large eye relief, high resolution, good image quality) is a complex endeavor, as outlined in section 2.2.3 when discussing AR display technologies. The limited FoV of today's state-of-the-art HMDs is primarily a consequence of the complex optics used in these devices, and large leaps forward are unlikely to occur in the next few years as there is "no Moore's Law for optics" [510].

Therefore, it is an important research direction to develop novel, software-based visualization approaches that are capable of providing users with information about virtual objects outside the currently visible FoV and visually guiding them towards these objects. Such visual guidance techniques do not aim to solve the small FoV limitation of current HMDs, but rather to mitigate the effects of this limitation for the user. This section presents the results of two user studies in which several of these novel visual guidance techniques for out-of-view objects were implemented and compared with other existing techniques. While the developed approaches can be applied directly within *VesARlius*, both user studies assumed a very generic application scenario that is not specific to collaborative anatomy learning. Since the problem of out-of-view objects can occur in virtually any HMD-based AR application, the contributions presented in this section are relevant not only for *VesARlius*, but in a much broader context. The first study proposes two novel techniques for visually guiding the attention of users to virtual out-of-view objects in HMD-based AR: the *3D Radar* and the *Mirror Ball*. Both techniques were compared with four other state-of-the-art visualization techniques during three different scenarios in which users were asked to collect virtual objects in their surrounding environment. In addition, the users' head rotation data was recorded and analyzed to investigate whether there were differences in the trajectories used to approach the virtual objects between the different visual guidance techniques. The second study had a much smaller scope and compared three different *3D Minimap* visualization techniques during a similar search and collection task already used in the first study. The three minimap visualizations were a top-down bird's-eye view minimap, a tilted bird's-eye view minimap, and the newly proposed stereographic fisheye minimap. All visualization techniques developed in this section are available as *Unity3D* plugins and can therefore be seamlessly integrated into the *VesARlius* anatomy learning application, but also into any HoloLens-based AR project.

4.3.1 Study I: Mirror Ball & 3D Radar

Understanding, navigating, and performing goal-oriented actions are very common tasks in many HMD-based AR applications and require adequate information conveyance about the location of all virtual objects in a scene. Providing this positional information to the user is a challenge because AR environments can potentially include a large number of these virtual objects at different locations in the user's extended environment, making it difficult to understand and navigate the AR scene. This problem is exacerbated by the fact that all

current state-of-the-art HMDs have a limited FoV, which is vastly inferior to that of the human visual system. As a result, only a small subset of the virtual objects is visible, and the vast majority of virtual objects are likely to reside outside the field of view. In the past, a number of different visualization techniques have been proposed to visually guide the attention of the user towards such out-of-view objects in both mobile and HMD-based AR environments. However, none of these proposed methods solves the problem universally. Among the most common disadvantages of existing methods are that the visualization takes up large parts of the screen, causes visual clutter, or introduces occlusion problems when a large number of objects is present in the scene. In addition, a fundamental analysis of how participants use a particular visual guidance technique for the task of locating virtual objects is generally missing from existing studies. Examining the users' head rotation path data for different visual guidance techniques could be a key factor in developing a comprehensive understanding of why certain techniques are superior to others.

In the present user study, two novel visual guidance techniques, the *Mirror Ball* and the *3D Radar*, aimed at overcoming the limitations of existing visualization approaches are proposed and compared with the current state-of-the-art techniques. The *Mirror Ball* resembles a reflective sphere and displays distorted reflections of virtual objects based to their position in the environment. The second novel visual guidance technique proposed within this section is the *3D Radar*, a technique that is commonly used in commercial computer games, especially in space simulators. As with conventional top-down minimaps and radars, virtual objects in space are substituted by small proxy icons on the *3D Radar*. While the position on the 2D radar plane signals the difference in horizontal angle between the virtual object and the user, the vertical angle is encoded by orthogonal lines from the 2D radar plane towards the proxy icon of the object. As part of a user study with twenty-four participants, the two proposed methods were compared with current state-of-the-art techniques for visualizing out-of-view objects. Task completion times were measured as performance indicators of the different visual guidance techniques in three different object collection scenarios that resembled real-world explorative and goal-oriented visual search tasks. In addition to the development of the *3D Radar* and the *Mirror Ball*, the second major contribution of this study is a new area-based algorithm for evaluating and classifying head rotation trajectory data. Two different object targeting approaches can be distinguished by the algorithm: 1) a direct, one-way approach for which both the horizontal and vertical angle between a starting point and a target point are aligned simultaneously, following the shortest path between the two; and 2) an indirect, two-way approach that successively aligns the horizontal and vertical angles in an L-shaped fashion.

Background & Related Work

Before providing a detailed description of the newly developed visual guidance techniques and the user study that was conducted for evaluation purposes, the following paragraphs provide a brief overview of important background information to help understand the contributions presented in this section. The overview is divided into two parts. First, existing techniques for visualizing out-of-view objects are surveyed. Subsequently, a short summary of previous work on trajectory analysis is given.

Visualization Techniques for Out-of-View Objects Existing techniques for visually guiding the attention of users towards out-of-view objects in AR environments can be divided into three categories. The first is known as *Overview & Detail*, and summarizes approaches that use two separate windows which are typically displayed on top of each other [374]. While the *Overview* window generally provides information about the user's extended surroundings, e.g. in the form of a map, the *Detail* window displays specific information about the direct, local environment, typically for the area the user is currently viewing. The second category of visualization techniques for out-of-view objects in AR environments is *Focus & Context*. Approaches that belong to this category use only one window to provide a distorted view of the user's environment, such as a fisheye projection [79, 167]. The transition between the undistorted *Focus* area, typically in the middle of the window, and the distorted *Context* area is usually smooth. The third and last category is referred to as *Contextual Views* [167, 216]. These techniques also distinguish between *focus* and *context*, but there is a sharp transition between the two, and the details window typically uses abstract indicators, such as arrows, to provide information about the location of objects outside the field of view.

Techniques for visualizing out-of-view objects can be further classified based on the dimensionality of the encoded information. Whereas 3D techniques allow the user to infer the position of virtual objects in 3D space, 2D techniques can only tell the user whether an object is to the left or right and in front or behind. However, no information is available about whether an object is above or below the user. In the past, a large number of 2D techniques have been proposed, the majority of which were developed specifically for desktop or mobile applications. Zellweger et al. developed *City Lights*, a 2D technique for desktop applications that employs highlights at the edges of the screen for indicating the position of windows outside the viewing area. Baudisch et al. introduced the *Halo* technique, which can be used to encode arbitrary out-of-view objects by drawing circles around the object positions whose radii encode the distance of these objects from the current location of the user [24]. The circles intersect with the screen and provide the user with information about both the direction and distance of objects. However, both *City Lights* and *Halo* can be difficult to interpret in the presence of multiple out-of-view objects. Gustafson et al. proposed another technique known as *Wedges* which uses 2D triangular wedges, starting from the position of non-visible objects and extending to the edges of the screen [167]. Two alternative techniques, *EdgeRadar* [168] and *2D Arrows* [75], also exploit the edges of the screen for displaying either 2D points or 2D arrows that indicate the position of objects that are out of view. Siu and Herskovic were inspired by these ideas and introduced the *sidebARs* visualization technique, in which the position of out-of-view objects is conveyed to the user in the form of small proxy icons that represent these out-of-view objects and which are displayed within two vertical bars at the left and right edges of the screen [429]. However, when several out-of-view objects are located in close proximity to each other, occlusion and clutter occurring at the edges of the screen are two common disadvantages of previous techniques.

For conveying information about the position of out-of-view objects in HMD-based AR environments—which are inherently 3-dimensional—the previously discussed 2D techniques are inadequate. For this reason, a number of techniques have been introduced to extend the provision of information on the location of such objects to 3D space. Two natural extensions of the previously mentioned *Halo* technique are *3D Halo* and *3D Halo Projection* [465]. Instead of using 2D circles, the techniques work by placing either 3D rings or spheres around

the position of objects outside the field of view. Another extension to 3D is the *3D Arrow* visualization technique, which, in accordance with the corresponding 2D technique, displays arrows pointing to the 3D position of out-of-view objects [408]. However, these techniques suffer from the same drawbacks (clutter and occlusions) as their 2D counterparts. *Parafrustum* [446] and *Attention Funnel* [50] are two comparable techniques that both use a tunnel-like visualization for guiding the user towards a single out-of-view object. Another approach is *AroundPlot*, which uses an orthogonal 2D fisheye projection to map the entire 3D space around the user to the boundaries of a rectangle that is slightly smaller than the size of the visible field of view and on which small proxy icons representing objects outside the field of view are shown, similar to the *sidebARs* visualization technique [216]. This approach suffers from the problem of corner density, since a large 3D space is encoded in the areas near the four corners of the rectangle. A similar approach was presented by Gruenefeld et al. with *EyeSee360* [162, 163], which displays an ellipse extending across the entire screen in combination with a smaller rectangle centered in the middle of the screen. While the latter represents the focus region, the area between the rectangle and the ellipse encodes the 3D space around the user. Several smaller ellipses and horizontal lines are used as helplines. A particular shortcoming of *EyeSee360* is that the technique occupies a large part of the field of view, which potentially degrades the perception of real-world objects. The *SWAVE* technique, which uses wave-like movements to guide the user's attention towards a target object, was recently introduced by Renner and Pfeiffer [387]. In the same paper, a different approach is mentioned by the authors, where screen flicker is used at different frequencies to indicate how close the user is to an out-of-view object. Matsuzoe et al. proposed a similar technique using circular vibrating icons at the edges of the screen [303]. However, these techniques are best suited for single out-of-view objects and would suffer from severe clutter in more complex AR environments.

The two novel visual guidance techniques proposed in this section also have some related work from other areas. The use of a *mirror ball* to visualize objects that are not within the current field of view has already been used in traditional 3D modeling applications by McCrae et al. [306]. The approach is characterized by the fact that the objects are grouped on the basis of their distance from the ball, which is divided into separate areas similar to a Voronoi diagram. Each of the sub-areas on the ball corresponds to a group of objects that have a similar distance to the ball. In this way, all objects appear about the same size on the ball regardless of their distance. A disadvantage of this method is that the distance information between the objects and the mirror ball is completely lost. The *3D Radar* is an extension from conventional 2D or top-down radar visualizations and uses a minimap-like visualization technique that is strongly inspired by commercial computer games. This technique is especially used in space simulator games such as *Elite: Dangerous* [515], *Eve: Valkyrie* [516], and *Star Citizen* [517] to provide the player with an overview of the 3D space around him. While radar visualizations have proven useful in 2D applications [74], the extension to 3D space has not yet been evaluated in the literature.

Head Rotation Trajectory Analysis To get a better understanding of how the different visual guidance techniques are utilized for the task of targeting virtual out-of-view objects, the users' head rotation trajectories were analyzed during the study. The primary goal of this analysis was to determine whether there is an *optimal* class of trajectories that is primarily used to target virtual objects in AR, and whether visual guidance techniques that favor such potentially optimal trajectories facilitate the localization of out-of-view objects. A trajectory is traditionally

defined as the path of a moving object, consisting of a set of successive positions in space as a function of time. During the user study, a continuous head rotation was defined as a trajectory by transforming the data into spherical coordinates and designating the individual positions of the trajectory as time-stamped tuples of both the horizontal and vertical angles.

Trajectory analysis is a diverse research topic with applications in many different areas, including surveillance security, activity recognition, traffic monitoring, or anomaly detection. Bian et al. published a recent survey of different trajectory analysis techniques, covering both supervised and unsupervised approaches for trajectory clustering and classification [35]. Two trajectories can be compared using a number of different similarity measures proposed in the past. Although each of these similarity measures has a different degree of complexity, they are typically based on the comparison of some type of distance between these trajectories. Among the most common metrics are the Euclidean distance [220], Dynamic Time Warping [332], Least Common Sub-Sequences [474], the Fréchet distance [4] and the Edit distance [81]. Another concept known as Minimum Bounding Rectangles (MBRs) was introduced by Anagnostopoulos et al. to approximate the distance calculations for sub-trajectories [5]. Wang et al. have published a comparative study on the effectiveness of some of these measures [484]. Although distance-based measures can be efficiently used to compare similar trajectories over time in many different scenarios, they always define a global measure and do not take into account that trajectories with the same distance measure can potentially define considerably different paths towards an object. In contrast, region-based measures as the one proposed by Lee et al., split the domain into a grid structure with the goal of classifying trajectories based on the identification of homogeneous grid cells that contain only a specific class of trajectories [263]. Such region-based approaches are generally very robust in case the classes of trajectories are very similar, but their performance decreases when the trajectory data exhibits a large variability, as is to be expected with the head rotation trajectories during the user study. Further comparison metrics from the literature are curvature [137], significant changing points [22, 23], and discontinuities [131].

During the present user study that was aimed at comparing different visual guidance techniques for out-of-view object localization, discriminating between two distinct types of trajectories—corresponding to different object targeting approaches—was of particular importance: 1) a direct, one-way targeting approach, characterized by a straight line between a starting head rotation and the orientation of the target point in spherical coordinates; and 2) an indirect, two-way targeting approach, which is defined by a (potentially rotated or mirrored) L-shaped trajectory in spherical coordinates. In both cases an optimal trajectory could be defined and a novel area-based trajectory classification approach was developed, which will be explained in detail in one of the following subsections.

Methods

The performance of the two novel visual guidance techniques (*Mirror Ball* and *3D Radar*) was evaluated in an experimental user study, which compared these two approaches with the most promising techniques from the literature. For this purpose, a Microsoft HoloLens application was implemented, in which participants were required to localize and collect a number of virtual objects that were positioned within the 3D space around them as quickly as possible using the different visual guidance techniques. Of the previously reviewed state-of-the-art techniques, four were selected for comparison within the study. Given that the task of the

user study was to collect *multiple* virtual objects, the techniques *Parafrustum*, *Attention Funnel*, *SWAVE*, as well as the two flicker-based approaches were not applicable, as they only support guiding the user’s attention towards a single out-of-view object. Moreover, *3D Halo* and *3D Halo Projection* were disregarded since they suffer from severe visual clutter in the presence of multiple objects. Designed with *EdgeRadar* as inspiration, *EyeSee360* has been proven to outperform *Halo*, *2D Arrows*, and *Wedge*. Therefore, only the superior *EyeSee360* technique was included in our comparison and all other approaches were excluded. Of the other 3D visualizations we included both *AroundPlot* and *3D Arrows*. Furthermore, a slightly modified version of the *sidebARs* technique was included that allows the encoding of locations in 3D space by moving the proxy icons both vertically and horizontally according to their location. There is no previous study that has shown a comparison between these visual guidance techniques, with the exception of one paper that compared *AroundPlot* and *3D Arrows* and found a comparable performance for a small number of objects. [216]. All six visualization techniques (*Mirror Ball*, *3D Radar*, *EyeSee360*, *sidebARs*, *AroundPlot*, and *3D Arrows*) were implemented in a *Unity3D* application running on the Microsoft HoloLens. In the following, a more detailed overview of the implementation details is provided. A side-by-side comparison of these six visualization techniques is depicted in Figure 4.15.

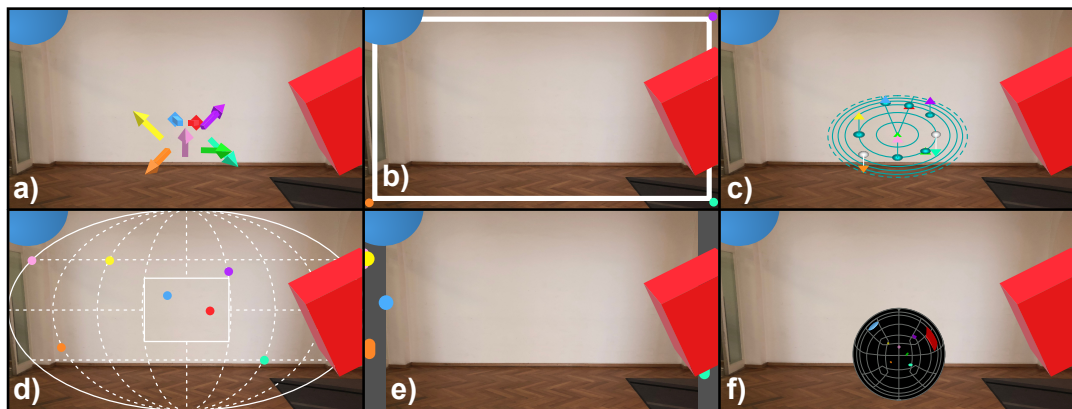


Fig. 4.15. Comparison of the six different visual guidance techniques that were compared with respect to their potential for guiding the user’s attention towards out-of-view objects in HMD-based AR environments: a) *3D Arrows*; b) *AroundPlot*; c) *3D Radar*; d) *EyeSee360*; e) *sidebARs*; and f) *Mirror Ball*.

3D Arrows The *3D Arrows* visualization technique was implemented similar to previous work [408]. All arrows are placed on a sphere, which is located directly in front of the user, slightly towards the lower part of the visible FoV. Each arrow points in the direction of a virtual object, with the length of the arrow scaled according to the distance of the object. Therefore, as the user targets a virtual object, the corresponding arrow moves along the sphere in such a way that its pointing direction coincides with the user’s viewing direction while simultaneously its length decreases. In contrast to the original implementation, the color of the arrows is defined by the color of the virtual target object, though several different approaches are possible.

sidebARs The original 2D *sidebARs* method uses the position of the small proxy icons within the two vertical bars at the edges of the screen to indicate where an object is placed relative to the user’s current position [429]. Proxy icons in the left bar indicate that the object is to the left of the user and vice versa. The vertical position within the bars indicates whether an object is above or below the user, such that objects in the middle of the bars have the same

vertical angle as the user. The (3D) *sidebARs* developed within this thesis and employed for the purpose of the present user study also varies the horizontal position of the proxy icons within the left and right sidebars to indicate the horizontal angle of a target object. In addition, the original 2D implementation superimposed the numerical distance (in cm) to the target objects on top of the proxy icons. However, in the present 3D visualization of *sidebARs*, the display of these distances was removed to avoid clutter and because no other visual guidance technique contained such quantitative values.

AroundPlot The implementation of *AroundPlot* used during the present user study is very similar to the original method [216]. Spherical coordinates are mapped to orthogonal fisheye coordinates so that the visible FoV corresponds to a rectangular area on the screen. Virtual objects in the scene are displayed as colored points positioned around the sides of the rectangle according to their horizontal and vertical angles. In contrast to the original method, the *Dynamic Magnification* function, which enlarges the rectangle in the direction of the user's movement, is excluded. Instead, the size of the rectangle is fixed and covers almost the same area as the HoloLens FoV.

EyeSee360 For the implementation of *EyeSee360*, a version with guides and a rectangular inner window was employed, which is similar to the one proposed by the authors of the original method, and which was also used for their implementation on a Google Cardboard [163]. However, in the implementation used for the present user study, the points representing objects outside the FoV have the same color as the objects they correspond to, as opposed to the distance-coding colors in a variant of the original method. Points positioned within the inner rectangle indicate objects that fall within the field of view and are therefore immediately visible to the user. All other objects are positioned within the ellipse according to their horizontal and vertical angles. In this way, points on the left and right edges of the ellipse correspond to objects located directly behind the user, while points on the top and bottom edges correspond to objects located directly above or below the user.

Mirror Ball The implementation for the *Mirror Ball* technique aims to imitate the nature of a real spherical mirror. While McCrea et al. use a similar technique for navigation purposes in a traditional 3D virtual environment [306], the *Mirror Ball* in the present implementation is not divided into different regions corresponding to clusters of objects at various distances. Instead, a virtual sphere is positioned in front of the user that shows the virtual reflections of all target objects on its surface. Closer objects appear as larger reflections on the sphere, while the reflections of more distant objects are much smaller. To provide the user with a better perception of depth, a cube map is employed that has a grid texture on each side as a skybox. Similar to the reflection of virtual objects, the reflection of this skybox is also visible on the *Mirror Ball*. Similar to a real-world spherical mirror, all reflections visible on the *Mirror Ball* are spherically distorted. While at first glance these distortions make it difficult to assess the position of virtual objects, in reality they provide the user with important positional cues that implicitly guide the user towards such objects.

3D Radar In contrast to all visual guidance techniques presented so far, which have their origin in the scientific visualization literature, the design and implementation of the *3D Radar* is strongly inspired by commercial video games. The *3D Radar* consists of several concentric

circles placed in front of the user and slightly tilted for improved perception of 3D. In the center of the radar, a small triangle indicates the current position and viewing direction of the user, while a forward facing cone represents the visible FoV. Each virtual object within the scene is displayed on the radar as a combination of a proxy symbol and a circle corresponding to the projection of the object in the 2D radar plane. In accordance with a conventional 2D radar, the projection indicates the horizontal angle between the target object and the user. To provide the user with additional information about the vertical angle, proxy icons in the form of colored triangles are used, located either directly above or below the projection circles and connected to the 2D projection circle on the radar through a thin line. To quickly provide information about the correspondence between proxy icons and their projection circle, a connecting line is used between the two. Lastly, the color of both the line and the projection circle depends on whether the virtual object is above or below the user.

Head Rotation Trajectory Classification

The study of head rotation trajectories is formulated as a classification problem. It was hypothesized that for all six visual guidance techniques, two different classes of trajectories can be distinguished, which are used for targeting virtual objects during the user study: the first class contains trajectories where the horizontal and vertical angle of the target object are aligned simultaneously and can therefore be defined as a direct, one-way targeting approach (T_{OneWay}). The second class of trajectories are those in which the two angles are successively aligned in an L-shape fashion, i.e. first the horizontal angle of the target object is aligned, followed by the vertical angle (or vice versa). Trajectories of this class therefore follow an indirect, two-way targeting approach (T_{TwoWay}). In spherical coordinates, A perfect one-way targeting approach towards a target point t is given in spherical coordinates by a straight line l_t which connects the target point and the starting point s (i.e. initial head rotation). Conversely, a perfect two-way approach is given by two connected straight lines forming the two legs of a right triangle defined by s , t , and the point on the x-axis $q = (t_x, 0)$ (or alternatively the point on the y-axis $q' = (0, t_y)$). Thus, the first line matches the horizontal angle of t , while the second line subsequently matches the vertical angle (or vice versa). An illustration of these two targeting approaches is provided in the first quadrant of Figure 4.16a. The blue trajectory corresponds to a one-way targeting approach that closely follows the line between the origin and t_{red} , while the green trajectory corresponds to a two-way targeting approach.

Any given head rotation trajectory can be described as a polygonal path V that consists of a set of vertices v_i corresponding to discrete angular measurements, such that $V = \{s, v_1, v_2, \dots, t\}$. The proposed classification algorithm for such polygonal paths V is based on the hypothesis that the previously described object targeting approaches T_{OneWay} and T_{TwoWay} can be distinguished according to the area of the region that is enclosed by l_t and V . Under the assumption that the starting point s is translated to the origin, a one-way approach is characterized by an area $A_V \approx 0$, while for a two-way approach $A_V \approx \frac{A_{R_t}}{2}$, where A_{R_t} is the area of the rectangle R_t , defined by the origin and t . For preventing misclassifications of polygon paths with large parts of their enclosing area A_V lying outside of R_t , A_V is further divided into the two parts A_V^{in} and A_V^{out} , such that $A_V = A_V^{in} + A_V^{out}$ and $A_V^{in} = V \cap R_t$. Two percentage thresholds α and β for A_V^{in} and A_V^{out} can be defined to account for a small error margin. The final trajectory classification with two additional classes for unclassifiable trajectories can now be defined as follows:

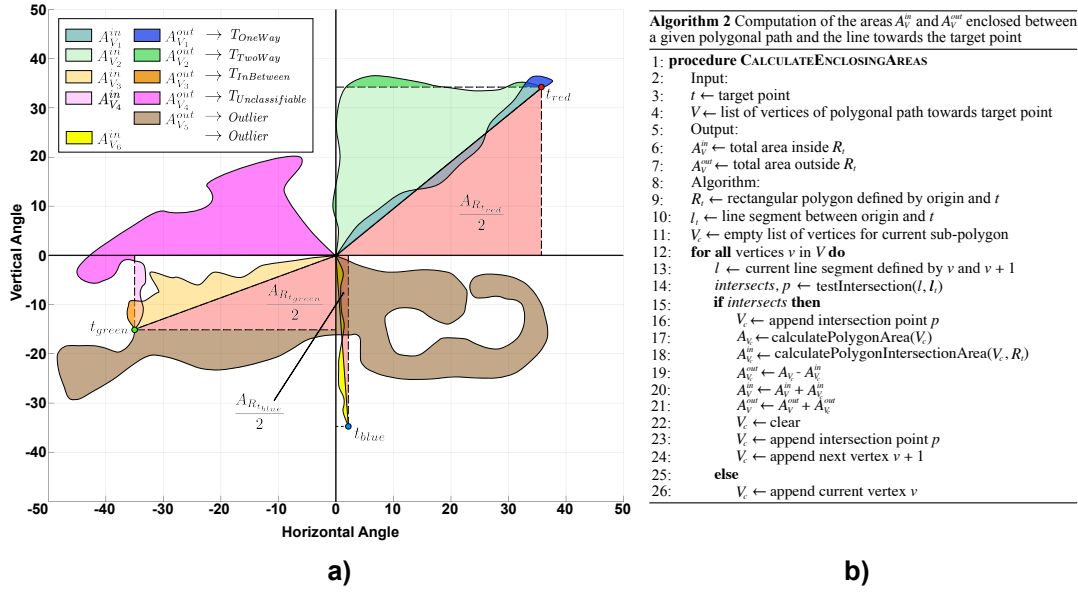


Fig. 4.16. Overview of the head trajectory classification. a) visual explanation of the two different areas A_V^{in} and A_V^{out} for six exemplary targeting trajectories V_1 (blue, classified as T_{OneWay}), V_2 (green, classified as T_{TwoWay}), V_3 (orange, classified as $T_{InBetween}$), V_4 (pink, classified as $T_{Unclassifiable}$), V_5 (brown, classified as *Outlier* due to long path), and V_6 (yellow, classified as *Outlier* due to horizontal angle of $t_{blue} \approx 0$); b) outline of the algorithm to calculate the two different areas.

$$f(V, t) = \begin{cases} T_{OneWay}, & \text{for } A_V^{in} < \alpha, A_V^{out} < \beta \\ T_{TwoWay}, & \text{for } A_V^{in} > 100 - \alpha, A_V^{out} < \beta \\ T_{InBetween}, & \text{for } 100 - \alpha \geq A_V^{in} \geq \alpha, A_V^{out} < \beta \\ T_{Unclassifiable}, & \text{for } A_V^{out} \geq \beta \end{cases} \quad (4.1)$$

Figure 4.16a visualizes the different area definitions by displaying six polygonal paths defining different trajectories towards three target points and their classification results.

The calculation of these individual subareas is based on the division of a polygonal path into several sub-polygons V_i , each of which is bounded by two consecutive intersections with the line l_t . These different line segments of the path are traversed and tested for intersections with l_t . In the case of an intersection, all vertices starting from the previous intersection to the current one define a sub-polygon V_i (for the first sub-polygon V_1 the origin is defined as the initial intersection). Each time a sub-polygon is closed in this way, the total area A_{V_i} of the sub-polygon is calculated. Finally, the intersection area A_V^{in} between the sub-polygon and the rectangle R_t is calculated using *polygon clipping* [448, 489]. The entire algorithm of calculating the areas A_V^{in} and A_V^{out} is shown in Figure 4.16b.

In its current form, the algorithm is not able to distinguish whether the vertical or horizontal angle is aligned first in a two-way target approach. In addition, the classification can be inaccurate for target points that are very close to the coordinate axes $x = 0$ or $y = 0$, for which the area of R_t is very small and can even approach 0 for target points that lie exactly on one of

the axes. In these cases, a classification is not meaningful due to the fact that one-way and two-way target approaches are almost identical and cannot be clearly distinguished. Furthermore, large values for A_V^{out} and thus misclassifications are very likely to occur in these cases. To take these edge cases into account, it is possible to simply discard these trajectories with target points near one of the axes and classify them as outliers. The disadvantage of this method is that target-oriented paths are treated in the same way as random trajectories. However, for the purpose of identifying patterns in the head rotation data for the six different visual guidance techniques, this can be tolerated. Another group of outliers are those trajectories whose length exceeds a certain percentage of l_t , i.e. a trajectory that is three times longer than the optimal path is discarded and classified as an outlier.

User Study

For the purpose of investigating the potential of the two proposed visualization techniques (*Mirror Ball* and *3D Radar*) to visually guide the view of users towards out-of-view objects in HMD-based AR, an experimental user study was designed. Following an interactive tutorial, the participants were asked to collect virtual objects positioned around them as quickly as possible during three different scenarios while using all six different visualization techniques. The task was designed to resemble a visual search and navigation task, which is very common in HMD-based AR. The completion time and the head rotation trajectories were recorded as performance indicators. The degree of perceived mental effort as well as the overall usability of all six visualization techniques were measured in a post-experimental survey.

Participants A total of twenty-four individuals between the ages of 22 and 47 years (19 male and 5 female) with an average age of 26.63 ± 7.05 years were recruited for the experiment. They were all unpaid volunteers and gave their informed consent to the experimental protocol. A precondition for participation was that all volunteers had good color vision, since differently colored virtual objects had to be distinguished quickly. All participants passed the screening with the standard Ishihara color vision deficiency test [203], consisting of different color charts that were shown to the participants on a smartphone application.

Task & Procedure The experiment was conducted in an open office space. At the beginning of the session, participants received a Microsoft HoloLens, which was used throughout the user study to collect and view virtual objects in the AR environment. Participants were also given the HoloLens clicker as an input device for collecting virtual objects, which proved to be more robust and beginner-friendly than the HoloLens *Tap* gesture. Subsequently, participants performed the calibration process using the pre-installed HoloLens calibration application to adjust the HMD display according to their individual interpupillary distance (IPD). In the next step, each participant completed a tutorial that familiarized them with the different visual guidance techniques. For each technique the tutorial consisted of text instructions and a visual demonstration. At the end of the tutorial, the users had to collect three demo objects using all six visual guidance techniques. There were no time restrictions during the entire tutorial and no head rotation trajectory measurements were taken.

Once the tutorial was successfully completed, the main part of the user study followed. In three different scenarios the participants were requested to use the six visualization techniques for the task of collecting a total of eight virtual out-of-view objects that were located in their

surrounding space as quickly as possible. The name of the current visual guidance technique and a start button were displayed prior to each collection task. Upon pressing the start button, the experiment began and the completion times and the head rotation paths were recorded. The order of the three object collection scenarios was identical for all participants, starting from the easiest to the most difficult one. After all objects were collected in one scenario using all six visual guidance techniques, the application moved on to the next scenario.

After completion of all three scenarios, participants were asked to fill out a survey collecting their demographic information, their experiences with virtual and augmented reality, and their experiences with computer games in general. In addition, all participants reported on the mental effort they invested while using the various visualization techniques on a 9-point scale of Paas [355]. Finally, participants had to complete a System Usability Scale (SUS) questionnaire for each visualization technique, with a SUS score above 68 considered above average and a score above 80.3 considered in the top 10th percentile. For each participant, the total duration of the experiment, including the tutorial and the post-experimental survey, was between 30 and 50 minutes. The following paragraph describes in more detail the three different object collection scenarios that users had to go through during the main part of the user study.

Object Collection Scenarios In the first scenario (*Sequential*) the virtual out-of-view objects had to be collected one after the other in sequential order. Only one single object was displayed at a time, and the visualization technique only showed visual guidance hints to this particular object. After collecting one object, the next one appeared until all objects were collected. This scenario is similar to use cases in which the user searches for a very specific virtual object and can pass this information on to the application. In this way it is possible to limit the visualization technique to the display of hints to the desired object.

In the second scenario (*Random*), the virtual out-of-view objects could be collected in an arbitrary, user-defined order. All objects were shown at the same time and the visual guidance techniques showed hints for all these objects. This second scenario was inspired by a more explorative search task which is very common in many AR applications. In such scenarios, the user tries to quickly understand the AR environment and all objects are potentially relevant for the user.

The third and last scenario (*Specific*) required the user to collect the virtual out-of-view objects one after the other in a specific, pre-determined order. Similar to the *Random* scenario, all objects were displayed at the same time and the visualization techniques showed hints for all these objects. However, the user could only collect a specific object for which a visual hint was displayed on the screen in the form of a text message (e.g. "Collect the yellow cube!"). As soon as the user had collected the correct object, the next hint for the next object was displayed on the screen until all objects were collected. This scenario resembles a situation where the user searches for something specific in a potentially confusing environment, but cannot pass the information on to the application. It is therefore not possible to limit the number of hints displayed. By artificially creating the incentive to search for a certain object, the user is required to collect exactly this object.

Object Placement The virtual objects that the participants had to collect during the user study were positioned pseudo-randomly around each individual user. An imaginary cube was placed at the position of the user's head, divided into $3 \times 3 \times 3$ inner cubes. The virtual objects were then positioned at random centers of these inner cubes, with no objects placed in the cubes directly in front of, above or below the users, resulting in 23 possible object positions. Figure 4.17 shows a schematic overview of this pseudo-random method of placing virtual objects. In every scene, a total of eight out-of-view objects with different shapes and uniquely identifiable colors were placed. All objects followed the translational movements of the user, making it impossible to move towards or away from an object.

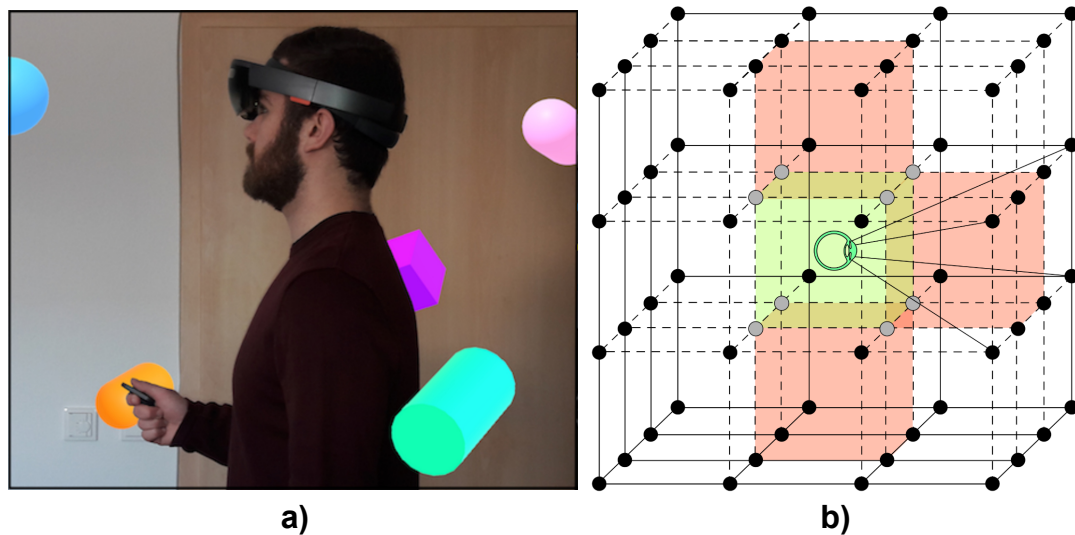


Fig. 4.17. Overview of the placement of objects during the experimental user study. a) participant wearing a HoloLens, with several virtual objects placed around his head; b) schematic overview of the pseudo-random object placement method. Virtual objects were positioned at positions corresponding to the centers of small sub-cubes within a larger $3 \times 3 \times 3$ cube, with the exception of cube centers directly in front of, above, or below the user.

Design In terms of study design, there were two independent variables. The first variable corresponded to the object collection scenario, i.e. the order in which virtual objects had to be collected, with three levels (*Sequential*, *Random*, or *Specific*). A fixed, difficulty increasing order of the object collection scenarios was deliberately chosen (i.e. 1. *Sequential*; 2. *Random*; and 3. *Specific*) to keep the user study as simple as possible for the participants. The second independent variable was used to control the visual guidance technique that was employed for conveying the 3D position of virtual out-of-view objects. Consequently, the user study had a 3×6 within-subjects design. For randomizing the experimental conditions across both study participants and object collection scenarios, a 6×6 balanced Latin square matrix was used during the tutorial and the three object collection scenarios [493]. Two dependent variables, corresponding to the task completion time and the head rotation trajectory, were employed. While the former determined the time required to collect all virtual objects for a particular visualization method and collection scenario, the head rotation trajectory (expressed in spherical coordinates) represented the path from the initial head rotation of a participant to the last target object and was recorded as the rotational component of the 3D pose of the HoloLens at isochronous intervals.

Hypotheses Considering the experimental setup, the following hypothesis was formulated, which was subjected to an extensive statistical evaluation:

- H1.** Mean task completion times with the newly introduced techniques (*Mirror Ball* and *3D Radar*) are lower or equal to existing state-of-the-art techniques.

Furthermore, it was expected that for each of the different visual guidance techniques, a specific class of head rotation trajectories is dominant. In particular, it was predicted that for the *3D Radar* the majority of head rotation trajectories follow an indirect, two-way targeting approach.

Results

After providing a detailed overview of the user study, this section presents an analysis of the study results. Overall, the two best performing techniques, both in terms of completion times and overall usability, were *EyeSee360* and the newly proposed *3D Radar*. Additionally, the results clearly demonstrate that for the *3D Radar* technique, the participants predominantly targeted out-of-view objects with the indirect, two-way object targeting approach. For all other visualizations, in particular for *EyeSee360*, the direct, one-way targeting approach was substantially more frequent.

Completion Times To compare the time required to collect all virtual objects in the three different scenarios, a two-way analysis of variance (ANOVA) with repeated measures ($\alpha = 0.05$) was employed, in conjunction with pairwise, Bonferroni-corrected post-hoc tests to reveal significant differences between the six visualization techniques in all three scenarios. A graphical summary of the results is depicted in Figure 4.18.

A strong significant main effect was found for the object collection scenario ($F_{2,46} = 70.79$, $p < 0.001$, $\eta^2 = 0.76$). During the *Random* scenario, participants were able to achieve significantly lower task completion times compared to both the *Sequential* scenario ($p < 0.001$) and the *Specific* scenario ($p < 0.001$). Additionally, task completion times were significantly lower in the *Sequential* scenario compared to the *Specific* scenario ($p < 0.001$). A statistically significant main effect was also found for the visual guidance technique ($F_{5,115} = 19.44$, $p < 0.001$, $\eta^2 = 0.46$). For the techniques *AroundPlot* ($p < 0.01$), *3D Arrows* ($p = 0.001$), *3D Radar* ($p < 0.001$), and *EyeSee360* ($p < 0.001$), mean completion times were all significantly lower than *sideARs*. In the same way, the completion times for the first three were significantly lower than for the *Mirror Ball* (*3D Arrows*: ($p = 0.02$); *3D Radar*: ($p < 0.01$); *EyeSee360*: ($p < 0.001$)). Lastly, participants achieved significantly lower completion times with *EyeSee360* compared to *3D Arrows* ($p = 0.03$) and *AroundPlot* ($p < 0.001$). There was also a significant interaction effect between the object collection scenario and the visualization technique on the task completion time, such that the effect of the visual guidance technique varied depending on the type of object collection scenario ($F_{10,230} = 3.03$, $p = 0.001$, $\eta^2 = 0.12$).

During all three object collection scenarios, the lowest mean completion times were achieved using the *EyeSee360* visual guidance techniques, closely followed by the *3D Radar*. In contrast, the two techniques *sideARs* and the *Mirror Ball* resulted in comparably high task completion times in all three scenarios. While the mean completion times for *AroundPlot* were low

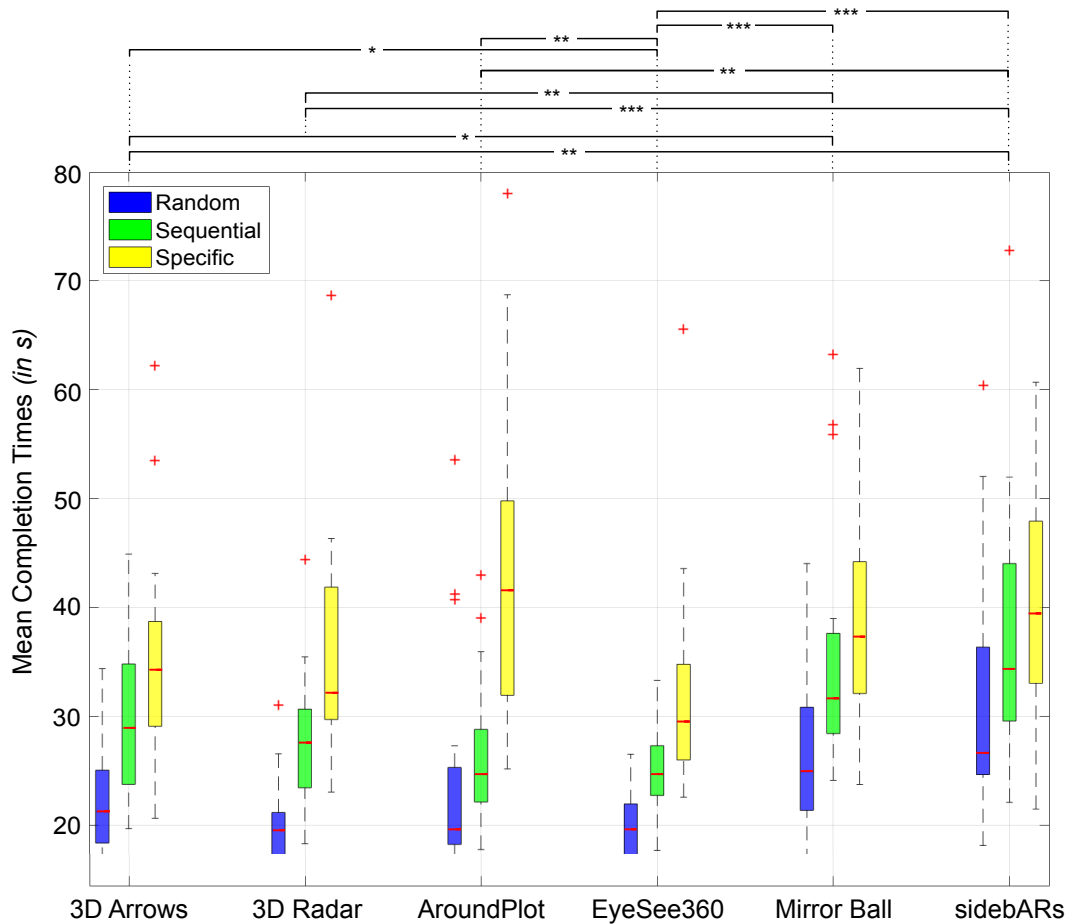


Fig. 4.18. Graphical summary of the mean completion times for the object collection study. In the three different scenarios (*Sequential*, *Random*, *Specific*), participants had to collect virtual shapes as quickly as possible using the six different visual guidance techniques. Significant time differences are indicated as * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$).

during the *Sequential* object collection scenario, the technique was worst during the *Specific* scenario. Table 4.3 provides a summary of all completion times for each of the six visualization techniques during the three scenarios.

Augmented Reality and Gaming Experience In order to evaluate whether previous experiences with AR and gaming had any effect on the completion times, we performed a median split on the reported experience levels and divided participants into two groups: one for *low* and one for *high* experience with AR and gaming respectively. The two experience levels E were reported as part of the post-experimental survey and adhered to a seven-point Likert scale. In terms of AR experience, the two groups had mean experiences $E_{AR}^{High} = 4.58 \pm 1.00$ and $E_{AR}^{Low} = 1.25 \pm 0.45$, while for computer gaming the mean experiences were $E_{Gaming}^{High} = 6.6 \pm 0.49$ and $E_{Gaming}^{Low} = 3.17 \pm 0.83$. While the mean completion times were slightly lower for all visualization techniques and in all three scenarios for the groups with a high degree of experience, these differences were not statistically significant.

Head Rotation Trajectory Analysis The previously discussed algorithm for classifying head rotation trajectories was used to analyze how people targeted the virtual out-of-view objects

Tab. 4.3. Overview of the mean completion times for all three object collection scenarios, as well as average SUS-scores and mental effort results for all six visual guidance techniques.

| Conditions | Completion Time | | | | | | SUS-Score | | Cognitive Load | |
|-------------|-----------------|-------------|------------|-------------|------------|-------------|------------|-------------|----------------|-------------|
| | Random | | Sequential | | Specific | | Mean μ | SD σ | Mean μ | SD σ |
| | Mean μ | SD σ | Mean μ | SD σ | Mean μ | SD σ | | | | |
| 3D Arrows | 21.86s | 4.68s | 29.30s | 7.04s | 34.81s | 9.15s | 71.29 | 17.34 | 3.87 | 1.96 |
| 3D Radar | 19.85s | 3.87s | 27.76s | 5.94s | 35.69s | 9.82s | 83.63 | 17.10 | 2.71 | 1.74 |
| AroundPlot | 23.17s | 9.40s | 26.40s | 6.23s | 43.03s | 13.45s | 79.19 | 12.82 | 3.13 | 1.23 |
| EyeSee360 | 18.58s | 3.63s | 24.76s | 4.04s | 31.84s | 9.38s | 89.27 | 10.31 | 1.55 | 0.68 |
| Mirror Ball | 26.61s | 9.38s | 37.23s | 7.40s | 39.88s | 15.29s | 44.35 | 19.87 | 5.45 | 2.11 |
| sidebARs | 31.32s | 10.01s | 38.66s | 10.76s | 40.91s | 14.95s | 51.05 | 19.67 | 5.26 | 2.35 |

with the different visual guidance techniques. Since in the *Random* scenario the object targeting trajectories can vary greatly and an optimal trajectory for collecting all objects in this scenario is difficult to define, the analysis of the head rotation data is limited to the other two scenarios with sequential and specific object collection orders. Figure 4.19 shows all 48 targeting trajectories (8 virtual objects \times 6 visualization techniques) of a particular participant for the *Sequential* scenario.

Prior to classification, two types of outlier trajectories were identified and removed from the data. The first type corresponds to trajectories whose length exceeds that of l_t (i.e. the line from the origin to the target point t) by a certain percentage. For the present analysis this percentage was set to 300, eliminating all trajectories whose length was three times longer than l_t . The second type of outlier trajectories were those where the virtual target object was close to one of the axes $x = 0$ or $y = 0$. In these cases no distinction can be made between a one-way and two-way targeting approach. For the purpose of the present analysis, a threshold of 10° was chosen for both the horizontal and vertical angles. For the *Sequential* scenario, the percentage of trajectories that were classified as outliers based on these two criteria was 19.26%, distributed as follows: *3D Arrows* (3.04%), *3D Radar* (2.60%), *AroundPlot* (2.69%), *EyeSee360* (2.86%), *Mirror Ball* (4.51%), and *sidebARs* (3.56%). In the *Specific* scenario, the percentage of outliers was almost the same with 19.10% of all trajectories: *3D Arrows* (3.56%), *3D Radar* (3.13%), *AroundPlot* (2.95%), *EyeSee360* (1.91%), *Mirror Ball* (3.47%), and *sidebARs* (4.08%).

For all other (*inliers*) trajectories, Algorithm 2 (see Figure 4.16b) was used to calculate the two areas A_V^{in} and A_V^{out} . According to the equation 4.1 the trajectories are classified as T_{OneWay} , T_{TwoWay} , $T_{InBetween}$, or $T_{Unclassifiable}$ based on these two metrics. As previously mentioned, these classes are used to describe which targeting approach towards a particular out-of-view object was chosen by the participant. The values for the thresholds α and β in the equation 4.1 were set to 20% and 30%, respectively, in order to have a more conservative estimate and to allow moderate error margins. In Figure 4.20, the distribution of $(\frac{A_V^{in}}{A_{Rt}}, \frac{A_V^{out}}{A_{Rt}})$ ratio pairs as well as the classification boundaries defined by the two thresholds α and β are illustrated for both the *Sequential* and *Specific* scenario.

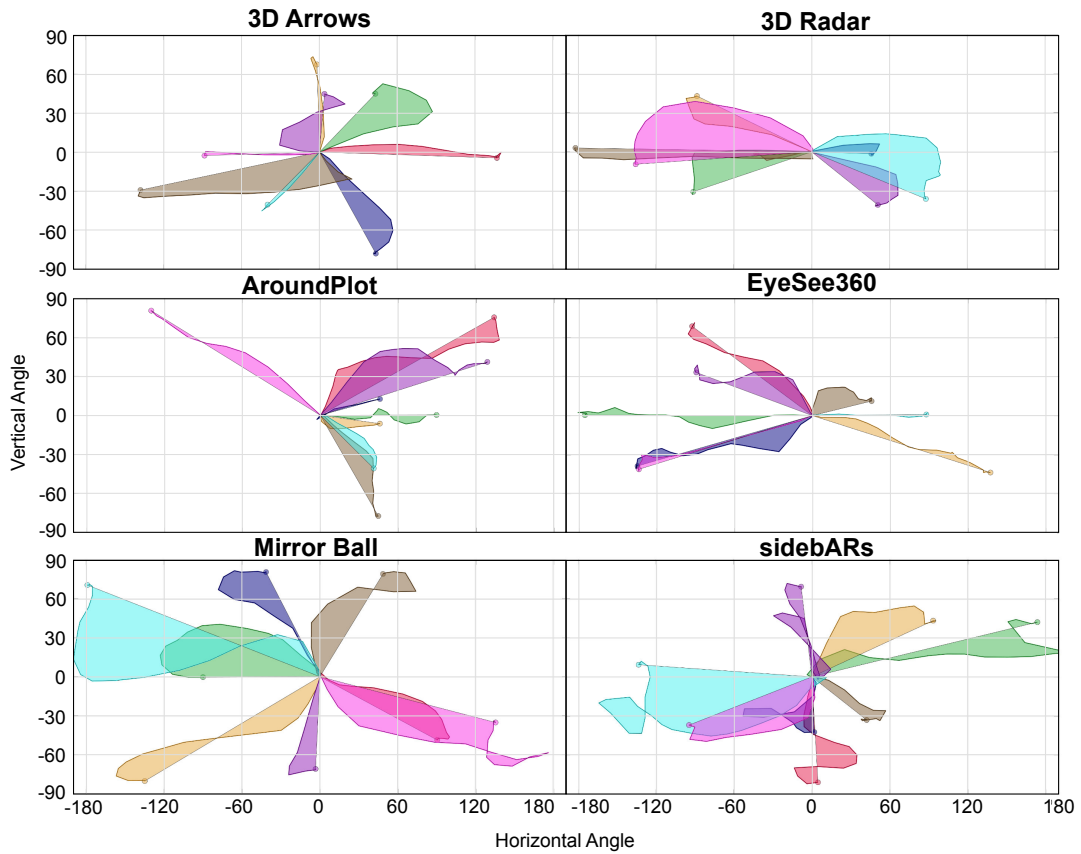


Fig. 4.19. Summary of all trajectories of a participant for the six different visualization techniques during the *Sequential* collection scenario. The different colors correspond to the colors of the virtual objects that were collected with the respective trajectory. Note: There is no difference between A_V^{in} and A_V^{out} .

Following the above removal of outlier trajectories, there was still a moderate percentage of trajectories that could not be classified due to relatively large values for A_V^{out} . For the *Sequential* scenario, an interesting observation was that the visual guidance techniques with the lowest percentages of unclassifiable trajectories also had the lowest mean completion times, namely *EyeSee360* (11.61%), *AroundPlot* (15.93%), and *3D Radar* (16.67%). The largest percentage of unclassifiable trajectories (28.16%) was recorded for the *Mirror Ball* technique. In total, the largest percentage of trajectories for all six visual guidance techniques was classified as $T_{InBetween}$. The relative percentage of A_V^{in} for these trajectories was in the range of $[\alpha, 100 - \alpha]$ such that no clear assignment to one of the two targeting approaches could be made, see Figure 4.20. Of the remaining trajectories, between 30% – 40% were classified as either T_{OneWay} or T_{TwoWay} , which is still an acceptable percentage in view of the large inter-operator variability when targeting virtual objects in HMD-based AR. The results show that for all visual guidance techniques, with the exception of the *3D Radar*, the participants predominantly chose a one-way targeting approach. This is most evident in the *EyeSee360* technique, where only 2.68% of all trajectories were classified as T_{TwoWay} , compared to 34.82% classified as T_{OneWay} . The *3D-Radar* was the only technique that clearly promoted a two-way targeting approach, with 26.47% of all trajectories being classified as T_{TwoWay} , compared to 10.78% for T_{OneWay} . Table 4.4 contains a summary of the exact percentages for all six visualization techniques.

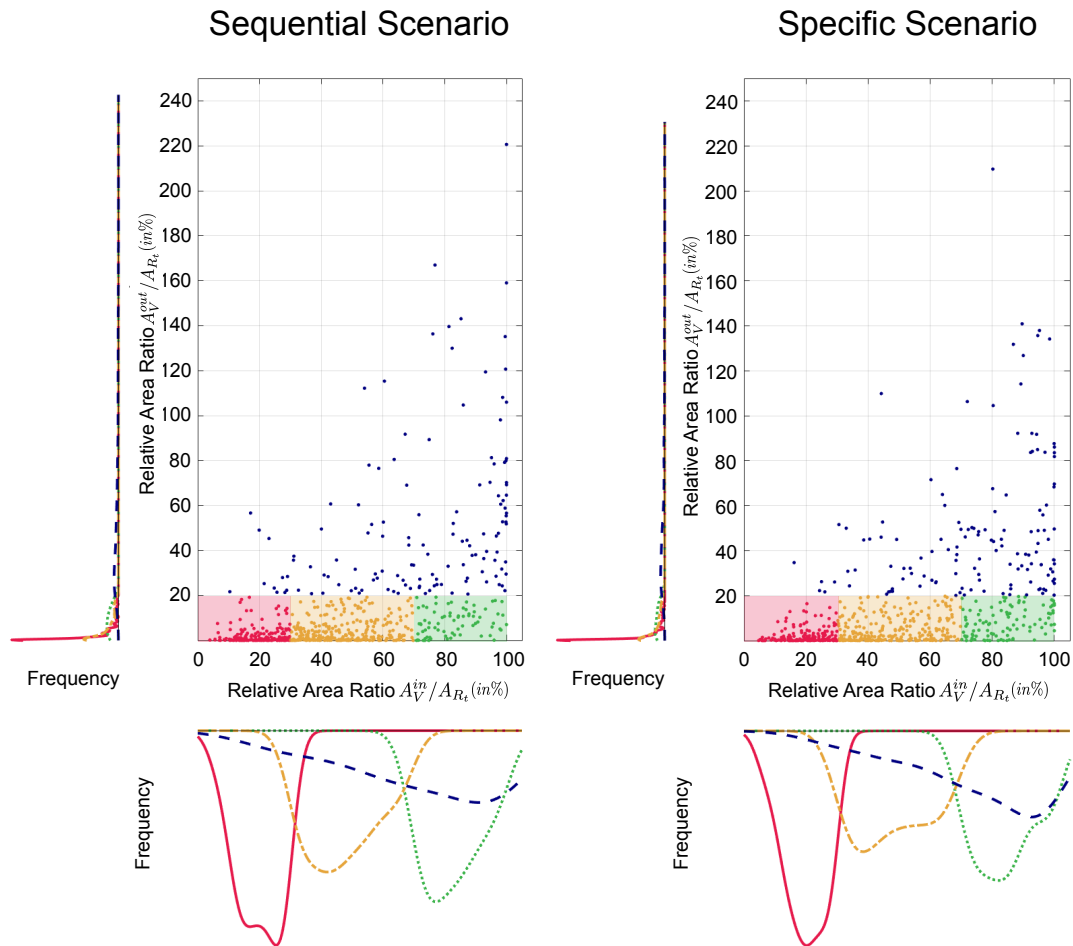


Fig. 4.20. Distribution of head rotation trajectories for the *Sequential* and the *Specific* collection scenario, excluding outliers. Each point corresponds to a trajectory described by the two ratios A_V^{in}/A_{R_t} and A_V^{out}/A_{R_t} . The classification boundaries are indicated by three colored rectangles: T_{OneWay} (red), $T_{InBetween}$ (yellow), T_{TwoWay} (green). All other trajectories (blue) are assigned to $T_{Unclassifiable}$.

The same general trends observed for the *Sequential* scenario were also found for the head trajectory data in the *Specific* object collection scenario, confirming the former. The participants predominantly employed the two-way targeting approach with the *3D Radar* visual guidance technique (24.77%, compared to 9.73% for T_{OneWay}). For all other techniques the one-way targeting approach was clearly preferred by the majority, again especially for *EyeSee360* ($T_{OneWay} = 40.37\%$; $T_{TwoWay} = 7.34\%$). Surprisingly, the total percentage of trajectories that could not be classified was higher than the (theoretically simpler) *Sequential* collection scenario.

System Usability Scale In order to evaluate the perceived usability of all six visual guidance techniques a SUS questionnaire was completed by all participants after the study. The results are summarized in Table 4.3. In accordance with completion time results, very high SUS scores were recorded for both *EyeSee360* (89.27 ± 10.31) and the *3D Radar* (83.63 ± 17.10), followed by *AroundPlot* (79.19 ± 12.82) and *3D Arrows* (71.29 ± 17.34). The other two techniques, *Mirror Ball* and *sideBARs*, received lower SUS scores of 44.45 ± 19.87 and 51.05 ± 19.67 respectively. A repeated measures ANOVA revealed a significant effect of the visual guidance technique on the SUS score ($F_{5,115} = 27.12, p < 0.001, \eta^2 = 0.54$). Post-hoc tests with Bonferroni correction

Tab. 4.4. Summary of the results for the classification of the head rotation trajectories. For the six different visual guidance techniques, the percentages of all four trajectory classes indicating different object targeting approaches are reported, both for the *Sequential* and *Specific* collection scenarios.

| Conditions | Sequential | | | | Specific | | | |
|-------------|------------|---------|------------|----------------|----------|---------|------------|----------------|
| | One-Way | Two-Way | In-Between | Unclassifiable | One-Way | Two-Way | In-Between | Unclassifiable |
| 3D Arrows | 25.69% | 8.26% | 41.28% | 24.77% | 26.55% | 10.62% | 43.36% | 19.47% |
| 3D Radar | 10.78% | 26.47% | 46.08% | 16.67% | 9.73% | 24.77% | 46.28% | 19.20% |
| AroundPlot | 21.24% | 11.50% | 51.33% | 15.93% | 32.08% | 20.75% | 33.96% | 13.21% |
| EyeSee360 | 34.82% | 2.68% | 50.89% | 11.61% | 40.37% | 7.34% | 41.28% | 11.01% |
| Mirror Ball | 29.13% | 12.62% | 30.10% | 28.16% | 26.61% | 11.93% | 32.11% | 29.36% |
| sidebARs | 21.37% | 17.95% | 36.75% | 23.93% | 21.90% | 14.29% | 42.86% | 20.95% |

showed that *3D Arrows*, *3D Radar*, *AroundPlot*, and *EyeSee360* received significantly higher usability ratings compared to the *Mirror Ball* ($p < 0.001$ for all four techniques) and *sidebARs* (*3D Arrows*: $p = 0.02$; for all other three techniques: $p < 0.001$). Additionally, *EyeSee360* achieved a significantly higher SUS score compared to *3D Arrows* ($p = 0.002$).

Mental Effort Lastly, another post-experimental questionnaire concerning the perceived mental effort while working with the different visual guidance techniques was taken by the participants. For the statistical analysis, non-parametric Kruskal-Wallis tests were used and a significant effect of the visualization technique on the experienced mental effort was found ($H(5) = 60.06, p < 0.001, \eta^2 = 0.40$). Post-hoc tests revealed significantly lower mental effort levels for *EyeSee360* compared to *3D Arrows* ($p < 0.001$), *AroundPlot* ($p = 0.007$), the *Mirror Ball* ($p < 0.001$), and *sidebARs* ($p < 0.001$). Additionally, the perceived mental effort was significantly lower for the *3D Radar* compared to the *Mirror Ball* ($p < 0.001$) and *sidebARs* ($p < 0.001$). A summary of the mental effort levels, all reported based on a 9-point Likert-scale according to Paas [355], is depicted in Table 4.3.

Discussion

From the results of the experimental user study, three main observations can be derived. First, the performance of the proposed *3D Radar* is equivalent to the most advanced techniques for visualizing objects outside the visible field of view in HMD-based AR. Although it does not surpass *EyeSee360* in terms of task completion times and usability, the results suggest that the *3D Radar* offers an intuitive way to quickly navigate and perform goal-oriented search tasks in AR environments. Unlike other techniques, the *3D Radar* has the potential to encode a variety of information in a small portion of the user's view, including both the direction to a target object and its distance. Even providing quantitative distance information to the user can potentially be achieved by varying the number and radius of the concentric circles of the *3D Radar*, which is not possible with techniques like *EyeSee360* or *3D Arrows*. With this approach, it is possible to use the inner circles to convey information about objects in close proximity, while the outer circles display objects that may be far away from the user. In the present study, a triangle pointing either up or down was used as a proxy symbol to indicate whether an object is above or below the user. This information is also encoded in the color of both the projection circle and the connecting line between the proxies and the projections.

Instead of the triangle proxies, it is therefore possible to use small icons or even small 3D models that represent the out-of-view objects to gain an even better understanding of the environment. Whereas the proxy icons in *AroundPlot* and *EyeSee360* could also be replaced by more specific object representations, the *3D Arrows* technique can hardly support this kind of encoding. Furthermore, the *3D Radar* takes up considerably less space on the screen than *EyeSee360*, and it is even possible to adjust the size of the radar depending on the user and the AR application. In cases where an unobstructed view of the real scene is an essential requirement, the *3D Radar* could be the preferred choice for the visualization of out-of-view objects. Further experiments are necessary to investigate these potential benefits.

The second important observation is the relatively poor performance of the *Mirror Ball* visual guidance technique, both in terms of object collection times and the general usability. Several factors may have contributed to these results. First, spherical mirrors are rather unusual objects and interactions with them hardly ever occur in our daily lives. Hence, the interpretation of the reflections on the *Mirror Ball* is not very intuitive and requires a great deal of cognitive load, as also confirmed by the highest mental effort scores during our post-experimental questionnaires. Secondly, deriving the location of objects by observing their reflections on the *Mirror Ball* is complicated by the fact that the physical environment is not reflected on the *Mirror Ball*. A potential way to achieve this is to create either a dynamic 3D model of the environment or a 360° video from the users' perspective. The resulting visualization, however, would no longer correspond to a visual guidance technique towards virtual objects, but to an alternative, spherically distorted representation of the real world. An attempt was made to improve the perception of the *Mirror Ball* by reflecting a skybox in the form of a spherical grid, which only partially accomplished its purpose. In addition, participants reported that identifying whether an object is behind or in front of the user is difficult because the user's body is not reflected by the *Mirror Ball*. This shortcoming could possibly be solved by incorporating a semi-transparent representation of the user's body in the virtual world. A technical problem that occurred especially with the *Mirror Ball* was *screen tearing* due to the limited computing power of the HoloLens. A custom shader that handles reflections more efficiently or displaying virtual objects as projections onto the *Mirror Ball* instead of reflections could potentially increase performance and reduce these screen tearing artifacts. While the current iteration of the HoloLens is computationally limited, future generations of hardware will probably solve this problem. Altogether, taking into account the first two observations, we can accept our hypothesis **H1** only for the *3D Radar* and must reject it for the *Mirror Ball*.

Finally, the third observation made during the experimental user study was the tendency of the participants to prefer indirect, two-way trajectories when using the *3D Radar* compared to a more frequent use of the direct, one-way targeting approach for all other visual guidance techniques, which confirmed our original assumption. The comparable task completion times of the *3D Radar* and *EyeSee360* are particularly interesting against the background of these observations, since the users with the *3D Radar* generally followed the longer, two-way targeting trajectories. The area-based algorithm for trajectory classification proved to be a suitable tool for distinguishing between the different approaches for targeting virtual objects. Conversely, most trajectories were still classified as a mixture of one-way and two-way targeting approaches for all visual guidance techniques, indicating that neither technique is clearly superior to the other. An *optimal* head trajectory towards a target object in HMD-based AR environments could be a much more complex function from an ergonomic point of view

than the two that were considered during the user study. It has been shown that humans perform physical tasks in a way that minimizes not only the length of the path, but also effort and discomfort. These concepts have been applied earlier in the field of robotics to enhance the human-like behavior of anthropomorphic robots [236, 237]. Although the present analysis of head rotation data is an important first step towards a better understanding of rotational motion patterns in AR environments, further studies are necessary to obtain a deeper comprehension of these concepts. A biomechanical model simulating the physiology of the head and neck could be used to better understand which parameters need to be optimized. The introduction of such a model into the head rotation trajectory analysis could help to implement visual guidance techniques that favor such physically motivated trajectories [264]. An additional phenomenon that commonly occurred for all different visualization techniques was *overshooting*, i.e. rotating the head too far in the direction of the target objects followed by a subsequent inversion of the head rotation. Similarly, directional corrections in which the users initially moved in the wrong direction could be observed—especially at the beginning of the head trajectories—but were not considered in the analysis of the results. The investigation of trajectory data with respect to these two patterns and the development of mitigation strategies will be an interesting area for future research. Another intriguing direction for future research is the integration of eye tracking, which could facilitate the investigation of how often and how long users focus on a particular visualization, and which could provide further insights into the perceptual aspects of visualizing objects outside the field of view.

Limitations

With regard to the study limitations, no baseline condition in the form of a *No Visualization* guidance towards virtual out-of-view objects was included in the present user study. The inclusion of such a baseline condition would have enabled measuring the exact quantitative advantages of the six different techniques compared to the lack of visual guidance. However, omitting such a baseline condition is consistent with previously published related papers (in particular with all four papers that presented the visual guidance techniques that served as comparisons during our user study). Furthermore, a *No Visualization* condition resembles a completely random search rather than an explorative or targeted search made possible by visual guidance techniques.

Another limitation of the experimental user study was the fact that the evaluation of different visual guidance techniques was limited to a context in which the virtual out-of-view objects were *static* in the environment. In the case of *dynamically* moving objects, the visual guidance techniques must continuously provide the user with information about the position of an object and possibly about the expected future trajectory. An interesting paper in this direction was recently published by Walker et al., which investigates how the intended motion of a robot can be communicated using AR in the context of human-robot interaction [483]. In particular for the visualization of expected trajectories as well as for the tracking of a moving object it is assumed that the *3D Radar* technique would be well suited, since it is able to convey information about absolute object positions. This is inherently difficult for all other visual guidance techniques because they primarily encode relative object positions. However, investigating the effects of visual guidance techniques on dynamically moving objects and confirming these hypothesis requires additional user studies in the future.

4.3.2 Study II: 3D Minimaps

In the previous study, two novel visual guidance techniques, the *3D Radar* and the *Mirror Ball*, were evaluated in an experimental user study with respect to their potential for directing users' attention towards virtual objects outside the visible FoV in HMD-based AR environments. While the former proved to be comparable to, and even exceeded, state-of-the-art techniques in certain criteria, the *Mirror Ball* did not achieve particularly good results due to the relatively high mental effort required to interpret the reflections of virtual objects on the surface of the *Mirror Ball*. A particular shortcoming of all six visual guidance approaches compared in the previous study is that they were all based on abstract visualizations that by their very nature do not provide context about the real environment. However, this information can potentially speed up the search process for virtual objects considerably. Current state-of-the-art HMDs such as the HoloLens are equipped with a variety of sensors to create a 3D map of the environment. These 3D reconstructions of the scene are generated using spatial mapping techniques such as SLAM (Simultaneous Localization and Mapping) and are used internally for tasks such as inside-out tracking.

Inspired by the two visual guidance techniques presented in the previous study as well as the observed limitations, especially the lack of context about the real environment, this section presents another preliminary user study evaluating a number of different *3D Minimap* visualizations for the task of localizing out-of-view objects in HMD-based AR. *Minimaps*, also known as *Worlds in Miniature*, were first proposed in the context of AR by Bell et al. in 2002 [28] and by default contain information about the real world in the form of a small map. The different *3D Minimap* visualizations presented in this study leverage the 3D reconstruction capabilities of the HoloLens and current state-of-the-art RGBD cameras to display a virtual 3D model of the real environment, including small proxy icons representing the various virtual objects within the scene. Three different types of *3D Minimap* visualizations are compared: 1) a traditional top-down bird's-eye view minimap; 2) a tilted bird's-eye view minimap; and 3) a novel type of minimap based on stereographic fisheye projection, which maps the area of a 180° hemisphere onto a circular 2D image plane. In a preliminary user study with six participants, these different 3D minimap visualizations were compared for the task of collecting virtual objects in an HMD-based AR environment, similar to the task of the user study presented in the previous section. The following subsections provide a short overview of the two different minimap types (bird's-eye view and stereographic fisheye view) and present the results of a preliminary user study comparing their effectiveness in locating out-of-view objects in HMD-based AR.

Bird's-Eye View Minimaps

Minimaps are best known from computer and video games, especially in genres such as real-time strategy and massively multiplayer online role-playing games (MMORPGs). They make it easier for players to find their way around the game world and vary depending on the level of detail that is encoded within the minimap. In the majority of scenarios, they provide a top-down 2D view of the game world, including both the position of the player and the location of objects of interest. In order to create a bird's-eye view minimap in the context of HMD-based AR, a 3D reconstruction of the environment can be used, which is created using various sensors that are integrated into the HMD for spatial mapping. A perspective

virtual camera with a specific FoV is placed at a certain distance above the 3D scene facing downwards. The movements of the user correspond directly to the movements of the virtual camera. By slightly rotating the virtual camera, tilted bird's-eye views can be achieved easily. Both the position of the user and the positions of the virtual objects can be integrated into the minimap via proxy icons. In this work a white triangle and a small proxy representation of the objects are used for this purpose. The absolute area that can be displayed with a bird's-eye view minimap is smaller than with a stereographic fisheye minimap due to the different projection mechanisms, but offers an undistorted view of the scene. A particular shortcoming of bird's-eye view minimaps are cut-offs at the edges of the scene, especially in large, non-square reconstructions. The only way to avoid this is to move the virtual camera upwards, which can severely limit the overall resolution of the minimap. Figures 4.21a and 4.21b depict the two previously described bird's-eye view minimaps in an HMD-based AR environment.

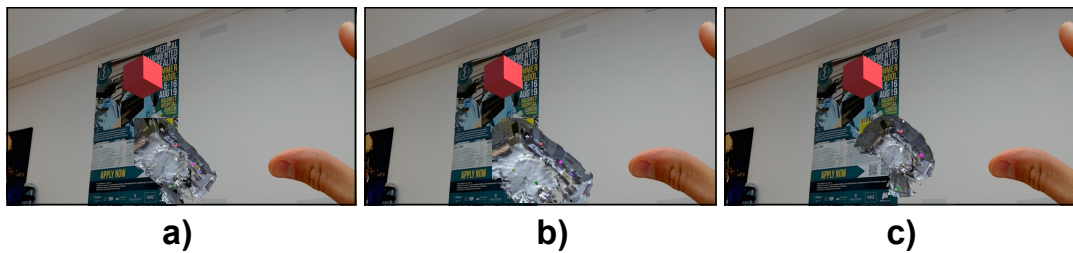


Fig. 4.21. Comparison of the three different *3D Minimap* visualizations for displaying out-of-view objects in HMD-based AR compared within the present user study. a) top-down bird's-eye view minimap; b) tilted bird's-eye view minimap; and c) stereographic fisheye minimap.

Stereographic Fisheye Minimap

Fisheye minimaps can be obtained by simply replacing the projective virtual camera that is used for bird's-eye view minimaps with a fisheye camera. Such fisheye cameras use fisheye lenses with extremely high angles of view to map the viewing sphere to an image plane and produce wide panoramic or hemispherical images. As a result, fisheye minimaps contain barrel distortions which causes straight lines to be bent during the projection process. There are several different types of fisheye projections, each with a different degree and type of distortion. The most popular fisheye projections include the equidistant projection, orthographic projection, and stereographic projection [183]. The latter is known as the conformal form of a fisheye projection, which preserves angles better and for which barrel distortions are less obvious. For Cartesian coordinates (x, y, z) on a sphere and (X, Y) on the image plane, the projection process as well as its inverse can be formulated as follows:

$$(X, Y) = \left(\frac{x}{1-z}, \frac{y}{1-z} \right), \quad (4.2)$$

$$(x, y, z) = \left(\frac{2X}{1+X^2+Y^2}, \frac{2Y}{1+X^2+Y^2}, \frac{-1+X^2+Y^2}{1+X^2+Y^2} \right). \quad (4.3)$$

For the stereographic fisheye minimap proposed in this section, the above formulas are employed to project the area of a 180° hemisphere onto a circular 2D image plane. Since the

total area of this hemisphere is considerably larger than the area of the viewing frustum used during the projection process for the bird's-eye view minimaps, the absolute area that can be projected with a stereographic fisheye minimap is much larger. Although the resolution decreases at the edges of the minimap, the stereographic fisheye minimap has no cut-offs and the entire 3D reconstruction including all virtual objects can be seen at all times. Figure 4.21c shows a comparison between the stereographic fisheye minimap and the two previously presented bird's-eye view minimaps.

Preliminary User Study

A preliminary user study was conducted to explore the potential of the three different *3D Minimap* visualizations for the conveyance of information about out-of-view objects in HMD-based AR. After a short introductory overview of the three minimaps, the participants were asked to use the Microsoft HoloLens to collect (via the HoloLens clicker) five virtual objects in an office environment as quickly as possible. All virtual objects were abstract representations of 3D shapes (cubes, spheres, and cylinders) and were randomly positioned around the user, similar to the positioning of the virtual objects in the previous user study from section 4.3.1. Small proxy icons corresponding to these shapes were displayed in all three minimaps, see Figure 4.21. A pre-computed 3D reconstruction of the scene was employed during the study, which was manually registered to the real scene. A total of six subjects (5 male, 1 female) with an average age of 28.17 ± 3.54 years participated in the experiment. All of the participants were unpaid post-graduate student volunteers without color deficiencies. To randomize the type of *3D Minimap* visualization among the study participants, a 6×6 balanced Latin square matrix was used to eliminate ordering effects. To assess the performance of the participants, we measured the time it took them to successfully collect all five virtual objects in the scene. In addition, they were asked to complete a System Usability Scale (SUS) survey for each of the three *3D Minimap* visualizations and optionally provide free text feedback.

Results

Overall, participants achieved the lowest mean completion times during the collection task using the stereographic fisheye minimap ($20.83 \pm 3.98s$), followed by the tilted bird's-eye view minimap ($23.43 \pm 7.04s$) and the top-down bird's-eye view minimap ($25.41 \pm 10.03s$). Similar results were obtained for the SUS questionnaire. While all three *3D Minimap* visualizations achieved high average SUS values, participants provided the highest values for the stereographic fisheye minimap (88.33 ± 10.57), followed again by the tilted bird's-eye view minimap (85.83 ± 5.16) and the top-down bird's-eye view minimap (75.83 ± 10.33). With regard to user free text feedback, three participants mentioned that the stereographic fisheye minimap provides the best means for understanding the height of virtual objects because of the relative size differences of the proxy symbols within the minimap, while this information is difficult to convey with the traditional top-down bird's-eye view minimap. One participant explicitly stated that the tilted bird's-eye view minimap is worse than the stereographic fisheye minimap to understand the parts of the scene behind the user, while another participant did not find any significant differences between the three minimaps.

Discussion & Future Work

The preliminary user study demonstrated the potential of *3D Minimap* visualizations for the localization of out-of-view objects in HMD-based AR environments. Participants were able

to achieve both the lowest task completion times and provided the highest usability ratings for the proposed stereographic fisheye minimap, showing advantages over more traditional bird's-eye view minimaps. Interestingly, the participants exploited the perspective distortions of the stereographic fisheye minimap for the purpose of better understanding the relative size differences between proxy icons to determine the height of virtual objects in the scene. In future work, these preliminary results need to be verified during a larger user study, including a comparison of the stereographic fisheye minimap with established visual guidance techniques for locating out-of-view objects in AR, similar to the study presented in section 4.3.1. Additionally, it could be intriguing to study the behavior of participants when using the *3D Minimap* visualizations in more detail. By tracking the user's gaze during the search process, a future study could investigate whether the *3D Minimap* visualizations allow the user to quickly gain an understanding of the location of a virtual object, or if a continuous look-and-verify process is necessary.

4.4 Summary

This chapter presented an overview of the *VesARlius* application for interactive and collaborative anatomy learning in HMD-based AR environments. Starting with a detailed description of the general concept of *VesARlius* and the main technical features of the application, in particular the basic elements of the user interface and the available collaborative paradigms, two evaluation studies were described in which the application was integrated into the medical curriculum. The first study aimed to determine the effectiveness and potential of *VesARlius* to enable collaborative anatomy learning in teams of co-located students and to serve as an additional pedagogical resource in the context of anatomical education. It was found that the use of *VesARlius* significantly increases the anatomical knowledge of students, even more so than within a group studying with textbooks and 3D models. In addition, the study participants highlighted a number of advantages of *VesARlius*, such as its potential to improve the 3D understanding of topographic anatomy, its increased student engagement, and its positive impact on fun and motivation. The second study evaluated the specific advantages of running *VesARlius* on an HMD compared to a standalone application running on a regular desktop computer. The results of the study suggest that learning gross anatomy with *VesARlius* using an HMD does indeed offer unique advantages, as the participants achieved significantly better results in a complex CT slice positioning task than the control group working on a desktop computer.

A particular limitation of running *VesARlius* on an HMD is the limited field of view (FoV) that all current state-of-the-art devices suffer from. For this reason, several different visualization techniques have been examined in section 4.3 of this chapter to mitigate the effects of this limitation on the user. In particular, these visualization techniques aim to provide the user with information about the location of virtual objects outside the visible FoV. Within the scope of two user studies, three different novel visualization approaches were proposed and evaluated. In the first study, the *3D Radar* and the *Mirror Ball* were compared with existing state-of-the-art techniques for visualizing out-of-view objects in HMD-based AR environments. Additionally, the participants' head rotation trajectories during the experimental task were analyzed using a novel trajectory classification algorithm. While the *3D Radar* was equal to the best techniques from the literature in terms of task completion time and usability, the *Mirror Ball* suffered

from a number of perceptual challenges, which have been discussed extensively. Moreover, the *3D Radar* was the only technique in which the participants chose a specific type of trajectory, which consisted of aligning the horizontal and vertical angle one after the other, whereas in all other techniques a direct targeting approach was predominant. The second study presented the preliminary results of a comparison between three different *3D Minimaps* visualization strategies, two bird's-eye view minimaps and a novel stereographic fisheye minimap.

Similar to the AR *Magic Mirror* platform presented in chapter 3, the *VesARlius* application—thanks to the results presented in this chapter—was integrated into the gross anatomy course at the LMU Munich in dedicated tutorial sessions with first-year medical students. While a number of open research questions remain, particularly with respect to visualization strategies for mitigating the effect of the limited FoV of current HMDs, novel pedagogical approaches such as *VesARlius*, which allow students to engage in a collaborative learning environment, have the potential to become an essential educational resource in modern, multimodal anatomy curricula that follow the recent paradigm shift towards more active, student-centered, and explorative learning.

Discussion & Outlook

In the introductory chapter of this thesis the following question was posed: ***What is the best way to learn and teach human gross anatomy?*** Considering the enormous degree of complexity that is associated with learning the subject of anatomy, as well as the diverse individual learning preferences of medical students, there is no simple and universally valid answer to this question. Developing a single anatomy learning paradigm that constitutes the perfect educational resource in all scenarios and for all students is neither feasible nor realistic. Historically, anatomy teaching has evolved into a heterogeneous and multimodal environment with a wide range of educational resources available to students. Today there is a general consensus among anatomists that the availability of novel multimedia resources for anatomy learning as complementary tools to established pedagogical methods such as cadaver dissection courses or learning with textbooks and 3D models provides immense opportunities to both students and educators alike. In particular, there is a growing demand for resources that promote self-directed, student-centered, and explorative learning of anatomical concepts. In most modern medical curricula, however, these novel learning tools are not yet included. One particular technique that is able to meet the above requirements is Augmented Reality (AR). AR-based anatomy learning solutions can use interactive, 3-dimensional content to facilitate the acquisition of anatomical knowledge and offer exciting new possibilities and unique advantages over existing anatomy learning paradigms.

Therefore, the present thesis investigated the potential of AR as a complementary pedagogical resource in the context of undergraduate gross anatomy education. For this purpose, two novel AR solutions were demonstrated that meet the requirements of contemporary anatomy education. These two solutions are the AR *Magic Mirror* platform and the *VesARlius* application. Both proposed AR solutions enable interactive, engaging, and explorative anatomy learning, placing the user at the center of the learning experience. In a series of user studies, the AR *Magic Mirror* platform and the *VesARlius* application were both integrated into the medical curriculum and evaluated within realistic learning environments with a large number of medical students. Although the key results were already discussed extensively in the individual sections describing these evaluation studies, this chapter provides a meta discussion of the meaning and relevance of these results and directions for potential future research, both for the AR *Magic Mirror* platform in section 5.1 and for the *VesARlius* application in section 5.2. Finally, section 5.3 shortly reflects on the future of AR-based anatomy learning in light of the results presented in this thesis.

5.1 The Magic Mirror Anatomy Learning Platform

The results of this thesis concerning the AR *Magic Mirror* platform can be categorized into three main areas: 1) technical results; 2) perceptual results; and 3) evaluation results. In the first category are all technical developments and innovations that were integrated into the software of the proposed AR *Magic Mirror* platform. These include the new split-screen user interface consisting of an AR view and an additional view displaying either the virtual anatomy model or medical section images, the improved interactive gesture controls, an advanced perceptual in-situ visualization, the implicit user calibration procedure, and most importantly the real-time skeleton animation functionality to achieve dynamic animation of the virtual 3D model according to the user's movements. The second category of results contains the findings of the comparative user study on *Reversing* and *Non-Reversing Magic Mirrors*. (RMM vs. NRMM), specifically the following three findings: 1) medical students were generally better able to identify the correct placement of virtual organs under the NRMM condition; 2) interaction performance for the NRMM was significantly inferior to a regular RMM; and 3) the influence of the mere-exposure effect, which resulted in senior medical students performing worse than junior students under the RMM condition. Finally, the third result category comprises all findings of the three evaluation studies in which the AR *Magic Mirror* platform was integrated into the undergraduate medical curriculum at the LMU Munich. During all three studies, the system was perceived by medical students as a valuable complementary modality for self-directed and personalized anatomy learning that offers significant advantages over other established learning resources, particularly in terms of increased motivation and improved 3-dimensional understanding of topographic anatomy.

5.1.1 Relevance & Implications

Considering the above results, the question arises which implications these contributions have for the broader field of anatomy education. First of all, the technological advances presented in this thesis make the proposed AR *Magic Mirror* platform the most advanced screen-based AR solution ever introduced for the purpose of anatomy learning. In comparison to the two previous iterations of the AR *Magic Mirror* as developed by Blum et al. [54] and Meng et al. [316], as well as similar setups from other groups, such as the system by Bauer et al. [25, 26], the current AR *Magic Mirror* platform constitutes a significant leap forward with a considerably enhanced user experience. The system is easy to use (no calibration required), easy to interact with (simple gesture-based control), and easy to deploy (few hardware components). In addition, it contains a sophisticated 3D anatomy model that encompasses all relevant anatomical structures, as well as clinical section images from CT and MRI. All these functionalities combined make the AR *Magic Mirror* platform the state-of-the-art tool for interactive and personalized anatomy learning.

The results of the comparative user study between RMM and NRMM designs have indicated, however, that such a *Magic Mirror* system, which presents the digital mirror image of the user on a large screen, superimposed with virtual anatomy models, is not an immediately obvious design concept for AR-based anatomy education. Medical students constantly exchange their own left and right with the patient's left and right and are familiar with this concept

from textbook illustrations, patient examinations, or even surgical procedures. Therefore, an NRMM that presents the true digital mirror image of the user is the more natural approach for visualizing anatomical structures in a screen-based AR system. Especially senior medical students have been thoroughly trained for this left-right reversal, which explains their inferior performance for the task of identifying correct organ placements under the regular RMM condition within the study. In terms of user interaction, however, an RMM is substantially more intuitive, and all students had great difficulty interacting with the NRMM. Against the background of these partly inconsistent results, it is intriguing to discuss the long-term effects of employing a regular AR *Magic Mirror* that is based on the RMM design concept for anatomy education. While one possible outcome could be an improved left-right discrimination ability and possibly even an enhanced mental rotation ability and 3D comprehension of anatomy due to the continuous study of an alternative, but also anatomically correct view, exactly the opposite could also be the case, as medical students could be confused by seeing conflicting views in different learning resources (i.e. textbook vs. RMM). In the worst case, an RMM design could even pose the risk of learning anatomy with the wrong laterality. The main conclusion of the perceptual study on RMM and NRMM designs is therefore that a proper explanation of the employed concept is crucial prior to student engagement and integration into the curriculum.

Finally, the results of three evaluation studies have demonstrated that the AR *Magic Mirror* platform has the potential to serve as a valuable complementary resource for gross anatomy learning and can be integrated effectively into the medical curriculum. During these three studies, a total of 1701 medical students worked with the AR *Magic Mirror* platform during specially designed tutorials or self-directed group learning sessions. Never before has such an extensive evaluation of a novel AR system been carried out within the context of anatomy education. In addition to increasing student motivation through a more interactive and engaging learning experience, a quantitative learning effect was measured, which confirms that the use of the system increases the level of anatomy knowledge among medical students. Furthermore, the AR *Magic Mirror* platform was found to increase the 3-dimensional understanding of topographic relationships within the human body, especially for students with lower spatial reasoning skills. Overall, these very encouraging results have confirmed the additional pedagogical value of the AR *Magic Mirror* platform. Within a modern undergraduate gross anatomy curriculum, the system can occupy an important place and serve as a complementary learning resource to other established teaching paradigms. The unique advantages of AR-based anatomy learning with the *Magic Mirror* platform have the potential to advance the entire field of anatomy education, facilitate the transfer of knowledge within such a complex field, and ultimately contribute to the long-term training of highly qualified physicians.

5.1.2 Limitations

Although the above discussion of the results clearly highlights the enormous potential of the AR *Magic Mirror* for anatomy education, there are a few limitations to the system as well as several areas for improvements that will be outlined in the following. First of all, students expressed a desire for more (clinically relevant) content in the form of additional CT or MRI volumes and an educational quiz mode that would make the entire learning experience

even more interactive and personalized by tailoring the content to the user's specific level of knowledge. While the development of these elements is not particularly appealing from a scientific perspective, it would certainly make the system more mature and further increase the benefits that medical students would derive from using the system. Another shortcoming mentioned by students during the evaluation studies was that for extended use of the *AR Magic Mirror* platform, the gesture-based user interaction was perceived as tiring by some students. Arm fatigue is a well-known problem for mid-air gesture-based user input in human-computer interaction [190]. Aside from alternative input methodologies such as gaze or a tangible pointer, several potential solutions have been proposed for reducing arm fatigue in gesture-based user interaction. These include recognizing gestures in a more relaxed arms-down position [173, 272, 395, 423] or tracking individual fingers in combination with raycasting approaches for selection and interaction purposes [304]. While these approaches have been proven to reduce arm fatigue during prolonged mid-air gesture interaction, directly integrating these techniques into the *AR Magic Mirror* platform is challenging due to the limited hand and finger tracking capabilities of the Microsoft Kinect. The tracking algorithm works best when the arms are extended from the body and suffers from severe inaccuracies when they are placed very close to it. Therefore, employing these alternative interaction methods within the *AR Magic Mirror* platform would require a different gesture detection algorithm. Finally, the fact that the *AR Magic Mirror* platform is limited to only a single user interacting with the system at a time was perceived as an additional limitation by some medical students. While the Kinect skeleton tracking algorithm is capable of tracking up to 6 people simultaneously, the user interface of the *Magic Mirror* is tailored to the single-user scenario and allowing multiple students to jointly interact with the system would require a significant overhaul of the UI. Enabling a collaborative anatomy learning experience in teams should be considered from the ground up when developing a novel educational resource, as in the case of the second AR-based solution proposed in this thesis, the *VesARlius* application.

5.1.3 Future Work

As for future work, there are ongoing studies to investigate the long-term benefits of the *AR Magic Mirror* platform on student learning outcomes that are expected to further manifest the role of the system as an indispensable new resource for interactive, student-centered, and personalized anatomy learning. Furthermore, a detailed study of how the use of the *AR Magic Mirror* platform leads to an improved 3D understanding of topographic anatomy and perhaps even assists in the acquisition of spatial reasoning skills would be a very compelling direction for future research. Such an understanding of the topographic relationships of anatomical structures is difficult to obtain with traditional 2D projections from anatomy atlases and textbooks. Previous research has found a correlation between spatial ability and performance in gross anatomy courses, both of which are predictive of each other [150, 284, 451, 479]. If a future study could prove that this correlation also applies to AR-based anatomy learning, and perhaps even strengthen it, this would be an important justification for a large-scale integration of novel AR-based learning resources such as the *AR Magic Mirror* platform into the curriculum. In addition, introducing the *AR Magic Mirror* platform directly into the dissection course, allowing students to see previously acquired section images of the respective organ donor, would represent an interesting scenario that could combine the advantages of both AR-based learning with the *Magic Mirror* platform with the undisputed benefits of a

cadaveric dissection course. Another promising direction for future research is the integration of monocular RGB-based skeleton tracking approaches, removing the need for a Microsoft Kinect. Although considerable progress has been made in this area over the past few years—as outlined in section 2.2.3—these approaches still require a significant amount of computing power, as the majority of them is based on deep learning. However, the successful integration of a robust monocular RGB-based tracking algorithm would allow the AR *Magic Mirror* to be used on a regular laptop or even as a web-based platform, allowing medical students to use the system for home-based anatomy learning.

Additional Application Scenarios

While this thesis exclusively explored the potential of the AR *Magic Mirror* platform as a complementary learning resource in the context of undergraduate anatomy education, it can also be effectively used for the education of the general public. During the course of this thesis, the system has been demonstrated in several exhibitions and museums, including the well-known exhibition *Real Bodies* (the equivalent of the German *Körperwelten*). In addition, a simplified version of the AR *Magic Mirror* platform offers interesting possibilities for use in K-12 education. Apart from medical education, there are two other potential application domains in which a screen-based AR system analogous to the *Magic Mirror* platform could be applied effectively. The first is rehabilitation, where the system can be used by patients to obtain immediate feedback on the correctness of the rehabilitation exercises performed. In case of an incorrect movement, the patient can be informed by the system and, if necessary, suggestions for improvement can be communicated. Especially in combination with *serious gaming* approaches, in which the patient performs the exercises in a playful manner and tries to achieve as many points as possible through correct and numerous repetitions, an increased motivation and thus a better patient compliance can be expected [240]. The skeletal tracking capabilities of such a system allow the approximate calculation of muscle activation during a given movement, which can be valuable information for deciding whether an exercise is conducted properly by the patient. Furthermore, it is possible to accurately measure the range of motion of a particular joint during rehabilitation exercises, as recently demonstrated by Yu et al. [502]. Thanks to the simple hardware setup and the low costs of the AR *Magic Mirror* platform, it can be easily deployed at the patient's home and the exercises can be performed in front of the TV, computer monitor, or even a laptop screen.

The second domain of application, in which a similar system as the AR *Magic Mirror* platform would offer a number of advantages, is doctor-patient communication and in particular patient education prior to surgical interventions. Complex processes and interrelationships of different anatomical structures can be explained using the AR *Magic Mirror* platform directly on the patient's own body, which could facilitate the exchange of information during patient interviews. Although certainly not all surgical procedures are suitable for patient education with such a system, certain elective procedures, including those in the field of endoprosthetics, where the position of a surgical implant can be shown to the patient at the respective site in advance, could benefit from a better understanding of the patient about the procedure, potentially leading to better informed consent and additional advantages such as reduced patient anxiety [197]. In addition, it would be possible to discuss the resulting short- and long-term restrictions of the treatment process with the patient before the intervention. Within the scope of patient education discussions, the AR *Magic Mirror* platform offers the possibility to play short, explanatory animations about the different steps of an intervention, to identify risk

structures, and to take patient-specific details into account. In spite of all potential advantages, an extensive evaluation is required to find out in which interventions patient education with the *AR Magic Mirror* platform is considered useful. In particular, time constraints, complexity of the intervention, and ethical aspects must be examined with regard to the added value of the system.

5.2 The VesARlius Anatomy Learning Application

Similar to the previous section, in which the key findings related to the *AR Magic Mirror* platform were discussed, this section provides a similar review and discussion of the most important results in the context of the *VesARlius* anatomy learning application. These results can be categorized into the same three areas: 1) technical results; 2) perceptual results; and 3) evaluation results. While both the technical and evaluation results are specific to the use of *VesARlius* for anatomy education, the perception results can be applied in many different HMD-based AR applications across different domains and are therefore relevant in a much broader context. The technical results include all the essential features that were developed throughout the entire engineering process of the *VesARlius* application, such as the general design of the user interface, the one-to-one correspondence between the 3D anatomy model and the medical section images, the virtual X-ray module, and most importantly, the different collaboration paradigms that allow multiple students to engage in a joint anatomy learning experience. The evaluation results were obtained from the two user studies in which the *VesARlius* application was integrated into the curricular environment of the LMU Munich and tested by medical students. *VesARlius* was found to provide a quantitative learning effect and increase the overall anatomical knowledge of students more than learning with textbooks and 3D models. Further advantages of the application were an enhanced involvement and motivation of the students, more fun while learning, and a perceived better 3D understanding of topographic anatomy. Additionally, the second study found distinct advantages of running *VesARlius* on an HMD compared to a standalone application running on a regular desktop computer. Finally, the perceptual results, while directly applicable in the context of *VesARlius*, can be used in more general scenarios and include a number of newly proposed visual guidance techniques for localizing out-of-view objects in HMD-based AR environments and a novel algorithm for classifying head rotation trajectories, both of which were evaluated in two experimental user studies.

5.2.1 Relevance & Implications

This subsection will discuss the implications and relevance of the above results for the field of undergraduate anatomy education and, in case of the perceptual results related to visual guidance techniques, for the broader field of HMD-based AR applications. In the same way that the proposed *AR Magic Mirror* platform is the most advanced screen-based AR system for anatomy learning, *VesARlius* is the most advanced HMD-based AR application that even allows multiple students to engage in a collaborative anatomy learning environment. Team-based collaborative learning with other fellow students is a key learning paradigm in medicine and has been shown to have a positive effect on the overall learning outcome of students, both within small-group learning [199, 341, 471, 472] and in near-peer teaching scenarios [134,

334, 336, 354]. *VesARlius* combines the benefits of peer learning with those of interactive AR environments, delivering a unique educational experience for medical students that fosters active and explorative learning of anatomical topics. In addition, the available collaboration paradigms, both for short-term and for more permanent highlighting of individual UI elements, offer effective measures to facilitate communication and dialogue between students. In other educational domains, such collaborative AR systems have been associated with significant benefits in terms of increased motivation, interaction, and learning outcomes [298, 369, 503]. Therefore, the introduction of *VesARlius* as the first collaborative, HMD-based AR application specifically built for anatomy learning provides the technical basis to fundamentally alter the currently existing anatomy learning landscape.

Before *VesARlius* can actually claim to be a valuable addition for anatomy learning, however, the actual benefits of using the application within collaborative anatomy learning sessions must be demonstrated under realistic curricular conditions and compared to established resources. For this purpose, an evaluation study was conducted, the first of its kind to integrate a novel HMD-based AR application into an undergraduate gross anatomy course. In this study, similar results as in the AR *Magic Mirror* evaluation studies were obtained. *VesARlius* was perceived as a valuable complementary learning resource that offers a number of advantages over learning with traditional textbooks and 3D models. These advantages included an increased engagement and motivation of the students, a positive quantitative learning effect, and even—according to subjective assessment—an increased 3D understanding of the topographic anatomy. On top of that, the ability to collaboratively learn anatomy within small teams was very well received by the students, although great care must be taken to make this experience as intuitive as possible without creating cognitive overload [83, 121, 369]. In a second evaluation study it was confirmed that the HoloLens as a medium for displaying the contents of *VesARlius* is superior to a standalone application running on a regular desktop computer. Students performed significantly better on a complex CT slice positioning task, suggesting that examining a 3D virtual model in AR has advantages over traditional 2D representations on a computer screen. Overall, the results of both studies strongly suggest that the HMD-based *VesARlius* application does indeed have the potential to become a valuable new teaching resource for collaborative, student-centered, and explorative anatomy learning within a modern, multimodal curriculum.

In both studies, however, the students mentioned several limitations regarding the HoloLens hardware, in particular the small field of view (FoV). This sparked the investigation of how well virtual objects outside the current FoV are perceived under certain visualization strategies and how well these visualizations can be used to draw the user's attention towards these objects. The newly proposed *3D Radar* visualization proved to be comparable with existing state-of-the-art methods in an experimental user study, and at the same time offers a number of advantages, such as additional options for encoding quantitative distance information. The second proposed visual guidance technique, the *Mirror Ball*, was found to suffer from several perceptual challenges, most prominently the high mental effort required to correctly interpret the spherically distorted reflections on its surface. Another interesting observation made during this study was that there were two prominent types of object targeting trajectories (direct, one-way vs. indirect, two-way), which could be distinguished with a novel head trajectory classification algorithm. In a further small evaluation study, different *3D Minimap* visualizations were compared, among them a newly proposed stereographic fisheye minimap,

whose potential was demonstrated as it surpassed conventional bird's-eye view minimaps in a simple search and collection task. These perceptual results are highly relevant, as the small FoV is a shortcoming for all currently available HMDs. Major advances in the next few years, perhaps even an HMD whose FoV matches that of the human visual field, are unlikely to be introduced due to the complex optical design of these devices [510, 519]. Therefore, the visual guidance techniques presented have the potential to mitigate the effects of this limitation for the user. In addition, the results are not restricted to being used within the *VesARlius* application, but can potentially be employed in a variety of AR applications across different fields.

5.2.2 Limitations

In terms of technical limitations and improvement suggestions, students in the first evaluation study reported almost the same points as for the AR *Magic Mirror* platform. The most frequently mentioned request was to extend the application with additional content, both in terms of additional 3D anatomy models and more medical section images, especially clinically relevant content and pathologies. In addition, the different anatomical structures within the model should be more fine-grained (e.g. splitting the liver into the different lobes or defining a model for each bone instead of a large model for the entire skeleton). The current 3D anatomy model is derived from a CT volume using a semi-automatic segmentation algorithm and translated into a 3D model using 3D modeling software. Although this procedure is feasible for a single anatomical model, it is not scalable to a large number of such models. Instead, fully automatic segmentation algorithms could be used, although these are generally tailored to a specific organ and multi-organ segmentation algorithms do not yet provide the desired granularity of differentiation mentioned above [177, 266, 486]. An alternative would be to include the same models as used within the AR *Magic Mirror* platform, although in this case no direct correspondence between these models and a CT volume can be established. Another limitation related to the evaluation of *VesARlius* is the relatively small number of students that worked with the application during the two user studies. The extent is not comparable with the large-scale evaluation of the AR *Magic Mirror* platform, which included a total of 1701 students. Against this background, the findings of the *VesARlius* evaluation are much more preliminary and must be confirmed in further studies. Nevertheless, these preliminary findings represent an important first step towards integrating *VesARlius* as an additional resource for collaborative anatomy learning into the curriculum. A further limitation concerns the evaluation of the use of the different collaboration paradigms available in *VesARlius*, which was only carried out by means of a post-experimental questionnaire. Although the students found these paradigms useful and sufficient to enable collaboration between them, no standardized analysis of the frequency of use of these different features was conducted in the evaluation study.

The limitations encountered during the experiments on the different visual guidance techniques for the localization of out-of-view objects in small-FoV HMDs mainly revolve around the fact that only static virtual objects were considered. While this is a valid assumption for *VesARlius*, which has a static UI, dynamic virtual objects can occur in many AR applications from other domains, thus the ability of novel visualization approaches for continuously providing the user with appropriate information about moving virtual objects needs to be

confirmed. Moreover, the results of the second evaluation study comparing the different *3D Minimap* visualizations were very preliminary and no comparison with the *3D Radar* or *EyeSee360* as the best performing methods from the first study was carried out. Finally, it was found that although the proposed trajectory classification algorithm was able to distinguish precisely between a direct, one-way and an indirect, two-way object targeting trajectory, a large number of trajectories were classified as between these two, indicating that many users follow a different type of trajectory, potentially one that minimizes their physical effort.

5.2.3 Future Work

While the results presented in this thesis have shown the potential of the *VesARlius* application to serve as a complementary resource for collaborative gross anatomy learning, additional studies are needed to verify and expand these results. In particular, longer-term evaluation studies with a larger number of participants and longer interaction times with the application, possibly even across multiple educational centers, will be pivotal in finding the perfect spot for *VesARlius* within a modern medical curriculum such that students can derive the maximum benefit from working with the application. These additional studies also need to examine to what extent and in what specific scenarios the different collaboration paradigms are used by students. This could help in the development of best practices and pedagogical guidelines to facilitate the use of *VesARlius* within a guided anatomy training course. Similar to the *AR Magic Mirror* platform, it was found that the *VesARlius* application improves students' subjectively perceived 3D understanding of topographic anatomy, suggesting that interactive AR systems in general offer the unique advantage of helping medical students acquire spatial reasoning skills to better understand the 3D relationship of anatomical structures within the human body. However, this data was only assessed subjectively and qualitatively, such that future studies are required that specifically explore the relationship between the acquisition of spatial reasoning skills and anatomy learning with an interactive AR solution such as *VesARlius* or the *Magic Mirror* platform.

Another intriguing idea, also proposed in the context of future work for the *AR Magic Mirror* platform, is the integration of *VesARlius* directly into the dissection course. While students explicitly stated during the evaluation studies that neither of the two AR solutions can replace a practical, hands-on cadaver dissection course, using these tools as supplementary resources during such a course would provide additional information, e.g. in the form of medical section images, that would enhance the overall experience of the course. Assuming that CT or MRI data of a cadaver is available, one could imagine registering the virtual model generated from this data and superimposing it directly onto the cadaver during the course. However, such a scenario requires precise tracking of the cadaver as well as advanced perceptual visualization strategies to make the AR experience appealing. As far as user interaction with *VesARlius* is concerned, the recent introduction of fully articulated hand tracking, which is available for both the second generation of Microsoft HoloLens and the Magic Leap One, opens up a number of new possibilities for interacting with the user interface. Novel gestures, e.g. to enlarge a certain anatomical structure, to place pins, or to slide the CT image across the virtual model, could be integrated and further enhance the overall user experience.

One component of *VesARlius* that was not evaluated explicitly is the virtual X-ray module, allowing the user to operate the model of a C-arm and take virtual X-ray images. C-arms are frequently used in orthopedic procedures and interventional radiology, but image quality and radiation levels can vary greatly depending on the knowledge and experience of the operator [65]. Therefore, a future study investigating whether this module contributes to a better understanding of topographic anatomy, or whether it might even be suitable for AR-based fluoroscopy training, could be interesting. Finally, another direction for future research on the *VesARlius* application is remote collaboration. The two evaluation studies presented in this paper were conducted for a collaboration scenario in which all medical students were co-located and shared the same physical workplace, allowing them to directly see and communicate with each other. In a remote collaboration scenario, on the other hand, the illusion is created that two or more distributed users share the same physical space by means of telepresence. Adapting *VesARlius* for such a scenario is trivial and only requires a means to transmit a voice stream over the network such that all users of a shared room can hear each other. A comparative study examining whether students have the same positive attitude towards the *VesARlius* application when used in such a remote collaboration scenario would be highly informative, especially against the background of the well-known benefits of regular peer learning in medicine.

Finally, future work on visual guidance techniques for out-of-view objects in HMD-based AR environments directly arises from the limitations described at the end of the previous subsection and can be divided into three areas: 1) the analysis of the proposed visual guidance techniques in the context of dynamically moving virtual objects; 2) the comparison of the novel stereographic fisheye minimap visualization with other state-of-the-art approaches such as the *3D Radar* or *EyeSee360*; and 3) the investigation of whether users tend to follow physically motivated trajectories that minimize physical effort while targeting out-of-view objects in HMD-based AR environments. All these aspects are not only relevant in the context of *VesARlius*, but possibly also for a variety of different applications from other areas, such as AR-based games or for navigation purposes.

5.3 The Future of Augmented Reality Anatomy Learning

Considering the results presented in this thesis, as well as the steadily increasing interest in Augmented Reality (AR)—not only in education, but in a variety of different areas—we may be on the verge of an important paradigm shift in anatomy education. While the field of anatomy, like medicine as a whole, is a rather conservative domain where innovation is rather slow and steady, novel AR solutions, such as the *AR Magic Mirror* platform or the *VesARlius* application, with their numerous advantages over many traditional anatomy learning modalities, have the potential to become an integral part of the future educational landscape in human gross anatomy. Both solutions were thoroughly integrated into a realistic curricular environment and evaluated by a large number of medical students in comparison to other established learning resources, such that representative educational conclusions could be drawn. Among the major advantages of these novel AR solutions are an increased motivation and engagement of medical students through interactive and explorative learning as well as an improved 3-

dimensional understanding of topographic anatomy. In addition, a quantitative learning effect was measured for both the AR *Magic Mirror* platform and the *VesARlius* application. Therefore, the results of the present thesis can serve as a *stepping stone* for a widespread integration of novel AR-based learning resources as complementary pedagogical tools—without having to abandon traditional learning paradigms—into the anatomy curriculum for students all over the world. In the future, however, many additional studies will be required to further delineate and specify the exact place of interactive AR solutions within these modern curricula such that students and educators alike can derive maximum benefit from these solutions.

Against this background, the question arises what the future of AR-based anatomy learning might look like and how the results presented in this thesis could influence the development of other novel AR solutions in the coming years. To answer these questions, the three types of AR systems from the taxonomy of Bimber and Raskar [45] are considered separately: hand-held, spatial, and head-attached displays. Hand-held AR is pervasive today and has become the most common platform for AR, far outweighing the other two categories, largely due to the rapid technological advances in smartphones and tablets. Both the computational power and the number of sensors integrated into these smart devices have increased dramatically over the last decade, with the latest iterations even incorporating a depth camera that allows virtual objects to be positioned at the correct depth in the scene, thus solving the occlusion problem. Most importantly, however, these devices are ubiquitous today and almost everyone carries an AR-enabled device in their pocket. Section 2.3 of this thesis presented many different hand-held AR solutions that were proposed in the literature for the purpose of anatomy education. In addition to these research prototypes, there is also a variety of different commercial applications available for this purpose today. While the results of this thesis have only very limited relevance for the development of future hand-held AR solutions for anatomy education, since the proposed solutions belong to the other two categories of Bimber and Raskar's taxonomy, it is still anticipated that the number of proposed hand-held AR solutions will increase significantly, such that hand-held AR will remain the predominant medium for experiencing AR in the near future. However, as has been shown in previous studies, hand-held AR is not the most optimal way to experience AR. The smartphone or tablet must be carried around continuously by the user and aimed at point of interest in the scene, resulting in a number of shortcomings, including arm fatigue during prolonged use, limited interaction possibilities, and often times a not very personal and engaging user experience.

AR systems that are based on spatial displays form the second category of Bimber and Raskar's taxonomy, for which the display is a stationary part of the environment. Due to the fact that only basic hardware components such as a video camera, a regular PC, and a display device are required to create an AR system of this category, a variety of different prototype solutions have been proposed for anatomy education in the past, specifically in the earlier days of AR. More recently, however, these solutions have been increasingly replaced by hand-held AR systems, as the latter are more readily available to the user and do not require any modification of the environment. The proposed AR *Magic Mirror* platform as a screen-based *virtual mirror* system falls into this category and allows the users to see an AR view of their digital mirror image on a large TV screen. The results of the present thesis demonstrate, however, that these AR solutions do have their justification and offer specific advantages over the other two categories. The conceptual design of the AR *Magic Mirror* platform is specifically tailored to deliver a personalized, interactive, and engaging learning experience. Especially the aspect of

personalization, which in the context of the AR *Magic Mirror* platform means seeing virtual anatomy models and medical section images in relation to one's own body, represents the unique selling point of the system, which was highly appreciated by the medical students during the evaluation studies. Learning human gross anatomy with the help of one's own body has proven to be a valid concept as it stimulated active learning among students and was found to improve their 3D understanding of topographic anatomy, since a direct correspondence between the virtual anatomy models and the user's own anatomy can be established. Despite the recent success of hand-held AR solutions, the positive evaluation results of the AR *Magic Mirror* platform show that research on novel AR solutions that employ spatial displays to create an AR experience, especially those in the *virtual mirror* category, should not be abandoned. Leveraging a person's own body as the primary interface for learning anatomy represents a promising concept for future AR solutions, whose development can greatly benefit from the findings presented in this thesis, with many open research questions still available, specifically in the areas of body tracking as well as making the interaction with the body as intuitive as possible.

The third and last type of AR systems according to the taxonomy of Bimber and Raskar are those that employ head-attached displays to create the AR experience for the user. The main representatives of this category are HMDs—either optical see-through (OST) or video see-through (VST)—which display virtual images directly in front of the user's eyes. The importance and prevalence of HMD-based AR solutions has increased considerably over the last five years, in particular driven by significant technological advances and the introduction of the first iteration of the Microsoft HoloLens in early 2015. Since then, a number of major technology companies have developed—or are anticipated to develop—their own AR HMD. Therefore, it is expected that the growing availability of HMDs will significantly increase the share of HMD-based AR solutions, such that these devices will become more and more prevalent over the next decade, with some even considering that these devices will usher in a new era of spatial computing. The recent technological advances in HMD technology have led to a number of studies evaluating the potential of such HMD-based AR systems in various disciplines, including anatomy education. However, this number is still quite small, suggesting that many more HMD-based AR solutions, specifically designed for use in anatomy education, will be developed in the future. The *VesARlius* application, which constitutes the second major contribution of this thesis besides the AR *Magic Mirror* platform, is one of these solutions and can therefore be counted among the early pioneers in this field. *VesARlius* offers medical students the possibility to interact with a detailed 3D anatomy model as well as with medical section images via an intuitive AR user interface. Unlike the AR *Magic Mirror* platform, the system also enables multiple co-located medical students to engage in a collaborative learning environment, with the entire state of the application synchronized across all students. Whereas the personalization feature was the unique selling point of the AR *Magic Mirror* platform, *VesARlius* stands out due to the fact that it enables team-based and collaborative learning. In the evaluation studies presented in this thesis, *VesARlius* was evaluated only for a co-located collaboration scenario where all users were present in the same physical space. It is expected, however, that telepresence-based remote collaboration will become more and more common in the future, both for individual anatomy learning sessions and possibly even for guided group learning sessions where an experienced anatomist could explain certain anatomical concepts directly on a 3D model in *VesARlius*. With regard to the impact of the results obtained in this thesis on the development of future HMD-based AR solutions, it can

be assumed that systems which also allow collaboration between different users will benefit in particular, since the different collaboration paradigms available in *VesARlius* have proven to be effective in facilitating communication between students. Finally, designing HMDs with a large FoV will be a very challenging task due to the complex optics of today's state-of-the-art OST-HMDs, especially if no other important design parameters such as eye relief, eye box size, or image quality of the HMD are to be sacrificed. Even if an HMD is introduced whose FoV corresponds to that of the human visual field, it is still possible that virtual objects are located far above, below, or behind the user, such that these objects do not fall within the visible FoV of the HMD. The novel visual guidance techniques presented in this thesis for the task of guiding the user's attention towards such out-of-view objects can serve as a benchmark for alternative visualization strategies that could be developed in the future.

On a more general note, three important insights can be derived from the results of this thesis, which are not specific to any of the three types of AR systems discussed above and which should be considered in the development and evaluation of any future AR system in the context of anatomy education. First of all, the findings of the evaluation studies provided supporting evidence that AR systems generally improve students' 3D understanding of topographic anatomy and may assist in the development of better spatial reasoning skills. While this assumption is particularly well supported in the case of the AR *Magic Mirror* platform due to the large extent of the evaluation, including **1701** medical students during three different studies, the pilot evaluation study on the *VesARlius* application also found that the system has the potential to improve the 3D understanding of topographic anatomy according to the subjective opinions of the students. Future AR systems should take this fact into account and design the AR learning experience in such a way that active learning of relationships between different anatomical structures is stimulated. Secondly, it was found that clinically relevant content in the form of medical section images constitutes an essential component of the two proposed AR solutions, which was considered to be highly beneficial by medical students during all evaluation studies. Incorporating techniques that help students to apply previously acquired theoretical knowledge of gross anatomy in a clinical context should be an essential design objective for future AR-based anatomy learning solutions, as it helps to deepen the level of understanding of anatomical concepts and combines knowledge from different disciplines to facilitate the acquisition of sustainable anatomical skills. Finally, the evaluation of novel AR solutions is of utmost importance and should be carried out as early as possible in the development process and within a realistic curricular environment. In the future, novel AR solutions are expected to be introduced at a rapidly increasing rate, such that carefully evaluating their benefits and finding the most optimal approaches for integrating these solutions into the curriculum will become even more important. Formal evaluation studies should therefore include a thorough comparison with both established as well as other state-of-the-art AR solutions for learning anatomy. Only then can the true potential of a novel AR solution for improving certain aspects of contemporary anatomy education be determined and representative pedagogical conclusions be drawn.

Conclusion

The present thesis investigated the potential of two novel Augmented Reality (AR) solutions to serve as complementary learning resources in the context of human gross anatomy education: 1) the AR *Magic Mirror* platform; and 2) the *VesARlius* application. The former allows users to virtually look inside their own bodies by superimposing 3D anatomy models directly onto their digital mirror image, which is captured by a camera and displayed on a large screen. In contrast, the *VesARlius* application is a Head-Mounted Display (HMD)-based AR solution that enables multiple users to jointly explore a virtual 3D anatomy model within collaborative and synchronized learning environments. Furthermore, both systems offer the possibility to interactively explore medical section images from different imaging modalities (CT, MRI, or cryosections). In addition to the contributions related to the technical development of these two novel AR-based anatomy learning solutions, another important contribution of this thesis is their integration into the undergraduate medical curriculum as well as their evaluation in a series of experimental user studies involving a large number of medical students. Within these studies, the particular advantages of AR-based anatomy learning with the *Magic Mirror* platform and the *VesARlius* application were explored. Both systems were found to increase student motivation to learn anatomy, provide an interactive and engaging learning experience, and improve the perceived 3D understanding of topographic anatomy. Most importantly, however, a positive quantitative learning effect could be measured for both solutions, which was even greater than for traditional anatomy learning paradigms such as textbooks and 3D plastic models. In the context of the AR *Magic Mirror* platform, the present thesis also examined the perceptual differences between two different *Magic Mirror* design concepts: 1) a *Reversing Magic Mirror*; and 2) a *Non-Reversing Magic Mirror*. Medical students, especially those with more experience, were able to identify the correct placement of virtual organs significantly better with an NRMM design. However, the RMM condition was significantly superior in terms of user interaction. Finally, due to the small field of view (FoV) of current HMDs, this thesis also investigated novel visualization techniques to guide the attention of users towards virtual objects located outside the FoV in HMD-based AR environments. Several approaches, including a *3D Radar*, a *Mirror Ball*, and a novel *stereographic fisheye minimap* were proposed and evaluated within two experimental user studies. The *3D Radar* in particular proved to be a very effective strategy for the localization of out-of-view objects, while at the same time offering distinct advantages in terms of additional information encoding opportunities over comparable state-of-the-art techniques. The proposed visualization strategies can be applied directly in the context of the *VesARlius* application, but also in a much broader context of AR applications from other domains. Overall, the present thesis has demonstrated the enormous potential of AR to become an integral part of the future educational environment in human gross anatomy and to provide a valuable complementary learning modality alongside other established resources. The contributions of this thesis have substantially advanced the state of the art in AR-based anatomy education and could serve as a stepping stone for an exciting educational paradigm shift that could lead to novel AR solutions becoming pervasive and indispensable tools for medical students around the world.

List of Authored and Co-authored Publications

The works with * indicate a first co-authorship.

2020

- [62] **Felix Bork**, Alexander Lehner, Ulrich Eck, Nassir Navab, Jens Waschke, and Daniela Kugelmann. "The Effectiveness of Collaborative Augmented Reality in Gross Anatomy Teaching: A Quantitative and Qualitative Pilot Study". *Anatomical sciences education*, (2020).
- [178] Jeremia Held, Kevin Yu, Connor Pyles, Janne Marieke Veerbeek, **Felix Bork**, Sandro-Michael Heining, Nassir Navab, and Andreas Rüdiger Luft. "Augmented Reality–Based Rehabilitation of Gait Impairments: Case Report". *JMIR mHealth and uHealth*, 8(5), e17804 (2020).

2019

- [61] **Felix Bork**, Leonard Stratmann, Stefan Enssle, Ulrich Eck, Nassir Navab, Jens Waschke, and Daniela Kugelmann. "The Benefits of an Augmented Reality Magic Mirror System for Integrated Radiology Teaching in Gross Anatomy". *Anatomical sciences education*, 12(6), pp. 585–598, (2019).
- [20] Roghayeh Barmaki, Kevin Yu, Rebecca Pearlman, Richard Shingles, **Felix Bork**, Greg Osgood, and Nassir Navab. "Enhancement of Anatomical Education using Augmented Reality: An Empirical Study of Body Painting". *Anatomical sciences education*, 12(6), pp. 599–609, (2019).
- [58] **Felix Bork**, Ulrich Eck, and Nassir Navab. "Birds vs. Fish: Visualizing Out-of-View Objects in Augmented Reality using 3D Minimaps". *IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pp.285–286, (2019).
- [64] **Felix Bork**, Alexander Kehner, Daniela Kugelmann, Ulrich Eck, Jens Waschke, and Nassir Navab. "VesARlius: An Augmented Reality System for Large-Group Co-located Anatomy Learning". *IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pp.122–123, (2019).

2018

- [63] **Felix Bork**, Christian Schnelzer, Ulrich Eck, and Nassir Navab. "Towards Efficient Visual Guidance in Limited Field-of-View Head-Mounted Displays". *IEEE Transactions on Visualization and Computer Graphics* 24(11), pp.2983–2992, (2018).
- [56] **Felix Bork**. "Interactive Augmented Reality Systems: Aids for Personalised Patient Education and Rehabilitation". *Der Unfallchirurg* 121(4), pp.286–292, (2018).

- [254] Daniela Kugelmann*, Leonard Stratmann*, Nils Nühlen*, **Felix Bork***, Saskia Hoffmann, Golbarg Samarbarksh, Anna Pferschy, Anna Marie von der Heide, Andreas Eimannsberger, Pascal Fallavollita, Nassir Navab, and Jens Waschke. "An Augmented Reality Magic Mirror as Additive Teaching Device for Gross Anatomy". *Annals of Anatomy-Anatomischer Anzeiger* 215(1), pp.71–77, (2018).

2017

- [59] **Felix Bork**, Roghayeh Barmaki, Ulrich Eck, Kevin Yu, Christian Sandor, and Nassir Navab. "Empirical Study of Non-Reversing Magic Mirrors for Augmented Reality Anatomy Learning". *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp.169–176, (2017).
- [60] **Felix Bork**, Roghayeh Barmaki, Ulrich Eck, Pascal Fallavollita, Bernhard Fürst, and Nassir Navab. "Exploring Non-Reversing Magic Mirrors for Screen-Based Augmented Reality Systems". *IEEE Virtual Reality (VR)*, pp.373–374, (2017).

2016

- [202] Naoto Ienaga, **Felix Bork**, Siim Meerits, Shohei Mori, Pascal Fallavollita, Nassir Navab, and Hideo Saito. "First Deployment of Diminished Reality for Anatomy Education". *IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*, pp.294–296, (2016).
- [288] Meng Ma*, Philipp Jutzi*, **Felix Bork***, Ina Seelbach, Anna Maria von der Heide, Nassir Navab, and Pascal Fallavollita. "Interactive Mixed Reality for Muscle Structure and Function Learning". *International Conference on Medical Imaging and Augmented Reality (MIAR)*, pp.117–128, (2016).
- [159] Christoph Graumann, Bernhard Fürst, Christoph Hennersperger, **Felix Bork**, and Nassir Navab. "Robotic Ultrasound Trajectory Planning for Volume of Interest Coverage". *IEEE international conference on robotics and automation (ICRA)*, pp.736–741, (2016).

2015

- [57] **Felix Bork**, Bernhard Fürst, Anja-Katharina Schneider, Francisco Pinto, Christoph Graumann, and Nassir Navab. "Auditory and Visio-Temporal Distance Coding for 3-Dimensional Perception in Medical Augmented Reality". *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp.7–12, (2015).

Abstracts of Publications not Discussed in this Thesis

Augmented Reality–Based Rehabilitation of Gait Impairments: Case Report

J. Held, K. Yu, C. Pyles, J.M. Veerbeek, **F. Bork**, S.M. Heining, N. Navab, and A.R. Luft

Gait and balance impairments are common in neurological diseases, including stroke, and negatively affect patients' quality of life. Improving balance and gait are among the main goals of rehabilitation. Rehabilitation is mainly performed in clinics, which lack context specificity; therefore, training in the patient's home environment is preferable. In the last decade, developed rehabilitation technologies such as virtual reality and augmented reality (AR) have enabled gait and balance training outside clinics. Here, we propose a new method for gait rehabilitation in persons who have had a stroke in which mobile AR technology and a sensor-based motion capture system are combined to provide fine-grained feedback on gait performance in real time. The aims of this study were (1) to investigate manipulation of the gait pattern of persons who have had a stroke based on virtual augmentation during overground walking compared to walking without AR performance feedback and (2) to investigate the usability of the AR system. We developed the ARISE (Augmented Reality for gait Impairments after Stroke) system, in which we combined a development version of HoloLens 2 smart glasses (Microsoft Corporation) with a sensor-based motion capture system. One patient with chronic minor gait impairment poststroke completed clinical gait assessments and an AR parkour course with patient-centered performance gait feedback. The movement kinematics during gait as well as the usability and safety of the system were evaluated. The patient changed his gait pattern during AR parkour compared to the pattern observed during the clinical gait assessments. He recognized the virtual objects and ranked the usability of the ARISE system as excellent. In addition, the patient stated that the system would complement his standard gait therapy. Except for the symptom of exhilaration, no adverse events occurred. This project provided the first evidence of gait adaptation during overground walking based on real-time feedback through visual and auditory augmentation. The system has potential to provide gait and balance rehabilitation outside the clinic. This initial investigation of AR rehabilitation may aid the development and investigation of new gait and balance therapies.

JMIR mHealth and uHealth, 2020

Enhancement of Anatomical Education using Augmented Reality: An Empirical Study of Body Painting

R. Barmaki, K. Yu, R. Pearlman, R. Shingles, **F. Bork**, G. Osgood, N. Navab



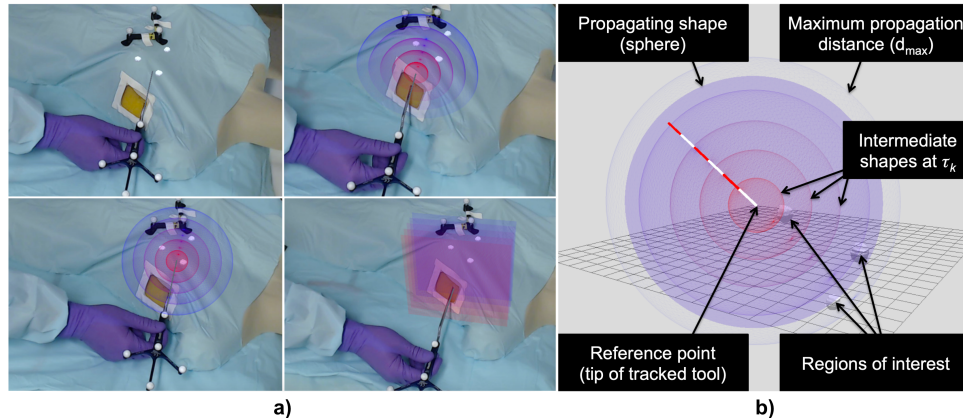
Study setup for participants in pairs to complete the painting activity using either (left) the REFLECT system in the experimental groups, or (right) the textbook and the Virtual Mirror system in the control groups.

Students in undergraduate premedical anatomy courses may experience suboptimal and superficial learning experiences due to large class sizes, passive lecture styles, and difficult-to-master concepts. This study introduces an innovative, hands-on activity for human musculoskeletal system education with the aim of improving students' level of engagement and knowledge retention. In this study, a collaborative learning intervention using the REFLECT (augmented reality for learning clinical anatomy) system is presented. The system uses the augmented reality magic mirror paradigm to superimpose anatomical visualizations over the user's body in a large display, creating the impression that she sees the relevant anatomic illustrations inside her own body. The efficacy of this proposed system was evaluated in a large-scale controlled study, using a team-based muscle painting activity among undergraduate premedical students ($n = 288$) at the Johns Hopkins University. The baseline knowledge and post-intervention knowledge of the students were measured before and after the painting activity according to their assigned groups in the study. The results from knowledge tests and additional collected data demonstrate that the proposed interactive system enhanced learning of the musculoskeletal system with improved knowledge retention ($F(10,133) = 3.14, P < 0.001$), increased time on task ($F(1,275) = 5.70, P < 0.01$), and a high level of engagement ($F(9,273) = 8.28, P < 0.0001$). The proposed REFLECT system will be of benefit as a complementary anatomy learning tool for students.

Anatomical Sciences Education, 2019

Auditory and Visio-Temporal Distance Coding for 3-Dimensional Perception in Medical Augmented Reality

F. Bork, B. Fürst, AK. Schneider, F. Pinto, C. Graumann, N. Navab



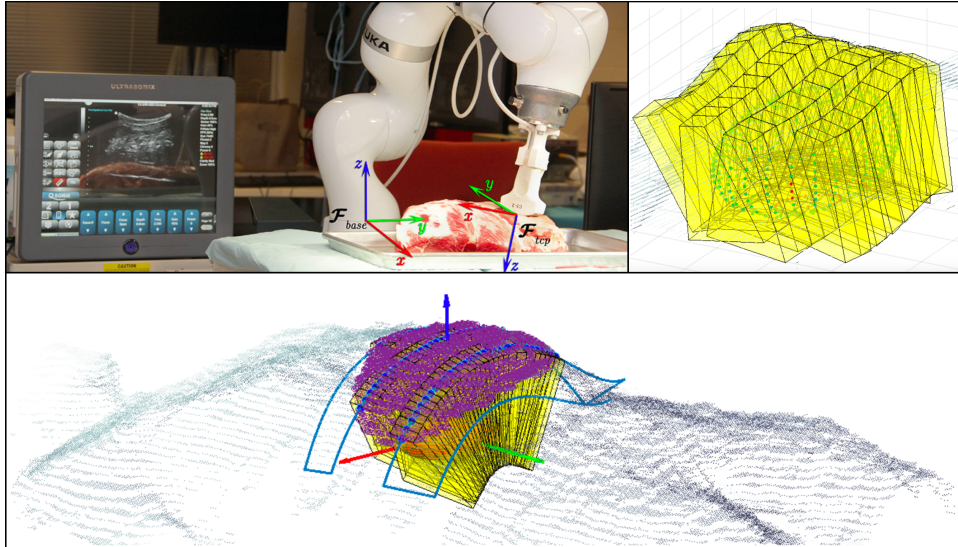
Overview of our proposed visualization technique based on Temporal Distance Coding (TDC). a) Localization of lymph nodes is enabled by different geometric primitives (hemisphere, sphere, and plane) that propagate from from the tip of a surgical instrument along its direction; b) Auditory signals are used to indicate the intermediate steps until the maximum propagation distance of a shape as well as intersection with target objects.

Image-guided medical interventions more frequently rely on Augmented Reality (AR) visualization to enable surgical navigation. Current systems use 2-D monitors to present the view from external cameras, which does not provide an ideal perception of the 3-D position of the region of interest. Despite this problem, most research targets the direct overlay of diagnostic imaging data, and only few studies attempt to improve the perception of occluded structures in external camera views. The focus of this paper lies on improving the 3-D perception of an augmented external camera view by combining both auditory and visual stimuli in a dynamic multi-sensory AR environment for medical applications. Our approach is based on Temporal Distance Coding (TDC) and an active surgical tool to interact with occluded virtual objects of interest in the scene in order to gain an improved perception of their 3-D location. Users performed a simulated needle biopsy by targeting virtual lesions rendered inside a patient phantom. Experimental results demonstrate that our TDC-based visualization technique significantly improves the localization accuracy, while the addition of auditory feedback results in increased intuitiveness and faster completion of the task.

IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 2015

Robotic Ultrasound Trajectory Planning for Volume of Interest Coverage

C. Graumann, B. Fürst, C. Hennersperger, **F. Bork**, N. Navab



Overview of the robotic ultrasound trajectory planning system. Top-Left: Experimental setup with an ultrasound probe attached to the robot flange. Top-Right: Exemplary plot of the volume coverage along a planned trajectory for a mock-up volume that is rendered as a point cloud. Green points were covered by the trajectory, while red points were not. Bottom: Example of a planned path on a human body point cloud with a sample volume of interest (red ellipsoid).

Medical robotic ultrasound offers potential to assist interventions, ease long-term monitoring and reduce operator dependency. Various techniques for remote control of ultrasound probes through telemanipulation systems have been presented in the past, however not exploiting the potential of fully autonomous acquisitions directly performed by robotic systems. In this paper, a trajectory planning algorithm for automatic robotic ultrasound acquisition under expert supervision is introduced. The objective is to compute a suitable path for covering a volume of interest selected in diagnostic images, for example by prior segmentation. A 3D patient surface point cloud is acquired using a depth camera, which is the sole prerequisite besides the volume delineation. An easily parameterizable path function generates single or multiple parallel scan trajectories capable of dealing with large target volumes. A spline is generated through the preliminary path points and is transferred to a lightweight robot to perform the ultrasound scan using an impedance control mode. The proposed approach is validated via simulation as well as on phantoms and on animal viscera.

IEEE International Conference on Robotics and Automation (ICRA), 2016

First Deployment of Diminished Reality for Anatomy Education

N. Ienaga, **F. Bork**, S. Meerits, S. Mori, P. Fallavollita, N. Navab, H. Saito

Understanding the anatomy of the human body is vital for everyone working in the medical domain. Augmented reality (AR) systems for anatomy teaching, which display virtual information directly on top of a users' body, have proven to facilitate mental mapping compared to traditional teaching paradigms. In this paper, we explore the potential of diminished reality (DR) in the context of anatomy education. As a first necessary step to achieving a DR anatomy education system, parts of the human body have to be extracted and diminished from the video stream. Our system diminishes either the arm or head of the user by projecting a background image recovered using RGB-D cameras. Such a system, if combined with an accurate overlay of virtual counterparts, could potentially improve the learning effect by attracting the users' attention to the virtual information and improve visual perception by avoiding the well-known floating effect of AR.

IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 2016

Interactive Augmented Reality Systems: Aids for Personalised Patient Education and Rehabilitation

F. Bork

In the context of patient education, the exchange of information plays a central role both for patient compliance with medical or rehabilitative treatments and for obtaining the consent of patients to an operation. In this paper the augmented reality system "Magic Mirror" is considered as a potential tool for patient education, rehabilitation and as a supporting educational resource for anatomy teaching. The Magic Mirror offers the user the possibility to interactively examine a detailed, anatomical 3D model of the human body as well as section images from volumetric data sets in the form of a digital mirror. First results from the field of rehabilitation and anatomy demonstrate the potential of the Magic Mirror. The system also offers interesting advantages over previous methods of patient education. New technologies like Augmented Reality open the door for many innovations in medicine. In the future, patient-oriented systems such as the Magic Mirror will be increasingly used in areas such as education and rehabilitation. In order to maximize the benefit of these systems, further evaluation studies are needed to investigate the exact application scenarios and initiate an iterative optimization process of the systems.

Der Unfallchirurg, 2018

Bibliography

- [1] J. G. Abreu, J. M. Teixeira, L. S. Figueiredo, and V. Teichrieb. “Evaluating sign language recognition using the myo armband”. In: *2016 XVIII Symposium on Virtual and Augmented Reality (SVR)*. IEEE. 2016, pp. 64–70 (cit. on p. 37).
- [2] M. J. Ackerman. “Accessing the visible human project”. In: *D-Lib Magazine* 1.4 (1995) (cit. on p. 80).
- [3] M. Akçayır and G. Akçayır. “Advantages and challenges associated with augmented reality for education: A systematic review of the literature”. In: *Educational Research Review* 20 (2017), pp. 1–11 (cit. on pp. 3, 98, 100, 124).
- [4] H. Alt and M. Godau. “Computing the Fréchet distance between two polygonal curves”. In: *International Journal of Computational Geometry & Applications* 5.01n02 (1995), pp. 75–91 (cit. on p. 136).
- [5] A. Anagnostopoulos, M. Vlachos, M. Hadjieleftheriou, E. Keogh, and P. S. Yu. “Global distance-based segmentation of trajectories”. In: *Proceedings of the 12th ACM SIGKDD international conference on Knowledge discovery and data mining*. ACM. 2006, pp. 34–43 (cit. on p. 136).
- [6] M. K. Anand and T. Singel. “A comparative study of learning with “anatomage” virtual dissection table versus traditional dissection method in neuroanatomy”. In: *Ind J Clin Anat Physiol* 4 (2014), pp. 177–180 (cit. on pp. 85, 98).
- [7] H. Ardiny and E. Khanmirza. “The Role of AR and VR Technologies in Education Developments: Opportunities and Challenges”. In: *2018 6th RSI International Conference on Robotics and Mechatronics (IcRoM)*. IEEE. 2018, pp. 482–487 (cit. on p. 3).
- [8] L.-A. Arráez-Aybar, I. Sánchez-Montesinos, R.-M. Mirapeix, B. Mompeo-Corredera, and J.-R. Sañudo-Tejero. “Relevance of human anatomy in daily clinical practice”. In: *Annals of Anatomy-Anatomischer Anzeiger* 192.6 (2010), pp. 341–348 (cit. on p. 1).
- [9] K. Aso, D.-H. Hwang, and H. Koike. “Generating Synthetic Humans for Learning 3D Pose Estimation”. In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE. 2019, pp. 1519–1520 (cit. on p. 36).
- [10] S. A. Azer and N. Eizenberg. “Do we need dissection in an integrated problem-based learning medical course? Perceptions of first-and second-year students”. In: *Surgical and Radiologic Anatomy* 29.2 (2007), pp. 173–180 (cit. on p. 1).
- [11] M. A. Aziz, J. C. Mckenzie, J. S. Wilson, R. J. Cowie, S. A. Ayeni, and B. K. Dunn. “The human cadaver in the age of biomedical informatics”. In: *The Anatomical Record: An Official Publication of the American Association of Anatomists* 269.1 (2002), pp. 20–32 (cit. on p. 1).
- [12] R. Azuma, Y. Baillet, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre. “Recent advances in augmented reality”. In: *IEEE computer graphics and applications* 21.6 (2001), pp. 34–47 (cit. on pp. 3, 39, 43).

- [13] R. T. Azuma. “A survey of augmented reality”. In: *Presence: Teleoperators & Virtual Environments* 6.4 (1997), pp. 355–385 (cit. on pp. 3, 22, 43).
- [14] G. Baader. “Die Schule von Salerno”. In: *Medizinhistorisches Journal* (1978), pp. 124–145 (cit. on p. 16).
- [15] J. Bacca, S. Baldiris, R. Fabregat, S. Graf, et al. “Augmented reality trends in education: a systematic review of research and applications”. In: (2014) (cit. on p. 100).
- [16] Z. Bai and A. F. Blackwell. “Analytic review of usability evaluation in ISMAR”. In: *Interacting with computers* 24.6 (2012), pp. 450–460 (cit. on pp. 39, 40).
- [17] M. Bajura, H. Fuchs, and R. Ohbuchi. “Merging virtual objects with the real world: Seeing ultrasound imagery within the patient”. In: *ACM SIGGRAPH Computer Graphics* 26.2 (1992), pp. 203–210 (cit. on pp. 25, 27).
- [18] I. Baran and J. Popović. “Automatic rigging and animation of 3d characters”. In: *ACM Transactions on graphics (TOG)* 26.3 (2007), 72–es (cit. on p. 63).
- [19] D. Baričević, T. Höllerer, P. Sen, and M. Turk. “User-perspective augmented reality magic lens from gradients”. In: *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology*. 2014, pp. 87–96 (cit. on p. 32).
- [20] R. Barmaki, K. Yu, R. Pearlman, et al. “Enhancement of anatomical education using augmented reality: An empirical study of body painting”. In: *Anatomical sciences education* 12.6 (2019), pp. 599–609 (cit. on pp. 2, 173).
- [21] D. S. Barry, F. Marzouk, K. Chulak-Oglu, D. Bennett, P. Tierney, and G. W. O’Keeffe. “Anatomy education for the YouTube generation”. In: *Anatomical sciences education* 9.1 (2016), pp. 90–96 (cit. on p. 2).
- [22] F. I. Bashir, A. A. Khokhar, and D. Schonfeld. “Object trajectory-based activity classification and recognition using hidden Markov models”. In: *IEEE transactions on Image Processing* 16.7 (2007), pp. 1912–1919 (cit. on p. 136).
- [23] F. I. Bashir, A. A. Khokhar, and D. Schonfeld. “Real-time motion trajectory-based indexing and retrieval of video sequences”. In: *IEEE Transactions on Multimedia* 9.1 (2007), pp. 58–65 (cit. on p. 136).
- [24] P. Baudisch and R. Rosenholtz. “Halo: A Technique for Visualizing Off-screen Objects”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’03. Ft. Lauderdale, Florida, USA: ACM, 2003, pp. 481–488 (cit. on p. 134).
- [25] A. Bauer, D. R. Neog, A.-H. Dicko, et al. “Anatomical augmented reality with 3D commodity tracking and image-space alignment”. In: *Computers & Graphics* 69 (2017), pp. 140–153 (cit. on pp. 46, 59, 158).
- [26] A. Bauer, A.-H. Dicko, F. Faure, O. Palombi, and J. Troccaz. “Anatomical mirroring: Real-time user-specific anatomy in motion using a commodity depth camera”. In: *Proceedings of the 9th International Conference on Motion in Games*. 2016, pp. 113–122 (cit. on pp. 46, 47, 59, 158).
- [27] N. S.-Y. Bay and B.-H. Bay. “Greek anatomist herophilus: the father of anatomy”. In: *Anatomy & cell biology* 43.4 (2010), pp. 280–283 (cit. on p. 12).
- [28] B. Bell, T. Höllerer, and S. Feiner. “An annotated situation-awareness aid for augmented reality”. In: *Proceedings of the 15th annual ACM symposium on User interface software and technology*. ACM. 2002, pp. 213–216 (cit. on p. 152).
- [29] H. Benko, R. Jota, and A. Wilson. “MirageTable: freehand interaction on a projected augmented reality tabletop”. In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2012, pp. 199–208 (cit. on p. 40).
- [30] G. R. Bernard. “Prosection demonstrations as substitutes for the conventional human gross anatomy laboratory”. In: *Academic Medicine* 47.9 (1972), pp. 724–8 (cit. on p. 2).

- [31] M. Bertamini. “Mirrors and the mind”. In: *Psychologist* 23.2 (2010), p. 112 (cit. on pp. 68, 69).
- [32] M. Bertamini and T. E. Parks. “On what people know about images on mirrors”. In: *Cognition* 98.1 (2005), pp. 85–104 (cit. on p. 68).
- [33] M. Bertamini, A. Spooner, and H. Hecht. “Naive optics: Predicting and perceiving reflections in mirrors.” In: *Journal of Experimental Psychology: Human Perception and Performance* 29.5 (2003), p. 982 (cit. on pp. 68, 69).
- [34] M. Bertamini, R. Lawson, L. Jones, and M. Winters. “The Venus effect in real life and in photographs”. In: *Attention, Perception, & Psychophysics* 72.7 (2010), pp. 1948–1964 (cit. on p. 68).
- [35] J. Bian, D. Tian, Y. Tang, and D. Tao. “A survey on trajectory clustering analysis”. In: *arXiv preprint arXiv:1802.06971* (2018) (cit. on p. 136).
- [36] S. N. Biasutto, L. I. Caussa, and L. E. C. del Río. “Teaching anatomy: cadavers vs. computers?” In: *Annals of Anatomy-Anatomischer Anzeiger* 188.2 (2006), pp. 187–190 (cit. on pp. 1, 20).
- [37] C. Bichlmeier. “Immersive, interactive and contextual in-situ visualization for medical applications”. PhD thesis. Technische Universität München, 2010 (cit. on p. 17).
- [38] C. Bichlmeier, F. Wimmer, S. M. Heining, and N. Navab. “Contextual anatomic mimesis hybrid in-situ visualization method for improving multi-sensory depth perception in medical augmented reality”. In: *2007 6th IEEE and ACM international symposium on mixed and augmented reality*. IEEE, 2007, pp. 129–138 (cit. on p. 39).
- [39] C. Bichlmeier, T. Sielhorst, S. M. Heining, and N. Navab. “Improving depth perception in medical ar”. In: *Bildverarbeitung für die Medizin 2007*. Springer, 2007, pp. 217–221 (cit. on p. 39).
- [40] M. Billinghurst and A. Duenser. “Augmented reality in the classroom”. In: *Computer* 45.7 (2012), pp. 56–63 (cit. on p. 123).
- [41] M. Billinghurst and H. Kato. “Collaborative augmented reality”. In: *Communications of the ACM* 45.7 (2002), pp. 64–70 (cit. on p. 37).
- [42] M. Billinghurst and H. Kato. “Collaborative mixed reality”. In: *Proceedings of the First International Symposium on Mixed Reality*. 1999, pp. 261–284 (cit. on p. 43).
- [43] M. Billinghurst, A. Clark, G. Lee, et al. “A survey of augmented reality”. In: *Foundations and Trends® in Human–Computer Interaction* 8.2-3 (2015), pp. 73–272 (cit. on pp. 22, 26).
- [44] M. Billinghurst, H. Kato, I. Poupyrev, et al. “Tangible augmented reality”. In: *ACM SIGGRAPH ASIA* 7.2 (2008) (cit. on p. 35).
- [45] O. Bimber and R. Raskar. “Modern approaches to augmented reality”. In: *ACM SIGGRAPH 2006 Courses*. ACM, 2006, p. 1 (cit. on pp. 3, 30, 32, 33, 41, 45, 47, 167).
- [46] O. Bimber and R. Raskar. *Spatial augmented reality: merging real and virtual worlds*. AK Peters/CRC Press, 2005 (cit. on p. 33).
- [47] O. Bimber, L. M. Encarnação, and D. Schmalstieg. “Augmented Reality with Back-Projection Systems using Transflective Surfaces”. In: *Computer Graphics Forum*. Vol. 19. 3. Wiley Online Library, 2000, pp. 161–168 (cit. on p. 32).
- [48] O. Bimber, L. M. Encarnação, and P. Branco. “The extended virtual table: An optical extension for table-like projection systems”. In: *Presence: Teleoperators & Virtual Environments* 10.6 (2001), pp. 613–631 (cit. on p. 33).
- [49] O. Bimber, B. Fröhlich, D. Schmalstieg, and L. M. Encarnação. “The virtual showcase”. In: *ACM SIGGRAPH 2006 Courses*. 2006, 9–es (cit. on p. 33).
- [50] F. Biocca, A. Tang, C. Owen, and F. Xiao. “Attention Funnel: Omnidirectional 3D Cursor for Mobile Augmented Reality Platforms”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '06. Montrécal, Québec, Canada: ACM, 2006, pp. 1115–1122 (cit. on p. 135).

- [51] J. Birt, Z. Stromberga, M. Cowling, and C. Moro. "Mobile mixed reality for experiential learning and simulation in medical and health sciences education". In: *Information* 9.2 (2018), p. 31 (cit. on p. 44).
- [52] K. C. Blits. "Aristotle: form, function, and comparative anatomy". In: *The Anatomical Record* 257.2 (1999), pp. 58–63 (cit. on pp. 11, 12).
- [53] B. S. Bloom. "Taxonomy of educational objectives: The classification of educational goals". In: *Cognitive domain* (1956) (cit. on pp. 91, 92, 115).
- [54] T. Blum, V. Kleeberger, C. Bichlmeier, and N. Navab. "mirracle: An augmented reality magic mirror system for anatomy education". In: *2012 IEEE Virtual Reality Workshops (VRW)*. IEEE. 2012, pp. 115–116 (cit. on pp. 46, 47, 52, 59, 60, 62, 101, 158).
- [55] A. Böckers, L. Jerg-Bretzke, C. Lamp, A. Brinkmann, H. C. Traue, and T. M. Böckers. "The gross anatomy course: an analysis of its importance". In: *Anatomical sciences education* 3.1 (2010), pp. 3–11 (cit. on p. 1).
- [56] F. Bork. "Interactive augmented reality systems". In: *Der Unfallchirurg* 121.4 (2018), pp. 286–292 (cit. on p. 173).
- [57] F. Bork, B. Fuers, A.-K. Schneider, F. Pinto, C. Graumann, and N. Navab. "Auditory and visio-temporal distance coding for 3-dimensional perception in medical augmented reality". In: *2015 IEEE international symposium on mixed and augmented reality*. IEEE. 2015, pp. 7–12 (cit. on p. 174).
- [58] F. Bork, U. Eck, and N. Navab. "Birds vs. Fish: Visualizing Out-of-View Objects in Augmented Reality using 3D Minimaps". In: *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. IEEE. 2019, pp. 285–286 (cit. on pp. 131, 173).
- [59] F. Bork, R. Barmaki, U. Eck, K. Yu, C. Sandor, and N. Navab. "Empirical study of non-reversing magic mirrors for augmented reality anatomy learning". In: *2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE. 2017, pp. 169–176 (cit. on pp. 67, 174).
- [60] F. Bork, R. Barmaki, U. Eck, P. Fallavolita, B. Fuerst, and N. Navab. "Exploring non-reversing magic mirrors for screen-based augmented reality systems". In: *2017 IEEE Virtual Reality (VR)*. IEEE. 2017, pp. 373–374 (cit. on pp. 67, 174).
- [61] F. Bork, L. Stratmann, S. Enssle, et al. "The benefits of an augmented reality magic mirror system for integrated radiology teaching in gross anatomy". In: *Anatomical sciences education* 12.6 (2019), pp. 585–598 (cit. on pp. 79, 123, 173).
- [62] F. Bork, A. Lehner, U. Eck, N. Navab, J. Waschke, and D. Kugelmann. "The Effectiveness of Collaborative Augmented Reality in Gross Anatomy Teaching: A Quantitative and Qualitative Pilot Study". In: *Anatomical sciences education* (2020) (cit. on pp. 113, 173).
- [63] F. Bork, C. Schnelzer, U. Eck, and N. Navab. "Towards efficient visual guidance in limited field-of-view head-mounted displays". In: *IEEE transactions on visualization and computer graphics* 24.11 (2018), pp. 2983–2992 (cit. on pp. 131, 173).
- [64] F. Bork, A. Lehner, D. Kugelmann, U. Eck, J. Waschke, and N. Navab. "VesARlius: An Augmented Reality System for Large-Group Co-located Anatomy Learning". In: *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. IEEE. 2019, pp. 122–123 (cit. on pp. 113, 173).
- [65] O. J. Bott, K. Dresing, M. Wagner, B.-W. Raab, and M. Teistler. "Informatics in radiology: use of a C-arm fluoroscopy simulator to support training in intraoperative radiography". In: *Radiographics* 31.3 (2011), E65–E75 (cit. on p. 166).
- [66] J. Brandt and W. Mackavey. "Left-right confusion and the perception of bilateral symmetry". In: *International Journal of Neuroscience* 12.2 (1981), pp. 87–94 (cit. on p. 73).

- [67] B. Brier and R. S. Wade. “Surgical procedures during ancient Egyptian mummification”. In: *Chungará (Arica)* 33.1 (2001), pp. 117–123 (cit. on p. 9).
- [68] J. Brooke, P. Jordan, B. Thomas, B. Weerdmeester, and I. McClelland. “Usability evaluation in industry”. In: *SUS: a’quick and dirty’usability scale* (1996), pp. 184–194 (cit. on p. 118).
- [69] B. Brown, S. Adhikari, J. Marx, L. Lander, and G. L. Todd. “Introduction of Ultrasound into Gross Anatomy Curriculum: Perceptions of Medical Students”. In: *The Journal of Emergency Medicine* 43.6 (2012), pp. 1098–1102 (cit. on p. 2).
- [70] J. Brown, S. Stonelake, W. Anderson, et al. “Medical student perception of anatomage—A 3D interactive anatomy dissection table”. In: *International Journal of Surgery* 1.23 (2015), S17–S18 (cit. on p. 85).
- [71] V. Buchmann, T. Nilsen, and M. Billinghamurst. “Interaction with partially transparent hands and objects”. In: (2005) (cit. on p. 39).
- [72] A. Bühler. “Konzeptionen der Vernunft in den Ärzteschulen der Antike”. In: (2009) (cit. on p. 12).
- [73] T. D. Burgess II and S. M. Sales. “Attitudinal effects of “mere exposure”: A reevaluation”. In: *Journal of Experimental Social Psychology* 7.4 (1971), pp. 461–472 (cit. on p. 77).
- [74] S. Burigat and L. Chittaro. “Navigation in 3D virtual environments: Effects of user experience and location-pointing navigation aids”. In: *International Journal of Human-Computer Studies* 65.11 (2007), pp. 945–958 (cit. on p. 135).
- [75] S. Burigat, L. Chittaro, and S. Gabrielli. “Visualizing Locations of Off-screen Objects on Mobile Devices: A Comparative Evaluation of Three Approaches”. In: *Proceedings of the 8th Conference on Human-computer Interaction with Mobile Devices and Services*. MobileHCI ’06. Helsinki, Finland, 2006, pp. 239–246 (cit. on p. 134).
- [76] J. L. Burton. “A bite into the history of the autopsy”. In: *Forensic science, medicine, and pathology* 1.4 (2005), pp. 277–284 (cit. on pp. 9, 16, 18).
- [77] M. V. L. Cabrera, J. G. Carrillo, J. P. Nigenda, R. T. González, J. E. Valdez-García, and B. C. C. Chavarría. “Assessing the Effectiveness of Teaching Anatomy with Virtual Reality”. In: *Proceedings of the 2019 11th International Conference on Education Technology and Computers*. 2019, pp. 43–46 (cit. on p. 43).
- [78] D. Cantor. *Reinventing Hippocrates*. Routledge, 2017 (cit. on p. 11).
- [79] M. S. T. Carpendale and C. Montagnese. “A Framework for Unifying Presentation Space”. In: *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology*. UIST ’01. Orlando, Florida: ACM, 2001, pp. 61–70 (cit. on p. 134).
- [80] A. Cave. *Ancient Egypt and the origin of anatomical science*. 1950 (cit. on p. 9).
- [81] L. Chen and R. Ng. “On the marriage of lp-norms and edit distance”. In: *Proceedings of the Thirtieth international conference on Very large data bases-Volume 30*. VLDB Endowment. 2004, pp. 792–803 (cit. on p. 136).
- [82] S. Chen, M. Chen, A. Kunz, et al. “SEMalpha: mobile sketch-gesture-video remote support for car drivers”. In: *Proceedings of the 4th Augmented Human International Conference*. 2013, pp. 69–76 (cit. on p. 40).
- [83] Y.-C. Chen. “Peer learning in an AR-based learning environment”. In: *16th international conference on computers in education*. Citeseer. 2008, pp. 291–295 (cit. on pp. 125, 163).
- [84] Y. Chen, Y. Tian, and M. He. “Monocular human pose estimation: A survey of deep learning-based methods”. In: *Computer Vision and Image Understanding* (2020), p. 102897 (cit. on p. 36).
- [85] K.-H. Cheng. “Reading an augmented reality book: An exploration of learners’ cognitive load, motivation, and attitudes”. In: *Australasian Journal of Educational Technology* 33.4 (2017) (cit. on p. 124).

- [86] K.-H. Cheng and C.-C. Tsai. "Affordances of augmented reality in science learning: Suggestions for future research". In: *Journal of science education and technology* 22.4 (2013), pp. 449–462 (cit. on pp. 3, 98, 124).
- [87] S. E. Chia, C. N. Ong, S. C. Foo, and H. P. Lee. "Medical students' exposure to formaldehyde in a gross anatomy dissection laboratory". In: *Journal of American College Health* 41.3 (1992), pp. 115–119 (cit. on p. 2).
- [88] C.-H. Chien, C.-H. Chen, and T.-S. Jeng. "An interactive augmented reality system for learning anatomy structure". In: *proceedings of the international multiconference of engineers and computer scientists*. Vol. 1. International Association of Engineers Hong Kong, China. 2010, pp. 17–19 (cit. on pp. 45, 123).
- [89] L. Chittaro and R. Ranon. "Web3D technologies in learning, education and training: Motivations, issues, opportunities". In: *Computers & Education* 49.1 (2007), pp. 3–18 (cit. on p. 43).
- [90] B. S. Chung, D. S. Shin, P. Brown, J. Choi, and M. S. Chung. "Virtual dissection table including the Visible Korean images, complemented by free software of the same data." In: *International Journal of Morphology* 33.2 (2015) (cit. on p. 85).
- [91] A. M. Codd and B. Choudhury. "Virtual reality anatomy: Is it comparable with traditional methods in the teaching of human forearm musculoskeletal anatomy?" In: *Anatomical sciences education* 4.3 (2011), pp. 119–125 (cit. on pp. 3, 42, 43).
- [92] P. S. Codellas. *Alcmaeon of Croton: His life, work, and fragments*. 1932 (cit. on p. 11).
- [93] F. J. Cole et al. "A history of comparative anatomy from Aristotle to the eighteenth century." In: *A history of comparative anatomy from Aristotle to the eighteenth century*. (1944) (cit. on p. 11).
- [94] P. G. Colucci, P. Kostandy, W. R. Shrauner, et al. *Development and utilization of a web-based application as a robust radiology teaching tool (radstax) for medical student anatomy teaching*. 2015 (cit. on p. 85).
- [95] N. E. Cookson, J. J. Aka, and G. M. Finn. "An exploration of anatomists' views toward the use of body painting in anatomical and medical education: An international study". In: *Anatomical sciences education* 11.2 (2018), pp. 146–154 (cit. on p. 2).
- [96] S. Corazza and E. Gambaretto. *Automatic generation of 3D character animation from 3D meshes*. US Patent 8.797.328. 2014 (cit. on p. 63).
- [97] C Corballis. "Much ado about mirrors michael". In: *Psychonomic Bulletin & Review* 7.1 (2000), pp. 163–169 (cit. on p. 69).
- [98] C. E. Cosans. "Aristotle's anatomical philosophy of nature". In: *Biology and Philosophy* 13.3 (1998), pp. 311–339 (cit. on pp. 11, 12).
- [99] C. E. Cosans. "History of Classical Anatomy". In: *eLS* (2001), pp. 1–7 (cit. on pp. 12, 13).
- [100] E. Crivellato and D. Ribatti. "A portrait of Aristotle as an anatomist: Historical article". In: *Clinical Anatomy: The Official Journal of the American Association of Clinical Anatomists and the British Association of Clinical Anatomists* 20.5 (2007), pp. 447–485 (cit. on p. 11).
- [101] T. M. Custer and K. Michael. "The utilization of the anatomage virtual dissection table in the education of imaging science students". In: *Journal of Tomography & Simulation* 1 (2015) (cit. on p. 85).
- [102] J. E. Cutting. "How the eye measures reality and virtual reality". In: *Behavior Research Methods, Instruments, & Computers* 29.1 (1997), pp. 27–36 (cit. on p. 40).
- [103] M. R. Dahl and E. O. Simonsen. "3D virtual table in anatomy education". In: *AMEE 2013-Association of Medical Education Europe Conference*. 2013 (cit. on p. 85).
- [104] W. Dalrymple-Champneys. *The medical student through the ages*. 1955 (cit. on pp. 11, 16).

- [105] K. E. Darras, S. J. Clark, D. K. Tso, et al. "Development of an undergraduate radiology curriculum: ten-year experience from the University of British Columbia". In: *Canadian Association of Radiologists' Journal* 68.3 (2017), pp. 237–242 (cit. on p. 85).
- [106] E. De Divitiis, P. Cappabianca, and O. De Divitiis. "The "schola medica salernitana": the forerunner of the modern university medical schools". In: *Neurosurgery* 55.4 (2004), pp. 722–745 (cit. on p. 16).
- [107] A. Debernardi, E. Sala, G. D'Aliberti, G. Talamonti, A. F. Franchini, and M. Collice. "Alcmaeon of croton". In: *Neurosurgery* 66.2 (2010), pp. 247–252 (cit. on p. 10).
- [108] D. M. DePietro, R. M. Kiefer, J. W. Redmond, et al. "Increasing medical student exposure to IR through integration of IR into the gross anatomy course". In: *Journal of Vascular and Interventional Radiology* 28.10 (2017), pp. 1455–1460 (cit. on p. 85).
- [109] A. Dey, M. Billinghamurst, R. W. Lindeman, and J. Swan. "A systematic review of 10 years of augmented reality usability studies: 2005 to 2014". In: *Frontiers in Robotics and AI* 5 (2018), p. 37 (cit. on pp. 39, 40).
- [110] P. Diegmann, M. Schmidt-Kraepelin, S. Eynden, and D. Basten. "Benefits of augmented reality in educational environments-a systematic literature review". In: *Benefits* 3.6 (2015), pp. 1542–1556 (cit. on pp. 3, 98, 124).
- [111] C. E. Dinsmore, S. Daugherty, and H. J. Zeitz. "Teaching and learning gross anatomy: dissection, prosection, or "both of the above?"". In: *Clinical Anatomy* 12.2 (1999), pp. 110–114 (cit. on p. 2).
- [112] I. Dixit, R. Prakritpong, P. Blumer, et al. "The Pocket Pelvis: Developing an Augmented Reality App for Better Understanding of Pelvis Anatomy". In: *The FASEB Journal* 33.1_supplement (2019), pp. 444–6 (cit. on p. 44).
- [113] A. A. Dmytriw, P. S. Mok, N. Gorelik, J. Kavanaugh, and P. Brown. "Radiology in the undergraduate medical curriculum: Too little, too late?" In: *Medical science educator* 25.3 (2015), pp. 223–227 (cit. on p. 99).
- [114] J. F. Dobson. "Herophilus of alexandria". In: *Proceedings of the Royal Society of Medicine* 18.Sect_Hist_Med (1925), pp. 19–32 (cit. on p. 12).
- [115] R. W. Doty. "Alkmaion's discovery that brain creates mind: A revolution in human knowledge comparable to that of Copernicus and of Darwin". In: *Neuroscience* 147.3 (2007), pp. 561–568 (cit. on p. 10).
- [116] I. Drabkin. "Medical education in ancient Greece and Rome". In: *Academic Medicine* 32.4 (1957), pp. 286–296 (cit. on pp. 10–14).
- [117] R. L. Drake. "Anatomy education in a changing medical curriculum". In: *The Anatomical Record: An Official Publication of the American Association of Anatomists* 253.1 (1998), pp. 28–31 (cit. on p. 20).
- [118] R. L. Drake, W. Vogl, A. Mitchell, et al. *Gray's atlas of anatomy. Philadelphia, PA: Churchill Livingstone*. 2015 (cit. on p. 117).
- [119] R. L. Drake, J. M. McBride, N. Lachman, and W. Pawlina. "Medical education in the anatomical sciences: The winds of change continue to blow". In: *Anatomical sciences education* 2.6 (2009), pp. 253–259 (cit. on pp. 2, 20).
- [120] D. Drascic and P. Milgram. "Perceptual issues in augmented reality". In: *Stereoscopic displays and virtual reality systems III*. Vol. 2653. International Society for Optics and Photonics. 1996, pp. 123–134 (cit. on pp. 38, 39).
- [121] M. Dunleavy, C. Dede, and R. Mitchell. "Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning". In: *Journal of science Education and Technology* 18.1 (2009), pp. 7–22 (cit. on pp. 125, 163).

- [122] A. Dünser, R. Grasset, and M. Billinghurst. *A survey of evaluation techniques used in augmented reality studies*. Human Interface Technology Laboratory New Zealand, 2008 (cit. on pp. 39, 40).
- [123] A. Dünser, K. Steinbügl, H. Kaufmann, and J. Glück. “Virtual and augmented reality as spatial ability training tools”. In: *Proceedings of the 7th ACM SIGCHI New Zealand chapter’s international conference on Computer-human interaction: design centered HCI*. 2006, pp. 125–132 (cit. on p. 40).
- [124] E. J. Edelstein and L. Edelstein. *Asclepius: collection and interpretation of the testimonies*. Vol. 1. JHU Press, 1998 (cit. on p. 10).
- [125] L Edelstein. “Review of Stella 1939”. In: *American Journal of Philology* 63 (1942), pp. 371–372 (cit. on p. 10).
- [126] H. Edriss, B. N. Rosales, C. Nugent, C. Conrad, and K. Nugent. *Islamic medicine in the middle ages*. 2017 (cit. on p. 15).
- [127] S Eickmeyer, J Wertsch, L Lewandowski, T Hoagland, and D Braza. “Teaching pelvic floor musculoskeletal anatomy using Anatomage”. In: *30th Annual Meeting of the American Association of Clinical Anatomists, Denver, Colorado*. Retrieved from http://clinical-anatomy.org/images/downloads/Past_Meeting_PDFs/denver.pdf. 2013 (cit. on p. 85).
- [128] A. M. Elhadi, S. Kalb, L. Perez-Orribo, A. S. Little, R. F. Spetzler, and M. C. Preul. “The journey of discovering skull base anatomy in ancient Egypt and the special influence of Alexandria”. In: *Neurosurgical focus* 33.2 (2012), E2 (cit. on p. 9).
- [129] S. R. Ellis and B. M. Menges. “Judgments of the distance to nearby virtual objects: Interaction of viewing conditions and accommodative demand”. In: *Presence: Teleoperators & Virtual Environments* 6.4 (1997), pp. 452–460 (cit. on p. 40).
- [130] S. R. Ellis and B. M. Menges. “Localization of virtual objects in the near visual field”. In: *Human factors* 40.3 (1998), pp. 415–431 (cit. on p. 40).
- [131] S. R. Ellis, B. D. Adelstein, and K. Yeom. “Human control in rotated frames: anisotropies in the misalignment disturbance function of pitch, roll, and yaw”. In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Vol. 56. 1. SAGE Publications Sage CA: Los Angeles, CA. 2012, pp. 1336–1340 (cit. on p. 136).
- [132] P. Emmanouil, M. Pavlos, E. D. Avgerinos, A. Sofia, and T. Christos. “Evolution of medical education in ancient Greece”. In: *Chinese medical journal* 121.21 (2008), pp. 2202–2206 (cit. on pp. 10–12).
- [133] M. Estai and S. Bunt. “Best teaching practices in anatomy education: A critical review”. In: *Annals of Anatomy-Anatomischer Anzeiger* 208 (2016), pp. 151–157 (cit. on pp. 2, 3, 20, 85, 99, 124).
- [134] D. J. Evans and T. Cuffe. “Near-peer teaching in anatomy: An approach for deeper learning”. In: *Anatomical sciences education* 2.5 (2009), pp. 227–233 (cit. on p. 162).
- [135] M. Fairén González, M. Farrés, J. Moyes Ardiaca, and E. Insa. “Virtual Reality to teach anatomy”. In: *Eurographics 2017: education papers*. European Association for Computer Graphics (Eurographics). 2017, pp. 51–58 (cit. on pp. 42, 43).
- [136] J. Falah, S. Khan, T. Alfalah, et al. “Virtual Reality medical training system for anatomy education”. In: *2014 Science and Information Conference*. IEEE. 2014, pp. 752–758 (cit. on p. 42).
- [137] D. R. Faria and J. Dias. “3D hand trajectory segmentation by curvatures and hand orientation for classification through a probabilistic approach”. In: *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*. IEEE. 2009, pp. 1284–1289 (cit. on p. 136).
- [138] S. Feiner, B. MacIntyre, T. Höllerer, and A. Webster. “A touring machine: Prototyping 3D mobile augmented reality systems for exploring the urban environment”. In: *Personal Technologies* 1.4 (1997), pp. 208–217 (cit. on pp. 25, 27).
- [139] S. Feiner, B. Macintyre, and D. Seligmann. “Knowledge-based augmented reality”. In: *Communications of the ACM* 36.7 (1993), pp. 53–62 (cit. on p. 25).

- [140] J Ferrer-Torregrosa, J Torralba, M. Jimenez, S García, and J. Barcia. “ARBOOK: Development and assessment of a tool based on augmented reality for anatomy”. In: *Journal of Science Education and Technology* 24.1 (2015), pp. 119–124 (cit. on pp. 46, 47).
- [141] M. Fjeld and B. M. Voegtli. “Augmented chemistry: An interactive educational workbench”. In: *Proceedings. International Symposium on Mixed and Augmented Reality*. IEEE. 2002, pp. 259–321 (cit. on p. 35).
- [142] N. A. Flack and H. D. Nicholson. “What do medical students learn from dissection?” In: *Anatomical sciences education* 11.4 (2018), pp. 325–335 (cit. on p. 1).
- [143] B. H. Fruhstorfer, J. Palmer, S. Brydges, and P. H. Abrahams. “The use of plastinated prosections for teaching anatomy—the view of medical students on the value of this learning resource”. In: *Clinical Anatomy* 24.2 (2011), pp. 246–252 (cit. on p. 20).
- [144] H. Fuchs, M. A. Livingston, R. Raskar, et al. “Augmented reality visualization for laparoscopic surgery”. In: *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer. 1998, pp. 934–943 (cit. on p. 39).
- [145] H. Fuchs, E. D. Pisano, W. F. Garrett, et al. “Towards performing ultrasound-guided needle biopsies from within a head-mounted display”. In: *International Conference on Visualization in Biomedical Computing*. Springer. 1996, pp. 591–600 (cit. on p. 25).
- [146] J. F. Fulton. “History of medical education”. In: *British medical journal* 2.4834 (1953), p. 457 (cit. on p. 16).
- [147] G. Fyfe, S. Fyfe, and D. Dye. “Use of Anatomage tables in a large first year core unit.” In: *ASCILITE-Australian Society for Computers in Learning in Tertiary Education Annual Conference*. Australasian Society for Computers in Learning in Tertiary Education. 2013, pp. 298–302 (cit. on p. 85).
- [148] S. Fyfe, G. Fyfe, D. Dye, H. Radley-Crabb, et al. “The Anatomage table: Differences in student ratings between initial implementation and established use”. In: *Focus on Health Professional Education: A Multi-disciplinary Journal* 19.2 (2018), p. 41 (cit. on pp. 85, 98).
- [149] G. Ganis and R. Kievit. “A New Set of Three-Dimensional Shapes for Investigating Mental Rotation Processes: Validation Data and Stimulus Set”. In: *Journal of Open Psychology Data* 3.3972 (Mar. 2015), pp. 701–7 (cit. on pp. 72, 92, 115).
- [150] A. X. Garg, G. Norman, and L. Sperotable. “How medical students learn spatial anatomy”. In: *The Lancet* 357.9253 (2001), pp. 363–364 (cit. on pp. 100, 124, 160).
- [151] A. X. Garg, G. R. Norman, K. W. Eva, L. Spero, and S. Sharan. “Is there any real virtue of virtual reality?: The minor role of multiple orientations in learning anatomy from computers”. In: *Academic Medicine* 77.10 (2002), S97–S99 (cit. on p. 41).
- [152] S. Gauglitz, B. Nuernberger, M. Turk, and T. Höllerer. “In touch with the remote world: Remote collaboration with augmented reality drawings and virtual navigation”. In: *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology*. 2014, pp. 197–205 (cit. on p. 38).
- [153] S. Gauglitz, B. Nuernberger, M. Turk, and T. Höllerer. “World-stabilized annotations and virtual scene navigation for remote collaboration”. In: *Proceedings of the 27th annual ACM symposium on User interface software and technology*. 2014, pp. 449–459 (cit. on p. 38).
- [154] T. Gelfand. “The “Paris manner” of dissection: student anatomical dissection in early eighteenth-century Paris”. In: *Bulletin of the History of Medicine* 46.2 (1972), pp. 99–130 (cit. on p. 19).
- [155] S. K. Ghosh. “Evolution of illustrations in anatomy: A study from the classical period in Europe to modern times”. In: *Anatomical sciences education* 8.2 (2015), pp. 175–188 (cit. on pp. 17, 18, 20).
- [156] S. K. Ghosh. “Human cadaveric dissection: a historical account from ancient Greece to the modern era”. In: *Anatomy & cell biology* 48.3 (2015), pp. 153–169 (cit. on pp. 16, 18).

- [157] G. J. Gormley, M Dempster, and R Best. “Right-left discrimination among medical students: questionnaire and psychometric study”. In: *BMJ* 337.dec16 1 (Dec. 2008), a2826–a2826 (cit. on p. 70).
- [158] R. Grasset, A. Dunser, and M. Billingham. “The design of a mixed-reality book: Is it still a real book?” In: *2008 7th IEEE/ACM International Symposium on Mixed and Augmented Reality*. IEEE, 2008, pp. 99–102 (cit. on p. 35).
- [159] C. Graumann, B. Fuerst, C. Hennersperger, F. Bork, and N. Navab. “Robotic ultrasound trajectory planning for volume of interest coverage”. In: *2016 IEEE international conference on robotics and automation (ICRA)*. IEEE, 2016, pp. 736–741 (cit. on p. 174).
- [160] R. L. Gregory. *Mirrors in mind*. Penguin Harmondsworth, UK, 1998 (cit. on p. 69).
- [161] B. Grignon, G. Oldrini, and F. Walter. “Teaching medical anatomy: what is the role of imaging today?” In: *Surgical and Radiologic Anatomy* 38.2 (2016), pp. 253–260 (cit. on pp. 2, 55, 85).
- [162] U. Gruenefeld, D. Hsiao, W. Heuten, and S. Boll. “EyeSee: beyond reality with Microsoft HoloLens”. In: *Proceedings of the 5th Symposium on Spatial User Interaction*. ACM, 2017, pp. 148–148 (cit. on p. 135).
- [163] U. Gruenefeld, D. Ennenga, A. E. Ali, W. Heuten, and S. Boll. “EyeSee360: Designing a Visualization Technique for Out-of-view Objects in Head-mounted Augmented Reality”. In: *Proceedings of the 5th Symposium on Spatial User Interaction*. SUI '17. Brighton, United Kingdom, 2017, pp. 109–118 (cit. on pp. 135, 138).
- [164] A. Guillot, S. Champely, C. Batier, P. Thiriet, and C. Collet. “Relationship between spatial abilities, mental rotation and functional anatomy learning”. In: *Advances in Health Sciences Education* 12.4 (2007), pp. 491–507 (cit. on p. 72).
- [165] C. Gunn, M. Hutchins, M. Adcock, and R. Hawkins. “Trans-world haptic collaboration”. In: *ACM SIGGRAPH 2003 Sketches & Applications*. 2003, pp. 1–1 (cit. on p. 33).
- [166] R. Gurunluoglu, A. Gurunluoglu, S. A. Williams, and S. Cavdar. “The history and illustration of anatomy in the Middle Ages”. In: *Journal of medical biography* 21.4 (2013), pp. 219–229 (cit. on p. 17).
- [167] S. Gustafson, P. Baudisch, C. Gutwin, and P. Irani. “Wedge: Clutter-free Visualization of Off-screen Locations”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '08. Florence, Italy: ACM, 2008, pp. 787–796 (cit. on p. 134).
- [168] S. G. Gustafson and P. P. Irani. “Comparing Visualizations for Tracking Off-screen Moving Targets”. In: *CHI '07 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '07. San Jose, CA, USA: ACM, 2007, pp. 2399–2404 (cit. on p. 134).
- [169] G. D. Guttman, R. L. Drake, and R. B. Trelease. “To what extent is cadaver dissection necessary to learn medical gross anatomy? A debate forum”. In: *The Anatomical Record* 281.1 (2004), pp. 2–3 (cit. on p. 2).
- [170] T. Ha, S. Feiner, and W. Woo. “WeARHand: Head-worn, RGB-D camera-based, bare-hand user interface with visually enhanced depth perception”. In: *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 2014, pp. 219–228 (cit. on pp. 36, 40).
- [171] O. Habbal. “The Science of Anatomy: A historical timeline”. In: *Sultan Qaboos University Medical Journal* 17.1 (2017), e18 (cit. on p. 9).
- [172] M. G. Hanna, I. Ahmed, J. Nine, S. Prajapati, and L. Pantanowitz. “Augmented reality technology using Microsoft HoloLens in anatomic pathology”. In: *Archives of pathology & laboratory medicine* 142.5 (2018), pp. 638–644 (cit. on pp. 47, 48).
- [173] J. T. Hansberger, C. Peng, S. L. Mathis, et al. “Dispelling the gorilla arm syndrome: the viability of prolonged gesture interactions”. In: *International Conference on Virtual, Augmented and Mixed Reality*. Springer, 2017, pp. 505–520 (cit. on p. 160).

- [174] C. Harrison, H. Benko, and A. D. Wilson. “OmniTouch: wearable multitouch interaction everywhere”. In: *Proceedings of the 24th annual ACM symposium on User interface software and technology*. 2011, pp. 441–450 (cit. on p. 35).
- [175] G. D. Hart. “Asclepius: the god of medicine”. In: (2000) (cit. on p. 10).
- [176] A. F. Healy, E. L. Wohldmann, and L. E. Bourne Jr. “How does practice with a reversed mouse influence subsequent speeded aiming performance? A test of global inhibition”. In: *Journal of Cognitive Psychology* 23.5 (Aug. 2011), pp. 559–573 (cit. on p. 78).
- [177] M. P. Heinrich, O. Oktay, and N. Bouteldja. “OBELISK-Net: Fewer layers to solve 3D multi-organ segmentation with sparse deformable convolutions”. In: *Medical image analysis* 54 (2019), pp. 1–9 (cit. on p. 164).
- [178] J. P. O. Held, K. Yu, C. Pyles, et al. “Augmented Reality–Based Rehabilitation of Gait Impairments: Case Report”. In: *JMIR mHealth and uHealth* 8.5 (2020), e17804 (cit. on p. 173).
- [179] S. J. Henderson and S. K. Feiner. “Augmented reality in the psychomotor phase of a procedural task”. In: *2011 10th IEEE International Symposium on Mixed and Augmented Reality*. IEEE. 2011, pp. 191–200 (cit. on p. 40).
- [180] A. Henrysson, M. Billingham, and M. Ollila. “Face to face collaborative AR on mobile phones”. In: *Fourth IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR’05)*. IEEE. 2005, pp. 80–89 (cit. on p. 40).
- [181] D. Henssen, L. van den Heuvel, G. De Jong, et al. “Neuroanatomy Learning: Augmented Reality vs. Cross-Sections.” In: *Anatomical sciences education* (2019) (cit. on pp. 44, 45).
- [182] N. Heptonstall, T. Ali, and K. Mankad. “Integrating radiology and anatomy teaching in medical education in the UK—the evidence, current trends, and future scope”. In: *Academic radiology* 23.4 (2016), pp. 521–526 (cit. on pp. 2, 55, 99).
- [183] T. J. Herbert. “Area projections of fisheye photographic lenses”. In: *Agricultural and Forest Meteorology* 39.2-3 (1987), pp. 215–223 (cit. on p. 153).
- [184] L. J. Hettlinger and G. E. Riccio. “Visually induced motion sickness in virtual environments”. In: *Presence: Teleoperators & Virtual Environments* 1.3 (1992), pp. 306–310 (cit. on p. 3).
- [185] D. Heylings. “Anatomy 1999–2000: the curriculum, who teaches it and how?” In: *Medical education* 36.8 (2002), pp. 702–710 (cit. on p. 3).
- [186] L. M. Hiatt and R. Simmons. “Coordinate frames in robotic teleoperation”. In: *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*. IEEE. 2006, pp. 1712–1719 (cit. on p. 78).
- [187] R. A. Hicks. *Wide angle substantially non-distorting mirror*. US Patent 8,180,606. 2012 (cit. on p. 69).
- [188] S. Hildebrandt. “Lessons to be learned from the history of anatomical teaching in the United States: The example of the University of Michigan”. In: *Anatomical sciences education* 3.4 (2010), pp. 202–212 (cit. on p. 19).
- [189] O. Hilliges, D. Kim, S. Izadi, M. Weiss, and A. Wilson. “HoloDesk: direct 3d interactions with a situated see-through display”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2012, pp. 2421–2430 (cit. on p. 36).
- [190] J. D. Hincapié-Ramos, X. Guo, P. Moghadasian, and P. Irani. “Consumed endurance: a metric to quantify arm fatigue of mid-air interactions”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2014, pp. 1063–1072 (cit. on p. 160).
- [191] M. Hirnstein, S. Ocklenburg, D. Schneider, and M. Hausmann. “Sex differences in left–right confusion depend on hemispheric asymmetry”. In: *Cortex* 45.7 (July 2009), pp. 891–899 (cit. on p. 69).

- [192] T. Hoang, M. Reinoso, Z. Joukhadar, F. Vetere, and D. Kelly. “Augmented studio: projection mapping on moving body for physiotherapy education”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 2017, pp. 1419–1430 (cit. on pp. 33, 46).
- [193] B. Hofmann. “Medicine as techne—A perspective from antiquity”. In: *The Journal of medicine and philosophy* 28.4 (2003), pp. 403–425 (cit. on p. 10).
- [194] T. Höllerer and S. Feiner. “Mobile augmented reality”. In: *Telegeoinformatics: Location-based computing and services* 21 (2004) (cit. on p. 27).
- [195] P. Holman, T. Bodnar, M. Ghomi, R. Choi, H. Moukhles, and C. Krebs. “3D neuroanatomy: using the HoloLens for an augmented reality approach in neuroanatomy education”. In: *The FASEB Journal* 32.1_supplement (2018), pp. 25–3 (cit. on p. 48).
- [196] A. Holynski and J. Kopf. “Fast depth densification for occlusion-aware augmented reality”. In: *ACM Transactions on Graphics (TOG)* 37.6 (2018), pp. 1–11 (cit. on p. 39).
- [197] P. M. House, S. Pelzl, S. Furrer, et al. “Use of the mixed reality tool “VSI Patient Education” for more comprehensible and imaginable patient educations before epilepsy surgery and stereotactic implantation of DBS or stereo-EEG electrodes”. In: *Epilepsy Research* 159 (2020), p. 106247 (cit. on p. 161).
- [198] E. Hsieh. “A review of ancient Chinese anatomy”. In: *The Anatomical Record* 20.2 (1921), pp. 96–127 (cit. on p. 9).
- [199] T. W. Huitt, A. Killins, and W. S. Brooks. “Team-based learning in the gross anatomy laboratory improves academic performance and students’ attitudes toward teamwork”. In: *Anatomical sciences education* 8.2 (2015), pp. 95–103 (cit. on p. 162).
- [200] M. Hussein and C. Nätterdal. “The benefits of virtual reality in education-A comparison Study”. In: (2015) (cit. on p. 3).
- [201] S. M. Hutchins. “Anatomage table: Are all organ systems created equal?” In: *Conference Proceedings. New Perspectives in Science Education*. *libreriauniversitaria.it Edizioni*. 2017, p. 276 (cit. on p. 85).
- [202] N. Ienaga, F. Bork, S. Meerits, et al. “First deployment of diminished reality for anatomy education”. In: *2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*. IEEE. 2016, pp. 294–296 (cit. on p. 174).
- [203] S. Ishihara. “Series of plates designed as tests for colour-blindness”. In: (1936) (cit. on p. 141).
- [204] H. Ishii and B. Ullmer. “Tangible bits: towards seamless interfaces between people, bits and atoms”. In: *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*. 1997, pp. 234–241 (cit. on p. 35).
- [205] W. H. Ittelson, L. Mowafy, and D. Magid. “The perception of mirror-reflected objects”. In: *Perception* 20.5 (1991), pp. 567–584 (cit. on p. 69).
- [206] S. G. Izard, J. A. J. Méndez, and P. R. Palomera. “Virtual reality educational tool for human anatomy”. In: *Journal of medical systems* 41.5 (2017), p. 76 (cit. on p. 42).
- [207] W. A. Jackson. “A short guide to humoral medicine”. In: *Trends in pharmacological sciences* 22.9 (2001), pp. 487–489 (cit. on p. 11).
- [208] T. G. Jacob. “History of teaching anatomy in India: From ancient to modern times”. In: *Anatomical sciences education* 6.5 (2013), pp. 351–358 (cit. on p. 8).
- [209] A. Jacobson, I. Baran, J. Popovic, and O. Sorkine. “Bounded biharmonic weights for real-time deformation.” In: () (cit. on p. 65).
- [210] A. Jacobson, I. Baran, L. Kavan, J. Popović, and O. Sorkine. “Fast automatic skinning transformations”. In: *ACM Transactions on Graphics (TOG)* 31.4 (2012), pp. 1–10 (cit. on p. 65).

- [211] A. A. Jaffar. "YouTube: An emerging tool in anatomy education". In: *Anatomical sciences education* 5.3 (2012), pp. 158–164 (cit. on p. 2).
- [212] N. Jain, P. Youngblood, M. Hasel, and S. Srivastava. "An augmented reality tool for learning spatial anatomy on mobile devices". In: *Clinical Anatomy* 30.6 (2017), pp. 736–741 (cit. on pp. 44, 45).
- [213] S. S. Jamali, M. F. Shiratuddin, K. W. Wong, and C. L. Oskam. "Utilising mobile-augmented reality for learning human anatomy". In: *Procedia-Social and Behavioral Sciences* 197 (2015), pp. 659–668 (cit. on p. 44).
- [214] H. A. Jamniczky, D. Cotton, M. Paget, et al. "Cognitive load imposed by ultrasound-facilitated teaching does not adversely affect gross anatomy learning outcomes". In: *Anatomical sciences education* 10.2 (2017), pp. 144–151 (cit. on p. 2).
- [215] C. Jang, K. Bang, S. Moon, J. Kim, S. Lee, and B. Lee. "Retinal 3D-augmented reality near-eye display via pupil-tracked light field projection on retina". In: *ACM Transactions on Graphics (TOG)* 36.6 (2017), pp. 1–13 (cit. on p. 32).
- [216] H. Jo, S. Hwang, H. Park, and J. hee Ryu. "Aroundplot: Focus+context interface for off-screen objects in 3D environments". In: *Computers & Graphics* 35.4 (2011). Semantic 3D Media and Content, pp. 841–853 (cit. on pp. 134, 135, 137, 138).
- [217] E. O. Johnson, A. V. Charchanti, and T. G. Troupis. "Modernization of an anatomy class: From conceptualization to implementation. A case for integrated multimodal-multidisciplinary teaching". In: *Anatomical sciences education* 5.6 (2012), pp. 354–366 (cit. on pp. 2, 3).
- [218] B. R. Jones, R. Sodhi, R. H. Campbell, G. Garnett, and B. P. Bailey. "Build your world and play in it: Interacting with surface particles on complex objects". In: *2010 IEEE international symposium on mixed and augmented reality*. IEEE. 2010, pp. 165–174 (cit. on p. 35).
- [219] N. A. Jones, R. P. Olafson, and J. Sutin. "Evaluation of a gross anatomy program without dissection." In: *Journal of medical education* 53.3 (1978), pp. 198–205 (cit. on p. 2).
- [220] R. Jonker, G De Leve, J. Van Der Velde, and A Volgenant. "Rounding symmetric traveling salesman problems with an asymmetric assignment problem". In: *Operations Research* 28.3-part-i (1980), pp. 623–627 (cit. on p. 136).
- [221] J. A. Juanes, D. Hernández, P. Ruisoto, E. García, G. Villarrubia, and A. Prats. "Augmented reality techniques, using mobile devices, for learning human anatomy". In: *Proceedings of the Second International Conference on Technological Ecosystems for Enhancing Multiculturality*. 2014, pp. 7–11 (cit. on p. 44).
- [222] D. Kalkofen, E. Veas, S. Zollmann, M. Steinberger, and D. Schmalstieg. "Adaptive ghosted views for augmented reality". In: *2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE. 2013, pp. 1–9 (cit. on p. 39).
- [223] D. Kalkofen, E. Mendez, and D. Schmalstieg. "Interactive focus and context visualization for augmented reality". In: *2007 6th IEEE and ACM International Symposium on Mixed and Augmented Reality*. IEEE. 2007, pp. 191–201 (cit. on p. 39).
- [224] D. Kalkofen, C. Sandor, S. White, and D. Schmalstieg. "Visualization techniques for augmented reality". In: *Handbook of Augmented Reality*. Springer, 2011, pp. 65–98 (cit. on p. 39).
- [225] A. R. Kancherla, J. P. Rolland, D. L. Wright, and G. Burdea. "A novel virtual reality tool for teaching dynamic 3D anatomy". In: *International Conference on Computer Vision, Virtual Reality, and Robotics in Medicine*. Springer. 1995, pp. 163–169 (cit. on p. 41).
- [226] V Kanellou. "Ancient Greek medicine as the foundation of contemporary medicine". In: *Techniques in coloproctology* 8 (2004), s3–s4 (cit. on p. 10).

- [227] S. Kasahara and J. Rekimoto. “JackIn: integrating first-person view with out-of-body vision generation for human-human augmentation”. In: *Proceedings of the 5th Augmented Human International Conference*. 2014, pp. 1–8 (cit. on p. 40).
- [228] H. Kato and M. Billinghurst. “Marker tracking and hmd calibration for a video-based augmented reality conferencing system”. In: *Proceedings 2nd IEEE and ACM International Workshop on Augmented Reality (IWAR'99)*. IEEE. 1999, pp. 85–94 (cit. on pp. 25, 30).
- [229] H. Kato, M. Billinghurst, I. Poupyrev, K. Imamoto, and K. Tachibana. “Virtual object manipulation on a table-top AR environment”. In: *Proceedings IEEE and ACM International Symposium on Augmented Reality (ISAR 2000)*. Ieee. 2000, pp. 111–119 (cit. on p. 35).
- [230] H. Kaufmann and D. Schmalstieg. “Mathematics and geometry education with collaborative augmented reality”. In: *ACM SIGGRAPH 2002 conference abstracts and applications*. 2002, pp. 37–41 (cit. on p. 37).
- [231] H. Kaufmann, D. Schmalstieg, and M. Wagner. “Construct3D: a virtual reality application for mathematics and geometry education”. In: *Education and information technologies 5.4 (2000)*, pp. 263–276 (cit. on p. 37).
- [232] L. Kavan. “Part I: direct skinning methods and deformation primitives”. In: *ACM SIGGRAPH*. 2014, pp. 1–11 (cit. on p. 66).
- [233] L. Kavan, S. Collins, J. Žára, and C. O’Sullivan. “Geometric skinning with approximate dual quaternion blending”. In: *ACM Transactions on Graphics (TOG) 27.4 (2008)*, pp. 1–23 (cit. on p. 66).
- [234] F. Khalid, A. I. Ali, R. R. Ali, and M. S. Bhatti. “AREd: Anatomy Learning Using Augmented Reality Application”. In: *2019 International Conference on Engineering and Emerging Technologies (ICEET)*. IEEE. 2019, pp. 1–6 (cit. on p. 44).
- [235] M. Khalil, T. Johnson, and C. Lamar. “Comparison of computer-based and paper-based imagery strategies in learning anatomy”. In: *Clinical Anatomy: The Official Journal of the American Association of Clinical Anatomists and the British Association of Clinical Anatomists 18.6 (2005)*, pp. 457–464 (cit. on p. 2).
- [236] O. Khatib, J. Warren, V. De Sapio, and L. Sentis. “Human-like motion from physiologically-based potential energies”. In: *On advances in robot kinematics*. Springer, 2004, pp. 145–154 (cit. on p. 151).
- [237] O. Khatib, L. Sentis, J. Park, and J. Warren. “Whole-body dynamic behavior and control of human-like robots”. In: *International Journal of Humanoid Robotics 1.01 (2004)*, pp. 29–43 (cit. on p. 151).
- [238] Z. Khot, K. Quinlan, G. R. Norman, and B. Wainman. “The relative effectiveness of computer-based and traditional resources for education in anatomy”. In: *Anatomical sciences education 6.4 (2013)*, pp. 211–215 (cit. on p. 2).
- [239] M. Kim, G. Pons-Moll, S. Pujades, et al. “Data-driven physics for human soft tissue animation”. In: *ACM Transactions on Graphics (TOG) 36.4 (2017)*, pp. 1–12 (cit. on p. 66).
- [240] P. Kinnersley, K. Phillips, K. Savage, et al. “Interventions to promote informed consent for patients undergoing surgical and other invasive healthcare procedures”. In: *Cochrane Database of Systematic Reviews 7 (2013)* (cit. on p. 161).
- [241] T. Kirsten, H. J. Van der Walt, and C. T. Viljoen. “Health, well-being and wellness: An anthropological eco-systemic approach”. In: *Health SA Gesondheid 14.1 (2009)* (cit. on p. 11).
- [242] K. Kiyokawa, H. Iwasa, H. Takemura, and N. Yokoya. “Collaborative immersive workspace through a shared augmented environment”. In: *Intelligent Systems in Design and Manufacturing*. Vol. 3517. International Society for Optics and Photonics. 1998, pp. 2–13 (cit. on p. 38).

- [243] G. Klein and D. Murray. “Compositing for small cameras”. In: *2008 7th IEEE/ACM International Symposium on Mixed and Augmented Reality*. IEEE. 2008, pp. 57–60 (cit. on p. 38).
- [244] C. F. Kleisiaris, C. Sfakianakis, and I. V. Papathanasiou. “Health care practices in ancient Greece: The Hippocratic ideal”. In: *Journal of medical ethics and history of medicine* 7 (2014) (cit. on p. 11).
- [245] C. Klestinec. “A history of anatomy theaters in sixteenth-century Padua”. In: *Journal of the History of Medicine and Allied Sciences* 59.3 (2004), pp. 375–412 (cit. on p. 18).
- [246] C. Klestinec. *Theaters of anatomy: Students, teachers, and traditions of dissection in renaissance Venice*. JHU Press, 2011 (cit. on p. 18).
- [247] M. Knecht, C. Traxler, O. Mattausch, W. Purgathofer, and M. Wimmer. “Differential instant radiosity for mixed reality”. In: *2010 IEEE International Symposium on Mixed and Augmented Reality*. IEEE. 2010, pp. 99–107 (cit. on p. 38).
- [248] B. Knight. *Discovering the human body: How pioneers of medicine solved the mysteries of the body’s structure and function*. Lippincott & Crowell, 1980 (cit. on p. 14).
- [249] H.-W. Korf, H. Wicht, R. L. Snipes, et al. “The dissection course—necessary and indispensable for teaching anatomy to medical students”. In: *Annals of Anatomy-Anatomischer Anzeiger* 190.1 (2008), pp. 16–22 (cit. on pp. 1, 20).
- [250] E. Kruijff, J. E. Swan, and S. Feiner. “Perceptual issues in augmented reality revisited”. In: *2010 IEEE International Symposium on Mixed and Augmented Reality*. IEEE. 2010, pp. 3–12 (cit. on p. 40).
- [251] S. Küçük, S. Kapakin, and Y. Göktaş. “Learning anatomy via mobile augmented reality: effects on achievement and cognitive load”. In: *Anatomical sciences education* 9.5 (2016), pp. 411–421 (cit. on pp. 44, 123).
- [252] F. Kudlien. “Dogmatische Aerzte”. In: *Pauly Wissowa, op. cit. Supplement X* (1965), pp. 179–180 (cit. on p. 12).
- [253] F. Kudlien. “Medical education in classical antiquity”. In: *The history of medical education* (1970), pp. 3–37 (cit. on pp. 10, 12–14).
- [254] D. Kugelmann, L. Stratmann, N. Nühlen, et al. “An augmented reality magic mirror as additive teaching device for gross anatomy”. In: *Annals of Anatomy-Anatomischer Anzeiger* 215 (2018), pp. 71–77 (cit. on pp. 79, 174).
- [255] M. H. Kurniawan, G. Witjaksono, et al. “Human anatomy learning systems using augmented reality on mobile application”. In: *Procedia Computer Science* 135 (2018), pp. 80–88 (cit. on p. 44).
- [256] B. M. Kyaw, N. Saxena, P. Posadzki, et al. “Virtual reality for health professions education: systematic review and meta-analysis by the Digital Health Education collaboration”. In: *Journal of medical Internet research* 21.1 (2019), e12959 (cit. on p. 43).
- [257] N. Lachman and W. Pawlina. “Integrating professionalism in early medical education: the theory and application of reflective practice in the anatomy curriculum”. In: *Clinical Anatomy* 19.5 (2006), pp. 456–460 (cit. on p. 2).
- [258] J. Langlois, C. Bellemare, J. Toulouse, and G. A. Wells. “Spatial abilities training in anatomy education: A systematic review”. In: *Anatomical sciences education* 13.1 (2020), pp. 71–79 (cit. on p. 43).
- [259] J. Lao, S. Gonzalez, D. Burbidge, et al. “A mixed reality technology as a supplemental learning tool of the cardiovascular system”. In: *CMBES Proceedings* 42 (2019) (cit. on p. 46).
- [260] R. Lawson. “The science of cycology: Failures to understand how everyday objects work”. In: *Memory & cognition* 34.8 (2006), pp. 1667–1675 (cit. on p. 68).

- [261] R. Lawson and M. Bertamini. “Errors in judging information about reflections in mirrors”. In: *Perception* 35.9 (2006), pp. 1265–1288 (cit. on p. 68).
- [262] A Lebedev. “Alcmaeon on plants: a new fragment in Nicolaus Damascenus”. In: *Parola del Passato* 48 (1993), pp. 456–460 (cit. on p. 10).
- [263] J.-G. Lee, J. Han, X. Li, and H. Gonzalez. “TraClass: trajectory classification using hierarchical region-based and trajectory-based clustering”. In: *Proceedings of the VLDB Endowment* 1.1 (2008), pp. 1081–1094 (cit. on p. 136).
- [264] S.-H. Lee and D. Terzopoulos. “Heads up!: biomechanical modeling and neuromuscular control of the neck”. In: *ACM Transactions on Graphics (TOG)* 25.3 (2006), pp. 1188–1198 (cit. on p. 151).
- [265] T. Lee and T. Hollerer. “Handy AR: Markerless inspection of augmented reality objects using fingertip tracking”. In: *2007 11th IEEE International Symposium on Wearable Computers*. IEEE, 2007, pp. 83–90 (cit. on p. 36).
- [266] Y. Lei, T. Wang, S. Tian, et al. “Male pelvic multi-organ segmentation aided by CBCT-based synthetic MRI”. In: *Physics in Medicine & Biology* 65.3 (2020), p. 035013 (cit. on p. 164).
- [267] M. Lerotic, A. J. Chung, G. Mylonas, and G.-Z. Yang. “Pq-space based non-photorealistic rendering for augmented reality”. In: *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer, 2007, pp. 102–109 (cit. on p. 39).
- [268] A. J. Levinson, B. Weaver, S. Garside, H. McGinn, and G. R. Norman. “Virtual reality and brain anatomy: A randomised trial of e-learning instructional designs”. In: *Medical education* 41.5 (2007), pp. 495–501 (cit. on p. 41).
- [269] L. Li. “Time-of-flight camera—an introduction”. In: *Technical white paper SLOA190B* (2014) (cit. on p. 29).
- [270] J. Lien, N. Gillian, M. E. Karagozler, et al. “Soli: Ubiquitous gesture sensing with millimeter wave radar”. In: *ACM Transactions on Graphics (TOG)* 35.4 (2016), pp. 1–19 (cit. on p. 37).
- [271] K. H. A. Lim, Z. Y. Loo, S. J. Goldie, J. W. Adams, and P. G. McMenemy. “Use of 3D printed models in medical education: A randomized control trial comparing 3D prints versus cadaveric materials for learning external cardiac anatomy”. In: *Anatomical sciences education* 9.3 (2016), pp. 213–221 (cit. on p. 2).
- [272] M. Liu, M. Nancel, and D. Vogel. “Gunslinger: Subtle arms-down mid-air interaction”. In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. 2015, pp. 63–71 (cit. on p. 160).
- [273] M. A. Livingston. “Evaluating human factors in augmented reality systems”. In: *IEEE Computer Graphics and Applications* 25.6 (2005), pp. 6–9 (cit. on p. 40).
- [274] G. Lloyd. “Alcmaeon and the early history of dissection”. In: *Sudhoffs Archiv* (1975), pp. 113–147 (cit. on pp. 10, 11).
- [275] G. E. Lloyd. “A note on Erasistratus of Ceos”. In: *The Journal of Hellenic Studies* 95 (1975), pp. 172–175 (cit. on p. 12).
- [276] G. E. R. Lloyd. *Early greek science: Thales to Aristotle*. Random House, 2012 (cit. on p. 11).
- [277] J. Lloyd. “The Hippocratics in Context: The Ethical Formation of the Hippocratic Physician”. PhD thesis. 2018 (cit. on p. 11).
- [278] I. M. Lonie. “Cos versus Cnidus and the historians: Part I”. In: *History of Science* 16.1 (1978), pp. 42–75 (cit. on p. 11).

- [279] M. Loukas, J. Ferraiuola, M. M. Shoja, R. S. Tubbs, and A. A. Cohen-Gadol. "Anatomy in ancient China: The yellow emperor's inner canon of medicine and wang qingren's correcting the errors in the forest of medicine". In: *Clinical Anatomy: The Official Journal of the American Association of Clinical Anatomists and the British Association of Clinical Anatomists* 23.4 (2010), pp. 364–369 (cit. on pp. 8, 9).
- [280] M. Loukas, A. Lanteri, J. Ferraiuola, et al. "Anatomy in ancient India: a focus on the Susruta Samhita". In: *Journal of anatomy* 217.6 (2010), pp. 646–650 (cit. on p. 8).
- [281] M. Loukas, M. Hanna, N. Alsaiegh, M. M. Shoja, and R. S. Tubbs. "Clinical anatomy as practiced by ancient Egyptians". In: *Clinical anatomy* 24.4 (2011), pp. 409–415 (cit. on p. 9).
- [282] M. Loukas, R. S. Tubbs, R. G. Louis Jr, J. Pinyard, S. Vaid, and B. Curry. "The cardiovascular system in the pre-Hippocratic era". In: *International journal of cardiology* 120.2 (2007), pp. 145–149 (cit. on p. 9).
- [283] J. Luce. "Greek medicine from Asclepius to Hippocrates". In: *Irish journal of medical science* 170.3 (2001), pp. 200–202 (cit. on p. 10).
- [284] R. S. Lufler, A. C. Zumwalt, C. A. Romney, and T. M. Hoagland. "Effect of visual–spatial ability on medical students' performance in a gross anatomy course". In: *Anatomical sciences education* 5.1 (2012), pp. 3–9 (cit. on pp. 124, 160).
- [285] R. S. Lufler, A. C. Zumwalt, C. A. Romney, and T. M. Hoagland. "Incorporating radiology into medical gross anatomy: Does the use of cadaver CT scans improve students' academic performance in anatomy?" In: *Anatomical sciences education* 3.2 (2010), pp. 56–63 (cit. on pp. 2, 85).
- [286] S. Lukosch, M. Billingham, L. Alem, and K. Kiyokawa. "Collaboration in augmented reality". In: *Computer Supported Cooperative Work (CSCW)* 24.6 (2015), pp. 515–525 (cit. on p. 37).
- [287] A. S. Lyons and R. J. Petrucelli. "Medicine: an illustrated history". In: (1978) (cit. on p. 8).
- [288] M. Ma, P. Jutzi, F. Bork, et al. "Interactive mixed reality for muscle structure and function learning". In: *International Conference on Medical Imaging and Augmented Reality*. Springer. 2016, pp. 117–128 (cit. on pp. 79, 174).
- [289] M. Ma, P. Fallavollita, I. Seelbach, et al. "Personalized augmented reality for anatomy education". In: *Clinical Anatomy* 29.4 (2016), pp. 446–453 (cit. on pp. 46, 79).
- [290] L. C. MacKinney. "Medical education in the Middle Ages". In: *Cahiers d'Histoire Mondiale. Journal of World History. Cuadernos de Historia Mundial* 2.4 (1955), p. 835 (cit. on pp. 15, 16).
- [291] A. Maimone and H. Fuchs. "Real-time volumetric 3D capture of room-sized scenes for telepresence". In: *2012 3DTV-conference: the true vision-capture, transmission and display of 3D video (3DTV-CON)*. IEEE. 2012, pp. 1–4 (cit. on p. 38).
- [292] D. Mandl, K. M. Yi, P. Mohr, et al. "Learning lightprobes for mixed reality illumination". In: *2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE. 2017, pp. 82–89 (cit. on p. 38).
- [293] S. Mann. "Mediated reality with implementations for everyday life". In: *Presence Connect* 1 (2002) (cit. on p. 23).
- [294] S. Mann. "Wearable, Tetherless, Computer-Mediated Reality (with possible future applications to the disabled)". In: *Technical report 260* (1994) (cit. on p. 23).
- [295] C. Manrique-Juan, Z. V. Grostieta-Dominguez, R. Rojas-Ruiz, M. Alencastre-Miranda, L. Muñoz-Gómez, and C. Silva-Muñoz. "A portable augmented-reality anatomy learning system using a depth camera in real time". In: *The American Biology Teacher* 79.3 (2017), pp. 176–183 (cit. on p. 46).

- [296] H. Maresky, A Oikonomou, I Ali, N Ditkofsky, M Pakkal, and B Ballyk. “Virtual reality and cardiac anatomy: Exploring immersive three-dimensional cardiac imaging, a pilot study in undergraduate medical anatomy education”. In: *Clinical Anatomy* 32.2 (2019), pp. 238–243 (cit. on p. 42).
- [297] S. Marks, D. White, and M. Singh. “Getting up your nose: a virtual reality education tool for nasal cavity anatomy”. In: *SIGGRAPH Asia 2017 symposium on education*. 2017, pp. 1–7 (cit. on pp. 42, 43).
- [298] J. Martín-Gutiérrez, P. Fabiani, W. Benesova, M. D. Meneses, and C. E. Mora. “Augmented reality to promote collaborative and autonomous learning in higher education”. In: *Computers in human behavior* 51 (2015), pp. 752–761 (cit. on pp. 125, 163).
- [299] A. C.d. A. Martins and C. Martins. “History of liver anatomy: Mesopotamian liver clay models”. In: *HPB* 15.4 (2013), pp. 322–323 (cit. on p. 9).
- [300] L. Mason and M. Holmes. “Immersive Virtual Reality as a teaching aid for anatomy”. In: *Proceedings of the Virtual and Augmented Reality to Enhance Learning and Teaching in Higher Education Conference 2018*. IM Publications Open. 2019 (cit. on p. 42).
- [301] Y. Masuoka, H. Morikawa, T. Kawai, and T. Nakagohri. “Use of Smartphone-Based Head-Mounted Display Devices to View a Three-Dimensional Dissection Model in a Virtual Reality Environment: Pilot Questionnaire Study”. In: *JMIR medical education* 5.1 (2019), e11921 (cit. on p. 43).
- [302] V. Mathiowetz, C.-H. Yu, and C. Quake-Rapp. “Comparison of a gross anatomy laboratory to online anatomy software for teaching anatomy”. In: *Anatomical sciences education* 9.1 (2016), pp. 52–59 (cit. on p. 85).
- [303] S. Matsuzoe, S. Jiang, M. Ueki, and K. Okabayashi. “Intuitive visualization method for locating off-screen objects inspired by motion perception in peripheral vision”. In: *Proceedings of the 8th Augmented Human International Conference*. ACM. 2017, p. 29 (cit. on p. 135).
- [304] F. Matulic and D. Vogel. “Multiray: multi-finger raycasting for large displays”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 2018, pp. 1–13 (cit. on p. 160).
- [305] J. M. McBride and R. L. Drake. “Use of unembalmed/fresh cadavers in anatomy teaching”. In: *Teaching Anatomy*. Springer, 2015, pp. 223–226 (cit. on p. 1).
- [306] J. McCrae, M. Glueck, T. Grossman, A. Khan, and K. Singh. “Exploring the Design Space of Multiscale 3D Orientation”. In: *Proceedings of the International Conference on Advanced Visual Interfaces*. AVI '10. Roma, Italy: ACM, 2010, pp. 81–88 (cit. on pp. 135, 138).
- [307] J. McKinley, M. Dempster, and G. J. Gormley. “‘Sorry, I meant the patient’s left side’: impact of distraction on left-right discrimination”. In: *Medical Education* 49.4 (Mar. 2015), pp. 427–435 (cit. on p. 70).
- [308] J. C. McLachlan. “New path for teaching anatomy: living anatomy and medical imaging vs. dissection”. In: *The Anatomical Record Part B: The New Anatomist: An Official Publication of the American Association of Anatomists* 281.1 (2004), pp. 4–5 (cit. on pp. 2, 20).
- [309] J. C. McLachlan and D. Patten. “Anatomy teaching: ghosts of the past, present and future”. In: *Medical education* 40.3 (2006), pp. 243–253 (cit. on p. 19).
- [310] J. C. McLachlan, J. Bligh, P. Bradley, and J. Searle. “Teaching anatomy without cadavers”. In: *Medical education* 38.4 (2004), pp. 418–424 (cit. on p. 2).
- [311] P. G. McMEnamin. “Body painting as a tool in clinical anatomy teaching”. In: *Anatomical sciences education* 1.4 (2008), pp. 139–144 (cit. on p. 2).
- [312] P. G. McMEnamin, M. R. Quayle, C. R. McHenry, and J. W. Adams. “The production of anatomical teaching resources using three-dimensional (3D) printing technology”. In: *Anatomical sciences education* 7.6 (2014), pp. 479–486 (cit. on p. 2).

- [313] P. McMenamin, J. McLachlan, A Wilson, et al. “Do we really need cadavers anymore to learn anatomy in undergraduate medicine?” In: *Medical teacher* 40.10 (2018), pp. 1020–1029 (cit. on p. 1).
- [314] D. Mehta, O. Sotnychenko, F. Mueller, et al. “Xnect: Real-time multi-person 3d human pose estimation with a single rgb camera”. In: *arXiv preprint arXiv:1907.00837* (2019) (cit. on p. 36).
- [315] S. Melchior-Bonnet and K. H. Jewett. *The mirror: A history*. Psychology Press, 2002 (cit. on p. 68).
- [316] M. Meng, P. Fallavollita, T. Blum, et al. “Kinect for interactive AR anatomy learning”. In: *2013 IEEE international symposium on mixed and augmented reality (ISMAR)*. IEEE. 2013, pp. 277–278 (cit. on pp. 46, 52, 53, 57, 59, 62, 80, 101, 158).
- [317] C. Michalski, M. Cowan, J. Bohinsky, R. Dickerson, B. James, and J. H. Plochocki. “Visualization of Heart Electrocardiographic Activity using a Mixed Reality System”. In: *The FASEB Journal* 33.1_supplement (2019), pp. 444–22 (cit. on p. 47).
- [318] K. Miles. “Diagnostic imaging in undergraduate medical education: an expanding role”. In: *Clinical radiology* 60.7 (2005), pp. 742–745 (cit. on pp. 2, 85).
- [319] P. Milgram and F. Kishino. “A taxonomy of mixed reality visual displays”. In: *IEICE TRANSACTIONS on Information and Systems* 77.12 (1994), pp. 1321–1329 (cit. on p. 23).
- [320] A. C. Miller. “Jundi-Shapur, bimaristans, and the rise of academic medical centres”. In: *Journal of the Royal Society of Medicine* 99.12 (2006), pp. 615–617 (cit. on p. 16).
- [321] K. E. Miller, M. Mims, D. E. Paull, et al. “Wrong-Side Thoracentesis”. In: *JAMA Surgery* 149.8 (Aug. 2014), pp. 774–6 (cit. on p. 69).
- [322] T. H. Mita, M. Dermer, and J. Knight. “Reversed facial images and the mere-exposure hypothesis.” In: *Journal of personality and social psychology* 35.8 (1977), p. 597 (cit. on p. 77).
- [323] D. Mogilev, K. Kiyokawa, M. Billinghamurst, and J. Pair. “Ar pad: An interface for face-to-face ar collaboration”. In: *CHI’02 extended abstracts on Human factors in computing systems*. 2002, pp. 654–655 (cit. on p. 38).
- [324] M. Mohring, C. Lessig, and O. Bimber. “Video see-through AR on consumer cell-phones”. In: *Third ieee and acm international symposium on mixed and augmented reality*. IEEE. 2004, pp. 252–253 (cit. on p. 25).
- [325] C. Moro, Z. Štromberga, A. Raikos, and A. Stirling. “The effectiveness of virtual and augmented reality in health sciences and medical anatomy”. In: *Anatomical sciences education* 10.6 (2017), pp. 549–559 (cit. on pp. 3, 43, 44, 124).
- [326] C. Moro, Z. Štromberga, and A. Stirling. “Virtualisation devices for student learning: Comparison between desktop-based (Oculus Rift) and mobile-based (Gear VR) virtual reality in medical and health science education”. In: *Australasian Journal of Educational Technology* 33.6 (2017) (cit. on p. 42).
- [327] B. J. Moxham and O. Plaisant. “The History of the Teaching of Gross Anatomy-How we got to where we are”. In: *Eur J Anat* 18.3 (2014), pp. 219–244 (cit. on pp. 8, 11, 12, 15–20).
- [328] B. Moxham and O. Plaisant. “Perception of medical students towards the clinical relevance of anatomy”. In: *Clinical Anatomy: The Official Journal of the American Association of Clinical Anatomists and the British Association of Clinical Anatomists* 20.5 (2007), pp. 560–564 (cit. on pp. 1, 20).
- [329] F. Mueller, F. Bernard, O. Sotnychenko, et al. “Ganerated hands for real-time 3d hand tracking from monocular rgb”. In: *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*. 2018, pp. 49–59 (cit. on p. 36).
- [330] F. Mueller, M. Davis, F. Bernard, et al. “Real-time pose and shape reconstruction of two interacting hands with a single depth camera”. In: *ACM Transactions on Graphics (TOG)* 38.4 (2019), pp. 1–13 (cit. on p. 36).

- [331] T. Murakami, Y. Tajika, H. Ueno, et al. “An integrated teaching method of gross anatomy and computed tomography radiology”. In: *Anatomical sciences education* 7.6 (2014), pp. 438–449 (cit. on pp. 2, 85).
- [332] C. Myers, L. Rabiner, and A. Rosenberg. “Performance tradeoffs in dynamic time warping algorithms for isolated word recognition”. In: *IEEE Transactions on Acoustics, Speech, and Signal Processing* 28.6 (1980), pp. 623–635 (cit. on p. 136).
- [333] D. M. Naeger, E. M. Webb, L. Zimmerman, and B. M. Elicker. “Strategies for incorporating radiology into early medical school curricula”. In: *Journal of the American College of Radiology* 11.1 (2014), pp. 74–79 (cit. on pp. 2, 85).
- [334] D. M. Naeger, M. Conrad, J. Nguyen, M. P. Kohi, and E. M. Webb. “Students teaching students: evaluation of a “near-peer” teaching experience”. In: *Academic radiology* 20.9 (2013), pp. 1177–1182 (cit. on p. 163).
- [335] N. Navab, A. Bani-Kashemi, and M. Mitschke. “Merging visible and invisible: Two camera-augmented mobile C-arm (CAMC) applications”. In: *Proceedings 2nd IEEE and ACM International Workshop on Augmented Reality (IWAR’99)*. IEEE. 1999, pp. 134–141 (cit. on p. 25).
- [336] A. J. Nelson, S. V. Nelson, A. M. Linn, L. E. Raw, H. B. Kildea, and A. L. Tonkin. “Tomorrow’s educators. . . today? Implementing near-peer teaching for medical students”. In: *Medical teacher* 35.2 (2013), pp. 156–159 (cit. on p. 163).
- [337] K. R. Nemet-Nejat. *Daily life in ancient Mesopotamia*. Greenwood Publishing Group, 1998 (cit. on p. 9).
- [338] F. H. Netter, J. SCOTT, et al. *Atlas d’anatomie humaine*. Elsevier Health Sciences, 2019 (cit. on p. 92).
- [339] T. Ni, A. K. Karlson, and D. Wigdor. “AnatOnMe: facilitating doctor-patient communication using a projection-based handheld device”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2011, pp. 3333–3342 (cit. on p. 33).
- [340] D. T. Nicholson, C. Chalk, W. R. J. Funnell, and S. J. Daniel. “Can virtual reality improve anatomy education? A randomised controlled study of a computer-generated three-dimensional anatomical ear model”. In: *Medical education* 40.11 (2006), pp. 1081–1087 (cit. on pp. 3, 41).
- [341] G. L. Nieder, D. X. Parmelee, A. Stolfi, and P. D. Hudes. “Team-based learning in a medical gross anatomy and embryology course”. In: *Clinical Anatomy: The Official Journal of the American Association of Clinical Anatomists and the British Association of Clinical Anatomists* 18.1 (2005), pp. 56–63 (cit. on p. 162).
- [342] J. Nnodim. “Learning human anatomy: by dissection or from prosections?” In: *Medical education* 24.4 (1990), pp. 389–395 (cit. on p. 2).
- [343] V. Novak, C. Sandor, and G. Klinker. “An AR workbench for experimenting with attentive user interfaces”. In: *Third IEEE and ACM International Symposium on Mixed and Augmented Reality*. IEEE. 2004, pp. 284–285 (cit. on p. 38).
- [344] J. F. Nunn. *Ancient egyptian medicine*. University of Oklahoma Press, 2002 (cit. on p. 9).
- [345] V. Nutton. *Ancient medicine*. Routledge, 2012 (cit. on p. 10).
- [346] V. Nutton. “From Galen to Alexander, aspects of medicine and medical practice in late antiquity”. In: *Dumbarton Oaks Papers* 38 (1984), pp. 1–14 (cit. on pp. 13, 14).
- [347] V. Nutton. “Galen in the eyes of his contemporaries”. In: *Bulletin of the History of Medicine* 58.3 (1984), pp. 315–324 (cit. on p. 13).
- [348] V. Nutton. “Museums and medical schools in Classical Antiquity”. In: *History of Education* 4.1 (1975), pp. 3–15 (cit. on p. 12).

- [349] V. Nutton. "The chronology of Galen's early career". In: *The Classical Quarterly* 23.1 (1973), pp. 158–171 (cit. on p. 13).
- [350] V. Nutton. "The fatal embrace: Galen and the history of ancient medicine". In: *Science in Context* 18.1 (2005), pp. 111–121 (cit. on p. 13).
- [351] S. H. Ofte and K. Hugdahl. "Rightleft Discrimination in Male and Female, Young and Old Subjects". In: *Journal of Clinical and Experimental Neuropsychology (Neuropsychology, Development and Cognition: Section A)* 24.1 (Feb. 2002), pp. 82–92 (cit. on p. 69).
- [352] J. Older. "Anatomy: a must for teaching the next generation". In: *The Surgeon* 2.2 (2004), pp. 79–90 (cit. on p. 3).
- [353] R. Olry. "Medieval neuroanatomy: the text of Mondino dei Luzzi and the plates of Guido da Vigevano". In: *Journal of the history of the neurosciences* 6.2 (1997), pp. 113–123 (cit. on p. 17).
- [354] A. M. Owen and P. Ward-Smith. "Collaborative learning in nursing simulation: near-peer teaching using standardized patients". In: *Journal of Nursing Education* 53.3 (2014), pp. 170–173 (cit. on p. 163).
- [355] F. G. Paas. "Training strategies for attaining transfer of problem-solving skill in statistics: A cognitive-load approach." In: *Journal of educational psychology* 84.4 (1992), p. 429 (cit. on pp. 118, 120, 125, 142, 149).
- [356] D. Paech, F. L. Giesel, R. Unterhinninghofen, H.-P. Schlemmer, T. Kuner, and S. Doll. "Cadaver-specific CT scans visualized at the dissection table combined with virtual dissection tables improve learning performance in general gross anatomy". In: *European radiology* 27.5 (2017), pp. 2153–2160 (cit. on pp. 85, 100).
- [357] D. Paech, K. Klopries, S. Doll, et al. "Contrast-enhanced cadaver-specific computed tomography in gross anatomy teaching". In: *European radiology* 28.7 (2018), pp. 2838–2844 (cit. on pp. 85, 100).
- [358] V. Papa, E. Varotto, M. Vaccarezza, R. Ballestriero, D. Tafuri, F. M. Galassi, et al. "The teaching of anatomy throughout the centuries: from Herophilus to plastination and beyond". In: *Medicina* 3.2 (2019), pp. 69–77 (cit. on p. 19).
- [359] L. M. Parker. "Anatomical dissection: why are we cutting it out? Dissection in undergraduate teaching". In: *ANZ journal of surgery* 72.12 (2002), pp. 910–912 (cit. on p. 1).
- [360] L. M. Parker. "What's wrong with the dead body?" In: *Medical journal of Australia* 176.2 (2002), pp. 74–76 (cit. on p. 1).
- [361] N. Pather. "Teaching anatomy: prosections and dissections". In: *Teaching Anatomy*. Springer, 2015, pp. 213–221 (cit. on p. 2).
- [362] F Paulsen, J Waschke, and A. d.A.d. M. Sobotta. *Band 1: Allgemeine Anatomie und Bewegungsapparat*. 2010 (cit. on pp. 92, 117).
- [363] W. Pawlina and N. Lachman. "Dissection in learning and teaching gross anatomy: rebuttal to McLachlan". In: *The Anatomical Record Part B: The New Anatomist: An Official Publication of the American Association of Anatomists* 281.1 (2004), pp. 9–11 (cit. on p. 2).
- [364] M. Pendergrast. *Mirror mirror: a history of the human love affair with reflection*. Basic Books, 2009 (cit. on p. 68).
- [365] T. V. N. Persaud. *Early history of human anatomy: from antiquity to the beginning of the modern era*. Thomas Springfield, IL: 1984 (cit. on pp. 8, 16).
- [366] M. Petovello and P Dabove. "What are the actual performances of GNSS positioning using smartphone technology?" In: *InsideGNSS* 9 (2014), pp. 34–37 (cit. on p. 27).

- [367] A. W. Phillips, S. G. Smith, C. F. Ross, and C. M. Straus. “Improved understanding of human anatomy through self-guided radiological anatomy modules”. In: *Academic radiology* 19.7 (2012), pp. 902–907 (cit. on pp. 2, 85).
- [368] A. W. Phillips, H. Eason, and C. M. Straus. “Student and recent graduate perspectives on radiological imaging instruction during basic anatomy courses”. In: *Anatomical sciences education* 11.1 (2018), pp. 25–31 (cit. on pp. 85, 86, 99, 124).
- [369] D. N. E. Phon, M. B. Ali, and N. D. A. Halim. “Collaborative augmented reality in education: A review”. In: *2014 International Conference on Teaching and Learning in Computing and Engineering*. IEEE. 2014, pp. 78–83 (cit. on pp. 37, 125, 163).
- [370] C. Pinhanez. “The everywhere displays projector: A device to create ubiquitous graphical interfaces”. In: *International conference on ubiquitous computing*. Springer. 2001, pp. 315–331 (cit. on p. 35).
- [371] T. Piumsomboon, Y. Lee, G. Lee, and M. Billinghamurst. “CoVAR: a collaborative virtual and augmented reality system for remote collaboration”. In: *SIGGRAPH Asia 2017 Emerging Technologies*. 2017, pp. 1–2 (cit. on p. 38).
- [372] T. Piumsomboon, D. Altimira, H. Kim, A. Clark, G. Lee, and M. Billinghamurst. “Grasp-Shell vs gesture-speech: A comparison of direct and indirect natural interaction techniques in augmented reality”. In: *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE. 2014, pp. 73–82 (cit. on p. 40).
- [373] T. Piumsomboon, A. Dey, B. Ens, G. Lee, and M. Billinghamurst. “The effects of sharing awareness cues in collaborative mixed reality”. In: *Frontiers in Robotics and AI* 6.5 (2019), p. 02 (cit. on p. 38).
- [374] C. Plaisant, D. Carr, and B. Shneiderman. “Image-Browser Taxonomy and Guidelines for Designers”. In: *IEEE Softw.* 12.2 (Mar. 1995), pp. 21–32 (cit. on p. 134).
- [375] D. Pohlandt, B. Preim, and P. Saalfeld. “Supporting Anatomy Education with a 3D Puzzle in a Virtual Reality Environment”. In: *Mensch und Computer 2019-Tagungsband* (2019) (cit. on pp. 42, 43).
- [376] T. Poston and L. Serra. “The virtual workbench: dextrous VR”. In: *Virtual reality software and technology*. World Scientific. 1994, pp. 111–121 (cit. on p. 33).
- [377] I. Poupyrev, D. S. Tan, M. Billinghamurst, H. Kato, H. Regenbrecht, and N. Tetsutani. “Tiles: A Mixed Reality Authoring Interface.” In: *Interact.* Vol. 1. 2001, pp. 334–341 (cit. on p. 35).
- [378] D. Preece, S. B. Williams, R. Lam, and R. Weller. ““Let’s get physical”: advantages of a physical model over 3D computer models and textbooks in learning imaging anatomy”. In: *Anatomical sciences education* 6.4 (2013), pp. 216–224 (cit. on p. 2).
- [379] B. Preim and P. Saalfeld. “A survey of virtual human anatomy education systems”. In: *Computers & Graphics* 71 (2018), pp. 132–153 (cit. on p. 41).
- [380] P. Pioreschi. *A History of Medicine: Greek Medicine*. Horatius Press, Omaha, 1996 (cit. on p. 10).
- [381] M. L. A. Puccetti, L. Perugi, and P. Scarani. “Gaetano Giulio Zumbo: The founder of anatomic wax modeling”. In: *Pathology annual* 30 (1995), p. 269 (cit. on p. 19).
- [382] R. Raskar, J. Van Baar, P. Beardsley, T. Willwacher, S. Rao, and C. Forlines. “iLamps: geometrically aware and self-configuring projectors”. In: *ACM SIGGRAPH 2006 Courses*. 2006, 7–es (cit. on p. 33).
- [383] R. Raskar, G. Welch, K.-L. Low, and D. Bandyopadhyay. “Shader lamps: Animating real objects with image-based illumination”. In: *Rendering Techniques 2001*. Springer, 2001, pp. 89–102 (cit. on p. 33).
- [384] J. Reinartz. “Towards a history of medical education in provincial England”. In: *History* 43.3 (2001), pp. 33–53 (cit. on p. 19).

- [385] J. Rekimoto and K. Nagao. "The world through the computer: Computer augmented interaction with real world environments". In: *Proceedings of the 8th annual ACM symposium on User interface and software technology*. 1995, pp. 29–36 (cit. on p. 25).
- [386] S. S. Rengachary, C. Colen, K. Dass, and M. Guthikonda. "Development of anatomic science in the late middle ages: the roles played by Mondino de Liuzzi and Guido da Vigevano". In: *Neurosurgery* 65.4 (2009), pp. 787–794 (cit. on pp. 16, 17).
- [387] P. Renner and T. Pfeiffer. "Attention Guiding Techniques using Peripheral Vision and Eye Tracking for Feedback in Augmented-Reality-based Assistance Systems". In: *2017 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 2017 (cit. on p. 135).
- [388] F. Retief and L. Cilliers. "Mesopotamian medicine". In: *South African Medical Journal* 97.1 (2007), pp. 27–29 (cit. on p. 9).
- [389] D. Ribatti. "William Harvey and the discovery of the circulation of the blood". In: *Journal of angiogenesis research* 1.1 (2009), p. 3 (cit. on p. 18).
- [390] L. J. Rizzolo and W. B. Stewart. "Should we continue teaching anatomy by dissection when...?" In: *The Anatomical Record Part B: The New Anatomist: An Official Publication of the American Association of Anatomists* 289.6 (2006), pp. 215–218 (cit. on pp. 20, 100).
- [391] L. J. Rizzolo, W. C. Rando, M. K. O'Brien, A. H. Haims, J. J. Abrahams, and W. B. Stewart. "Design, implementation, and evaluation of an innovative anatomy course". In: *Anatomical sciences education* 3.3 (2010), pp. 109–120 (cit. on p. 20).
- [392] C. Rodriguez-Pardo, S. Hernandez, M. Á. Patricio, A. Berlanga, and J. M. Molina. "An augmented reality application for learning anatomy". In: *International Work-Conference on the Interplay Between Natural and Artificial Computation*. Springer. 2015, pp. 359–368 (cit. on p. 44).
- [393] L. Rosner. *The anatomy murders: being the true and spectacular history of Edinburgh's notorious Burke and Hare and of the man of science who abetted them in the commission of their most heinous crimes*. University of Pennsylvania Press, 2010 (cit. on p. 18).
- [394] L. Rozenblit and F. Keil. "The misunderstood limits of folk science: An illusion of explanatory depth". In: *Cog. science* 26.5 (2002), pp. 521–562 (cit. on p. 68).
- [395] J. Ruiz and D. Vogel. "Soft-constraints to reduce legacy and performance bias to elicit whole-body gestures with low arm fatigue". In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2015, pp. 3347–3350 (cit. on p. 160).
- [396] J. G. Ruiz, D. A. Cook, and A. J. Levinson. "Computer animations in medical education: a critical literature review". In: *Medical education* 43.9 (2009), pp. 838–846 (cit. on p. 2).
- [397] D. Saakes, H.-S. Yeo, S.-T. Noh, G. Han, and W. Woo. "Mirror mirror: An on-body t-shirt design system". In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 2016, pp. 6058–6063 (cit. on p. 33).
- [398] A. Saber. "Ancient Egyptian surgical heritage". In: *Journal of Investigative Surgery* 23.6 (2010), pp. 327–334 (cit. on p. 9).
- [399] M. Saenz, J. Strunk, K. Maset, J. H. Seo, and E. Malone. "FlexAR: anatomy education through kinetic tangible augmented reality". In: *ACM SIGGRAPH 2015 Posters*. 2015, pp. 1–1 (cit. on p. 46).
- [400] A. Saha, R. A. Roland, M. S. Hartman, and R. H. Daffner. "Radiology Medical Student Education: An Outcome-based Survey of PGY-1 Residents". In: *Academic Radiology* 20.3 (2013). Education Issue, pp. 284–289 (cit. on p. 2).
- [401] A. Salajegheh, A. Jahangiri, E. Dolan-Evans, and S. Pakneshan. "A combination of traditional learning and e-learning can be more effective on radiological interpretation skills in medical students: a pre-and post-intervention study". In: *BMC medical education* 16.1 (2016), p. 46 (cit. on p. 85).

- [402] H. Sallam. “The ancient Alexandria school of medicine”. In: *Gynecologie, obstetrique & fertilitate* 30.1 (2002), pp. 3–10 (cit. on p. 12).
- [403] C. Sandor, A. Cunningham, A. Dey, and V.-V. Mattila. “An augmented reality x-ray system based on visual saliency”. In: *2010 IEEE International Symposium on Mixed and Augmented Reality*. IEEE, 2010, pp. 27–36 (cit. on p. 39).
- [404] M. Sato, I. Poupyrev, and C. Harrison. “Touché: enhancing touch interaction on humans, screens, liquids, and everyday objects”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2012, pp. 483–492 (cit. on p. 35).
- [405] J. B.d.C. M. Saunders. *The transitions from ancient Egyptian to Greek medicine*. University of Kansas Press, 1963 (cit. on p. 12).
- [406] E. Savage-Smith. “Attitudes toward dissection in medieval Islam”. In: *Journal of the History of Medicine and Allied Sciences* 50.1 (1995), pp. 67–110 (cit. on p. 15).
- [407] G. Schall, E. Mendez, E. Kruijff, et al. “Handheld augmented reality for underground infrastructure visualization”. In: *Personal and ubiquitous computing* 13.4 (2009), pp. 281–291 (cit. on p. 27).
- [408] T. Schinke, N. Henze, and S. Boll. “Visualization of Off-screen Objects in Mobile Augmented Reality”. In: *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services*. MobileHCI ’10. Lisbon, Portugal: ACM, 2010, pp. 313–316 (cit. on pp. 135, 137).
- [409] D. Schmalstieg and T. Hollerer. *Augmented reality: principles and practice*. Addison-Wesley Professional, 2016 (cit. on pp. 22, 26, 28, 29, 35).
- [410] D. Schmalstieg, A. Fuhrmann, and G. Hesina. “Bridging multiple user interface dimensions with augmented reality”. In: *Proceedings IEEE and ACM International Symposium on Augmented Reality (ISAR 2000)*. IEEE, 2000, pp. 20–29 (cit. on p. 35).
- [411] D. Schmalstieg, A. Fuhrmann, Z. Szalavari, and M. Gervautz. “Studierstube—an environment for collaboration in augmented reality”. In: *CVE’96 Workshop Proceedings*. Vol. 19. 1996 (cit. on p. 25).
- [412] B. Schwerdtfeger and G. Klinker. “Supporting order picking with augmented reality”. In: *2008 7th IEEE/ACM International Symposium on Mixed and Augmented Reality*. IEEE, 2008, pp. 91–94 (cit. on p. 40).
- [413] S. C. Seiden. “Wrong-Side/Wrong-Site, Wrong-Procedure, and Wrong-Patient Adverse Events”. In: *Archives of Surgery* 141.9 (Sept. 2006), pp. 931–9 (cit. on p. 69).
- [414] S. A. Seixas-Mikelus, A. Adal, T. Kesavadas, et al. “Can image-based virtual reality help teach anatomy?” In: *Journal of endourology* 24.4 (2010), pp. 629–634 (cit. on p. 41).
- [415] J. H. Seo, B. M. Smith, M. Cook, et al. “Anatomy builder VR: Applying a constructive learning method in the virtual reality canine skeletal system”. In: *International Conference on Applied Human Factors and Ergonomics*. Springer, 2017, pp. 245–252 (cit. on p. 42).
- [416] J. H. Seo, B. M. Smith, M. Bruner, et al. “Muscle action VR: to support embodied learning foundations of biomechanics in musculoskeletal system”. In: *SIGGRAPH Asia 2018 Virtual & Augmented Reality*. 2018, pp. 1–2 (cit. on pp. 42, 43).
- [417] I. Serageldin. “Ancient Alexandria and the dawn of medical science”. In: *Global cardiology science & practice* 2013.4 (2013), p. 395 (cit. on p. 12).
- [418] N. J. Shanks and D. Al-Kalai. “Arabian medicine in the middle ages.” In: *Journal of the Royal Society of Medicine* 77.1 (1984), p. 60 (cit. on p. 16).
- [419] A. H. Sheikh, D. S. Barry, H. Gutierrez, J. F. Cryan, and G. W. O’Keeffe. “Cadaveric anatomy in the future of medical education: What is the surgeons view?” In: *Anatomical sciences education* 9.2 (2016), pp. 203–208 (cit. on pp. 2, 85).

- [420] R. N. Shepard and J. Metzler. "Mental rotation of three-dimensional objects". In: *Science* 171.3972 (1971), pp. 701–703 (cit. on pp. 72, 92, 115).
- [421] M. M. Shoja and R. S. Tubbs. "The history of anatomy in Persia". In: *Journal of anatomy* 210.4 (2007), pp. 359–378 (cit. on pp. 15, 16).
- [422] H. Si-Mohammed, F. A. Sanz, G. Casiez, N. Roussel, and A. Lécuyer. "Brain-computer interfaces and augmented reality: A state of the art". In: 2017 (cit. on p. 37).
- [423] S. Siddhpuria, K. Katsuragawa, J. R. Wallace, and E. Lank. "Exploring At-Your-Side Gestural Interaction for Ubiquitous Environments". In: *Proceedings of the 2017 Conference on Designing Interactive Systems*. 2017, pp. 1111–1122 (cit. on p. 160).
- [424] T. Sielhorst, C. Bichlmeier, S. M. Heining, and N. Navab. "Depth perception—a major issue in medical AR: evaluation study by twenty surgeons". In: *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer. 2006, pp. 364–372 (cit. on p. 39).
- [425] H. E. Sigerist. *A history of medicine: Early Greek, Hindu, and Persian medicine*. Vol. 2. Oxford University Press, 1987 (cit. on p. 10).
- [426] M. M. da Silva, J. M. X. Teixeira, P. S. Cavalcante, and V. Teichrieb. "Perspectives on how to evaluate augmented reality technology tools for education: a systematic review". In: *Journal of the Brazilian Computer Society* 25.1 (2019), p. 3 (cit. on pp. 39–41).
- [427] V. Singh and P. Kharb. "A paradigm shift from teaching to learning gross anatomy: meta-analysis of implications for instructional methods". In: *Journal of the Anatomical Society of India* 62.1 (2013), pp. 84–89 (cit. on pp. 85, 99, 124).
- [428] N. G. Siraisi. *Medieval and early Renaissance medicine: an introduction to knowledge and practice*. University of Chicago Press, 2009 (cit. on pp. 14, 15).
- [429] T. Siu and V. Herskovic. "SidebARs: Improving Awareness of Off-screen Elements in Mobile Augmented Reality". In: *Proceedings of the 2013 Chilean Conference on Human - Computer Interaction*. ChileCHI '13. Temuco, Chile: ACM, 2013, pp. 36–41 (cit. on pp. 134, 137).
- [430] W. D. Smith. "Galen on Coans versus Cnidians". In: *Bulletin of the History of Medicine* 47.6 (1973), pp. 569–585 (cit. on p. 11).
- [431] K. Sriharan. "The rise and fall of anatomy". In: *BMJ* 331.Suppl S3 (2005), p. 0509332 (cit. on p. 3).
- [432] C. Stapleton, C. Hughes, and J. M. Moshell. "Mixed reality and the interactive imagination". In: *Proceedings of the First Swedish-American Workshop on Modeling and Simulation*. 2002, pp. 30–31 (cit. on p. 24).
- [433] C. Stapleton and J. Davies. "Imagination: The third reality to the virtuality continuum". In: *2011 IEEE International Symposium on Mixed and Augmented Reality-Arts, Media, and Humanities*. IEEE. 2011, pp. 53–60 (cit. on p. 24).
- [434] C. Stapleton, C. Hughes, M. Moshell, P. Micikevicius, and M. Altman. "Applying mixed reality to entertainment". In: *Computer* 35.12 (2002), pp. 122–124 (cit. on p. 24).
- [435] A. State, D. T. Chen, C. Tector, et al. "Observing a volume rendered fetus within a pregnant patient". In: *Proceedings Visualization'94*. IEEE. 1994, pp. 364–368 (cit. on p. 25).
- [436] P. Stefan, P. Wucherer, Y. Oyamada, et al. "An AR edutainment system supporting bone anatomy learning". In: *2014 IEEE Virtual Reality (VR)*. IEEE. 2014, pp. 113–114 (cit. on p. 46).
- [437] R. M. Stelmack and A. Stalikas. "Galen and the humour theory of temperament". In: *Personality and Individual Differences* 12.3 (1991), pp. 255–263 (cit. on p. 13).
- [438] K. Stepan, J. Zeiger, S. Hanchuk, et al. "Immersive virtual reality as a teaching tool for neuroanatomy". In: *International forum of allergy & rhinology*. Vol. 7. 10. Wiley Online Library. 2017, pp. 1006–1013 (cit. on p. 43).

- [439] G. Stetten, V. Chib, D. Hildebrand, and J. Bursee. “Real time tomographic reflection: Phantoms for calibration and biopsy”. In: *Proceedings IEEE and ACM International Symposium on Augmented Reality*. IEEE. 2001, pp. 11–19 (cit. on p. 32).
- [440] M Stojanovska, G Tingle, L Tan, et al. “Mixed reality anatomy using Microsoft HoloLens and cadaveric dissection: a comparative effectiveness study”. In: *Medical Science Educator* (2019), pp. 1–6 (cit. on p. 48).
- [441] M. D. STORFER. “PROBLEMS IN LEFT-RIGHT DISCRIMINATION IN A HIGH-IQ POPULATION”. In: *Perceptual and Motor Skills* 81.2 (Oct. 1995), pp. 491–497 (cit. on p. 69).
- [442] C. M. Straus, E. M. Webb, K. L. Kondo, et al. “Medical student radiology education: summary and recommendations from a national survey of medical school and radiology department leadership”. In: *Journal of the American College of Radiology* 11.6 (2014), pp. 606–610 (cit. on p. 2).
- [443] B. Subbarayappa and B. Subbarayappa. “The roots of ancient medicine: an historical outline”. In: *Journal of Biosciences* 26.02 (2001) (cit. on p. 8).
- [444] K. Sudhoff. “Konstantin der Afrikaner und die Medizinschule von Salerno”. In: *Sudhoffs Archiv für Geschichte der Medizin* H. 4 (1930), pp. 293–298 (cit. on p. 16).
- [445] K. Sugand, P. Abrahams, and A. Khurana. “The anatomy of anatomy: a review for its modernization”. In: *Anatomical sciences education* 3.2 (2010), pp. 83–93 (cit. on pp. 1–3, 20, 85, 99, 124).
- [446] M. Sukan, C. Elvezio, O. Oda, S. Feiner, and B. Tversky. “ParaFrustum: Visualization Techniques for Guiding a User to a Constrained Set of Viewing Positions and Orientations”. In: *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*. UIST ’14. Honolulu, Hawaii, USA: ACM, 2014, pp. 331–340 (cit. on p. 135).
- [447] I. E. Sutherland. “A head-mounted three dimensional display”. In: *Proceedings of the December 9-11, 1968, fall joint computer conference, part I*. 1968, pp. 757–764 (cit. on pp. 25, 27).
- [448] I. E. Sutherland and G. W. Hodgman. “Reentrant polygon clipping”. In: *Communications of the ACM* 17.1 (1974), pp. 32–42 (cit. on p. 140).
- [449] J. E. Swan and J. L. Gabbard. “Survey of user-based experimentation in augmented reality”. In: *Proceedings of 1st International Conference on Virtual Reality*. Vol. 22. 2005, pp. 1–9 (cit. on pp. 39, 40).
- [450] J. E. Swan, A. Jones, E. Kolstad, M. A. Livingston, and H. S. Smallman. “Egocentric depth judgments in optical, see-through augmented reality”. In: *IEEE transactions on visualization and computer graphics* 13.3 (2007), pp. 429–442 (cit. on p. 40).
- [451] K. Sweeney, J. A. Hayes, and N. Chiavaroli. “Does spatial ability help the learning of anatomy in a biomedical science course?” In: *Anatomical sciences education* 7.4 (2014), pp. 289–294 (cit. on pp. 100, 160).
- [452] Z. Szalavári and M. Gervautz. “The personal interaction Panel—a Two-Handed interface for augmented reality”. In: *Computer graphics forum*. Vol. 16. 3. Wiley Online Library. 1997, pp. C335–C346 (cit. on p. 40).
- [453] Y. Takano. “Mirror reversal of slanted objects: A psycho-optic explanation”. In: *Philosophical Psychology* 28.2 (2015), pp. 240–259 (cit. on p. 69).
- [454] Y. Takano. “Why does a mirror image look left-right reversed? A hypothesis of multiple processes”. In: *Psychonomic bulletin & review* 5.1 (1998), pp. 37–55 (cit. on p. 69).
- [455] D. J. Tan, N. Navab, and F. Tombari. “Looking beyond the simple scenarios: Combining learners and optimizers in 3d temporal tracking”. In: *IEEE transactions on visualization and computer graphics* 23.11 (2017), pp. 2399–2409 (cit. on p. 39).
- [456] E. K. Teall. “Medicine and doctoring in ancient mesopotamia”. In: *Grand Valley Journal of History* 3.1 (2014), pp. 1–8 (cit. on p. 9).

- [457] B. Thomas, V. Demczuk, W. Piekarski, D. Hepworth, and B. Gunther. "A wearable computer system with augmented reality to support terrestrial navigation". In: *Digest of Papers. Second International Symposium on Wearable Computers (Cat. No. 98EX215)*. IEEE. 1998, pp. 168–171 (cit. on p. 27).
- [458] M. S. Thomas, S. Kini, and K. Mala. "Factors affecting the right and left discrimination ability among dental students". In: *Journal of Education and Ethics in Dentistry* 3.2 (2013), pp. 66–5 (cit. on p. 70).
- [459] P. Thomas and W. David. "Augmented reality: An application of heads-up display technology to manual manufacturing processes". In: *Hawaii International Conference on System Sciences*. 1992, pp. 659–669 (cit. on pp. 25, 27).
- [460] R. G. Thomas, N. William John, and J. M. Delieu. "Augmented reality for anatomical education". In: *Journal of visual communication in medicine* 33.1 (2010), pp. 6–15 (cit. on p. 45).
- [461] S. Tibi. "Al-Razi and Islamic medicine in the 9th century". In: *Journal of the Royal Society of Medicine* 99.4 (2006), pp. 206–207 (cit. on p. 15).
- [462] B. Tillmann. *Atlas der Anatomie des Menschen: mit Muskeltrainer*. Springer-Verlag, 2006 (cit. on p. 117).
- [463] L. H. Toledo-Pereyra. "Galen's contribution to surgery". In: *Journal of the history of medicine and allied sciences* 28.4 (1973), pp. 357–375 (cit. on p. 13).
- [464] K. S. Topp. "Prosection vs. dissection, the debate continues: rebuttal to Granger". In: *The Anatomical Record Part B: The New Anatomist* 281.1 (2004), pp. 12–14 (cit. on p. 2).
- [465] M. Trapp, L. Schneider, C. Lehmann, N. Holz, and J. Döllner. "Strategies for visualising 3D points-of-interest on mobile devices". In: *Journal of Location Based Services* 5.2 (2011), pp. 79–99 (cit. on p. 134).
- [466] C. Triepels, D. Koppes, S. Van Kuijk, et al. "Medical students' perspective on training in anatomy". In: *Annals of Anatomy-Anatomischer Anzeiger* 217 (2018), pp. 60–65 (cit. on p. 124).
- [467] J. Tsafirir and A. Ohry. "Medical illustration: from caves to cyberspace". In: *Health Information & Libraries Journal* 18.2 (2001), pp. 99–109 (cit. on p. 8).
- [468] D. W. Tschanz et al. "Arab roots of European medicine". In: *Heart Views* 4.2 (2003), p. 9 (cit. on p. 16).
- [469] B. W. Turney. "Anatomy in a modern medical curriculum". In: *The Annals of The Royal College of Surgeons of England* 89.2 (2007), pp. 104–107 (cit. on pp. 2, 3, 19, 20).
- [470] R. Vaillant, L. Barthe, G. Guennebaud, et al. "Implicit skinning: real-time skin deformation with contact modeling". In: *ACM Transactions on Graphics (TOG)* 32.4 (2013), pp. 1–12 (cit. on p. 66).
- [471] N. S. Vasan, D. O. DeFouw, and S. Compton. "A survey of student perceptions of team-based learning in anatomy curriculum: Favorable views unrelated to grades". In: *Anatomical sciences education* 2.4 (2009), pp. 150–155 (cit. on p. 162).
- [472] N. S. Vasan, D. O. DeFouw, and S. Compton. "Team-based learning in anatomy: An efficient, effective, and economical strategy". In: *Anatomical sciences education* 4.6 (2011), pp. 333–339 (cit. on p. 162).
- [473] I. Veith. *The yellow emperor's classic of internal medicine*. Univ of California Press, 2015 (cit. on p. 9).
- [474] M. Vlachos, G. Kollios, and D. Gunopulos. "Discovering similar multidimensional trajectories". In: *Data Engineering, 2002. Proceedings. 18th International Conference on*. IEEE. 2002, pp. 673–684 (cit. on p. 136).

- [475] U Von Jan, C Noll, M Behrends, and U.-V. Albrecht. “mARble–augmented reality in medical education”. In: *Biomedical Engineering/Biomedizinische Technik* 57.SI-1 Track-A (2012), pp. 67–70 (cit. on p. 44).
- [476] H. Von Staden. “Anatomy as rhetoric: Galen on dissection and persuasion”. In: *Journal of the history of medicine and allied sciences* 50.1 (1995), pp. 47–66 (cit. on p. 13).
- [477] H. Von Staden. “The discovery of the body: human dissection and its cultural contexts in ancient Greece.” In: *The Yale Journal of Biology and Medicine* 65.3 (1992), p. 223 (cit. on p. 12).
- [478] H. Von Staden, H. Chalcedonius, et al. *Herophilus: the art of medicine in early Alexandria: edition, translation and essays*. Cambridge University Press, 1989 (cit. on p. 12).
- [479] M. A. Vorstenbosch, T. P. Klaassen, J. G. Kooloos, S. M. Bolhuis, and R. F. Laan. “Do images influence assessment in anatomy? Exploring the effect of images on item difficulty and item discrimination”. In: *Anatomical Sciences Education* 6.1 (2013), pp. 29–41 (cit. on pp. 100, 124, 160).
- [480] D. Wagner and D. Schmalstieg. “First steps towards handheld augmented reality”. In: *Seventh IEEE International Symposium on Wearable Computers, 2003. Proceedings*. IEEE. 2003, pp. 127–135 (cit. on p. 25).
- [481] B. Wainman, G. Pukas, L. Wolak, S. Mohanraj, J. Lamb, and G. R. Norman. “The Critical Role of Stereopsis in Virtual and Mixed Reality Learning Environments”. In: *Anatomical sciences education* (2019) (cit. on pp. 123, 126).
- [482] K. G. Wakim. “Arabic medicine in literature”. In: *Bulletin of the Medical Library Association* 32.1 (1944), p. 96 (cit. on pp. 15, 16).
- [483] M. Walker, H. Hedayati, J. Lee, and D. Szafir. “Communicating Robot Motion Intent with Augmented Reality”. In: *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*. ACM. 2018, pp. 316–324 (cit. on p. 151).
- [484] H. Wang, H. Su, K. Zheng, S. Sadiq, and X. Zhou. “An effectiveness study on trajectory similarity measures”. In: *Proceedings of the Twenty-Fourth Australasian Database Conference-Volume 137*. Australian Computer Society, Inc. 2013, pp. 13–22 (cit. on p. 136).
- [485] P. Wang, S. Zhang, X. Bai, et al. “Head Pointer or Eye Gaze: Which Helps More in MR Remote Collaboration?” In: *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE. 2019, pp. 1219–1220 (cit. on p. 38).
- [486] Y. Wang, Y. Zhou, W. Shen, S. Park, E. K. Fishman, and A. L. Yuille. “Abdominal multi-organ segmentation with organ-attention networks and statistical fusion”. In: *Medical image analysis* 55 (2019), pp. 88–102 (cit. on p. 164).
- [487] R. Wareham and J. Lasenby. “Bone glow: An improved method for the assignment of weights for mesh deformation”. In: *International Conference on Articulated Motion and Deformable Objects*. Springer. 2008, pp. 63–71 (cit. on p. 65).
- [488] W. Watson. *Non-reversing mirror device with perceived depth perspective*. US Patent 4,580,880. 1986 (cit. on p. 69).
- [489] K. Weiler and P. Atherton. “Hidden surface removal using polygon area sorting”. In: *ACM SIGGRAPH computer graphics*. Vol. 11. 2. ACM. 1977, pp. 214–222 (cit. on p. 140).
- [490] D. Wenig, J. Schöning, A. Olwal, M. Oben, and R. Malaka. “WatchThru: Expanding Smartwatch Displays with Mid-air Visuals and Wrist-worn Augmented Reality”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 2017, pp. 716–721 (cit. on p. 32).
- [491] J. Westwood et al. “Gunner Goggles: implementing augmented reality into medical education”. In: *Medicine Meets Virtual Reality 22: NextMed/MMVR22* 220 (2016), p. 446 (cit. on p. 44).

- [492] E. Whitmire, F. Salemi Parizi, and S. Patel. "Aura: Inside-out electromagnetic controller tracking". In: *Proceedings of the 17th Annual International Conference on Mobile Systems, Applications, and Services*. 2019, pp. 300–312 (cit. on p. 27).
- [493] E. Williams. "Experimental designs balanced for the estimation of residual effects of treatments". In: *Australian Journal of Chemistry* 2.2 (1949), pp. 149–168 (cit. on pp. 74, 143).
- [494] J. S. Wilson, J. Alvarez, B. C. Davis, and A. J. Duerinckx. "Cost-effective teaching of radiology with preclinical anatomy". In: *Anatomical sciences education* 11.2 (2018), pp. 196–206 (cit. on p. 85).
- [495] L. L. Wiltse and T. G. Pait. "Herophilus of Alexandria (325-255 BC): The father of anatomy". In: *Spine* 23.17 (1998), pp. 1904–1914 (cit. on p. 12).
- [496] A. Winkelmann, S. Hendrix, and C. Kiessling. "What do students actually do during a dissection course? First steps towards understanding a complex learning experience". In: *Academic Medicine* 82.10 (2007), pp. 989–995 (cit. on p. 1).
- [497] S. M. Wolf. "Difficulties in right-left discrimination in a normal population". In: *Archives of Neurology* 29.2 (1973), pp. 128–129 (cit. on p. 69).
- [498] K. C. Wong, L.-t. Wu, et al. "History of Chinese Medicine. Being a Chronicle of Medical Happenings in China from Ancient Times to the Present Period." In: *History of Chinese Medicine. Being a Chronicle of Medical Happenings in China from Ancient Times to the Present Period*. (1932) (cit. on p. 9).
- [499] H.-K. Wu, S. W.-Y. Lee, H.-Y. Chang, and J.-C. Liang. "Current status, opportunities and challenges of augmented reality in education". In: *Computers & education* 62 (2013), pp. 41–49 (cit. on p. 100).
- [500] V. L. Yeager. "Learning gross anatomy: dissection and prosection". In: *Clinical Anatomy: The Official Journal of the American Association of Clinical Anatomists and the British Association of Clinical Anatomists* 9.1 (1996), pp. 57–59 (cit. on p. 2).
- [501] S.-j. Yeom. "Augmented reality for learning anatomy". In: *Changing Demands, Changing Directions. Proceedings ascilite Hobart* (2011), pp. 1377–1383 (cit. on p. 46).
- [502] K. Yu, R. Barmaki, M. Unberath, et al. "On the accuracy of low-cost motion capture systems for range of motion measurements". In: *Medical Imaging 2018: Imaging Informatics for Healthcare, Research, and Applications*. Vol. 10579. International Society for Optics and Photonics. 2018, 105790G (cit. on p. 161).
- [503] S. C.-Y. Yuen, G. Yaoyuneyong, and E. Johnson. "Augmented reality: An overview and five directions for AR in education". In: *Journal of Educational Technology Development and Exchange (JETDE)* 4.1 (2011), p. 11 (cit. on pp. 125, 163).
- [504] S. Zafar and J. Zachar. "Evaluation of augmented reality application for learning dental anatomy as a novel educational tool". In: *European Journal of Dental Education* (2020) (cit. on p. 48).
- [505] L. Zhang, T. Luczak, E. Smith, R. F. Burch, et al. "Using Microsoft HoloLens to improve memory recall in anatomy and physiology: A pilot study to examine the efficacy of using augmented reality in education". In: *Journal of Educational Technology Development and Exchange (JETDE)* 12.1 (2019), p. 2 (cit. on p. 48).
- [506] E. R. Zorzal, M. Sousa, D. Mendes, et al. "Anatomy studio: A tool for virtual dissection through augmented 3D reconstruction". In: *Computers & Graphics* 85 (2019), pp. 74–84 (cit. on p. 48).
- [507] K. G. Zysk. "The evolution of anatomical knowledge in ancient India, with special reference to cross-cultural influences". In: *Journal of the American Oriental Society* (1986), pp. 687–705 (cit. on p. 8).

Online Resources

- [508] D. AG. *DocCheck Flexicon - Liver*. URL: <https://flexikon.doccheck.com/en/Liver> (visited on Apr. 23, 2020) (cit. on pp. 107, 108).
- [509] E. Chudler. *Right-Left Confusion? Online*: <https://faculty.washington.edu/chudler/java/hands1.html> (accessed: 2017-03-03) (cit. on p. 73).
- [510] K. Gutttag. *Saying "Moore's Law or Apple" Does Not Make AR a Consumer Product*. 2019. URL: <https://www.kgutttag.com/2019/10/24/saying-moores-law-or-apple-does-not-make-ar-a-consumer-product/> (visited on May 7, 2020) (cit. on pp. 132, 164).
- [511] B. Lander, C. Johnson-Grau, and C. Roche. *Teaching and Learning Anatomy: a 500 Year History*. Ed. by U. of Nottingham Medical School The College of Physicians of Philadelphia Digital Library. 2019. URL: <https://www.cppdigitallibrary.org/exhibits/show/histanat> (visited on Dec. 12, 2019) (cit. on p. 18).
- [512] J. J. Mark. *Ancient Egyptian Medicine: Study and Practice*. *Ancient History Encyclopedia*. 2017. URL: <https://www.ancient.eu/article/50/ancient-egyptian-medicine-study--practice/> (visited on Nov. 14, 2019) (cit. on p. 9).
- [513] J. J. Mark. "Health Care in Ancient Mesopotamia." *Ancient History Encyclopedia*. 2014. URL: <https://www.ancient.eu/article/687/health-care-in-ancient-mesopotamia/> (visited on Nov. 14, 2019) (cit. on p. 9).
- [514] NHS. *England, London (UK). Never Events reported as occurring between 1 April 2015 and 31 March 2016 - final update*. Online: <https://improvement.nhs.uk/resources/never-events-data/> (accessed: 2017-03-01) (cit. on p. 69).
- [515] https://en.wikipedia.org/wiki/Elite:_Dangerous. URL: https://en.wikipedia.org/wiki/Elite:_Dangerous (visited on Mar. 11, 2018) (cit. on p. 135).
- [516] https://en.wikipedia.org/wiki/Eve:_Valkyrie. URL: https://en.wikipedia.org/wiki/Eve:_Valkyrie (visited on Mar. 11, 2018) (cit. on p. 135).
- [517] https://en.wikipedia.org/wiki/Star_Citizen. URL: https://en.wikipedia.org/wiki/Star_Citizen (visited on Mar. 11, 2018) (cit. on p. 135).
- [518] D. Wagner. *DEPTH CAMERAS FOR MOBILE AR: FROM IPHONES TO WEARABLES AND BEYOND*. 2018. URL: <https://daqri.com/blog/depth-cameras-for-mobile-ar/> (visited on Jan. 30, 2020) (cit. on pp. 28, 29).
- [519] D. Wagner, L. Noui, and A. Stannard. *Why is making good AR displays so hard?* 2019. URL: <https://www.linkedin.com/pulse/why-making-good-ar-displays-so-hard-daniel-wagner/> (visited on Feb. 4, 2020) (cit. on pp. 32, 164).

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