Investigating Real-time Touchless Hand Interaction and Machine Learning Agents in Immersive Learning Environments

by

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in

School of Computer Science and Informatics

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CONTENTS

LIST OF TABLES

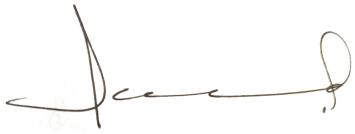
LIST OF FIGURES

ABSTRACT

The recent surge in the adoption of new technologies and innovations in connectivity, interaction technology, and artificial realities can fundamentally change the digital world. eXtended Reality (XR), with its potential to bridge the virtual and real environments, creates new possibilities to develop more engaging and productive learning experiences. Evidence is emerging that this sophisticated technology offers new ways to improve the learning process for better student interaction and engagement. Recently, immersive technology has garnered much attention as an interactive technology that facilitates direct interaction with virtual objects in the real world. Furthermore, these virtual objects can be surrogates for real-world teaching resources, allowing for virtual labs. Thus XR could enable learning experiences that would not be possible in impoverished educational systems worldwide. Interestingly, concepts such as virtual hand interaction and techniques such as machine learning are still not widely investigated in immersive learning. Hand interaction technologies in virtual environments can support the kinesthetic learning pedagogical approach, and the need for its touchless interaction nature has increased exceptionally in the post-COVID world. By implementing and evaluating real-time hand interaction technology for kinesthetic learning and machine learning agents for self-guided learning, this research has addressed these underutilized technologies to demonstrate the efficiency of immersive learning. This thesis has explored different hand-tracking APIs and devices to integrate real-time hand interaction techniques. These hand interaction techniques and integrated machine learning agents using reinforcement learning are evaluated with different display devices to test compatibility. The proposed approach aims to provide self-guided, more productive, and interactive learning experiences. Further, this research has investigated ethics, privacy, and security issues in XR and covered the future of immersive learning in the Metaverse.

Statement of Authorship

I hereby certify that the submitted work is my own work, was completed while registered as a candidate for the degree stated on the Title Page, and I have not obtained a degree elsewhere on the basis of the research presented in this submitted work.

Signature: 

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Dedicated to my beloved parents, Mr. & Mrs. MUHAMMAD IQBAL who have always shown endless love, supported and encouraged me to do my best in all that I pursue.

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Publications

Journal Papers

1. Iqbal, Muhammad Zahid, and Abraham G. Campbell. ***From luxury to necessity: Progress of touchless interaction technology***. Technology in Society (2021).

2. Iqbal, Muhammad Zahid, Mangina, Eleni, and Abraham G. Campbell. ***Current Challenges and Future Research Directions in Augmented Reality for Education***. Multimodal Technologies and Interaction (2022).

3. Iqbal, Muhammad Zahid, and Abraham G. Campbell. ***Adopting Smart Glasses Responsibly: Potential Benefits, Ethical and Privacy Concerns with Ray-Ban Stories***. AI and Ethics (2022).

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5. A Dengel, M.Z. Iqbal, S Grafe, E Mangina. ***A Review on Augmented Reality Authoring Toolkits for Education***. Frontiers in Virtual Reality (2022).

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8. Iqbal, M.Z., and Campbell, A.G., ***Metaverse as Tech for Good: Current Progress and Emerging Opportunities***. Entertainment Computing (*Under Review*).

Conference Papers

1. Iqbal, Muhammad Zahid, Mangina, Eleni, and Abraham G. Campbell. ***Exploring the Real-Time Touchless Hand Interaction and Intelligent Agents in Augmented Reality Learning Applications***. 7th International Conference of the Immersive Learning Research Network (iLRN 2021).

2. Iqbal, Muhammad Zahid, and Abraham G. Campbell. ***Investigating Challenges and Opportunities of the Touchless Hand Interaction and Machine Learning Agents to Support Kinesthetic Learning in Augmented Reality***. 26th International Conference on Intelligent User Interfaces (IUI 2021).

3. Iqbal, Muhammad Zahid, and Abraham G. Campbell. ***Touchless Hand Interaction and Machine Learning Agents to Support Kinesthetic Learning in Augmented Reality***. 52nd ACM Technical Symposium on Computer Science Education 2021.

4. Iqbal, Muhammad Zahid, Mangina, Eleni, and Abraham G. Campbell. ***Exploring the use of augmented reality in a kinesthetic learning application integrated with an intelligent virtual embodied agent***. 2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)

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2. Iqbal, Muhammad Zahid, and Abraham G. Campbell. ***The emerging need for touchless interaction technologies***. Interactions 27 (4), 51-52.

Book Chapters

1. Iqbal, Muhammad Zahid, X. Xuanhui, M. Scanlon, V. Nallur, and A. G. Campbell, ***Security, ethics and privacy issues in the remote extended reality education***, in Mixed Reality for Education (ACCEPTED), 2022.

2. X. Xuanhui, Iqbal, M.Z., E. Mangina, and A. G. Campbell, ***History of mixed reality applications in tertiary veterinary education: A systematic review***, in Mixed Reality for Education (ACCEPTED), 2022.

CHAPTER

ONE

Introduction

Immersive technology which includes virtual, augmented, and mixed reality [92] is a powerful tool rapidly emerging for developing human-centric Technology Enhanced Learning (TEL) experiences. Providing 3D environments, immersive technology enables user interaction with the latest technologies and engagement in collaborative learning scenarios. It combines real life's physical, spatial, and visual dimensions in computer-generated simulations. eXtended Reality(XR), an umbrella term used for virtual, augmented, and mixed reality, merges ubiquitous [184], tangible, and social computing to provide completely simulated environments, superimposing virtual objects on real-world environments or merging real and virtual worlds. These capacities of different immersive technology forms create broader scope for its use in various domains, including education and training. For example, the immersive experience with full potential can create a digital classroom that can develop virtual collaboration almost indistinguishable from a physical one with superior interaction and realism approach [146]. Figure 1.1 explains the difference between the different forms of XR, starting with physical reality to an utterly blended environment.

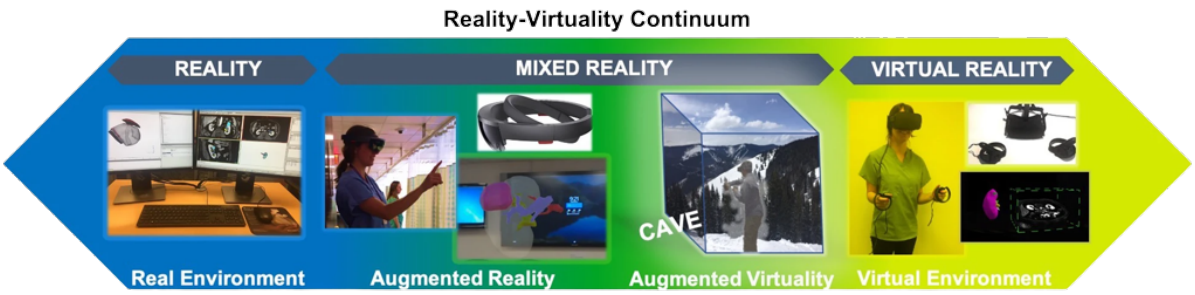


Figure 1.1: Milgram's Reality-virtuality Continuum about Real Environment, Augmented Reality, Augmented Virtuality and Virtual Reality [299]

- ***Augmented Reality:*** overlaying computer-generated digital contents into the real world environment
- ***Virtual Reality:*** replacing real-environment with completely digital environments to create interaction using controllers or hand-tracking technology
- ***Mixed Reality:*** blending real-world environment with computer-generated contents where both real and digital environment coexists and enables interaction

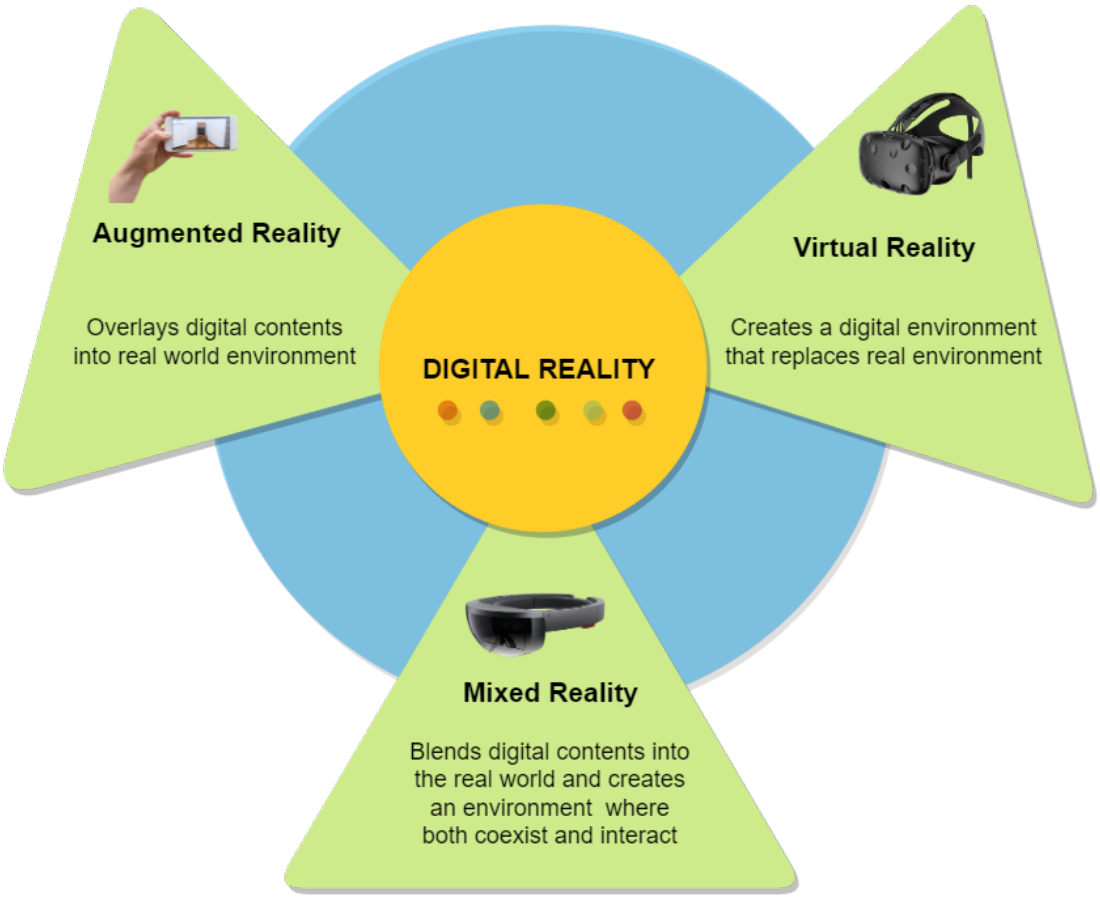


Figure 1.2: Defining different forms of digital reality

With the progress in hardware, graphic power, internet speed, and software, immersive technologies have become mainstream. This technological progress has created accessibility, portability, and affordability in immersive technology experiences, making this technology very popular as a learning technology. Further developments in this domain, like the emergence

of the Metaverse concept and haptic sense, immersive technology is becoming the future of computing.

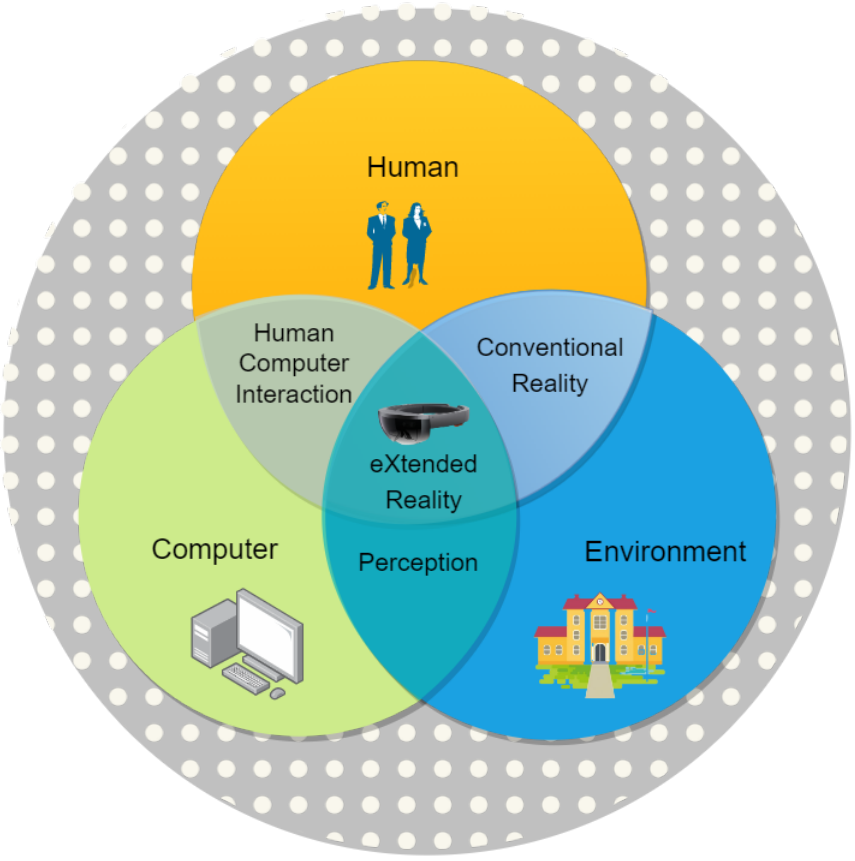


Figure 1.3: Relations of eXtended Reality with different factors involved in the process

Using XR offers limitless opportunities for many sectors like education [332], health [9], military [186], fire department, and emergency services. It can help us innovate educational systems, deliver remote healthcare [277], and plan urban spaces [197]. In addition, the hybrid working and learning concept can bring more sustainability opportunities for governments, lowering the cost of running a system.

As the social structure of societies has been affected by technological advances, it is also reflected in education to create the adoption of innovations in learning tools. Virtual learning in education has stimulated the use of XR approaches as blended and digital reality. The different forms of XR have specific traits that can support educational objectives at all levels. Different XR devices are presented in Figure 1.4.

Figure 1.4: Different devices used for creating XR environments

Intelligent agents are not widely explored to promote intelligence in immersive learning, which can facilitate self-guided learning. A self-guided learning process, also called self-directed or self-paced learning, can allow users to engage with learning content at their own pace, where intelligent agents can play a role as end-user training. The use of intelligent agents is further discussed in Chapter 4, and an approach to integrate these agents in immersive technology is presented in Chapter 5 and onwards.

It has been suggested that "Combining XR with intelligent tutoring systems can potentially enhance learning on psychomotor and kinaesthetic tasks." Bradley, et al. [127].

1.1 Research Motivation

Immersive technology is becoming increasingly popular and accessible as a mainstream learning technology. But the current research lacks the use of intelligent agents, real-time hand interaction, and hands-on learning pedagogies needed to adopt XR in STEM education

effectively. When integrated into STEM, immersive technology can motivate students to use their problem-solving abilities to explore challenges, learn technical concepts in a better way, and adopt self-guided learning. The research motivation behind this thesis is to investigate self-guided learning support using intelligent agents and kinesthetic learning pedagogy, which involves hands-on experiments with real-time hand interaction in immersive learning environments. According to research studies, kinesthetic learning is the most effective approach compared to auditory and visual learning [209, 252]. This investigation aims to create more engaging learning environments where the user can interact more with 3D content to replace the physical material in resource-constrained environments and adopt self-guided learning using intelligent agents. It involves desktops, handheld devices, and Head-Mounted Displays (HMDs) with different SDKs, APIs, and hardware. This research focuses mainly on STEM education, where students need interactive virtual laboratory experience. In addition, this research examines the ethics, privacy, and security issues in immersive learning. Immersive technology can change students' perceptions about STEM subjects, as many students find mathematics, chemistry, physics, or biology tedious and challenging to understand. By choosing immersive technology for learning, we can make these subjects much more attractive and engaging for students.

1.2 Research Questions

RQ1: What are the current challenges and future research opportunities in XR for learning?

RQ2: What are the possibilities of real-time hand interaction with handheld, desktop and standalone XR to increase the productivity in kinesthetic (hands-on) learning?

RQ3: How can intelligent agents facilitate self-guided learning and end-user training in immersive learning environments?

RQ4: How can 3D virtual material in XR help to replace the physical material in resource-constrained environments?

1.3 Objectives

The objectives of this thesis are:

1. To investigate current progress in XR learning and find opportunities with new technological developments to solve the current challenges.
2. To explore touchless or controller-free hand interaction technologies in immersive learning systems;
3. To investigate kinesthetic learning or hands-on learning in immersive learning environments with the latest hand-tracking technologies
4. To explore the use of intelligent agents in interactive XR environments for self-guided learning and training end-users;
5. To develop a distributed XR Learning framework that facilitates kinesthetic learning using hand interaction technology and machine learning agents as user trainers;
6. To investigate the human factors and usability of the proposed XR technology;
7. To explore the security, privacy, and ethics issues with the XR as learning technology in remote environments;
8. To investigate the future of immersive technology as Metaverse in education

1.4 Contributions

The main contributions presented in this thesis are:

1. The creation of prototypes to evaluate the research gaps discovered in reviewing existing challenges in immersive learning. These prototypes demonstrated the possibility of innovative solutions for kinesthetic learning pedagogy and self-guided learning in immersive environments.

2. Development of AGILEST approach for handheld devices (smartphones & tablets) using Machine Learning Agents (ML-Agents) and hand-interaction technology in immersive learning.

3. Provided a road map for future development of agent-oriented immersive environments by evaluating the AGILEST approach with expert XR researchers.

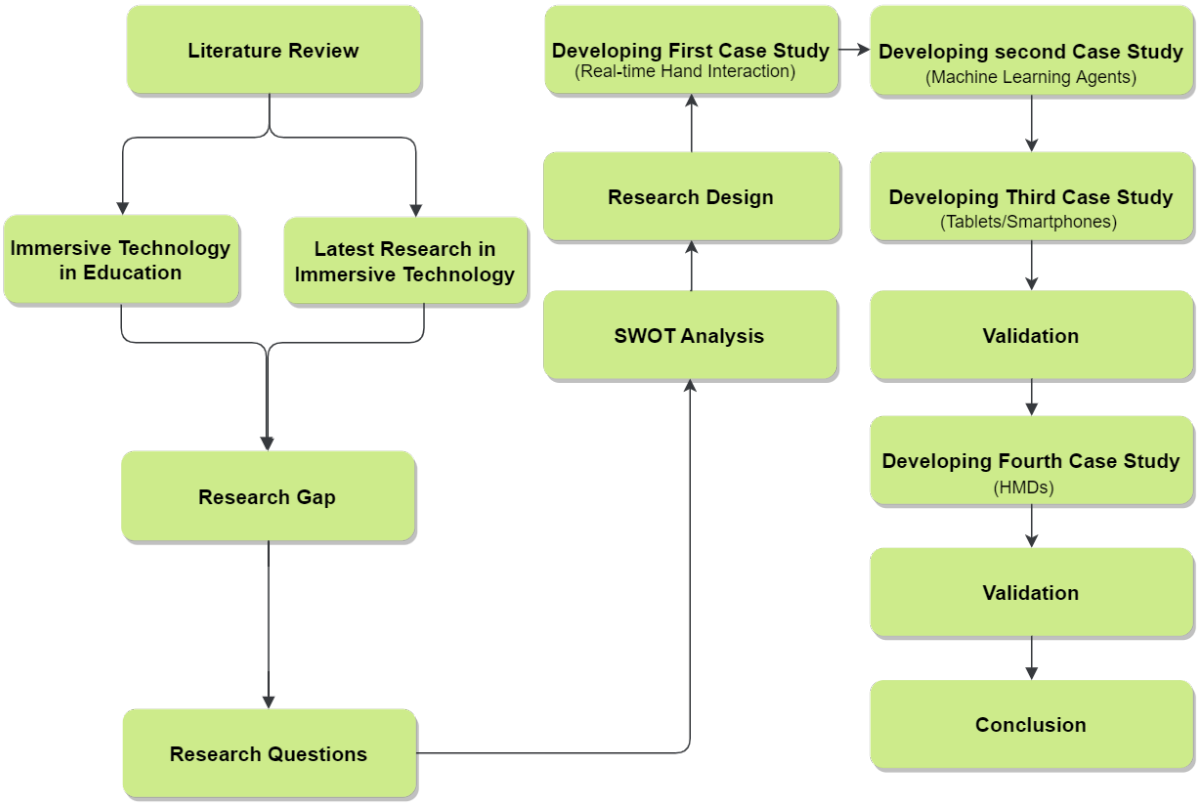


Figure 1.5: Research Work Flow of Thesis

1.5 Thesis Overview

Chapter 2: provides a detailed related work review about using XR as a learning technology in different domains. It is further analyzed according to the educational level, domain, interaction level, collaboration capacity, display devices, used libraries, and agency.

Chapter 3: provides a review of touchless interaction technologies, APIs, hardware, real-world use cases, and adoption in educational technology.

Chapter 4: provides detail about intelligent agents & implementation of Unity machine learning agents.

Chapter 5: provides a methodology of using machine learning technology for self-guided learning and real-time touchless hand interaction technology together in learning systems. This chapter has presented the AGILEST approach.

Chapter 6: provides a detailed architecture of AGILEST approach with two case studies for handheld & HMDs devices with complete learning flow using hand interaction technology for kinesthetic learning and machine learning agents for self-guided learning

Chapter 7: provides a qualitative and quantitative evaluation of the AGILEST approach with handheld devices & HMDs. This evaluation was conducted remotely with expert reviewers.

Chapter 8: provides a detailed discussion about ethics, privacy, and security-related issues with XR technology. It also discussed those issues faced during the evaluations of the AGILEST approach. Furthermore, in the next section, this chapter has provided a detailed discussion about Metaverse as the future of learning technology.

Chapter 9: provides the conclusion of the thesis with novel contributions and achievements with future work opportunities

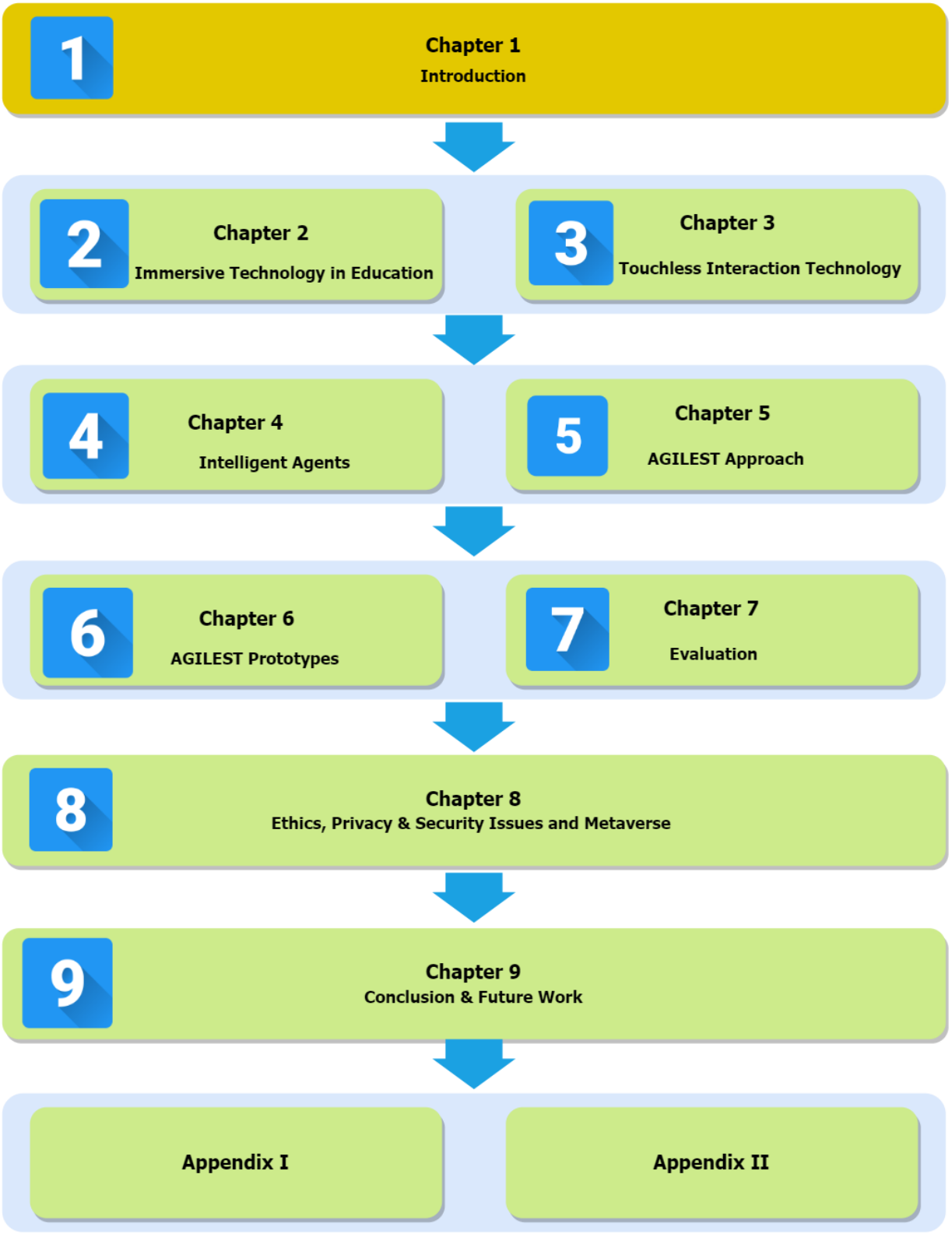


Figure 1.6: Flow of Thesis Chapters

CHAPTER

TWO

Immersive Technology in Education

Immersive learning refers to the use of immersive technologies such as AR, VR, or MR to create engaging and interactive learning experiences. Immersive learning aims to create a learning environment that simulates a real-life scenario and enables learners to engage in experiential learning.

The term "Immersive Learning" represents using immersive media or immersive technology in the educational process. Based on the different aspects of using immersive media in the learning process, Andreas Dengel provided three definitions of immersive learning [80];

From a researcher's perspective, "Immersive Learning investigates the educational benefits provided by artificial experiences perceived as non-mediated".

From a learner's perspective, "Immersive Learning is the active construction and adaption of cognitive, affective, and psychomotor models through artificial experiences perceived as non-mediated." These artificial experiences are possible with augmented, virtual or mixed reality.

From a teacher (instructor)'s perspective, "Immersive Learning is an educational method where artificial experiences perceived as non-mediated are used as learning tools."

Learning assisted with immersive technology enables ubiquitous [49], collaborative [296], and localized learning [117]. It facilitates the magic manifestation of a virtual object displayed in real-time in a real-world or virtual space that can engage a user in the learning process like no other medium can do. XR is an emerging technology with high potential for learning, teaching, and creative training [311]. XR in its different forms allows for the superimposing of computer-generated virtual 3D objects on top of a real environment in real-time or creating a completely virtual world [199].

Immersive learning can provide several benefits in the learning process, including:

- Increasing engagement and motivation: Immersive learning environments are more engaging than traditional learning or other e-learning solutions and provide more advanced learning experiences to increase motivation in the learning process.

- Improving retention and recall: Experimental learning with immersive technology can help improve information retention and recall because of its engaging nature.
- Providing safe and controlled environment: Immersive learning can provide a safe and controlled environment for learners for hands-on practice and experiments without harm.
- Real-world simulations: In immersive learning, simulations of real-world scenarios can allow learners an opportunity for practical experience in a controlled environment.
- Personalized learning: Immersive learning can be personalized according to individual needs, allowing them to learn at their own pace and in a way that suits their learning habits.
- Cost-effective: Immersive learning, when applied effectively, can be a cost-effective solution for high-quality training and education, especially in simulating real-life scenarios.

When applying XR for training, AR-based training has advantages over VR as AR training takes place in the real world, and users can access real tactile feedback when performing training tasks. Other benefits include the instructions and location-dependent information directly linked to physical objects [300].

XR brings a natural enticement to create attractiveness and engagement in learning. It can be with desktops, tablets, smartphones, or Head Mounted Displays (HMDs) as display devices. It allows the students to visualize different concepts in real-time and interact with them in a digital world, making knowledge more accessible through experiential learning opportunities. Moreover, it is portable and adaptable in different scenarios to enhance the learning process in the traditional classroom, special education, and outside the classroom [10]. The large-scale study of EARLS reported the highest ratings on "Usefulness of learning Ecosystems" [134]. However, previous research presented results of reviewing different methods of augmenting educational content, testing at different education levels and subject domains [273], game-based learning [236], XR in remote learning [105, 219] and systematic review of XR in STEM [23,

274] but it lacks focus on new interaction techniques, involvement of intelligent agents and collaboration capabilities in the AR application.

XR technologies are considered as future computing platforms; these headsets are the potential successors of ubiquitous technologies such as smartphones and desktops but with very high capability to get into our lives. With higher ergonomics and better design, these systems can offer personal, private, increased availability of sensing and augmented reality, allowing a near-constant flow of digital content delivery [113].

2.1 XR Learning Applications

There are different goals and objectives for implementing XR as a learning technology. STEM education is an area where immersive technology is becoming increasingly popular. It increases students' capabilities to learn science topics effectively and helps to develop social and emotional skills. It is permeating into the lower rungs of the education system. Integrating XR technology offers impressive benefits in learning that surpass traditional classroom learning models. However, it requires different approaches, hardware, software tools, and technical human resources.

XR as a learning technology has been categorized into five different formats [321]. These categories are as follows:

- ***AR Books:*** Overlaying 3D digital contents on the traditional books using AR markers
- ***XR Educational Games:*** Using gamification elements in XR for engaging learning
- ***XR Discovery-based learning applications:*** Using XR for discovery-based learning like astronomy
- ***XR for modeling real-world objects for interaction:*** Using XR for interaction with 3D material in resource-constraints environments

- ***XR projects exploring skill based training:*** Using 3D material or overlaying instructions on physical material for skill training

Based on these categories, Section 2.2 has provided a detail review of studies with different domains. In review, studies conducted at the early level up to 5th grade are considered primary school & from 6th to 8th grade are considered elementary school. Therefore, both primary & elementary schools are considered early education in the analysis, while upper classes before undergraduate are considered secondary levels (high school). After secondary, all the upper classes are considered a university (tertiary education).

Finally, this includes studies focusing on four XR learning scenarios explained in Figure 2.1.

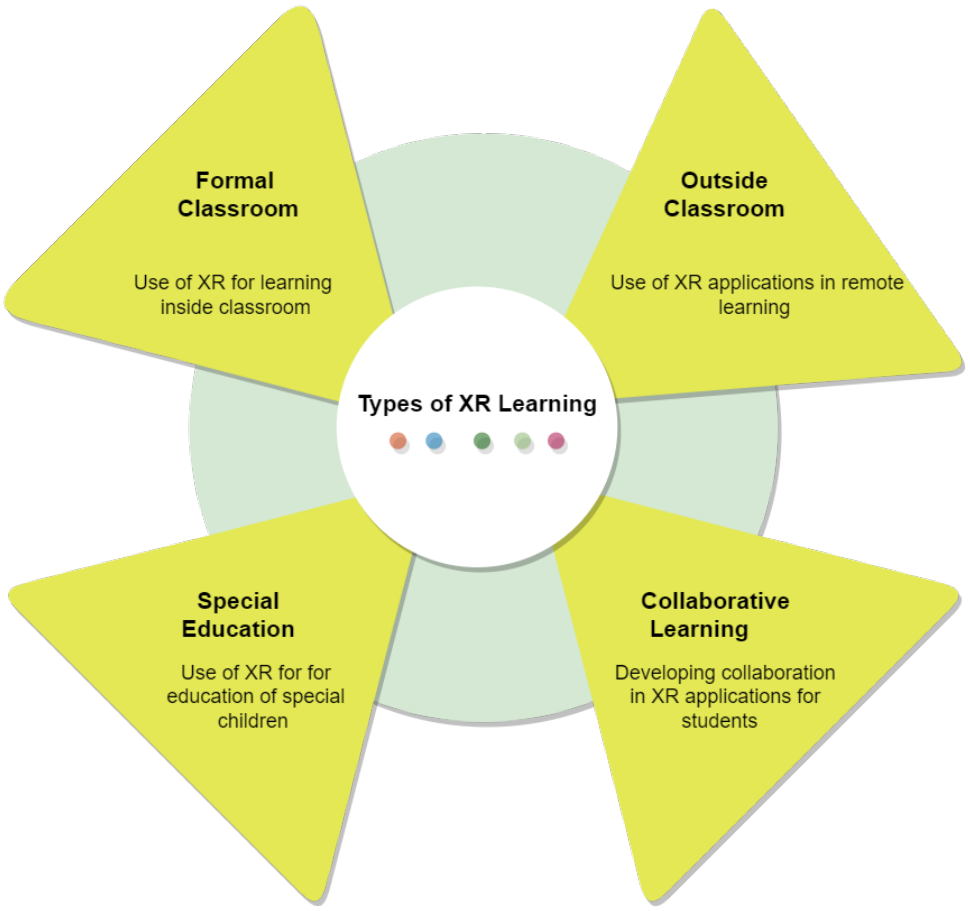


Figure 2.1: Types of XR Learning included in this study

These scenarios are further explained below in detail according to their different learning goals.

2.1.1 XR Learning in Formal Classrooms

In the classroom setting, XR allows students to learn through the combination of both real and computer-generated content [56]. It helps to understand the different topics with different scenarios either in AR, VR or MR. The future scope of handheld devices, CAVE simulations, and HMD devices is equally considered productive in the classroom setting [149, 226]. This is the most popular learning scenario in previous studies where instructors get the help of digital reality to provide students with interaction-rich experiences.

2.1.2 XR Learning in Special Education

XR can create learning opportunities for special children and play a role in overcoming physical or mental barriers. In addition, it can bring high-quality interactive educational content on top of the real-world environment to students with learning and physical disabilities in special education classrooms.

2.1.3 XR Learning Outside the Classroom

Starting with a standard smartphone XR application, an immersive reality learning experience can be created outside the formal classroom. It is a kind of self-assisted learning. XR can create immersive learning opportunities by overlaying digital content from field trips to virtual laboratories in a personalized space.

2.1.4 XR for Collaborative Learning

The technology employed with XR does not need to be exclusive to the XR experience. If an educator is looking to model scientific practice, XR provides the opportunity to support the multifaceted world of scientific exploration. The need for collaborative learning has increased recently due to the growing need for remote and independent learning where students need to connect with other mates and teachers.

2.2 Immersive Learning in Different Domains

Immersive technology has been tested and adopted in different educational domains and levels based on scenarios and formats discussed in Section 2.1. This section will provide a detailed discussion of those studies, and further analysis of this discussion is presented in Section 2.3.

2.2.1 Interactive Learning for Early classes

AR books are the most adopted learning pedagogy in AR learning, like *MagicBook* [32]. This concept involves converting traditional books into interactive AR books by overlaying 3D content. A study reported that using AR, regardless of grade level or subject area, allows students to engage in the learning process actively [31]. The concept of *Augmented Instructions* to convert a physical book to virtuality [13], and *ARGarden* [227] as an interactive flower gardening AR system created a positive learning engagement by adding visualization in the learning process.

Figure 2.2: Teaching gardening in AR, ARGarden [227]

Another study presented *Mixed Reality Book* to provide a multimedia reading experience for early class students by creating the interactive learning experience [110].

Similarly, study findings [101] about AR for teaching basic concepts of transportation, Toys++ [269] and AR magical playbook to digitize the traditional storytelling by [290] shows the role of AR as an engaging factor in the learning process. At early class, mostly XR experiences are

designed with tablets, desktops, and smartphones.

Malinka and Georgi presented an experience using low-cost interactive marker-based AR [145], using Autodesk 3DSMax for 3D scene creation and ARMedia Plugin for augmentation. It provided a highly interactive human-computer interface for model manipulation and observation in 3D space. This approach helped the students get involved in the interaction with learning objects and create new 3D learning objects.

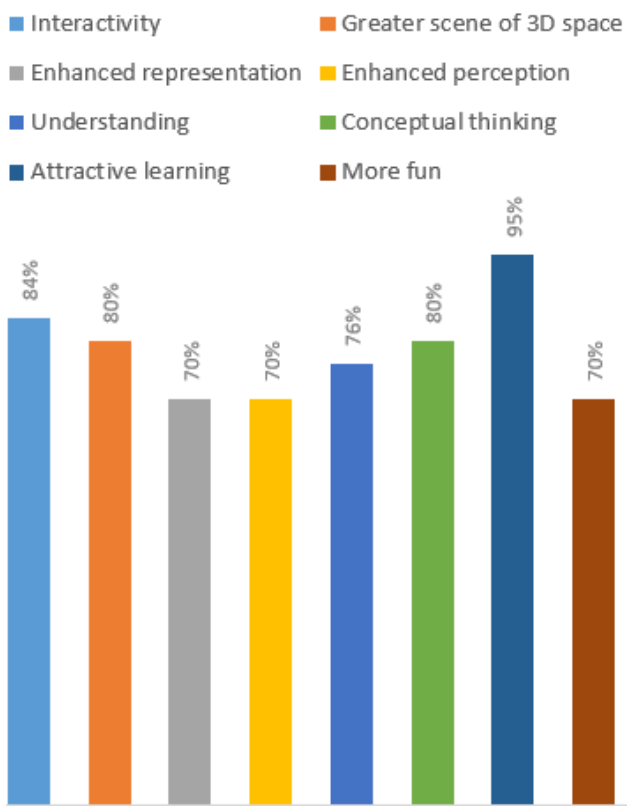


Figure 2.3: Analysis of different benefits of using AR in learning. [145]

Adding more to interaction, an inquiry-based AR learning environment *AIBLE* [99] manipulates the virtual representations of the Sun, the Moon, and the Earth, which helped to investigate the concept of task mobilization and active learning in AR.

Chih-Ming et al. used AR to enhance the learner's interest in the Chinese library classification scheme supported using a physical presentation agent [61]. To learn the role of parents in child learning, the concept of an AR picture [64] identified four behavioral patterns: parent as dominator, child as dominator, communicative child-parent pair, and low communicative

child-parent pair.

2.2.2 Interactive Learning for Higher Classes

Interactive learning in XR through simulations, visualizations, and other forms of experiential learning can help to increase learning outcomes by increasing engagement and motivation and providing learning opportunities with hands-on practice. For high school, Fotis et al. developed a Multimedia Augmented Reality Interface for E-learning (MARIE) to use the potential of AR by superimposing Virtual Multimedia Content (VMC) information in an AR tabletop setting [177]. It enables the user to interact with the VMC composed of three-dimensional objects and animations. To find the effectiveness of AR, ARCS model (Attention, Relevance, Confidence, Satisfaction) of motivation was applied by Xiaodong et al. using *AR Creative-Classroom* and *AR Creative-Builder* [301]. A pilot study provided evidence of the proposed teaching scheme significantly improving the learning motivation and student creativity in teaching creative design courses.

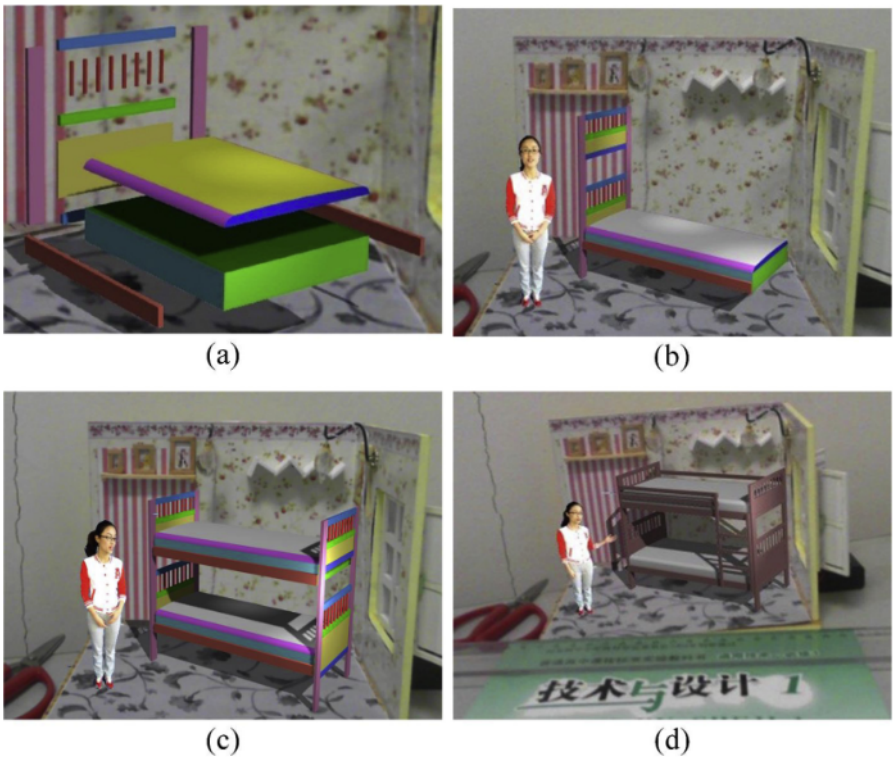


Figure 2.4: 3D modelling using AR Creative-Classroom [301]

To convert traditional books into interactive AR books, *miBook* (Multimedia Interactive Book) reflects the development of a new concept of virtual interpretation of conventional textbooks and audio-visual content [83]. This idea of virtual interpretation impacted learning outcomes by adding visualization to a regular textbook. In a similar approach, *ARIES* system [306] showed the physical markers as significant impact creators in usability and perceived enjoyment which provided evidence that these are more critical factors than perceived usefulness.

To enhance the reading and writing of physical books, *SESIL* combines book and page recognition and handwriting recognition using the AR camera [201]. It is considered robust and reliable for practical use in education as it yielded positive results. In addition, Jeonghye Han [118] conducted an exploratory study to empirically examine children's observations toward the computer- and robot-mediated AR systems, which reported positive results in dramatic play and interactive engagement. Figure 2.5(a) explains Computer-mediated AR where a webcam receives images of actors with markers, and on the other hand, Figure 2.5(b) explains robot-mediated AR where a robot leads the dramatic play with text-to-speech and actions [118]. This study helped to analyze childrenâs perception of AR dramatic play. Computer-mediated AR approach can be used in various contexts in education, entertainment, and healthcare.

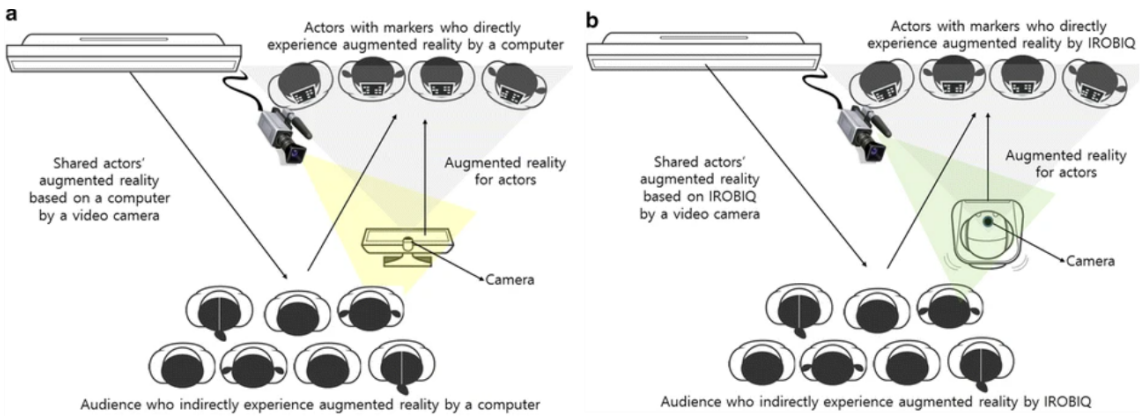


Figure 2.5: (a) Computer-mediated AR experience environment and (b) robot-mediated AR experience environment [118]

At the high school level, XR has provided more engaging and interactive learning experiences to improve learners' understanding and retention of complex topics. On the psychological side, it successfully fosters creativity and critical thinking skills in students, which are essential for

success [144].

2.2.3 STEM(Science, Technology, Engineering, and Mathematics) Education

One of the first use cases of XR learning in secondary education has been within STEM subjects. XR allows teachers to incorporate new technology and techniques in the classroom, which is one of the primary scenarios outlined in Section 2.1.1. STEM is taught in secondary and tertiary level education, which will be discussed in the overview of education Level given in Section 2.3.1. Given the link between the technologies that enable XR and STEM, it naturally has become one of the primary domains where immersive learning experiences are becoming popular, as discussed in Section 2.3.2.

Some of the best examples of XR learning come from looking into the possible use cases in Chemistry. Yu-Chien et al. investigated how students interact with AR models as compared to physical models to learn amino acid structure in 3D environment [63]. For learning chemistry with ARChemist [310] and through gestures tested in CHEMOTION [3] to provide a virtual interaction with chemicals using hand tracking technology.

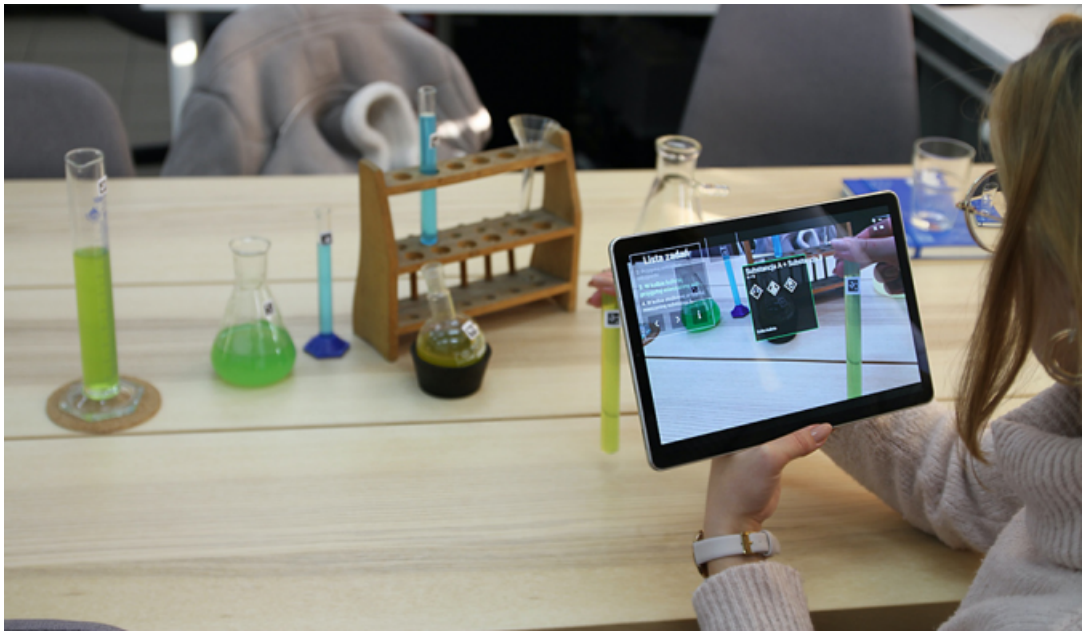


Figure 2.6: Learning chemistry with ARchemist [310]

Based on the exciting use of XR in chemistry using the virtual laboratory concept and reported productive results, learning chemistry is included in the case studies using the proposed AGILEST approach in Chapter 6.

By mixing the interactive concept maps with AR technology, support of an excellent instructional technique and scaffolds improved the learning outcomes when mixed in to develop a new learning pedagogy [60].

Like Chemistry, astronomy is one of the first topics to be covered using AR learning. The use of the AR to learn the earth-sun relationship [267], Earth-Moon System [181] and Live Solar System (LSS) [271] which helped to enhance meaningful engagement in learning astronomy concepts and conceptual thinking. An AR study to assist in learning gravity and planetary motion with an interactive simulation increased the learning gain significantly [180], as shown in Figure 2.7. It increased the positive attitudes of the students.

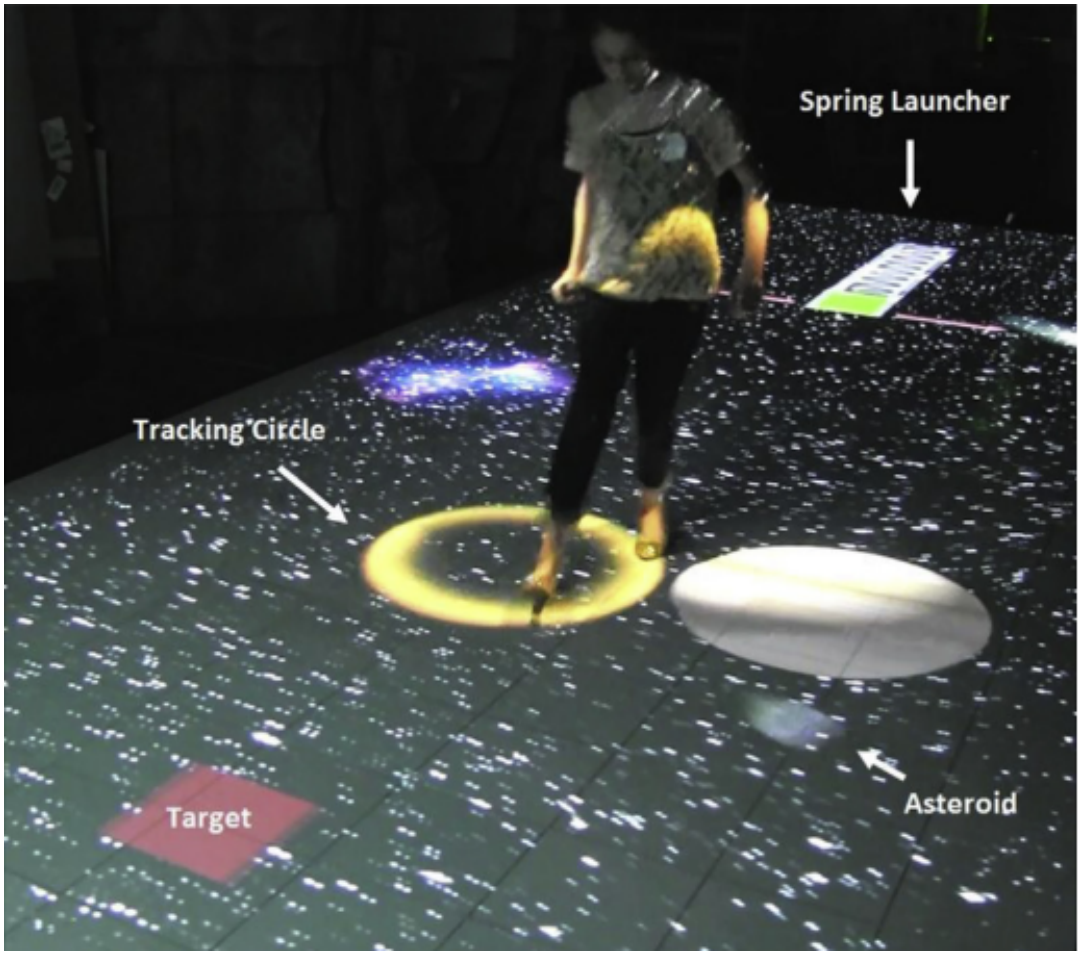


Figure 2.7: The MEteor simulation [180]

Visualization techniques of biology processes with AR allow students to understand usually hidden processes. Stefan et al. [222] developed an AR framework ProteinScanAR as an assistive tool for engaging lessons on molecular biology topics using AR. Science Center To Go (SCeTGo) [41] investigated the role of teachers' and students' acceptance and found AR pedagogical efficiency very constructive. Likewise, at the high school level, there are many AR studies at the university level for learning anatomy [151] [22] [36] [193] [206] & [20]. These studies presented AR anatomy learning systems for learning the exterior to the interior of the body by introducing the innovative, hands-on study of the human musculoskeletal system. Also, the use of leapmotion for 3D body anatomy learning was tested to use hand tracking for interacting with 3D models [216] and [295] as in Figure 2.8.

Figure 2.8: Anatomy learning with leapmotion interaction [295]

Teaching engineering subjects is a cornerstone of STEM, and there are multiple examples of immersive learning applications in this area. This includes using AR and 3D web tools in engineering education to help the multidimensional augmentation of teaching materials [176] [288] in technology and design engineering. *Learning Physics through Play Project (LPP)* helps

to learn concepts of physics about force and motion [89] and *LightUp* [55] for learning concepts of electronics like circuit boards, magnets, and plastic sheets. LightUp was developed to help school children learn different concepts within electronics. The user can augment a physical construction kit that is given to them in real life. This kit then has virtual phenomena such as the flow of electricity made visible by 3D animations, seen through an informational virtual lens (Tablet with AR-enabled camera) [55].

By combining modern mobile AR technology and pedagogical inquiry activities, Hsin-Yi et al. [57] used AR for teaching Nuclear Power Plant activities with more effective digital visualization. Adding more to learning electronics concepts, ElectARmanual [202] and AR-based flipped learning system [58] helped to achieve better learning outcomes by using the AR guiding mechanism. ElectARmanual was a markerless AR training application developed to support electrical engineering students in a practice laboratory and provide training to use different electrical machines. It was developed with an electrical engineering academic notebook. The results showed excellent usability but like similar applications, it lacks a complete structural and working cycle of electrical machines [202]. Collaboration within an AR environment is a vital AR learning scenario as outlined in section 2.3.8. In keeping with the Chemistry theme, one example of a tangible interaction focused on chemistry, *Augmented Chemistry (AC)*, reported higher user acceptance by interacting with the 3D models in the lab [98]. The Tangible User Interface (TUI) could be one area that helps collaborative learning. Still, the nature of tangible interaction can require additional resources. In the current COVID crisis, alternative touchless interaction approaches could be a better solution. Other prominent examples of collaboration using *SMALLab* found extensive evidence as a powerful approach to learning in a design experiment with secondary earth science students [34]. Furthermore, AR has the collaboration capability to engage with the Internet of Things(IoT) to create productivity in Engineering education with different scenarios [245]. Finally, AR as a learning tool in the mathematics tested with Construct 3D [155] and *GeoAR* [162] to support learning geometry provided a highly positive impact concerning its educational potential. Construct3D is an AR application developed for mathematics and geometry education to enhance the face-to-face

collaboration of teachers and students.

Field trips are one example of AR outside the classroom. Embodied experiences at the field trips for the science classrooms with situated simulations got valuable and effective results about student engagement and their connection with the experiential learning from the curriculum [179].

The kinesthetic learning approach has been adopted in AR for training technical people with maintenance and assembly skills for various industries [300]. For a trainee, interaction with real-world objects and machinery parts while getting the virtual information for learning can provide an advantage of using AR for training compared to traditional learning.

2.2.4 Language Learning

Immersive technology for language learning is related to the formal classroom learning section 2.1.1, tested successfully in different studies. For example, the use of AR Flashcards for learning about the English alphabet and animals [256] and an AR-based game for Kanji learning [298] reported AR as a tool of motivation and visual presentation to learning languages. Furthermore, to test the ubiquitous games in the learning approach for language learning, HELLO (Handheld English Language Learning Organization) [185] and another handheld language learning approach [258] showed improved retention of words which increased student satisfaction and attention.

The use of MR HMDs with a portable sensing system for teaching American sign language found statistically significant improvement in learning signs as compared to traditional learning with desktop system [266]. Similarly, *TeachAR* using kinect [76] tested for teaching essential English words (colors, shapes, and prepositions) and game-based foreign language learning [322] which provided evidences to enhance engagement in the learning process significantly. The use of Microsoft Hololens for vocabulary learning as compared with traditional flashcard-based learning produced higher productivity and effectiveness in learning outcomes [136]. For language learning in higher classes, a mobile learning tool Explorez [238]

for improving French learning by interacting with objects to enhance their French language skills, which received acceptance as “useful” and “motivating” for students.

2.2.5 Collaborative Learning

The collaborative learning approach, as defined in Section 2.1.4, provides the opportunity for collaboration either teacher-to-student or student-to-student. In collaborative learning, co-creation activities with other students and teachers are more productive and help reduce the cognitive load during the learning process. Research has shown ample proof that learning experiences that are active, social, contextual, more engaging, and purely student-owned can give better learning gain and understanding. Pair-learning, a form of collaborative learning, is beneficial for increasing learning outcomes and social presence by increasing content immersion and students’ engagement and interest.

AR as collaborative learning [33] with *SMALLab*, which is a Student Centered Learning Environment(SCLE) to use interactive digital media in a multimodal sensing framework which reported promising results in social and collaboration aspects. Further in the collaborative learning approach, [67] with ARClassNote, which is an AR application that allows users to save and share handwritten notes over optical see-through HMDs. It makes it easier to achieve communication between instructors and students by sharing written class materials.

AR game concept, “Locatory” was introduced by combining game logic with collaborative gameplay and personalized mobile AR visualization, which provides different perspectives of interactive 3D visualization to learn the content with AR and identify positive experiences [280]. Further identified collaboration opportunities as discussed in Section 2.3.8 and as a recommended approach in Section 5.1.3.

2.2.6 Environment & History Learning

Taking AR to location-based learning for learning about environment and history as Section 2.1.3 has provided positive evidences in terms of learning engagement. A study of learning

environment [65] and location-based experiments [154] reported the use of AR learning engagement factor by providing virtual media over the top of the physical environment. Singh et al. developed the inquiry-based learning application CI-Spy that seeks to engage students in history using an augmented reality environment [272]. This enabled a comprehensive understanding of historical inquiry for students by combining AR experiences with strategic learning. Lu et al. chose game-based learning for a marine learning application with interactive storytelling and interactive game-based test [188]. It helped the students to learn in the virtual context, thus deepening their involvement in the learning experience.

The idea of *iARBook* captures video input and sends it to the Vuforia, which processes frames in real-time to detect and find the images in the database [25]. Once it recognizes an image, the related scene is rendered over the video frame as a learning object.

Figure 2.9: Speaking Robot as interactive learning scenario [25]

By considering the goals of learning achievement and attitude, the Ecosystems Augmented Reality Learning System (EARLS) promoted a positive learning attitude among students over Keyboard/Mouse-based Computer-Assisted Instruction (KMCAI) approach [134].A playful VR experience is provided in the “Ancient Rome” application allowing users to learn historical concepts by reproducing different buildings and civil constructions. In addition, it enables users to create ancient Roman cities [251].

2.2.7 Special Education

XR learning in special education, as defined in the section 2.1.2 can increase the learning gain by enhancing the representation of content for students with special needs. To explore XR learning in special education, Jazheel et al. [190] created 3D Learning Objects using AR for an online learning program for ADHD (Attention Deficit Hyperactivity Disorder) affected students. It further developed as AHA project in a comprehensive study as a web-based AR learning system [200]. The evaluation study highlighted the potential of AR for interactive learning and allowing users to become more engaged with learning content [66]. In addition, it provided opportunities for additional educational engagement and process reiteration for learners.

2.2.8 MOOC (Massive Open Online Courses)

MOOC (Massive Open Online Courses) represents Section 2.1.3 as it facilitates learning outside the classrooms. Its importance has been increased recently due to remote learning adoption throughout the world in an emergency situation due to the pandemic. MOOC as a remote

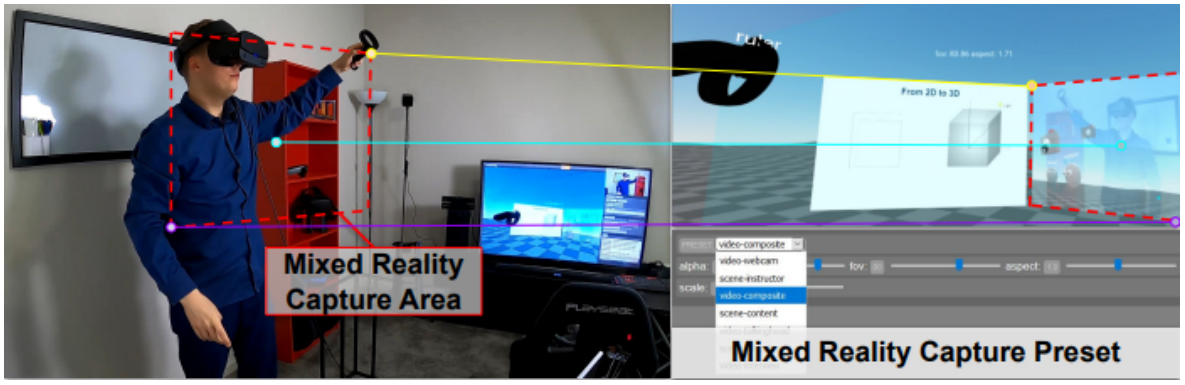


Figure 2.10: XRStudio: implementing a three-point calibration technique for MOOC [218]

learning environment, can lack the hands-on approach of other learning approaches. XRStudio developed a to give lectures in VR which enables live compositing using the real-time output to traditional video [218] as shown in Figure 2.10. Use of AR in the MOOC has been taken into account to generate interactive and extra appealing online contents, which helped to create more productivity by improving visualization, support of individualism and enlightening the interest

factor [59] & [47].

2.2.9 Technical Training

As discussed in the background section 2.1, XR has been taken as a learning tool in skill-based training. Immersive technology has solid evidence to incorporate innovative interaction into technical training [167, 239]. It improves vocational and technical skill training by integrating digital content into real training environments with augmented or mixed reality. In technical training, the concept of kinesthetic learning is important for hands-on learning. The integration of intelligence in the Intelligent Tutoring Systems (ITS) for training users how to assemble components on a computer motherboard, including identifying individual components and installing them on the motherboard [302].

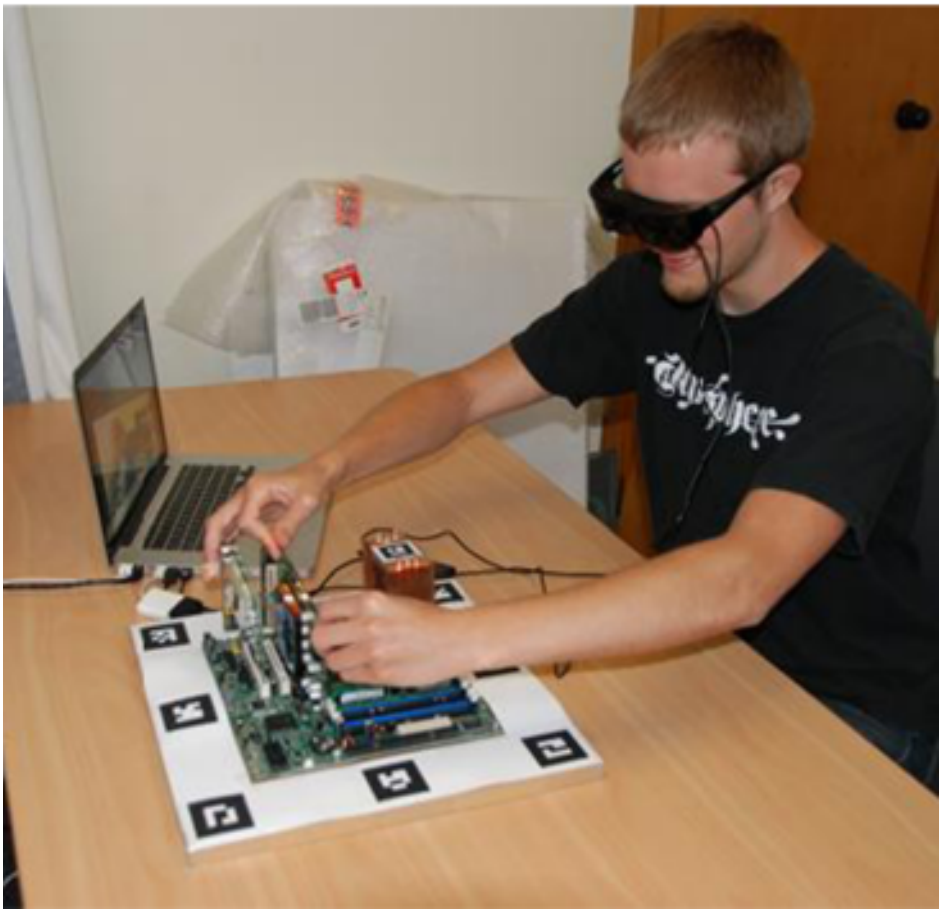


Figure 2.11: Using of ITS for learning assembling of motherboard [302]

This approach of adaptive guidance helped this intelligent AR system show faster performance than an AR training system without intelligent support. Using AR for a technical training workshop by Joanne et al. to perform the threading task to facilitate better learning helped improve students' learning experience and understanding of the complex concepts [316]. Vocational training is also closely relevant to co-creation; mobile AR is explored in this context in the Paint-cAR application, which encourages the use of inclusive learning design where users can actively participate [15]. In Section 3.3.1, this concept is taken into account along with a focus on adding intelligence in the technical skills learning and doing more with a hands-on in resource constraints environment. These training experiences also require the introduction of authoring tools to allow for the rapid development of customized experiences, further discussed in Section 2.2.10. The COVID pandemic has increased the need for XR learning technology to develop technical training experienced in simulated environments. The use of XR as Metaverse for practical and vocational training has been further discussed in Section 8.4.6, which is an important research area regarding innovative XR. The future of XR for technical skill training is linked with different other technologies and innovations that can play an important role in enhancing the effectiveness and engagement of skill training. These developments can help to address the growing demand for skilled workers and provide learners with the skills they need to succeed in their careers.

2.2.10 XR Authoring Tools

XR authoring toolkits are applications that provide educators or programmers with a complete toolset for creating XR experiences with very little or no programming need. XR toolkits aim to solve common problems for content creators or programmers to spend more time developing XR content than developments. The need for authoring tools is the more important work in XR learning, which still has open opportunities. There is very little work on authoring tools in XR, presented in a detailed review [81]. These authoring tools can be used by developers, designers, and content creators to produce immersive experiences without or with very little programming experience. These tools play an important role in reducing the barriers to the XR

content creation process and providing more access to this emerging technology [72].

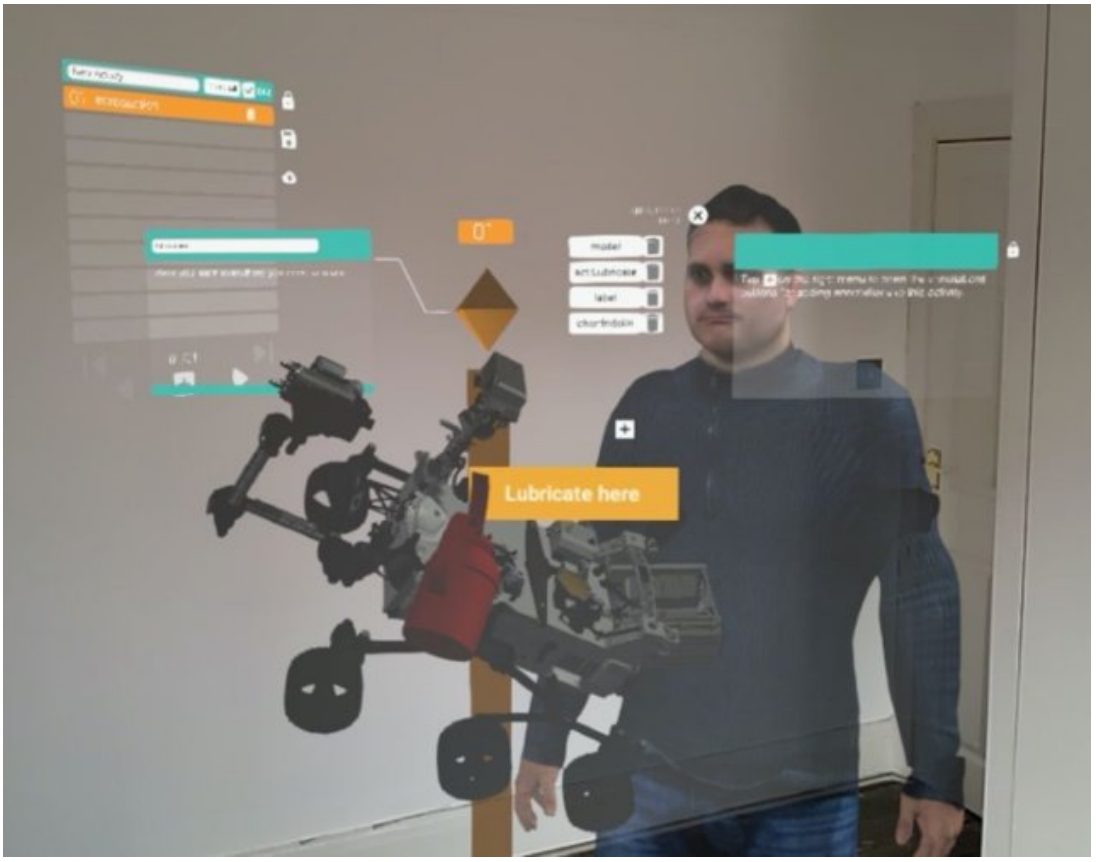


Figure 2.12: MirageXR as authoring toolkit allows learning in the Real World using Augmented Reality and Wearable Technology [112]

In an immersive XR authoring tool where users are authorized to create a dynamic learning environment with immersive content, allowing users to create content is the most demanding need for an authoring tool [147]. It reduces the workload for the teacher in creating and managing AR learning experiences. This can be directly aided by introducing different forms of artificial intelligence, one such approach is discussed in Section 5.1.1 and the background to this work will be discussed in the next section. MirageXR authoring toolkit provides cross-platform for creating content with a low programming language for teaching and training [112]. FlowMatic is an immersive authoring tool that helps create interactive VR scenes [326]. It allows users to define reactive behaviors, reduce complexity, and create/destroy objects programmatically in a VR scene.

2.2.11 Intelligent Agents in XR

Intelligent agents in XR refer to digital entities which have the capacity to interact with users or train user in AR or VR environments using artificial intelligence techniques such as natural language processing, computer vision, and machine learning. A detail about these agents and their properties is provided in Chapter 4. These agents include virtual assistants, chatbots, machine learning agents, or game characters, which can help users with tasks, providing information, or social interactions. These agents have the potential to enhance user engagement and performance in the immersive experience of XR. Agency is a word that started appearing frequently in the XR [123, 221, 243], primarily when intelligent, collaborative, and gaming experiences are in focus. In both use cases, formal classroom or remote learning, as explained in Section 2.1.1 and 2.1.3, incorporating the agents can play a significant role in creating intelligent learning environments. These agents can empower self-guided and self-paced learning concepts, which are further described in research methodology Chapter 5 and implemented in Chapter 6. It refers to users' level of control or empowerment in the XR space. For example, providing agency in an XR environment gives the user more control and power, which refers to self-paced or self-guided learning in education.

Using interacting intelligent agents in AR can bring more productive results. The use of self-directed animated agents in the AR as AR Puppet [19] which is validated in *AR Lego*, helped in the autonomous decisions based on perception of the real environment. A multi-agent system using *SRA* agent helped to increase the motivation, using the principle of "learn by doing" or kinesthetic learning in an immersive environment [54].

Figure 2.13: Use of AR Puppet as an animated agent [19]

Kid Space is an advanced, centralized projection device that creates multi-modal interactivity and intelligently projects AR content across surfaces using a visible agent to help in learning by playing [8]. The initial study showed children actively involved with the projected character during a math exercise.

FenAR is an AR system following the Problem-Based Learning (PBL) approach [215]. The evaluation of this study indicated that integrating AR with PBL activities improved students' learning achievement and increased their positive attitudes toward physics subjects. Alexandru Balog examined the aspects of perceived enjoyment in the students' acceptance of an Augmented Reality Teaching Platform (ARTP) [18] developed using Augmented Reality in School Environments(ARiSE) [37] with test cases in biology and chemistry. This research found perceived usefulness and ease of use as extrinsic and perceived enjoyment as intrinsic to this new learning environment. The integration of intelligent agent is one of the main contributions of this thesis which is explained in detail in Section 5.1.1 and further implemented in Chapter 6.

The below table shows the XR learning studies according to their domains, educational levels, interaction capacity, collaboration capacity, and agency. The User Interaction (UI) is categorized as (Low, Medium, and High), *Low* means only placing the 3D objects in the real environment, *High* means a higher interaction like hand interaction or gestures. The level of agency is "Yes" or "No" and the same with collaboration capacity. It has been divided based on simple marker-based interaction to real-time touchless hand interaction.

Project	Research Objective	Education Level	Participants	Display Devices	UI Level	Collaboration	Agent
HELLO [185]	Using agents in AR for language learning	Elementary	64	Smartphone	Medium	Yes	Yes
ARBOOK [97]	Basic anatomy learning using 3D model placement on markers	Secondary	211	Desktop	Low	No	No
MIRRACLE [36]	Human anatomy learning with Kinect gestures	Secondary	-	Desktop	High	No	No
ARTP [37]	Teacher student collaborative concept in AR	Elementary	7	Desktop	Low	Yes	No
ARGarden [227]	Learning about environment using ARToolKit	Primary	-	Smartphone	Medium	No	Yes
AIBLE [99]	Astronomy concepts learning using AR markers	Elementary	69	Laptop	Medium	No	No
MARIE [177]	AR for engineering concepts with 3D object placement on trained markers	University	-	HMDs	Medium	No	Yes
LPP [89]	Learning Physics with simulated experiments using AR markers & Kinect body tracking	University	43	Desktop	Medium	Yes	No
MAT [302]	Learning motherboard assembly using intelligent Agent & marker based guidance	University	16	HMDs	High	No	Yes
Immersive Authoring [147]	Authoring tool for storytelling	University	142	Desktop	Low	No	No
SSI on Nuclear Energy [57]	Learning about nuclear reactor phenomenon using AR simulation	Secondary	22	Tablets	Medium	No	No
AHA [200]	Vocabulary learning for ADHD affected students with audio and animated object placement	Primary	117	Web AR	Low	No	No

Project Name	Research Objectives	Education Level	Evaluations (Subjects)	Display Devices	UI Level	Collaboration	Agent
Locatory [280]	Location based educational gaming using GPS	Secondary	3	Smartphone	Low	No	No
EARLS [134]	Kinesthetic learning activities guided by AR gestures	University	1211	Desktop	Medium	Yes	No
Kanji learning [298]	Collaborative Kanji Learning using ARToolKit	Secondary	-	PDA	Low	Yes	No
AR marine learning [188]	Marine science topics learning using AR projector	Secondary	51	Laptop	Medium	No	No
iARBook [25]	XR learning using audio instructions & object placement on markers	University	30	Tablets/ Smartphone	Low	No	No
Construct 3D [156]	Collaborative learning geometry with 3D models	Secondary	14	HMDs	Medium	Yes	No
Kid Space [8]	Early age math learning with an external agent	Primary	16	Desktop	Medium	No	Yes
SaCI [54]	Discovery based learning using SRA agent, GPS & AR marker	University	100	Smartphone	High	No	Yes
Carmen's Anatomy Learning [151]	Learning interior of human body Anatomy using ARToolkit	Primary	40	Desktop, HMDs	Medium	No	No
AR Solar System [267]	Sun-Earth relationship learning in solar system	University	30	HMDs	Low	No	No
EcoMOBILE [154]	Situated learning about environment using GPS & FreshAir App	Elementary	71	Smartphone	Medium	Yes	No
miBook [83]	AR Storytelling using markers and audios	Primary	5	Desktop	Medium	No	Yes
AR Flashcards [256]	Use of AR Flashcards for Language Learning	Primary	42	Tablets/ iPads	Low	No	No
SMALLab [33]	Student-intructor interactive learning using audio sensing	Secondary	-	Desktop	Medium	Yes	No

Project Name	Research Objectives	Education Level	Evaluations (Subjects)	Display Devices	UI Level	Collaboration	Agent
Explorez [238]	Language Learning using situated gaming with GPS	University	11	Smartphone	Medium	No	No
ALE [39]	AR Game based learning	Secondary	188	Desktop	Medium	Yes	No
REFLECT [20]	Using Microsoft Kinect gestures to learn human anatomy	University	288	Desktop	Medium	No	No
Daineko et al. [75]	Using hand tracking with leapmotion for learning Physics	University	-	Desktop	Medium	No	No
CHEMOTION [3]	Leapmotion hand tracking for Chemistry learning	Secondary	16	Desktop	Medium	No	No
SCeTGo [41]	Marker based 3D object placement for learning science	Secondary	-	Desktop	Low	No	No
LightUp [55]	Simple electronic kits learning using AR	University	12	Smartphone, Tablets	Medium	No	No
LSS [271]	Learning about solar system by rotating multi-target markers	Secondary	30	HMDs	Medium	No	No
AR picture book [64]	AR picture book for learning behavioral patterns and cognitive attainment	Secondary	33	Smartphone	Low	No	No
SESIL [201]	AR Books for learning in early classes	Primary	-	Desktop	Low	No	No
AR Lego [19]	Use of a virtual agent as guider in AR for assembling tasks	Primary	-	Desktop	Medium	No	Yes
LearnHeart [161]	Learning heart anatomy with ARToolkit with Flex SDK	University	3	Web AR	Low	No	No
ARiSE [37]	Learning cultural history with remote collaborations between players	Secondary	-	PC, PDA	Low	Yes	No

Project Name	Research Objectives	Education Level	Participants	Display Devices	UI Level	Collaboration	Agent
ProteinScanAR [222]	Use of AR marker with FLARToolkitfor for Biology learning with object placement	Secondary	16	Web AR	Low	No	Yes
ARbis Pictus [136]	AR for tracking objects and labeling physical objects to learn vocabulary	University	52	HMDs	Low	No	No
TeachAR [76]	English learning using object placement using speech recognition feature of Kinect	Primary	4	Desktop	Low	No	No
Elect ARmanual [202]	Use of AR for practical Manual for electronics using remote instructions	University	50	Web AR	Medium	No	No
Opera2222 [179]	Using simulations for teaching about historical places	Secondary	2	Smartphone	Low	No	No
AR English Learning [166]	Learning English vocabulary using pictures as markers	Secondary	122	Smartphone	Low	No	No
Augmented Chemistry [98]	Learning chemistry with simple markers	Secondary	0	Desktop	Medium	No	No
Magical-Playbook [290]	Storybook with AR book	Secondary	3	Smartphone	Low	No	No
ARIES [306]	Learning chemistry with 3D model placement on markers	Secondary	42	Desktop	Medium	No	No
AR Creative -builder [301]	Enabling students with adding 3-models for chemistry learning	Secondary	33	Desktop	Low	No	No
ARLIS [61]	Use of Agent for library instructions in AR	Elementary	116	Desktop	Medium	No	Yes
MEteor [180]	Astronomy learning with a laser-based motion tracking system	Elementary	113		High	Yes	No
AR-Flipped Learning [58]	Learning activities for physics topics at early school	Primary	111	Smartphone, Tablet	Medium	No	No

Project Name	Research Objectives	Education Level	Participants	Display Devices	UI Level	Collaboration	Agent
Handheld AR system [258]	Situated vocabulary learning using markers placement on physical objects	University	45	Tablets	Low	No	No
CI-Spy [272]	Learning about Historical places using AR labels and GPS	Primary	16	Tablet/ Smartphone	Medium	No	No
CMAR [60]	Learning science topics using AR animation	Elementary	71	Tablets	Medium	No	No
AR-infused robot [118]	AR robotic interaction using markers attached to body	Primary	81	Desktop	Low	Yes	No
AR Sewing Video [316]	Providing AR tutorial for sewing as Workshop	Technical	46	Smartphone	Low	No	No
GeoAR [162]	Geometry learning with marker based object placement and virtual buttons	Elementary	6	Desktop	Low	No	No
FenAR [215]	Use of virtual buttons and markers for teaching science subjets	Elementary	91	Smartphone, Tablet	Medium	No	No
Toys++ [269]	Physical object tracking and labeling	Primary	-	Laptop	Low	No	No
ARClassNote [67]	Taking notes classroom to collaborate between students and teachers	Secondary	-	HMDs	Low	Yes	No
Inquiry-based learning [65]	Environmental learning using GPS situation learning scenarios	Elementary	57	Smartphone	Low	No	No
Nainggolan et al. [216]	Interacting with human skeleton models using leapmotion hand tracking	University	30	Desktop	High	No	No
Erman et al. [322]	Use of Kinect tracking for language learning	University	62	Desktop	Medium	No	No
Meng et al. [193]	Anatomy Learning using Kinect body Tracking	University	72	Desktop	Medium	No	No
ARIFLite [176]	Using Web3D for learning mechanical parts in AR	University	-	Web AR	Medium	No	No

Project Name	Research Objectives	Education Level	Participants	Display Devices	UI Level	Collaboration	Agent
Hong-Quan et al. [172]	Geometry Learning with leapmotion hand tracking	Secondary	27	Desktop	Medium	No	No
Ryosuke et al. [295]	Using Leapmotion hand tracking for interactive anatomy Learning	University	2	Desktop	Medium	No	No
Scaravetti et al. [261]	Mechanical design	University	59	Tablet	Medium	No	No
Earth-Moon System [181]	Learning astronomy using three dimensional models on vuforia markers	Secondary	35	Tablet	Medium	No	No
ARVR Microscope [330]	Virtual microsocpe for Biology experiments using marker tracking	Secondary	-	Smartphone	Medium	No	No
ARChemist [310]	Chemistry learning using markers on physical models	University	2	Tablets	Medium	No	No
Barrow, John [22]	Learning human anatomy with vuforia marker based tracking	University	90	Tablets	low	No	No
GeoGebra 3-D [303]	Geometry learning with GeoGebra 3-D	Secondary	72	Desktop	Low	No	No
IVALA [182]	Veterinary Cardiac Anatomy with IVALA	University	36	Tablets	Medium	No	No
Save the planet [249]	Use for minigames for storytelling in early childhood	Primary	50	Smartphone	Medium	No	No
METAL [233]	Anatomy learning using Looking glass with Azure Kinect & Hololens	University	10	Looking Glass, HMD	High	Yes	No
IWB [250]	Leapmotion hand gestures with interactive white board for early education	Primary	20	Desktop	High	No	No
HoloYolo [297]	Use of machine learning algorithms for markerless navigation in surgery	University	-	HMD	Low	No	Yes

Table 2.1: XR Studies with their status of domain, education level, libraries, display devices, user interaction, collaboration capacity and agents

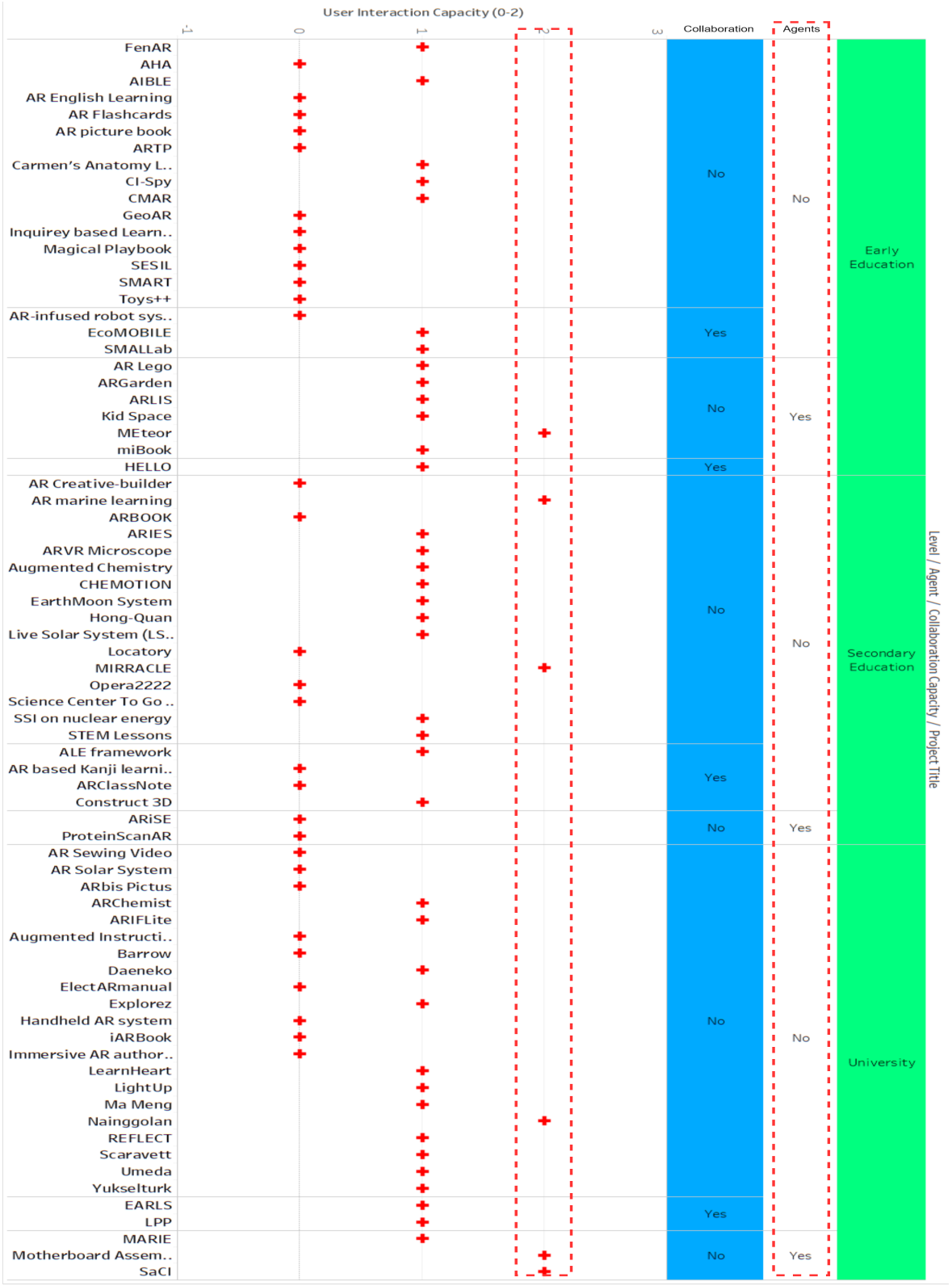


Figure 2.14: Visual representation of different AR applications according to their User Interaction capacity, Collaboration capacity, Agents, and educational level- The dotted red line shows the research gap which is part of further research in this thesis.

2.3 Analysis

Examining current and past projects using different aspects like educational level, domain, tracking, collaboration capacity, agents, and interaction level, leads naturally to identifying specific future research areas. Based on the detailed review provided in Section 2.2, this section has analyse these studies according to different characteristics. The XR application design requirements suggested in [157], being flexible of the content that the teacher can adapt according to the children's needs, guiding the exploration to maximize the learning opportunities in a limited time, and attention to curriculum needs.

2.3.1 Education Level

The above analysis found that XR has been tested and becoming equally effective at all three educational levels; early (primary & elementary school), secondary (high school) & tertiary education (university) presented in the Section 2.1. In addition, there is a trend towards its use in medical education; however, there is a lack of focus on technical or vocational evaluation [316] of its use in teaching.

Table 2.2 and Figure 2.15 provides detail about educational levels.

Educational Level	**XR Research Studies**
Early Level (Primary & Elementary School)	26
Secondary Level (High School)	22
Tertiary Level (University)	26

Table 2.2: XR Studies Distribution According to Educational Level

Planning to use rapidly evolving immersive technology is a real challenge at all educational levels and depends on the availability of resources and instructors. This aspect also belongs to the development of authoring toolkits that allow instructors to generate content without any programming knowledge.

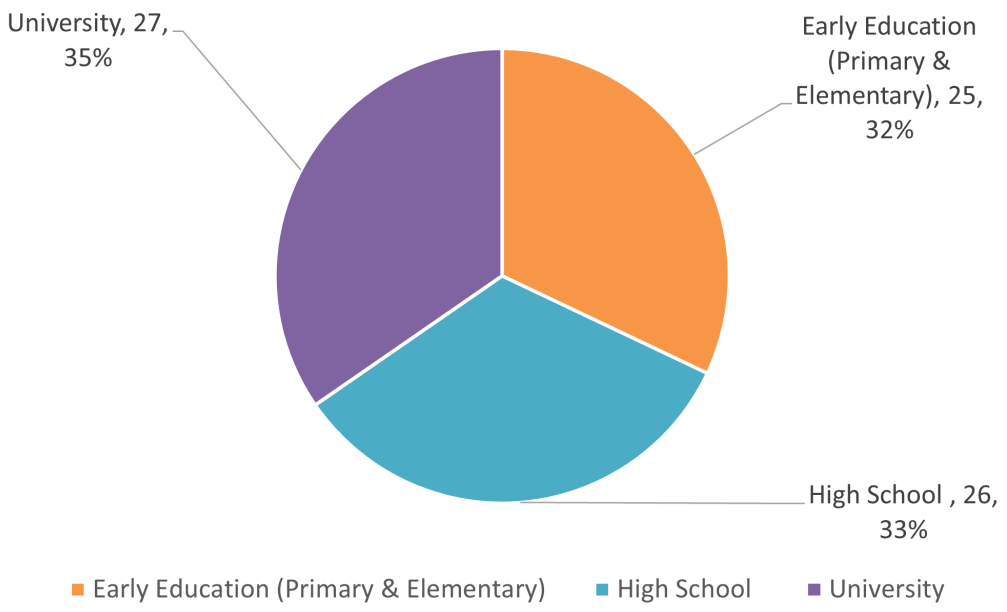


Figure 2.15: XR Studies Distribution According to Educational Level

2.3.2 Educational Domain

At early level education (primary & elementary schools), most of the studies are using AR for alphabet learning like [256], vocabulary learning, or early level science topics as [99]. At the secondary level (high school) & tertiary level (university), it has been used as a learning enhancement source for STEM subjects as discussed in 2.2.3. The STEM field has shown outstanding and productive research opportunities in XR research which are further implemented in Chapter 6. XR technology can be a practical resource for students to teach those topics or skill training where actual material is not affordable or not possible in the class setting.

2.3.3 Experiments Conducted to Evaluate XR Education

Most large-scale studies have conducted experiments using a control group and experiment group. The focus of the studies is to seek an increase in students' attention, get more relevance to the study topics, gained confidence and satisfaction compared to the traditional learning resources. Some studies are evaluated at a large scale, just like EARLS [134]. Figure 2.16

presented a comparison of subjects involved in evaluations for some important case studies.

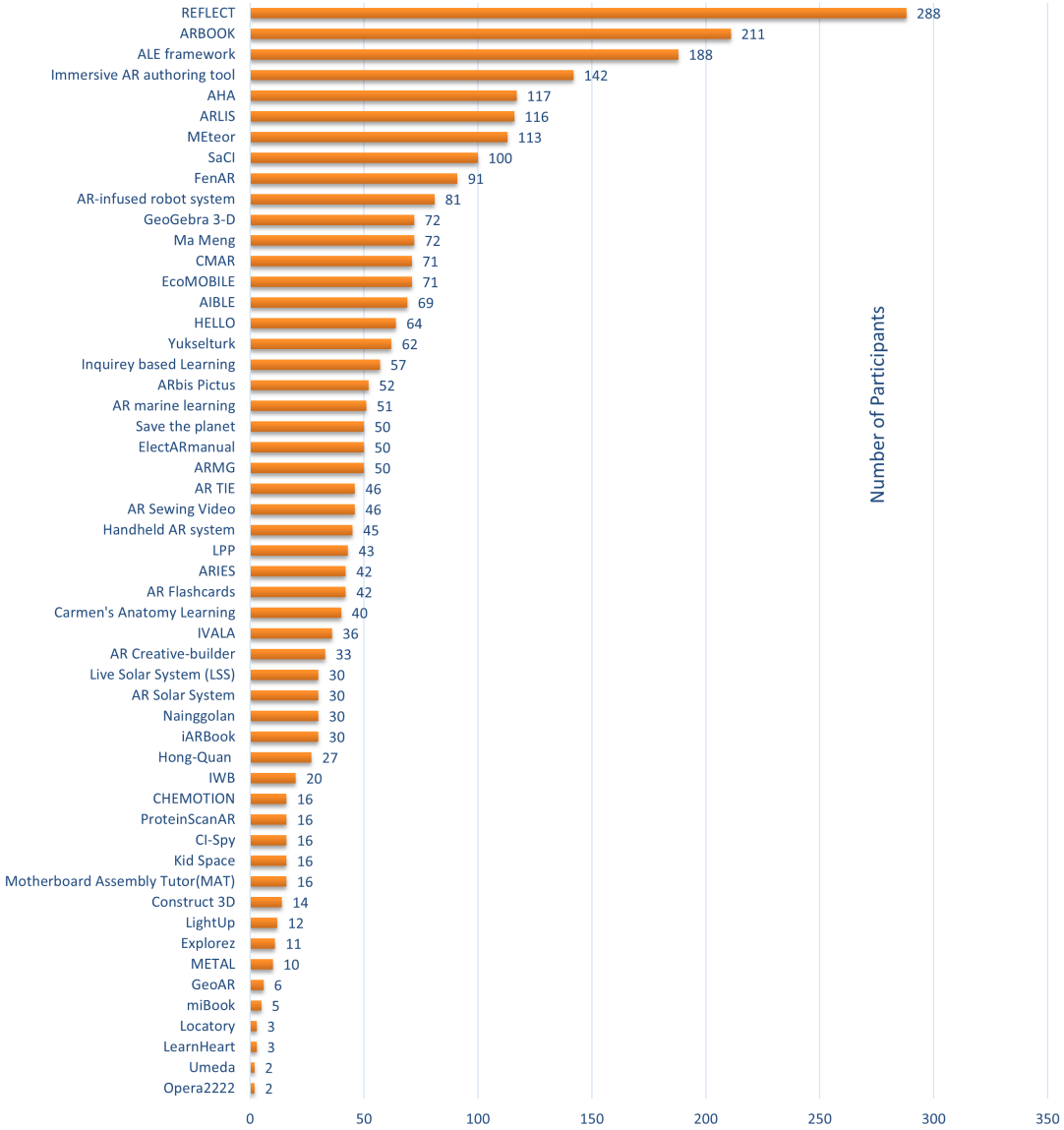


Figure 2.16: XR Studies analysis according to the scale of experiments (Participants)

2.3.4 Libraries Used

GPS has been used in location-based learning applications. Vuforia has been used as tracking SDK for most of the studies, just like [25]. ARKit, ARCore ARFoundation, EasyAR and AR.js are the other main libraries used for tracking. These are compatible with new series of high-end devices. In addition, there are lots of custom-made solutions used. In MR, MRTK (MixedReality Toolkit for HoloLens) is one of the most popular SDK for developing

mixed-reality experiences. Oculus SDK is popular in creating VR experiences. Unreal and Unity 3D game engine are mostly used as development platforms.

2.3.5 Devices

In the previous studies, desktop displays have been used as a major device for AR applications and further, become more prevalent in smartphones, and HMDs [302]. For VR & MR standalone headsets like Oculus Quest, Microsoft Hololens are getting popularity among users due to freedom of portability. However, with the saturation of smartphones and tablets, they are getting higher adoption rates due to portability, accessibility, and availability features. Specifically, in Secction 2.2.3, there is a higher possibility of using a smartphone due to the availability of personal devices.

Display Device Type	No. of Studies
Desktop	36
Tablets / Smartphones	22
HMDs	10
Web AR	5

Table 2.3: XR Studies Distribution According to Display Devices

Smartphones & tablets are the most reliable devices for AR in education due to affordability because the cost of good HMDs is much higher than smartphones. But now, HMDs are becoming more accessible and affordable, like Oculus Quest, one of the best standalone HMDs. Also, the legacy desktops are moving more towards smartphones and HMDs like Magic Leap & Hololens.

Based on the methodology presented in Chapter 5; case studies are presented for desktop displays in Section 5.2, handheld smartphones, tablets and HMDs in Chapter 6 with evaluation results in Chapter 7.

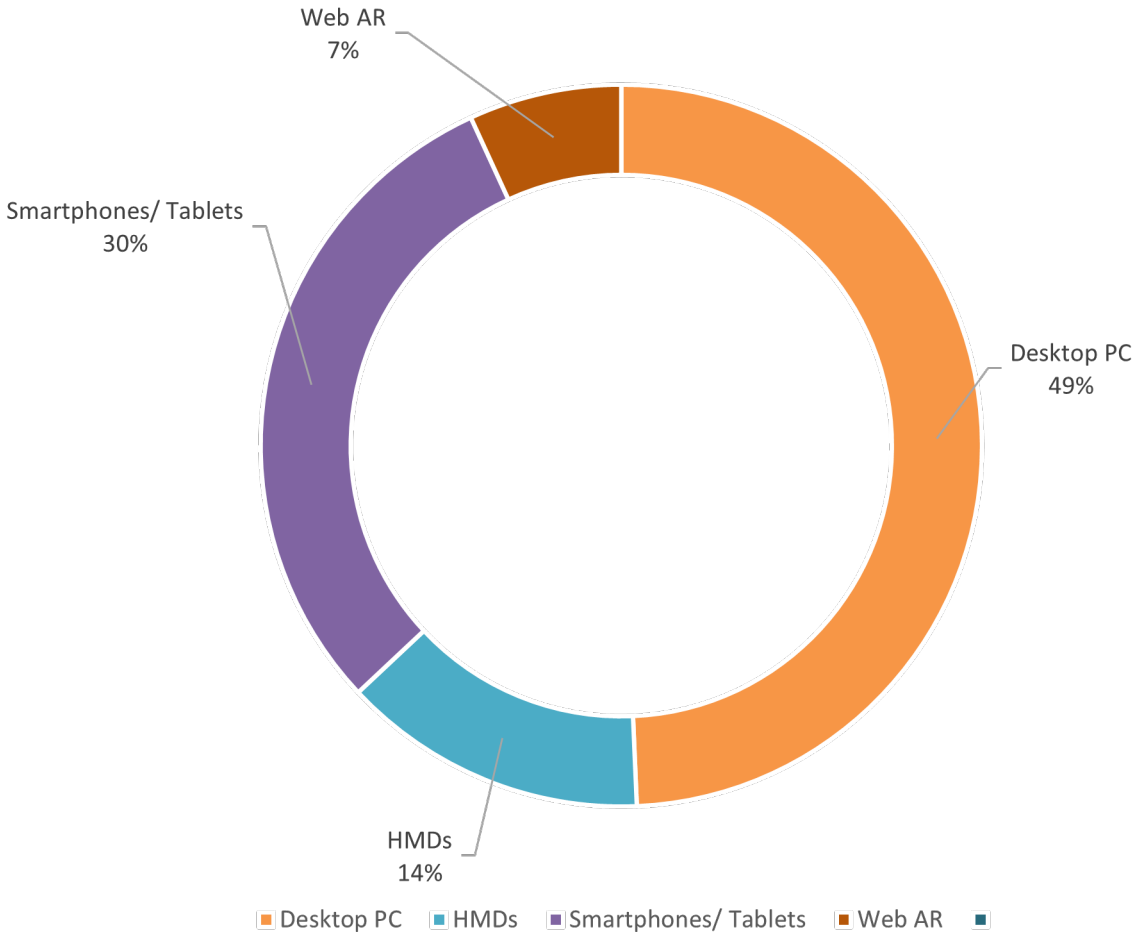


Figure 2.17: Distribution of display devices used in XR educational applications

With the addition of new abilities of hand tracking and rapidly growing updates in Oculus Quest design, it is becoming a popular and affordable device in HMDs.

2.3.6 Tracking

Most of the studies have used marker tracking implemented with Vuforia as *iARBook* [25], and recent studies started using markerless tracking with ARCore or ARKit (moved to plane tracking) in AR applications which allows the users to use the application in a plain environment instead of a specified marker. However, markers are still crucial in situations requiring high accuracy and tangible interaction with virtual objects. Studies involving location-based learning use GPS as field trips study [179] and learning mathematics [244]. For devices not supported by ARCore, ARFoundation with ARCore XR Plugin has been adopted to get a similar experience.

It is essential as AR conducted in the classroom requires good lighting conditions, which is not always possible in the classrooms. There is a lack of studies using the hand tracking technology; presented further with new methodology in Chapter 3.

2.3.7 User Interaction

Few studies in XR learning use hand tracking and gesture-based interaction. User interaction with different techniques has a vast opportunity to work in the future. The use of Kinect for anatomy learning is an excellent example [206]. There are opportunities to discover new forms of interaction, gesture versus real-time hand interaction (further discussed in Chapter 3), and possibilities of tactile learning. Leapmotion technology is not widely explored yet in AR learning applications. Recent innovations in the smartphone's machine vision-based hand tracking technology [137] is also a very recent opportunity to explore, which is still going through testing stages to get stability.

2.3.8 Collaboration

Collaborating with the other students and teachers in an XR learning setting is still not a focused area in the previous studies but is a crucial aspect of XR learning as outlined in Section 2.1.4.

There are few studies attempted for collaborative learning, like interactive simulation for learning astronomy [180], HELLO [185], EARLS by [134] and ARClassNote [67]. There is a need for collaborative learning in the remote learning setup where the teacher can access students and students can collaborate.

2.3.9 Agents

From all of the above studies discussed, there are only a few that have considered agents (as shown in Figure 2.14 with dotted line) presented in Section 2.2.10 like Kid Space [8] and [215] for problem-based learning. On the other hand, machine learning agents are pretty new and

have not been effectively implemented in any XR studies for education, discussed in detail in chapter 4 and Section 5.1.1. Experiments are required to demonstrate this logical next step in developing AR learning applications where agents can enhance the learning process hence outcomes.

2.3.10 Potential Future Benefits of XR in Remote Education

Immersive XR will get more adoption in the near future in higher education due to the growing accessibility of 5G technology and edge computing. XR usage in remote education and formal education, in general, is only in its infancy. This is the time when these issues need to be addressed so we can help to protect users in remote immersive learning.

XR due to its compelling features for learning; getting attention from researchers and policymakers across the world in different disciplines from formal to informal learning explained in Figure 2.18. New technologies come up with their own complexities but over time through multiple versions, evaluation of the technology acceptance approach brings a change in usability. XR in education can help with two approaches; technology-driven or learner-driven. In the technology-driven approach, the capabilities of the technology are used for the development of learning material while the learner-driven approach is focusing on pedagogical frameworks to improve them with technology integration.

Collaborative Learning: The broader use of XR devices and growing adoption can lead towards the creation of new potential for content authoring [81]. It can progress towards more sustainable open-source communities for collaborations to develop virtual world platform development [331]. This collaboration naturally feeds in the potential of XR remote education, where both teacher and peer can exist in a shared environment. This may take the form of a VR space but example devices like the Hololens within an AR space are more suitable for longer experiences.

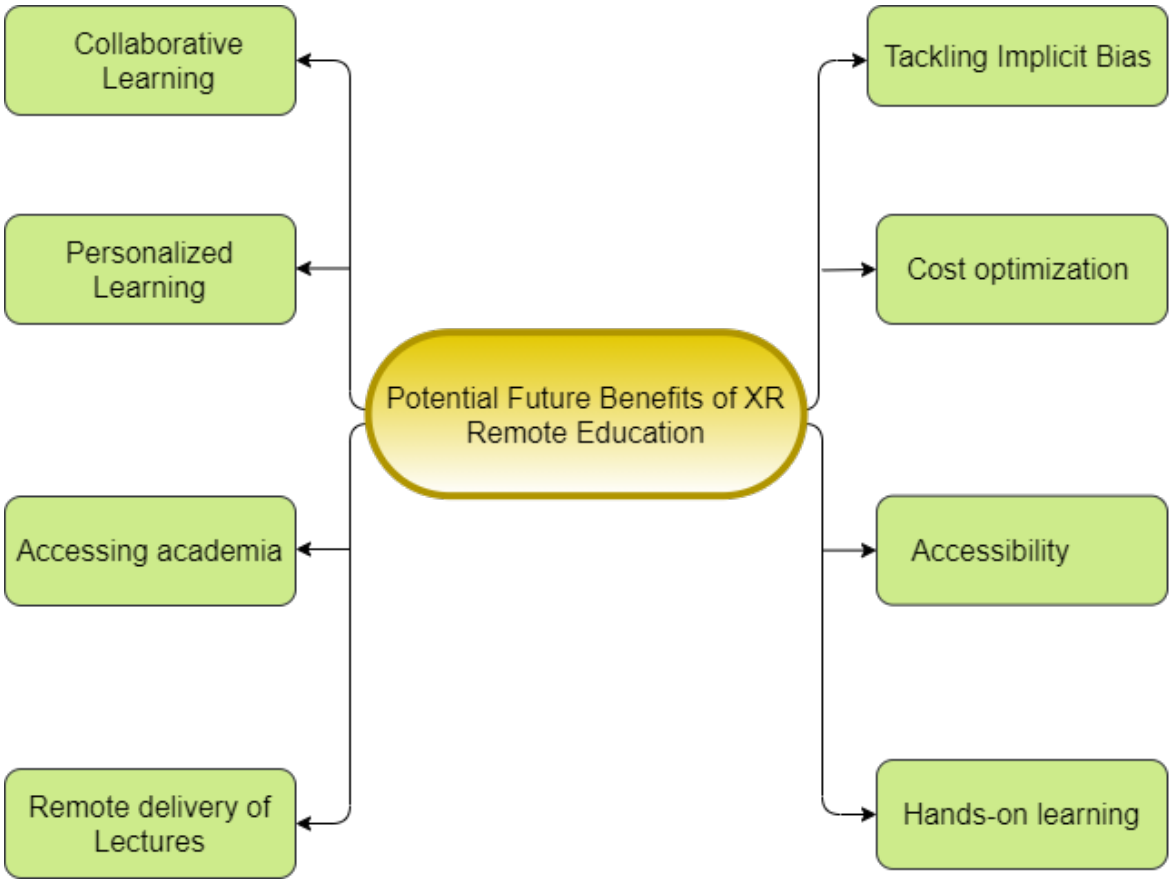


Figure 2.18: Potential Future Benefits of XR Technology in Remote Learning

Personalized Learning: When integrated with intelligent agents, XR can enhance evidence-based personalized learning significantly which reflects individual choices, preferences, performance, and effectiveness of the instructional design.

Accessing Academia: The rise of online conferences in VR, and the success of conferences like Immersive Learning Research Network (iLRN Virtual Campus) allow researchers and teachers from across the world to meet and discuss education online [194].

Remote Delivery of Lectures: Converting remote learning into a virtual classroom concept as in Figure 2.19, immersive VR has the potential which can move virtual learning closer to the real world environment [317].

Figure 2.19: Immersive Virtual Reality Classroom for Remote Learning [104]

Tackling Implicit Bias: One of the key tasks of educationists is to help nurture a student cohort that is both aware of implicit biases as well as taking steps to avoid it. With a virtual world where students can embody avatars of different races, ethnicities, and gender to help combat these implicit biases.

Cost Optimization: With the provision of virtual learning material, XR technologies are drastically lowering the cost of learning as compared to physical laboratories and costly scientific equipment. It also saves the maintenance and operational costs linked with physical laboratories which can make the use of XR much more economical in the long run.

Accessibility: XR technology as being a nascent technology can offer exciting equity and inclusion opportunities with a more diverse user experience. These opportunities include potential as an empathy tool, adapting to meet the accessibility needs of people with disabilities, and trying to minimize the barriers arising due to physical distance to enhance person-to-person interaction.

Hands-on Learning in Resource-Constrained Environment: In resource-constrained environments, immersive technology provides virtual learning material to learn skill-based learning or technical topics with the interaction ability of hand tracking [116].

2.3.11 Limitations

XR has been applied in education for visualization, annotation, and storytelling in STEM and early education. Still, there is a lack of intelligent agents, hand tracking, and especially real-time hand interaction needed for personalized and practicing hands-on learning for STEM subjects in resources constraint environments. The hand tracking technology with real-time hand interaction, touchless and gesture-based interaction is further presented in detail in Chapter 3 and for education in Section 3.3. The major contribution of this thesis presented in Chapter 5, 6, 7, is to address these research gaps and propose a system that can use a real-time hand interaction approach in an immersive environment facilitated by a self-guided learning approach using the agent-oriented approach. There are very few studies that have performed evaluations on a large scale. Despite the listed advantages, certain drawbacks should be considered when building educational solutions with XR: Some teachers may need the necessary skills to use these new technologies. There is a need for instructors willing to engage with new technologies and educational institutions to adapt their infrastructure with applications of XR in the classroom. Chapter 7 presented evaluation with the involvement of STEM teachers to engage the subject matters in the development and usability testing process. Hardware availability is a limitation for the uptake of XR in schools, but it is time for governments and policymakers to consider the investment in XR devices, given their long-term impact on knowledge retention and students' enhanced engagement with educational content and activities. Once the XR in education is well established, hand-tracking technology will also be explored in the emerging need for touchless interfaces and real-time hand interaction.

2.4 Conclusion

This chapter has provided a detailed overview of research studies tested in all levels of education based on different domains with new APIs, interaction capability, agency, and collaboration levels. From STEM to foreign language learning, immersive technologies are becoming effective and result-oriented tools in creating more interactive learning environments. In

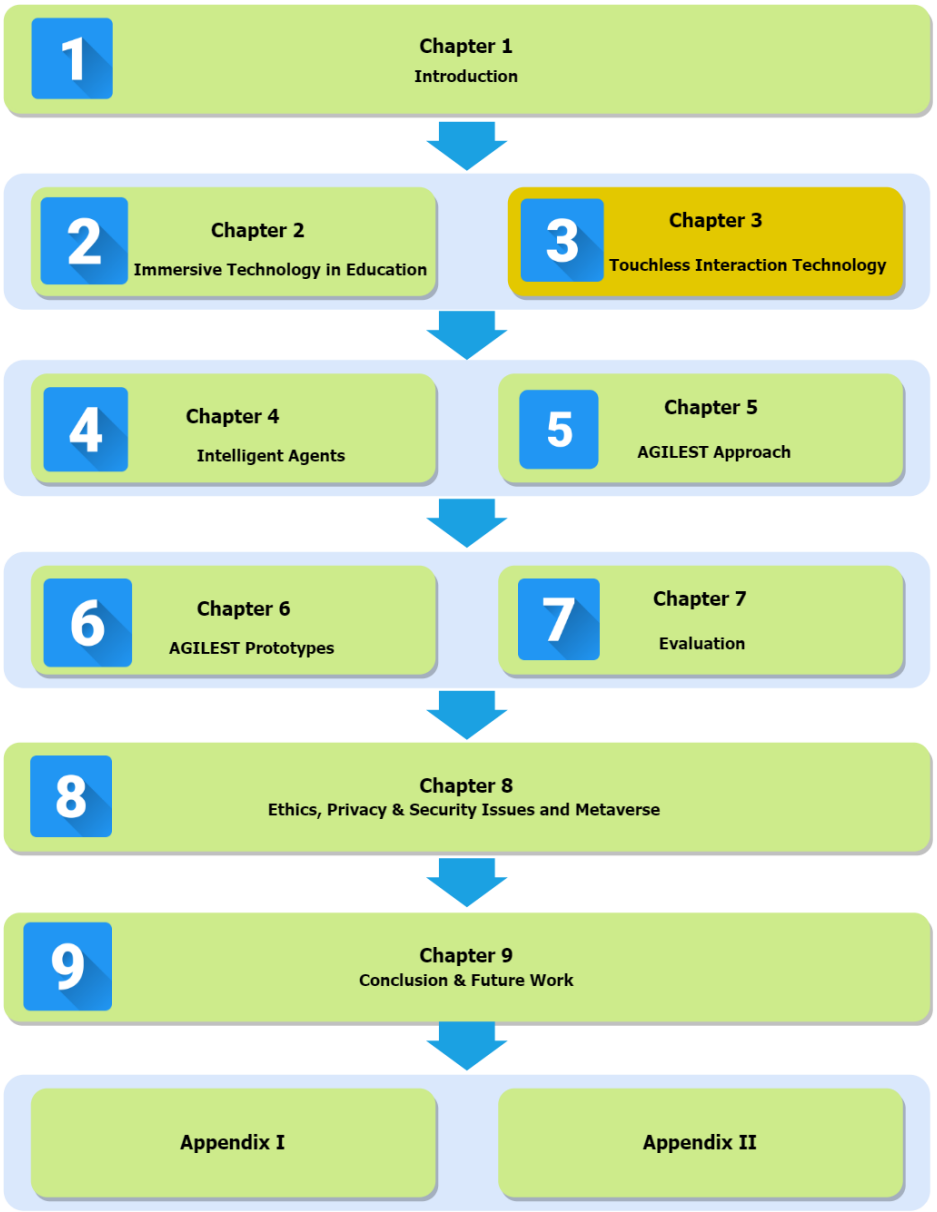
particular, XR enables more sophisticated, interactive, and discovery-based forms of learning. Of course, the portability and compatibility of the contents between devices matter; however, practically, it is impossible to provide the XR contents with the same quality on all devices.

The next logical step in XR-based learning discovered from reviewing the current literature is the development of applications that can enable self-guided learning and remote assessment, explained in methodology in Chapter 5. Future technology challenges are user acceptance, proving its educational effect, and further development of the frameworks to develop these innovative applications. In addition, as the cost of hardware and software decreases, AR technology will become more affordable and thus allowing it to be widespread at all educational levels. Virtual lab-based practical learning, where augmented objects can fill the need for physical material, allows the user to "learn by doing" even if they are in a deprived education system that cannot afford real physical learning materials. Based on the literature review findings and research gaps, this research has addressed the need to incorporate higher user interaction with hand-tracking and hand-interaction technologies that allow users to interact with virtual objects like physical ones, making the learning experience more immersive and engaging. This approach is particularly useful for science subjects such as chemistry, biology, or physics where learners can manipulate virtual objects to understand concepts better. The second major gap this thesis highlighted and proposed solution is the need to incorporate intelligent agents in immersive learning environments to make the future of immersive learning more user-centered and self-guided. To emphasize the higher level of interaction in virtual environments, the next chapters have presented new findings about hand-tracking technology. Based on the discussion about agents in Section 2.3.9, Chapter 4 provides a detailed discussion about intelligent agents and integrating the agent-oriented machine learning approach for reducing cognitive load and adopting self-guided learning in an immersive environment is presented in Chapter 5. This discussion is further developed to the AGILEST approach, its prototypes, and its evaluation.

CHAPTER

THREE

Touchless Interaction Technology



To extend the discussion about user interaction in Section 2.3.7, this chapter investigated touchless interaction technology, an emerging immersive technology needed for the future of digital interactions. Touchless or "freehand" interaction technology facilitates digital technology towards Zero User Interface (UI) [140], which can be considered a future interaction technology due to hygiene requirements in interactive digital devices. Zero UI enables user interaction with digital devices through hand gestures, hand interaction, voice commands, eye tracking, and biometrics such as facial recognition and contactless fingerprints. Smart devices, IoT sensors, smart appliances, smart TVs, intelligent assistants, and consumer robotics are great examples of Zero UI technology and are becoming more popular. These control interfaces provide a natural sense of interaction modes such as voice or gestures. This chapter will briefly discuss touchless technology and its potential in immersive learning environments.

3.1 What is Touchless Technology?

Touch screen technology is currently known as the most "interactive" technology, but this concept is changing now as the COVID-19 pandemic has encouraged to adopt touchless interaction technology like gestures, motion sensors, hand interaction, and screen takeover with personal devices for health safety. During the last two decades, touchscreen technology was the most dominating interaction technology in the world, but the COVID-19 crisis has changed the public's demand significantly and raised health safety issues in shared touchscreens. These touch-free interactions were already present around us but considered a luxury.

What is Zero User Interface (UI)

Zero UI means interacting with digital machines without physically touching screens or buttons [285]. In contrast with traditional Graphics User Interfaces (GUI), touchless hygienic interactions include technologies like voice control, remote mobile screen takeover, biometrics, and gesture control. With the new advancements in image recognition, sensors, and natural language processing, powered by advanced computer vision and deep learning, Zero UI is now becoming the future of interaction technology.

Taking this technology from automatic doors, toilets, sanitizing dispensers [77], faucets, and hand dryers to Apple's Face ID [16] and Visa's Tap to Pay, companies are pursuing innovative ways to make public places more convenient and more hygienic in the near future. Moreover, it has gained logical recognition as health-centric technology as it is now easy to understand the need for this technology in digital interactions, from vending machines [111] to identity checks at airports [173].

From gesture control to virtual keyboards [324], touchless technology is now helping retailers, museums, the travel industry, and other businesses and will continue to dominate in the future. The use of touchless interaction as learning technology has been discussed in the section 3.3. These solutions have created the foundation of the growing demand for touchless environments in the modern world, but these solutions were not designed for health and safety. For example, RFID was actually designed for asset tracking, identification of animals, and proximity cards such as IDs [30]. However, these touchless solutions need to be chosen correctly for their implementation to be functional and more productive. For example, RFID may be touchless but is only accurate to a few meters. Precise movements require technology such as gesture recognition and motion detection, which are more appropriate examples as automatic touchless soap & sanitizing dispensers become more popular, convenient, and easier to use when compared to their manual counterparts. In Section 3.2 of the chapter, different software solutions for touchless interaction have been discussed in detail according to their suitability with varying usage scenarios.

3.2 Types of Touchless (Contactless) Interfaces

Touchless technology is a type of interaction that does not need physical touch with digital devices to operate them. Different strategies are being developed using IoT devices that allow avoiding contact with digital devices to follow COVID-related hygiene policies. Different types of touchless technologies have been commonly employed to prevent touching digital surfaces;

- Screen Takeover, enabling users to control public screens with their mobile phones

- Live AR, enabling virtual interaction with Augmented Reality in the real world [141]
- Voice Control, interaction with virtual assistants using voice interaction
- Reactive Display, systems using motion sensors to enable interaction
- Eye Tracking, enabling interaction with screens using eye-tracking technology

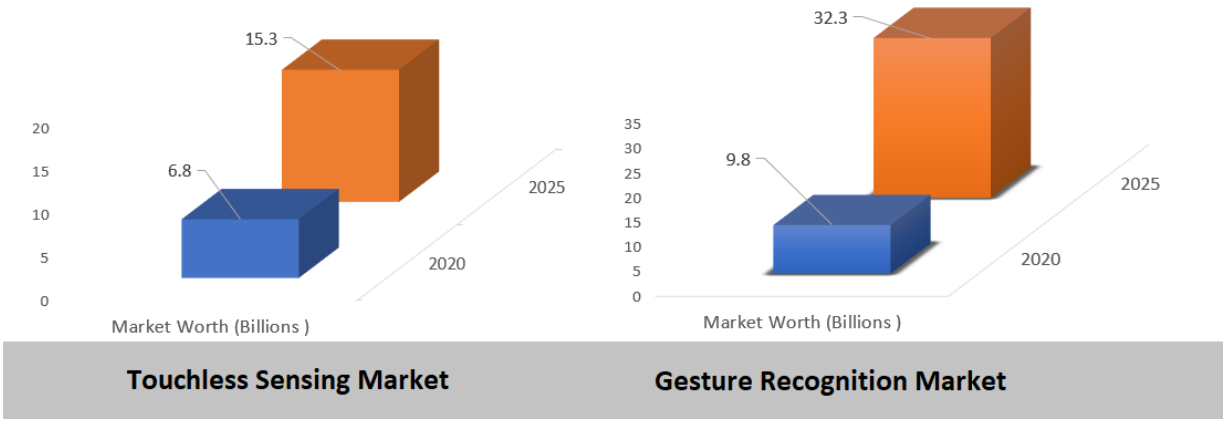


Figure 3.1: Projected 5-year increase in the Touchless sensing and gesture recognition market analysis

As graphs of Figure 3.1 explain, the touchless sensing market was estimated to reach USD 15.3 billion in 2025, from USD 6.8 billion in 2020 at a CAGR(Compound annual growth rate) of 17.4% and the gesture recognition market will grow from $9.8 billion in 2020 to $32.3 billion in 2025 [1]. Figure 3.2 explains the different touchless interaction technologies with their potential in various industries according to suitability, range, and scenarios.

This adoption has gained traction from different use cases of contact-free interfaces in the healthcare, education, and travel industry. The touchless gesture technology concept can vary widely: from simple gesture tracking to advanced real-time hand interaction. Gesture recognition and hand interaction technologies are commonly considered the same, but technically, these are different approaches. In addition, touchless technology varies depending on the input source. The range of different touchless technologies interaction is explained in Table 3.1.

[1] https://www.marketsandmarkets.com/Market-Reports/touchless-sensing-gesturing-market-369.html

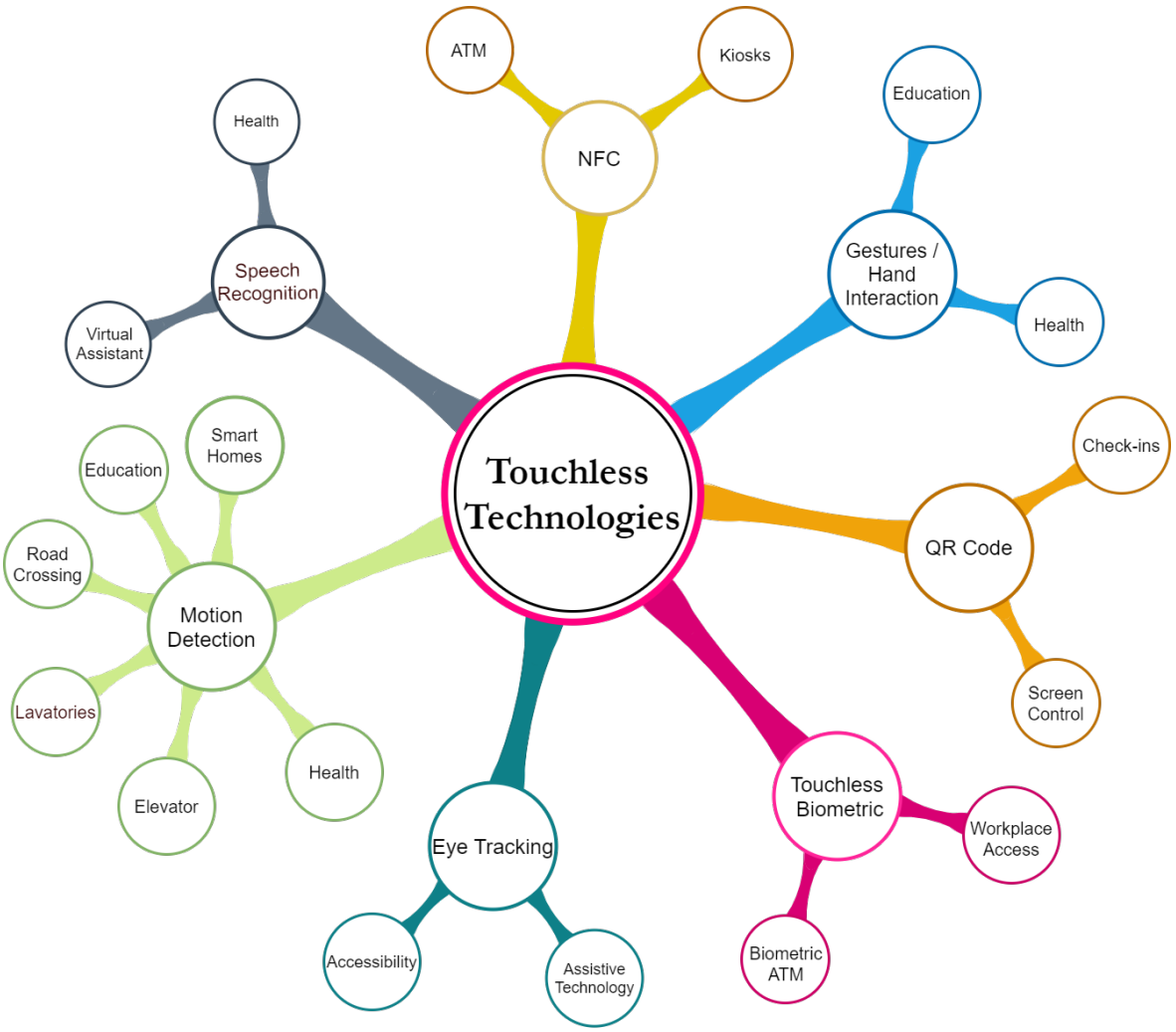


Figure 3.2: Types of Touchless technologies and their potential uses in different industries. This diagram is created based on the existing software and hardware solutions to enable touchless interaction

Technology/Device	Detection Range	Use Cases
Infrared	up to 10 meters (30 ft)	Doors, elevators, lavatories, health
NFC	10 centimeters	Payments
Personal Device	Depends on Wifi Range	Public Screens, smart homes
Leapmotion	25 to 600 millimeters (1 inch to 2 ft)	Education, Health
Microsoft Kinect	1.2 - 3.5 meters (3.9 - 11.5 ft)	Education, Health
QR Code	Depends on size of QR code	Kiosks, Payments, Screen takeover

Table 3.1: Types of Technology/Devices, Working Range and Use Cases

3.2.1 Personal Devices for Touchless Interaction

Touchless interaction is possible by using personal smartphone devices to allow for scanning QR Codes [109] for taking over a screen, connecting by Bluetooth and to pay using NFC.

Using mobile devices for proxemic interactions can help to stop the spread of infections [237]. This touch-free experience is actually very simple and intuitive to get control over screens without the need to download any applications. Many businesses are considering replacing interactive touchscreens with touch-free interfaces to provide a better customer experience and a more health-centric working environment.

3.2.2 Gesture Recognition & Hand Interaction

Hand gesture is a well-adopted touchless interaction allowing humans to interact with machines and it is the next level in the evolution of motion sensors. Devices like Leapmotion, kinect, Azure kinect and deep learning-based developments like Google Mediapipe[2] and Manomotion[3] provide the ability of gesture-based touchless interfaces or more enhanced real-time hand interaction. This section is further extended to Section 3.3 and major part of this thesis in methodology Chapter 5. Chapter 6 has presented two case studies that are using real-time hand interaction to provide a virtual chemistry lab experience.

3.2.3 Motion Sensing

The use of motion sensors as touchless interaction is the oldest touchless technology which is the most common and indeed it is the most affordable touchless technology. These sensors detect if a person is occupying a precise space. Motion sensing allows touchless interaction with different types of infrared sensors where sensors detect humans to activate the system operation

[2]https://google.github.io/mediapipe/
[3]https://www.manomotion.com/

like triggering automatic doors, hand dryers, taps, and lights. Table 3.1 explains the range of these sensors.

3.2.4 Eye/Gaze Tracking

Eye tracking is the process of measuring the motion of eyes with eye trackers. Eye tracking technology is not new, it has a long history and is now an important tool in many domains [51]. Use of eye tracking as touchless technology adopted in Tobii Rex. It used a pair of infrared sensors to track the user's eyes allowing interaction with computers like with a mouse cursor [178].

3.2.5 Touchless Typing

Touchless typing allows typing with a keyboard or keypad without touching it physically. It is mainly known as a unique assistive technology to enable the operation of standard electronic equipment or typical computers. Just like Airwriting technology that allows writing text messages or composing emails by writing in the air [7].

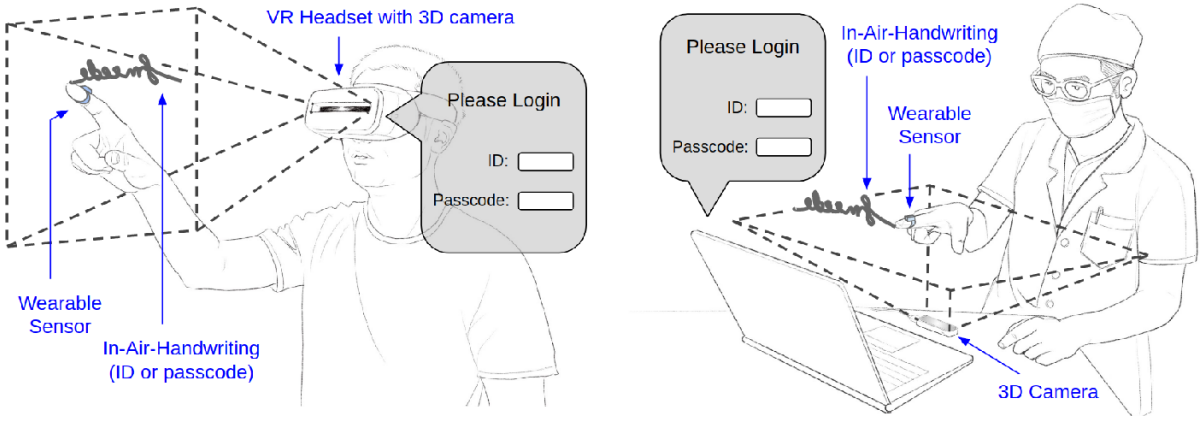


Figure 3.3: Airtyping concept [7]

3.2.6 Contactless Payments

Contactless card payments using Radio Frequency Identification (RFID) technology and the use of Near Field Communication (NFC) technology allow contactless payments with the kiosks, exchanging digital contents and shopping centers [196]. Moreover, it works within a 10 cm radius as a better security option, making it more ideal for secure data exchange. Like a teacher logging on using NFC card, a customer making a payment with Google Pay, or creating a contactless interaction for a shared or public device.

3.2.7 Voice Control / Virtual Assistant

Interaction with digital devices using vocal instructions or voice commands is a form of touchless interaction technology used in Amazon Alexa, Google Home, or Apple's Siri, which is widely adopted in robots as well. Voice recognition technology uses Natural Language Processing (NLP) [247], which enables computing machines or programs to recognize spoken language and, as a result, understand and carry out voice commands to perform different tasks. The technology giants behind voice assistant technology are working to create a more accessible, branded experience for consumers in healthcare and the auto industry.

Figure 3.4: Amazon and Google Voice Assistants Echo Dot & Google Home

Voice and gesture control primarily apply in different fields for specific tasks, but it is getting into more diverse industries. Digital interaction in public shared spaces in every field of life, such as in health, education, workplaces, travel, and social life, touchless technology has gained real attention to become potential future interaction technology. Section 3.3 has provided a review of touchless technologies in educational applications and its potential future with new developments.

3.3 Touchless Technology in Education

Education is one of those fields which was affected massively due to the shutdown of education institutes during COVID-19. It created a need for safety in shared learning spaces and empowering learning technology in personal spaces. It also created a need to redesign classroom settings where touchless technology can play a role in solving the new hygiene policy requirements in the new normal [103]. The use of sensor technology in mitigating COVID-19 can help in the future to minimize human contact with potentially contaminated surfaces and objects in educational institutes [135]. This raises the question of a potential new goal in the future where completely touch-free interactive learning experiences are possible for students. Different interaction techniques have been testing AR, VR, and MR applications which include the use of tracking markers, body tracking, voice, and gestures [76] and some other case studies in the Section 2.2.3; but there is very limited research about real-time touchless hand interaction which can help to implement the effective kinesthetic learning approach for technical subjects. This research gap ties into the future direction of tracking and user interaction in the further research process. In touchless hand interaction, there is nothing to hold in your hands, no buttons to push, no need for a mouse, keyboard, or touching the display screen or tablets; it all works with the help of a depth sensor camera, motion sensor camera, infrared technology and machine learning algorithms which help to interact with the digital contents.

There are research studies using kinect [327] and leapmotion tested gesture-based touchless interaction with learning objects. Hololens provides gesture-based interaction with the 3D

environment, as it has been used for vocabulary learning approach [136]. Kinect and leapmotion devices are working only with desktop displays and hololens is too costly to afford as a personalized learning solution.

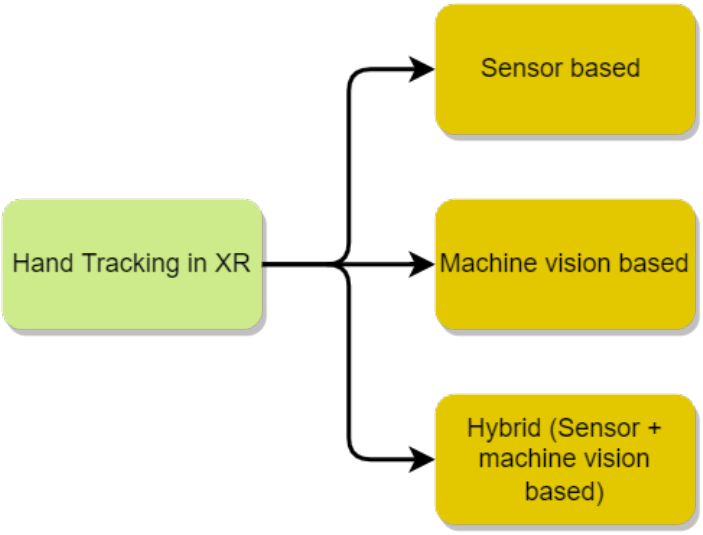


Figure 3.5: Types of hand tracking in XR devices

The current shift of the learning spaces is moving towards more independent, affordable, and portable, where personal devices can be the top priority for learning technology. Recent development of the Google mediapipe [4] [189] and Manomotion [5] for hand tracking in smartphones has opened new opportunities for touchless interaction technologies on the affordable devices.

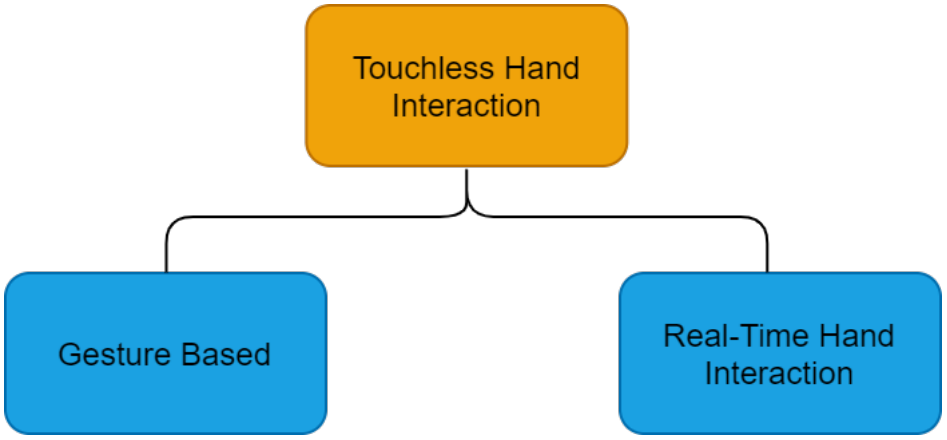


Figure 3.6: Types of touchless hand interaction in AR

[4]https://mediapipe.dev/
[5]https://www.manomotion.com/

Google mediapipe has been further expanded in different Web XR platforms for hand tracking.

Touchless interaction by hand tracking technology is of two types as visualized in Figure 3.6 ; interacting with gestures and real-time hand interaction with the virtual objects. Real-time hand interaction has way better interaction capability as compared to gesture-based interaction as it allows full hands-on working just like in the physical environment and allows users to play with the virtual objects just as real.

	Tracking Device/ SDK/API		Initial Release Date	Type of Interaction
1	Oculus Quest		Early 2020	Gestures & hand interaction
2	Google media Pipe	MediaPipe	August 19, 2019	Gesture-based interaction
3	Hololens 2		February 24, 2019	Gesture-based interaction
4	Magic Leap		August 8, 2018	Gesture-based interaction
5	ManoMotion	MANOMOTION	September 2017	Gesture-based interaction
6	Hololens 1		March 30, 2016	Gesture-based interaction
7	LeapMotion		July 22, 2013	Allow gesture interaction and hand interaction
8	Kinect		November 4, 2010	Gesture-based tracking

Figure 3.7: Devices/ APIs used in augmented reality for interaction to allow hand tracking and gestures

Figure 3.7 shows the different available hand tracking APIs & devices which are providing

real-time touchless hand interaction or gesture-based interaction ability to the user for interaction in virtual and augmented environments. Figure 3.7 shows different APIs and devices which provide hand-tracking functionality in XR environments.

The difference between Hololens 1 and Hololens 2 is that Hololens 2 can provide full real-time hand interaction which is limited to gestures only in Hololens 1. Practical exploration of leapmotion is presented in Section 5.2, Manomotion hand tracking in Section 6.1.3, and Oculus Quest in Section 6.2.3 and evaluations conducted with expert reviewers are presented in Chapters 6-7 with complete results and analysis.

3.3.1 Kinesthetic Learning

Kinesthetic learning is a form of learning which allows the user to "learn by doing the task" [26] instead of reading, listening, or watching. Particularly in the STEM (Science, technology, engineering, and mathematics) subjects, this learning approach is required to help students in learning technical concepts.

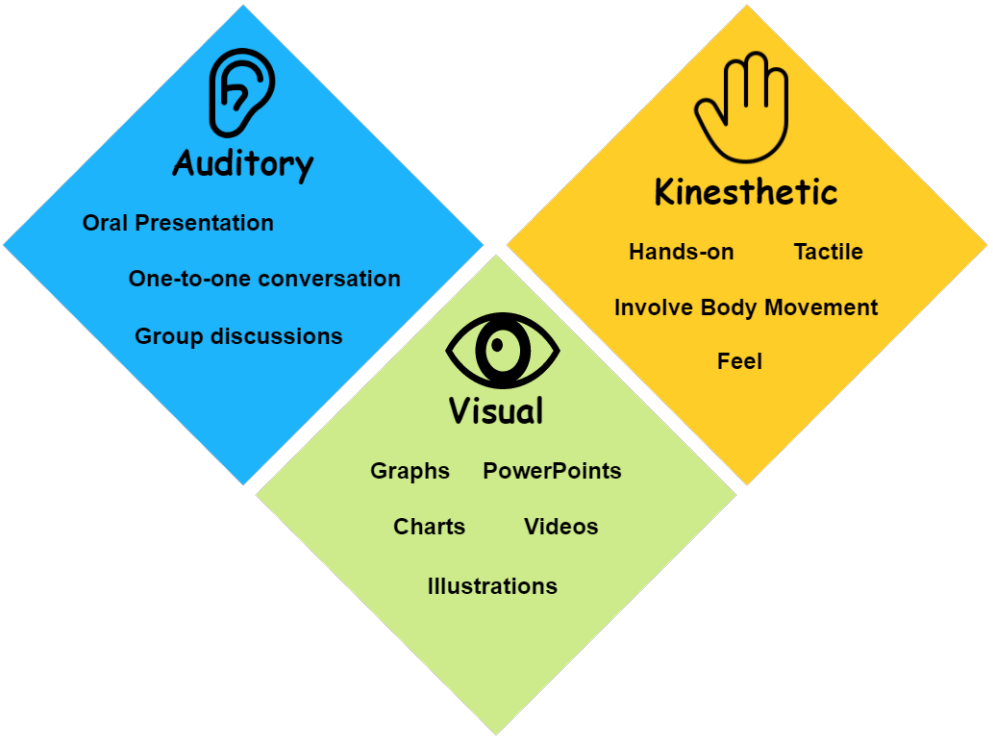


Figure 3.8: Different Learning Styles; Auditory, Visual and Kinesthetic, explained by [124]

Those subjects where practical learning is involved, have many challenges for both learners and instructors where access to hands-on experiences is sometimes not possible due to access to resources or mobility issues. When considering remote learning for technical and scientific topics, the use of hands-on learning activities is preferred for acquiring better knowledge. A kinesthetic learning approach with touchless hand interaction can bring this power to AR learning. It can positively impact learning and skills acquisition when integrated effectively. To implement a kinesthetic learning approach in immersive learning environments, real-time hand interaction with the 3D objects is required, providing user interaction ability.

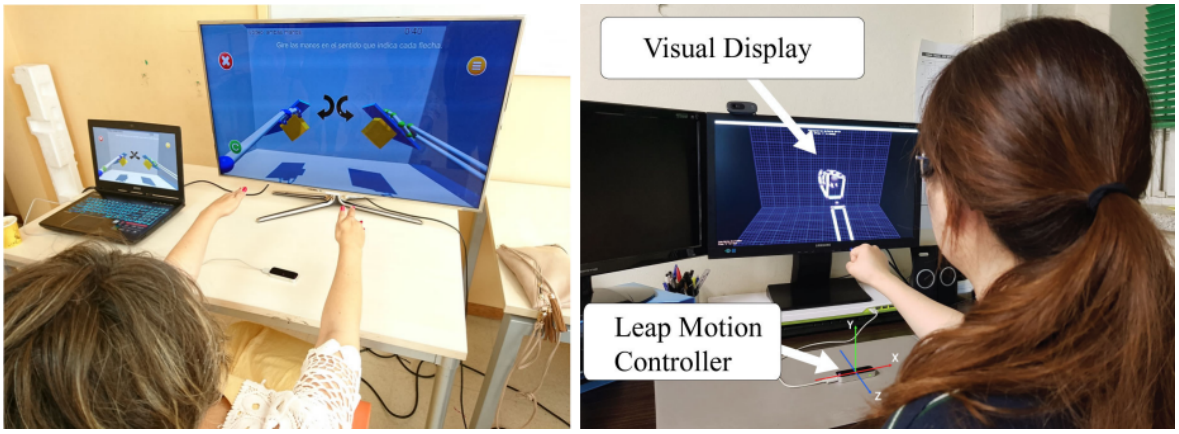


Figure 3.9: Touchless hand interaction technology using leapmotion [96] (ii) Using leapmotion touchless hand interaction hand for learning American Sign Language [68]

One possibility is XR which provides touchless interaction using leapmotion [142], microsoft kinect [174], azure kinect [289] and the latest SDKs as described in Section 2.2. It allows for embodied digital learning apps with motion and hand tracking cameras which enables interactions with 3D learning material like a remote laboratory [1] and allows avoiding touching physical learning materials. Table 3.2 presents the studies that used simple gesture recognition or touchless hand interaction in the different XR learning applications. In Chapter 5, a detailed methodology has been presented for XR learning applications combining the touchless hand interaction and Intelligent agents. The use of XR technology goes beyond STEM subjects; for instance, improvements in teaching literacy skills have been demonstrated [291]. But this research is focusing on STEM subjects due to a higher demand for hands-on learning or "kinesthetic learning" in these subjects.

Authors	Domain	Device/API Used	Interaction Type
Sun, Minghui, et al. [284]	Early School	Leapmotion	Gesture Recognition
Nainggolan, et al. [216]	Anatomy Learning	Leapmotion	Gesture Recognition
Le, Hong-Quan et al. [172]	Geometry Learning	Leapmotion	Gesture Recognition
Nicola, Stelian, et al. [223]	Anatomy Learning	Leapmotion	Gesture Recognition
Yukselturk E et al. [322]	Language learning	Kinect	Hand Interaction
Cai, X., et al. [45]	Learning Game	Leapmotion	Hand Interaction
Deb, Suman et al. [79]	Boolean Logic	Leapmotion	Gesture Recognition
Selleh, et al. [265]	Anatomy Learning	Leapmotion	Hand Gestures
Kourakli, Maria, et al. [163]	Learning Game	Kinect	Hand Interaction
Ma, Meng, et al. [193]	Anatomy Learning	Kinect	Gesture Recognition
Sivaramakrishnan, KR et al. [275]	Radiology procedure	Leapmotion	Gesture Recognition
Umeda, Ryosuke et al. [295]	Anatomy Learning	Leapmotion	Hand Interaction
Daineko, Ye A., et al. [75]	Learning Physics	Leapmotion	Gesture Recognition
Raziq, N. and Latif, S. [248]	Sign Language learning	Leapmotion	Gesture Recognition
Al-Khalifa, Hend S [3]	Chemistry	Leapmotion	Gesture Recognition
Yusof, CS et al. [323]	Interactive Play	Leapmotion	Hand Interaction
Chuan, Ching-Hua, et al. [69]	Sign Language learning	Leapmotion	Gesture Recognition
Kim, Minseok et al. [160]	3D object Interaction	Leapmotion	Gesture Recognition
Moro, Christian et al. [212]	Anatomy Learning	Hololens	Gesture Recognition
Hanna, Matthew G et al. [120]	Anatomic pathology	Hololens	Gesture Recognition
Seif, Mohamed Atef et al. [263]	Anatomy Learning	Leapmotion	Hand Interaction

Table 3.2: Research studies using touchless hand interaction and gestures in the learning applications

The use of immersive technology to create digital content for learning science and technical topics developed with marker-based, markerless, or GPS tracking technology has shown

exciting results [274]. In addition, interaction techniques with virtual objects in immersive or real environments provide enhanced interactiveness, and better engagement in the learning process [62]. For interaction in AR applications, several different types of sensors and input devices can be used, including GPS, gyroscopes, accelerometers, compasses, wireless sensors, touch recognition, speech recognition, gesture recognition, tracking markers, hand tracking, and eye tracking. In addition, new developments in AR, VR SDKs and APIs have allowed for an increasingly more productive AR experience in educational applications by providing more interaction and empowering the end users.

There are multiple studies conducted with hand gestures and hand interaction in XR for anatomy learning for medical students, like; using leapmotion tracking SDK [216] [163] [295] [263] [223] and also with the Microsoft kinect for full body tracking [193]. It involves the interaction with 3D anatomy models to enable students to learn with better understanding without having physical models. These studies enhance the capability of user interaction with hand-free interaction for learning anatomy. Use of gesture recognition tested for early school children for simple interaction with virtual objects [284] and the learning games [163]. Along with this, some hand interaction work is also found with leapmotion for 3D learning games [323] [45]. Using different gestures helps to create a more interactive play environment. Some studies have also shown effective results of using hand gestures in learning sign languages [248], [69], [322]. Indeed sign language learning is one of the perfect case studies for the gesture recognition approach. Hand-tracking in chemistry has been tested using the leapmotion gesture-based approach [328] [3]. For learning geometry by interacting with 3D shapes, gesture interaction was introduced with leapmotion, which helped to increase the interaction with learning objects in the virtual space [172]. Similarly, another study used leapmotion gestures for learning Boolean logic [79], and found meaningful interaction with the 3D environment. Kim et al. tested leapmotion gestures for interaction in smartphone devices by sending gesture data from the desktop system to the smartphone using a network connection as leapmotion, although it is not providing SDK for smartphones [160]. It has created meaningful interaction in smartphones to a certain extent, but it depends on the desktop PC network connection due to compatibility

issues. In collaborative learning, AR with hand gestures and real-time hand interaction create possibilities for achieving touchless learning environments.

Use of hand interaction technology in immersive learning, including haptic feedback and gesture recognition can empower the immersive experiences with kinesthetic learning approach. This can help to provide learners with more interaction capability and engagement in immersive environment. Active involvement of learners to manipulate virtual objects and physical engagement with environment using hand interaction technology can make the learning process more closer to realistic interactions. The recent changes in the learning environments, challenges with traditional learning and access to advanced technology have created new opportunities for developing more interactive technologies infrastructure to address these challenges. By combining the latest developments in sensor technology and artificial intelligence, the future of touchscreen technology will be touchless [207]. According to Sensorimotor embodied cognition theory [100], actions and gestures both are important types of movements linked thinking and perception in an environment. An action is always goal-directed, which is connected to real-time hand interaction in immersive technology, while gestures are primarily used to communicate with the system. In immersive technology, hand interaction is definitely a more powerful approach, but it needs more mobility and effort to create realistic interaction.

All types of touchless technologies, including IoT sensors [294], gestures, real-time hand interaction [**?**], and NFC will be part of that future. Seeking the best interaction will be the developers goal, and so regardless of the differences between technologies, the benefits of improved safety and convenience using touchless technology will become standard across all industries. For ubiquitous touchless access, technologies will still be under constant development, for example, research on crafting millimeter wave solutions for touchless systems promises to provide large performance benefits compared to current systems. As the touchless trend continues to surge, now is a fascinating time to explore touchless technology options and build a strategy for the future. Eye tracking technology is not much explored yet as touchless interaction technology [85], but it can be a potential option for creating touch-free interfaces.

It is time to look towards new solutions as touchless technology is an evolving process. For example, the innovation in eye-tracking technology for the effective use of eye patterns can bring new interaction techniques as standard features in new-generation smart devices for human communication. Furthermore, the recent progress in hand-tracking technology with deep learning can become more realistic without the need to wear any sensors. The high initial cost involved with touchless technology products and their implementation is the major bottleneck with its adoption, but it will decrease with time.

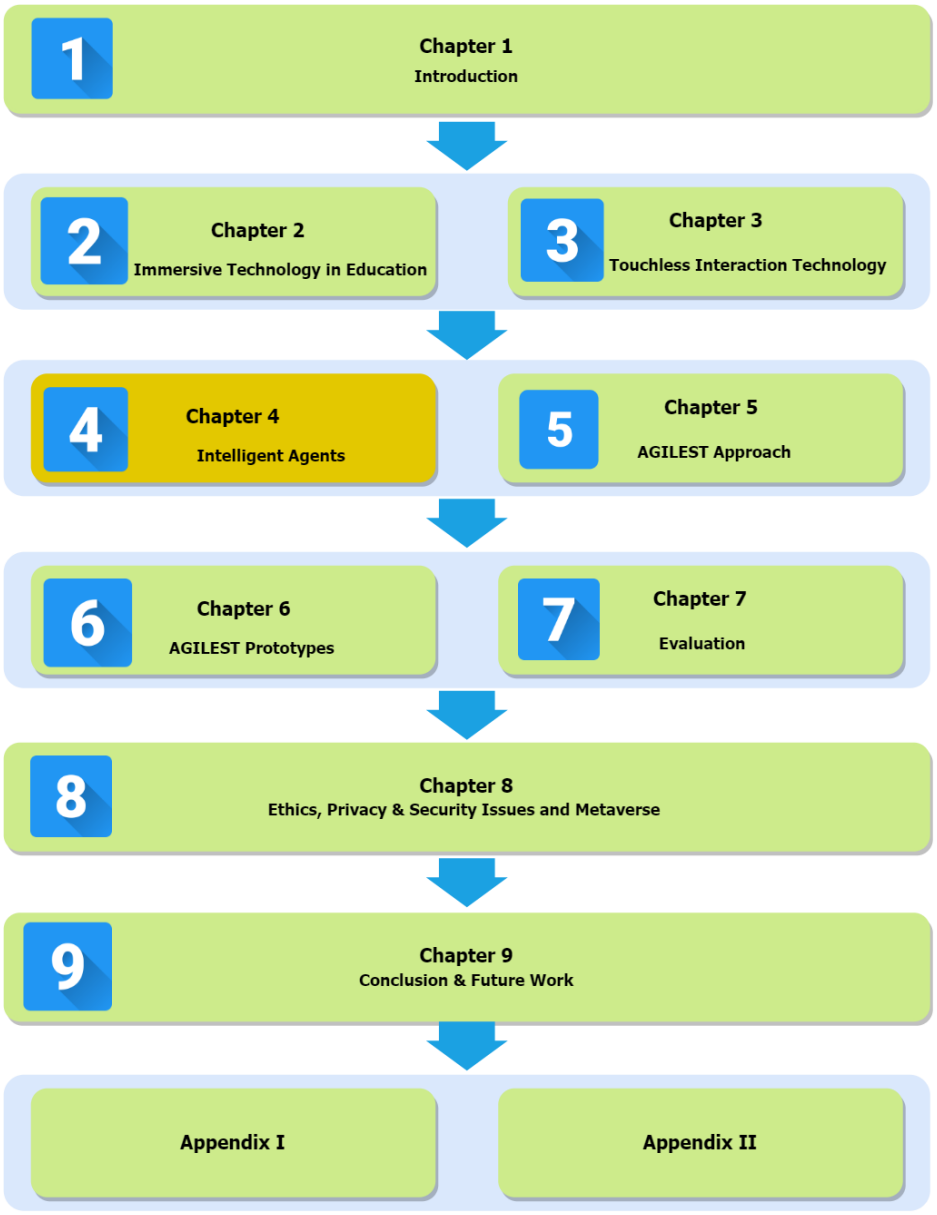
3.4 Conclusion

This chapter has discussed the importance of touchless interaction technology and the opportunities it can bring in learning technology with increasing adoption to make learning environments more hygienic and interactive. Section 3.1 provided an overview of the recent development in touchless technology with the Zero UI concept and outlined the crucial role it will play in our future interactions with digital devices. In Section 3.2, different available solutions for touchless interactions are presented. With the rise of ubiquitous computing, where every object around us could potentially have the computational capability to a certain level, it will change people's perceptions of how they interact with technology. The COVID-19 crisis has created an awareness of the potential invisible risks linked with physical touchpoints, and the goal of touch-free interaction has become paramount for all major industries where human interaction is involved. Using enhanced versions of hand-tracking technology and other touch-free interaction methods in virtual environments will create new pedagogical approaches in learning technology. Based on the review of touchless interaction technologies presented in this chapter, the subsequent chapters have provided practical implementation and exploration of new devices and APIs in Chapters 5-7.

CHAPTER

FOUR

Intelligent Agents



The use of intelligent agents in immersive learning is one of the major components of this thesis. This chapter will provide detail about intelligent agents and the specific context of applying these agents in this thesis. The use of intelligent agents or agent-oriented approaches is one of the most vibrant areas of research emerging in recent years.

4.1 Defining an Intelligent Agent

Defined by Jennings and Wooldridge (1995), an Intelligent Agent (IA) is an autonomous entity capable of observing, analyzing, and responding to an environment using sensors and actuators to achieve the expected objectives [148]. In addition, as explained by Michael Winikof et al. (2001), the IA possesses coordination, integration, mobility, and assistance to achieve the desired goal [305]. An agent program is a tool or process that supports intelligent agents' implementation. IA can respond to results in coefficients or feedback components, which affects eventual actions (Russel and Norvig (1995) [255]. Intelligent agents are also called a bot, which is a short form of robots [231]. As an IA can make decisions or perform services based on its environment, user input, learned behaviors, and experiences; it can autonomously gather information on a regular, programmed schedule or when prompted by the user in real-time. Examples of intelligent agents in AI include driverless cars [53], and the Siri virtual assistant [232].

The concept of agency is now broadly used in computer programming for specific characteristics and, more abstractly, as a new metaphor for analyzing, specifying, and implementing complex software systems [71]. But, of course, different kinds of agent characteristics and sophisticated features are always needed to make them work intelligently in their environments. Among the two main properties of an agent, autonomous and situated, according to Muller (1996), autonomous means that agents are independent and can make decisions on their own that distinguish them from objects [213] [107]. When considering a system consisting of several agents, then a consequence of the agents being autonomous is that the system tends to be decentralized [93] To facilitate rapid prototyping in intelligent agents, Collier and O'Hare

developed *Agent Factory* [73]. Agent Factory is a tool that promotes communication between agents using Agent Communication Languages (ACLs).

The situatedness property does not constrain the notion of an agent very much, as virtually all software can be considered situated in an environment. An agent-oriented system can be used where the environment is challenging; more specifically, typical agent environments are dynamic. These environments are dynamic to respond to changes in the environment rapidly. Rapidly means that the agent should not consider that environment will remain static when trying to achieve a goal. In particular, this means that an agent must respond to significant changes in its defined environment [17].

According to Etzioni Daniel (1995), agents are required to be reactive, which means they must respond promptly to changes in the environment. Another essential property of agents is to pursue goals over time, making them proactive. Finally, one property of agents is that they are persistent, making agents more robust and allowing them to continue attempting to achieve a goal despite failed attempts [91].

4.2 Why Agents are Useful?

There are a variety of applications where agents are useful because of their ability to provide a flexible and modular way of implementing intelligent systems which can have the capability of interacting with the environment and performing different tasks autonomously. To understand how agents are useful, there is a need to know how the distinctive features of agents translate into properties of software systems designed and built using the agent. The primary relationship of usefulness depends on the application, which means it is essential to understand these software-system properties are relevant to application types [308]. According to Wooldridge (2003), anything which can make decisions, either a person or a piece of a program, can be a rational agent [309]. These rational agents always have an environment that has another agent. Because these agents can learn and process things hence known as intelligent agents. For learning technology, agents are useful for several reasons, which include:

- **Personalization:** Agents in learning applications can be used to personalize the learning experience for learners according to their needs, preferences, and progress [313]. Considering the student's level, the agent allows for adapting specific content and pace for the delivery of instruction. The inclusion of agents in the learning process can help students to achieve learning goals more effectively with better learning outcomes [29].

- **Engagement:** Agents can help to develop interactive and engaging content to make the learning process more effective as compared to traditional lecturing styles. By using multimedia, simulations, and games, agents can make learning more enjoyable and memorable.

- **Feedback:** Using agents in learning applications can help to provide immediate and constructive feedback to learners. This feedback can help to identify strengths and weaknesses to improve learning performance. By providing feedback on specific aspects of their learning, such as grammar, vocabulary, or pronunciation, agents can help students improve their skills more efficiently.

- **Flexibility:** Agents can provide learning opportunities without constraints of time and place, anytime and anywhere, making it easier for students to fit learning into their busy schedules. According to Zhao, Leon (1998), recent advancements and future developments are increasing flexibility in software systems with intelligent agents [329]. For learning applications, agents can be used for a variety of devices, including smartphones, tablets, and laptops which can provide device independence for students.

- **Data collection:** To measure student learning gain and performance, agents can collect data that can be used to improve the learning experience and personalize content. Agents can be used to track students' progress and behavior to provide insights about students' learning.

4.3 Rules of Agents

An intelligent agent must possess these rules (Wooldridge, 1999) [307] as explained below:

1. It must have the capability to perceive the environment.
2. It needs to collect observations from the environment, which are needed to make decisions.
3. The decision means taking action based on the collected observations according to policy.
4. AI agents must take rational actions to maximize performance and deliver the best positive outcome.

4.4 Types of Agents

There are different types of intelligent agents, defined according to their range of capabilities and intelligence levels:

4.4.1 Reflex Agents

According to Frederick Mills and Robert Stufflebeam (2005), reflex agents work in the current environment and respond using the Event Condition Action (ECA) rule [208]. This rule applies when a user starts an event, and the agent goes to pre-set rules and conditions that provide pre-programmed outcomes. A reflex agent is an AI agent which takes actions to respond to its environment by using a simple mapping between sensory inputs and environment [208].

4.4.2 Model-based Agents

Model-based Agents have a more comprehensive view of the environment when compared to Reflex Agents. The environmental model is programmed into the internal system by

incorporating the agent's history. These kinds of agents are more flexible and adaptable when compared with reflex agents. However, model-based agents are computationally expensive and need more resources than reflex agents. David and Shaul (1998) explained the interaction strategy of model-based agents as "need of less number of interactions and using more computational resources" [50].

4.4.3 Goal-based Agents

Goal-based agents build on goal information or data about expected outcomes and situations collected by Model-based Agents. According to Frederick Mills and Robert Stufflebeam (2005), there are three main components of a goal-based agent: a goal formulation component, a problem-solving component, and an execution component. The goal formulation component of the agent is mainly responsible for deciding the agent's objectives or goals [208]. The problem-solving component of the goal-based agent uses a variety of techniques to achieve the agent's goals. The execution component executes the plan provided by the problem-solving component. Goal-based agents are effective in situations where the objective of the implementation is well-defined, and there is a clear understanding of the environment in which it has to work [268].

4.4.4 Utility-based Agents

Compared to goal-based agents, utility-based agents provide measurement as an extra utility [208]. This measurement means rating each possible scenario according to the desired result and selecting an action that can maximize the required outcome.

4.4.5 Learning Agents

Learning agents have an additional learning element that can gradually improve to become more knowledgeable about an environment over time [214]. In addition, the learning component in

the agent provides feedback which helps to decide how performance should increase for more improvement.

4.5 Properties of Intelligent Agents

According to IBM intelligent agent strategy [108], there are three attributes to measure the system properties of an intelligent agent system: agency, intelligence, and mobility, as explained in Figure 4.1.

4.5.1 Agency

The degree of independence that an agent exhibits. It concerns the resources and services that agents depend on and can work without availability (IBM intelligent agent strategy [108]). When talking about AI agents, agency refers to their ability to work independently without relying on human input or guided support, or other specific other resources. Agents that exhibit a very higher level of independence are considered more robust and flexible, with resistance to changes in their environment or dependency on resources (Wooldridge, Michael 1999) [307]. It is always a challenging task to achieve a high degree of independence because it requires agents to be more adaptive to changes in the circumstances, make decisions about incomplete information, and learn from their experiences. Developing AI agents with a higher degree of independence is a demanding research direction in the field of AI and machine learning.

4.5.2 Intelligence

According to Magedanz et al. (1996), the ability of an agent to accommodate and assimilate to a domain by using user requests and assets available to the agent [198]. There are diverse approaches for designing and implementing intelligent agents, and each of these has its own strengths and limitations. These approaches include rule-based systems, expert systems, decision trees, artificial neural networks, and reinforcement learning. Considering any

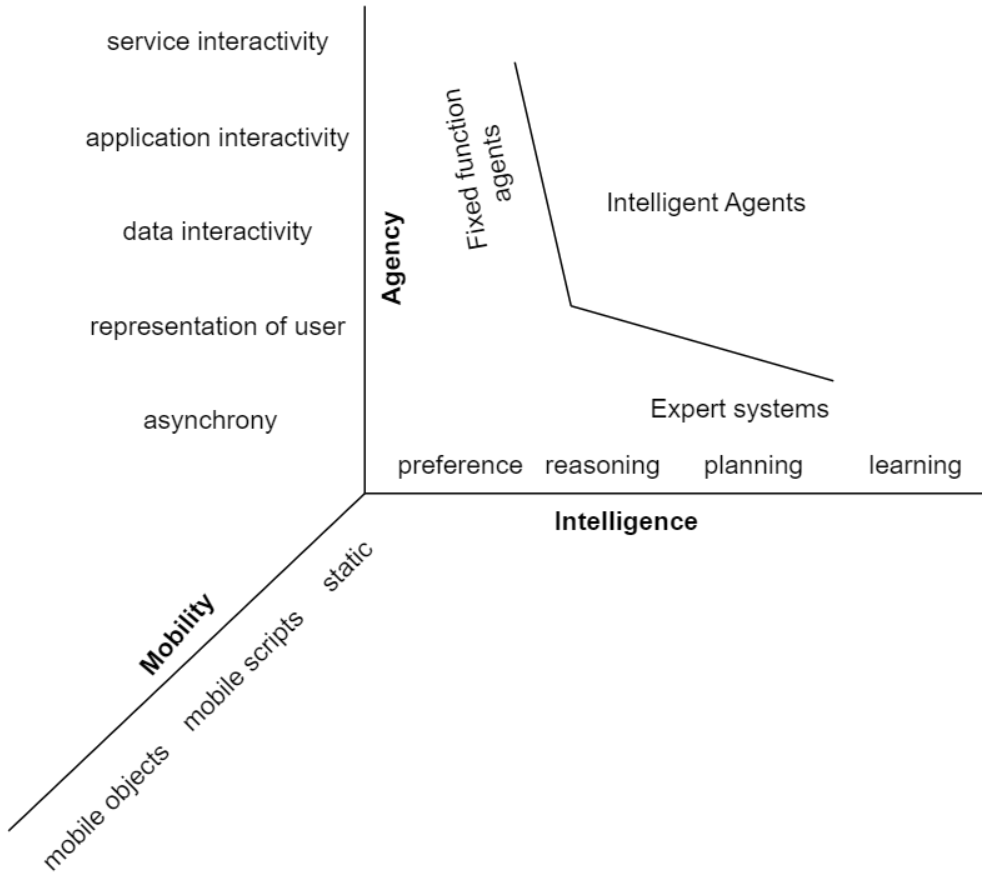


Figure 4.1: Gilbert's scope of intelligent agents: agency, intelligence, and mobility [108]

approach, the main purpose of designing intelligent agents is to develop such systems that have the capacity to adopt new situations, learn, and make decisions to maximize the probability of achieving goals in complex environments [307].

4.5.3 Mobility

The degree to which agents move through the network is the agent's mobility [198]. O'Hare, Greg (2000) defined mobility as "ability of a user/artifact to move within a given space" [229]. Mobility is an important property of intelligent agents because it allows them to move within the environment to perceive and act [128]. It can be physical movements, like in the case of robots or autonomous vehicles. In the case of software agents, mobility can be through virtual movements between different computers or networks. Physical mobility in intelligent agents depends on mechanisms for locomotion which include wheels, legs, hands, propellers,

or sensors for perceiving the environment and actuators for manipulating it [318]. On the other hand, virtual mobility needs communication networks and protocols to allow software agents to move between different systems or devices. Some agents can be static and reside on the client machine or server. On the other hand, some agents can be mobile, transporting from machine to machine during execution and carrying accumulated state data [198].

4.6 Training Intelligent Agents

Machine learning algorithms are used to train agents by using data called training data to learn how to do particular tasks without being programmed to do so. Computer systems can develop more effective algorithms for completing tasks compared to humans [159]. The principal output we can achieve with machine learning is prediction by training an algorithm on a historical data set and using this data training experience to make a prediction. Machine learning can also help in taking action to achieve goals.

4.6.1 Types of Machine Learning Algorithms

Machine learning is classified into three different types:

Supervised Learning

Supervised learning focuses on training data and human feedback. It involves establishing the relationships between specified inputs and outputs [74]. Supervised learning can be used for a wide range of applications which include image recognition, natural language processing, speech recognition, and decision-making. The supervised learning method can learn from examples and generalize to new situations, which is a powerful tool for intelligent agents. However, it needs a large amount of data for achieving good performance.

Unsupervised Learning

Unsupervised learning establishes patterns in input data [130]. Compared with supervised learning, unsupervised learning does not need labeled examples, and the agent has more responsibility to discover the underlying structure of the data with its own capacity. In intelligent

agents, unsupervised learning can be useful in a wide range of applications, including data clustering, anomaly detection, and generative modeling.

Reinforcement Learning

Reinforcement learning is a learning process that maximizes rewards based on actions taken. It is helpful in scenarios when the input training data is limited or the output is specified clearly. To learn, the system must gain experience through interacting with the environment [304]. Reinforcement learning is useful for intelligent agents where there is a need to make decisions in complex and dynamic environments, including robotics, game playing, learning applications, and any kind of resource management. When using reinforcement learning, the agent learns through trial and error by collecting observations, taking actions, and receiving rewards/punishments as feedback, maximizing the expected reward over time.

4.7 Unity ML-Agents

Unity ML-Agents is a free and open-source toolkit originally developed to integrate AI with machine learning in gaming. Unity ML-Agents are developed by Unity [1]. It is an add-on for Unity 3D platform, which provides the ability to develop complex 3D environments and train intelligent agents within the powerful Unity game engine. This plugin has the capability to provide a framework for training agents and then deploying in real-world applications, such as games, educational applications, and other Unity 3D experiences. Referring to the types of Machine learning algorithms (discussed in Section 4.6.1) for training agents, ml-agents use reinforcement learning. This plugin in Unity also allows experimenting with state-of-the-art reinforcement learning algorithms without the need for a formal setup or installing any additional libraries. Using these agents within the Unity platform allows getting the benefit of the powerful game engine, high-quality graphics, and a friendly user interface. The Unity ML-Agents Toolkit has developed over time and offers more stability with every new release. These new releases come up with additional features, and slowly it is becoming possible to

[1] https://unity.com/products/machine-learning-agents

implement complex learning systems within the Unity platform. The first beta version of the Unity ml-agents was released in 2017 as ML-Agents Beta 0.1, which has progressed through many developments over time with new features and ease of use [2]. This toolkit includes a number of intuitive features, which are;

- ML-Agents offer support for multiple environment configurations, which also include different training scenarios
- It offers a flexible software development kit that can be integrated into the game or custom Unity scene
- One can train the games using two deep reinforcement learning algorithms, i.e., Proximal Policy Optimisation (PPO) and Soft Actor-Critic (SAC)
- It has built-in support for imitation learning through Behavioral Cloning as well as Generative Adversarial Imitation Learning
- It offers a self-play mechanism for training agents in adversarial scenarios
- Train robust agents using environment randomization
- Flexible agent control with on-demand decision making
- Train using multiple concurrent Unity environment instances
- Unity environment control from Python Wrap Unity learning environments

Unity ML-agents can be used to implement gamification concepts in the learning experiences by creating game-based learning environments, which can make the learning process more engaging and interactive. Chapters 5 & 6 have provided a detailed implementation of Unity ml-agents.

[2] https://github.com/Unity-Technologies/ml-agents/releases

4.8 Unity ML-Agents in Immersive Learning

Unity ML-agents previously explored in the context of custom gameplay [319], shooting game [169], e-sports [175], and other kinds of gaming environments. The use of agents in immersive technology, especially in the context of immersive learning technology, is not explored yet to a level where this toolkit can help to develop a learning environment for STEM subjects. This thesis has demonstrated Unity ml-agents to implement in immersive technology specifically for learning applications. Previously these agents were trained based on the keyboard, mouse, or other external hardware to get input for training agents; this thesis contributed toward training these agents based on hand tracking and touchless hand interaction data. Integrating agents in immersive learning applications aims to support users through guided learning and training based on previously trained environments.

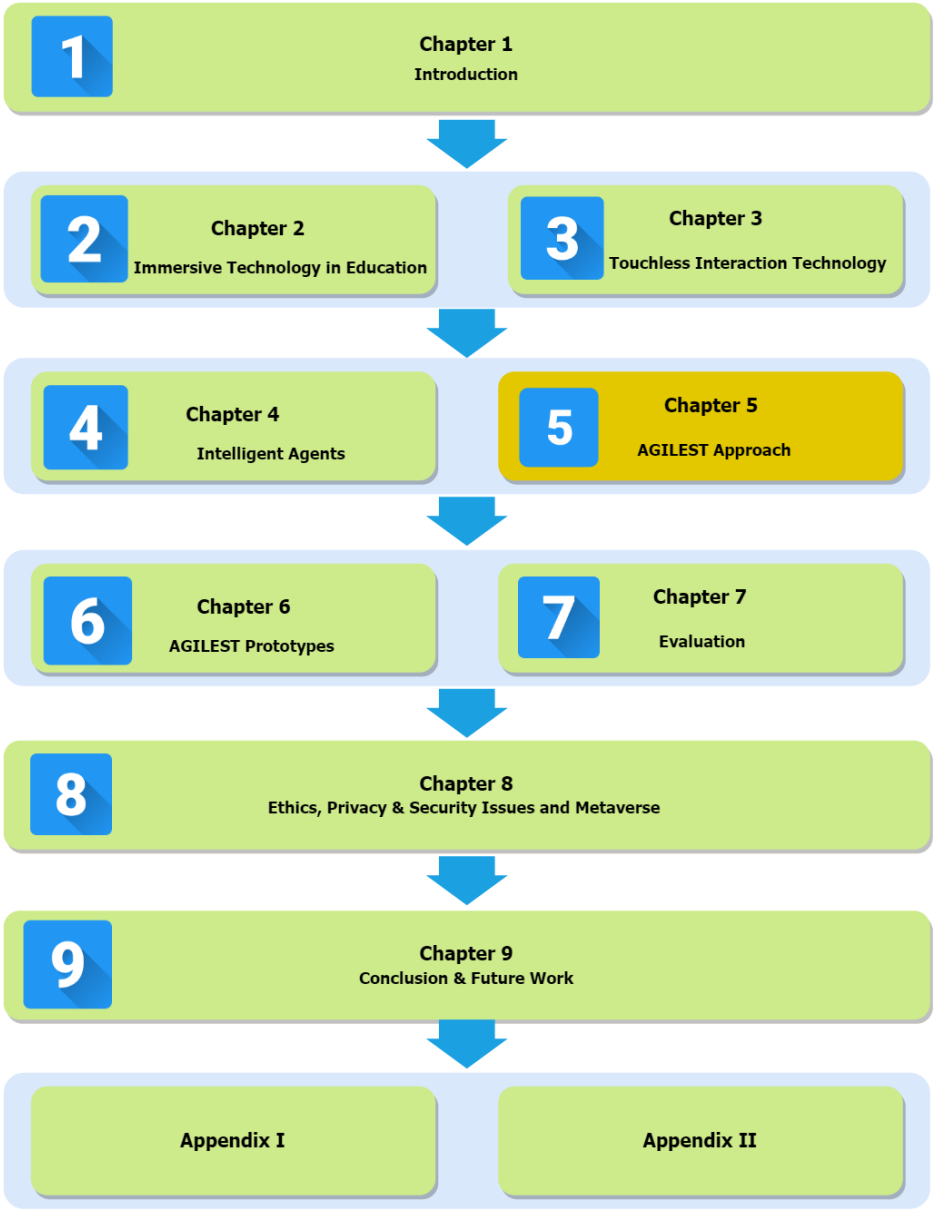
4.9 Conclusion

With the exponential growth in computational power and recent technological advancements in artificial intelligence research, intelligent agents are rapidly evolving. This chapter has provided a detailed explanation of agents, their types, rules, structure, and use of machine learning agents in immersive technology, which is addressed a research question of this thesis about using intelligent agents in immersive learning (RQ3). Designing and implementing intelligent agents need careful consideration of goals, capabilities, limitations, and the characteristics of their environment where they need to work. There are different ways where intelligent agents can be applied in learning applications, especially in immersive learning. Even though AI and XR are different in origin and primary objectives, combining these technologies is emerging to address prominent AI and XR challenges and look for more opportunities for the cross-development of more robust solutions. For investigating the AI-XR combination, the next chapters of the thesis have presented the implementation and evaluation of the agents in immersive learning.

CHAPTER

FIVE

AGILEST Approach



Based on the learning of Chapter 2, the importance of hand interaction technologies in Chapter 3 and intelligent agents in Chapter 4, this chapter focuses on proposing a new design methodology in integrating these elements in immersive learning environments to make the learning process more interactive and productive.

This chapter provides a detailed methodology for further implementation in this thesis. Further methodology of the thesis following the design thinking process is explained in Figure 5.1 which is considered as an effective and productive tool for Innovation [293]. Design thinking is a core iterative approach to understanding the end-users, and potential challenges, redefining problems, innovative prototyping and testing.

Figure 5.1: Design Thinking Process involved in this research

The design thinking process emphasizes creativity and innovation, considering the user's needs. By using this process, we can apply the design thinking ideology to real-world problems. This process puts the needs and requirements of the user first by focusing on empathy with users and understanding their needs and expectations. In addition, this process helps to engage the users or experts in prototyping and evaluations to get feedback. To get help at different stages of this process, this research used SWOT analysis, which helps to find the strengths and weaknesses in terms of available resources and opportunities, and challenges, discussed in Chapter 2.1. Learning about ethics, privacy and security issues during research are reported in detail in Chapter 8.

5.1 AGILEST Approach

This Chapter proposed AGILEST Approach *AGents to facilitate Interactive kinesthetic LEarning in STEM education using a Touchless interaction* based on the research gap, findings, and recommendations made in previous chapters. This research gap includes how to hand-free real-time touchless hand interaction, kinesthetic learning, machine learning agents, and remote learning components can help in XR learning applications.

This research tends more toward finding new types of user interfaces and integrating agents to create more productive learning contexts and new formats of learning pedagogies. So there are four major components to be explored in future chapters. It includes real-time hand interaction, its use for kinesthetic learning "hands-on learning practices", machine learning agents for self-guided learning, and expanding the XR learning scenarios in remote environments. These four main components are explained in Figure 5.2. Its implementation is discussed with two case studies in Chapter 6 and evaluation in Chapter 7.

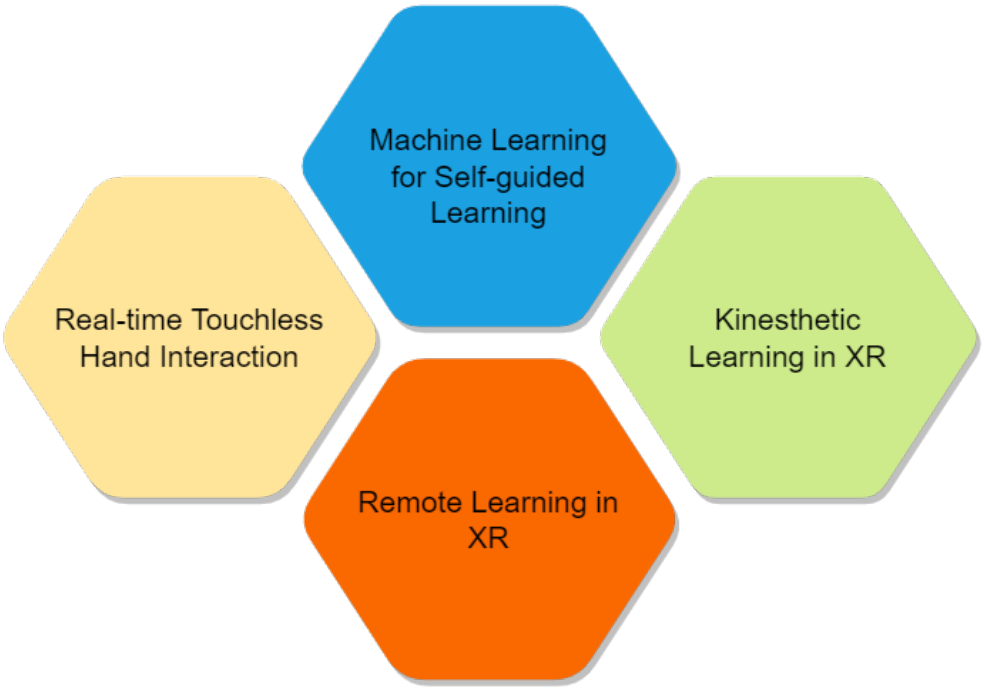


Figure 5.2: Four core components focused in this thesis

5.1.1 Machine Learning Agents for self-guided learning

Learning independently is a challenging task, even for self-motivated students. *Self-guided Learning* is a process that encourages and facilitates learners to learn without the help of others. Changing imperative of the current learning state is moving towards independent learning or self-guided learning. The use of XR for autonomous learning and self-guided learning has been discussed in detail in previous studies [202] [254].

As discussed in Section 2.3.9, machine learning agents can transform the future of learning if implemented in the AR application intelligently. Using intelligent agents play a role between artificial intelligence and human interaction by utilizing the collected data. Mostly self-guided learning approach is considered for practice-based learning outside the formal classroom. Self-guided learning approach can be differentiated into three categories [170] which are;

- Goal-oriented: focusing on achieving defined objectives to achieve end goals
- Activity-oriented: focusing on one-to-one social interaction
- Learning-oriented: focusing on increasing knowledge and skill set tendency

5.1.2 Unity Machine Learning Agent (Unity ML-Agents)

As introduced in Chapter 4, with ML-Agents, various training scenarios are achievable by collecting and recording different observations to make decisions, as explored by using reinforcement learning [48], explained in Figure 5.3. The environment means "Training environment" of the agent in the Unity 3D platform where the training process takes place within the Unity game view. To add an agent through the Unity ml-agents platform, this thesis has used the term RL-agent.

Reinforcement learning is a method of training machine learning models to reward desired behaviors and punish errors when doing undesired tasks. Generally, reinforcement learning can perceive and interpret its environment. As a result, it can take action and learn through trial and error. This mediated agent-oriented approach is supposed to help the user to learn

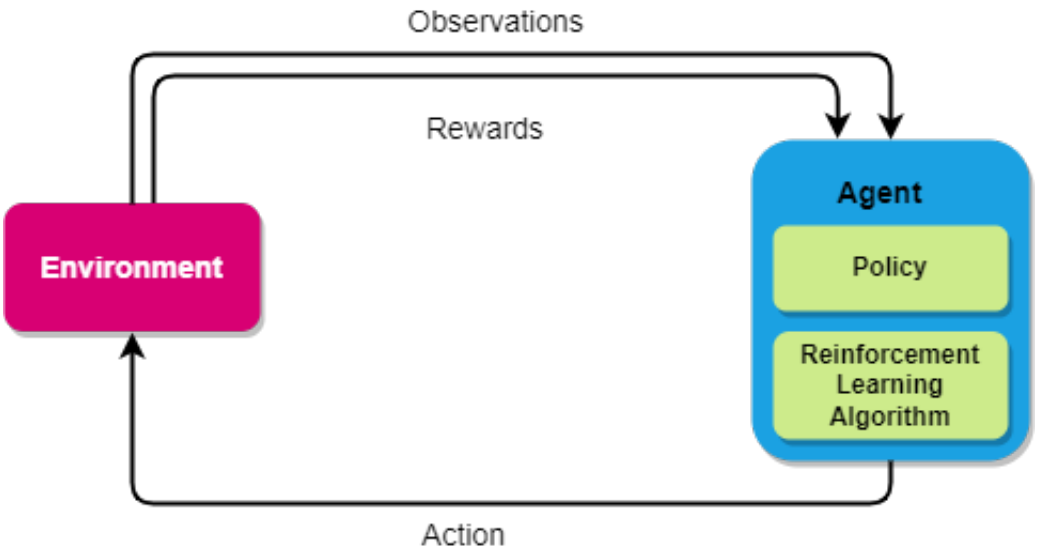


Figure 5.3: Process flow of RL-agent, following the reinforcement learning concept

which elements or molecules they will use to create different reactions. To achieve this goal, the RL-agent integrates machine learning as agency in the Unity game engine which allows the development of intelligent gameplay and learning experiences for users through deep reinforcement learning. In general, the Unity ML-agents plugin allows the creation of new or using pre-made environments for training agents to integrate into the Unity 3D application. Figure 5.4 explains the process of using ml-agents in the Unity application in five steps. This case study is developed in Unity version 2019.4.

This package offers these core functionalities in the Unity platform:

Defining Agents: defining characters whose behavior will be learned in the training process. It included observations (through sensors), actions taken, and received rewards from the environment as a process of decision-making.

Defining Agent Behaviors: defining those entities to those an agent should follow to act. One scene can have multiple behaviors, and multiple agents can share the same behavior.

Recording demonstrations: recording demonstration of an agent in the Editor, which can train a behavior for an agent.

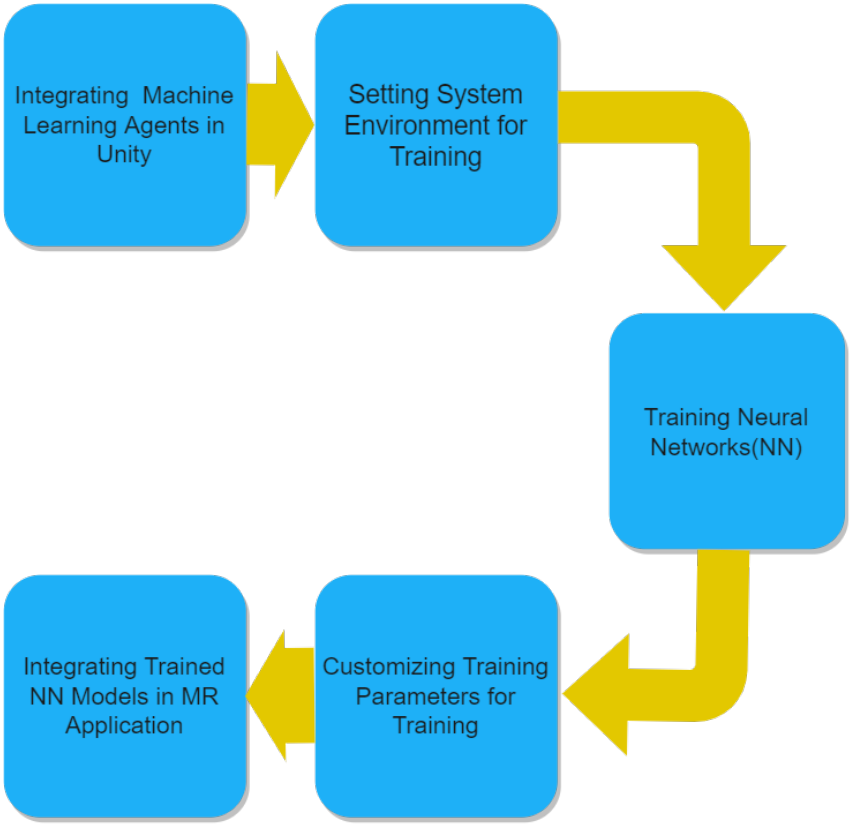


Figure 5.4: Five steps of ML-agents integration in Unity

Embedding a trained behavior: embedding a trained agent into the scene through Inference Engine.

Training a New Neural Network

To train a new neural network model, these steps are followed:

-Opening the command line or terminal window.

-Navigate to the folder ml-agents repository.

-Running `mlagents-learn` to verify everything works

-Running

```
mlagents-learn
config/ppo/PCAgent.yaml--run-id=firstPCAgentRun.
```

Learning components of the ml-agent are explained in Figure 5.5, which provides basic and advanced functionalities for game developers and researchers.

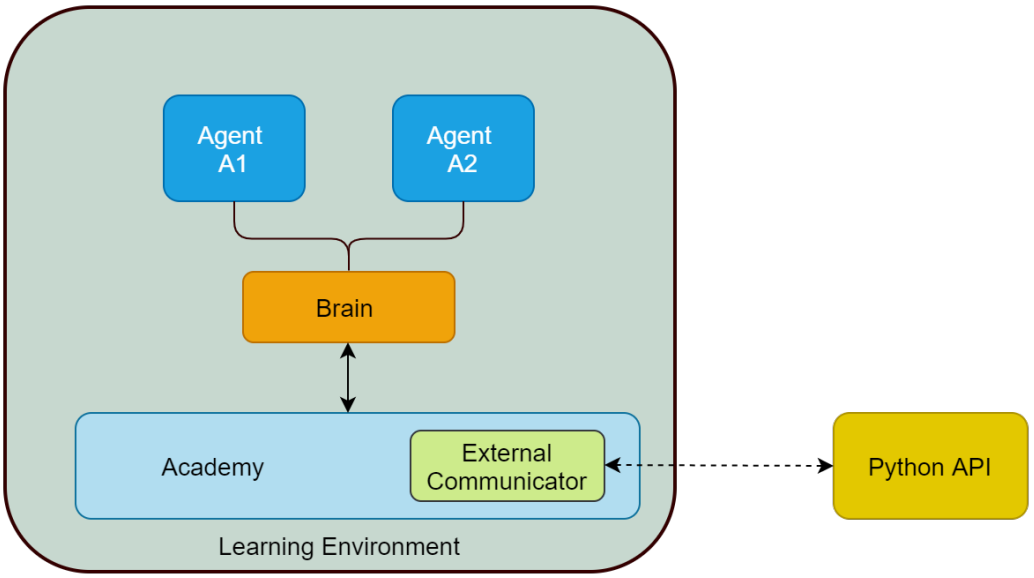


Figure 5.5: Learning Component of the ML-agent system

By default, `config/ppo` is the path to a training configuration file in the ml-agents package. `config/ppo/PCAgent.yaml` is the training configuration file used for training the NN model as shown in Figure 5.6. run-id is a unique name for this training session. After running the comment `--run-id=firstPCAgentRun.`, when "Start training by pressing the Play button in the Unity Editor" is displayed on the screen, there is a need to press the "Play" button in Unity to start the training process in the Unity Editor. These agents use Python APIs to train the learning behavior.

RL-agent collects observation of the user's hand moves, picks, grabs, and creates reactions which lead to rewards by using functions of *CollectObservations(VectorSensor sensor)*, *sensor.AddObservation* and *OnActionReceived (float[] vectorAction)*. The code is further provided in Appendix I.

To get better stability, this was tested over different sessions and evaluated with different increasing buffer sizes (shown in Figure 5.6) to achieve consistency as better results in the Tensorboard Graphs.

Inspector content for *Decision Requester* (Figure 5.7) is used to set a number of steps where the agent needs to make decisions during the training process.

```
PCAgent:
    batch_size: 32
    normalize: false
    num_layers: 1
    hidden_units: 20
    beta: 5.0e-3
    buffer_size: 256
    max_steps: 5.0e5
    summary_freq: 5000
    time_horizon: 3
    reward_signals:
        extrinsic:
            strength: 1.0
            gamma: 0.9
```

Figure 5.6: Parameters used in the trainer configuration for agent training

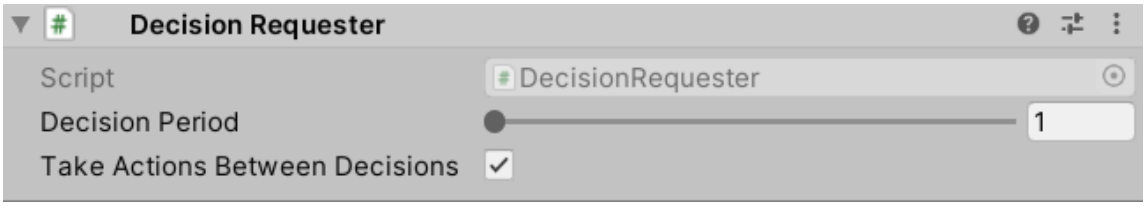


Figure 5.7: Decision requester of ml-agents in Unity inspector view

The training progress during neural network training can be seen in Figure 5.8, which shows the number of steps and time elapsed. The training process can only run in the Unity Editor on Windows, Linux, and MacOS. Along with input from the mouse and keyboard, Unity editor can also take input from external devices like leapmotion, Manomotion SDK through smartphones, or Oculus Quest, which is used to train the agent in real-time training sessions.

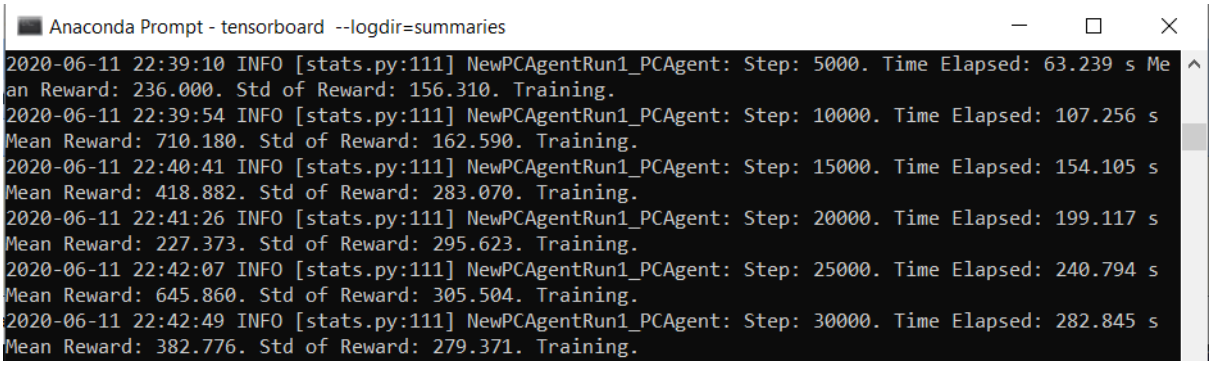


Figure 5.8: Agent training progress; Tensorboard

After training is completed, NN model saved in the `models` folder in the main `ml-agents`

folder, which can be dragged to integrate in the “Model” field in “Behavior Parameters”, can be seen in Figure 5.9.

Integration of trained neural network in Unity is shown in Figure 5.9, which allows choosing *space size* and *Behaviour Type*. After training the NN model, `NNModel` is dragged to add in `Model` field.

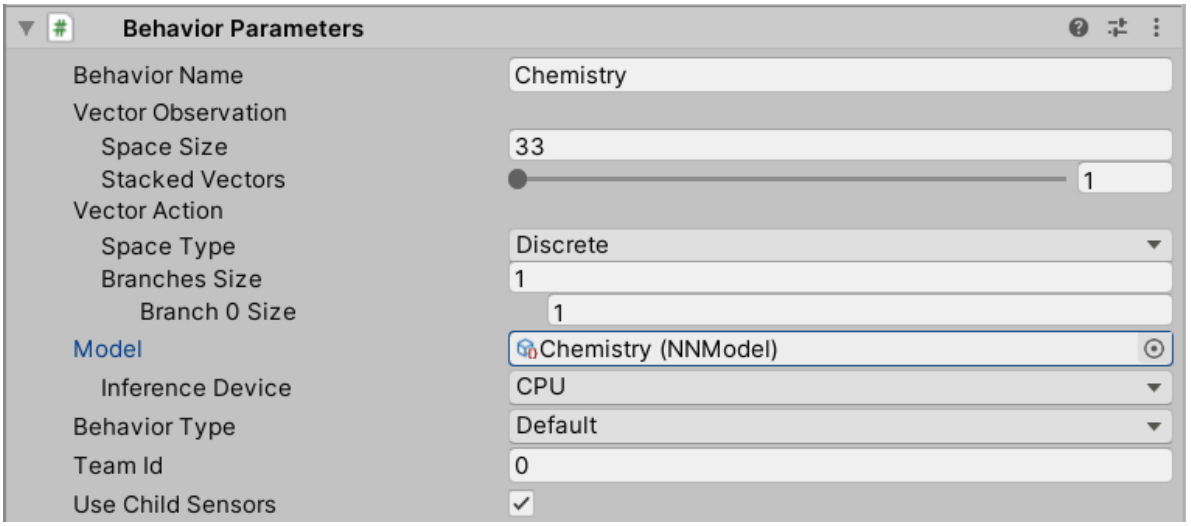


Figure 5.9: Embedding of trained Neural Network(NN) model after training

To get the trained Neural Network(NN) models for integration in unity, hand interaction data is taken as input when creating chemical reactions by completing multiple episodes. To process through multiple episodes, each episode ends with the restart of the scene, which continues until the training process stop. `TrainChemistry` is the Unity scene name. When all the molecules (products) are present in the scene after all reactions are done, the `TrainChemistry` scene needs to restart for another episode.

To observe the training process, TensorBoard provides a graph in detail. TensorBoard accessed through command;

```
tensorboard --logdir results
```

Then navigating to `localhost:6006` in the browser which provides the progress of training in graphs. This integration and implementation process of RL-agent is further used in Chapter 6.

5.1.3 Empowering Remote Learning in XR

With the latest high graphic power and growing internet speed, remote learning in XR environment is becoming possible, which can significantly increase the use XR for remote education in the future. Through XR, learning can become dynamic and user-centered when implementing the latest interventions. All of the previous studies in XR are implemented in the context of the classroom environment, but it has not been explored in personal devices and wearable outside the classroom with an organized system like ARETE [203]. In AGILEST Approach, a Firebase database[1] is integrated into the final assessment QUIZ, which focuses on establishing the concept of remote learning, where an instructor can access the student learning gain.

This proposed AGILEST Approach allows for a remote assessment, as explained in [38] in VR application for skill training. This approach can allow for large-scale remote assessment with hundreds if not thousands of participants. COVID-19 has led to a global acceleration in remote learning adoption as the realization sets in that this is the 'new normal' [139]. A remote evaluation approach has been discussed in Chapter 7, which addresses the challenge of remote outreach for XR evaluation.

5.2 Learning PC Assembling (Testing Approach in Desktops)

By considering the design components proposed in the AGILEST approach, hand interaction, kinesthetic learning, and machine learning agent used to galvanize this concept for practical implementation.

It focuses on learning PC assembling as a necessary component of computer science education. Initially, a desktop environment was considered as a display device to explore the possible hand interaction APIs and devices to integrate hand tracking and interaction with virtual objects. By

[1] https://firebase.google.com/

testing Kinect and leapmotion devices, it was found that leapmotion is more effective when a close interaction with small virtual objects is needed in the learning environment. Leapmotion is a small sensor device presented in Figure 5.11, consisting of two cameras and three infrared LEDs. Therefore, as a first test to integrate hand tracking in the Unity application, leapmotion was used. However, the primary goal of this thesis is to focus on portable and standalone devices, but as leapmotion is not working with Android OS, it is tested with a desktop display with Windows OS.

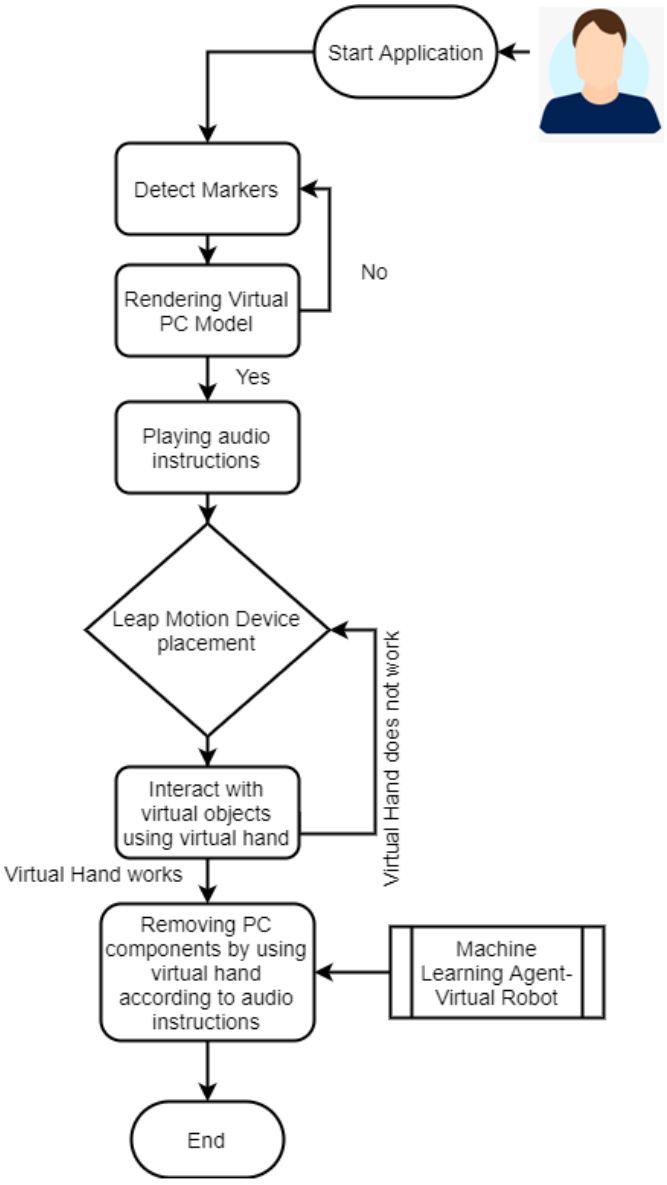


Figure 5.10: Flow diagram of the application framework

The technical components are the Unity 3D Engine, Unity machine learning agents (Ml-agents)

[2] [152], leapmotion hand tracking SDK [3], leapmotion device (Figure 5.11) and 3D models. The

Figure 5.11: Leapmotion device used for hand tracking

prototype was developed using Unity 3D for rendering the virtual 3D models and Vuforia SDK to enable an AR camera with marker tracking. In this system, the leap motion device [158] facilitates touchless hand interaction with virtual objects using its capability of hand tracking. Figure 5.10 shows the application's process flow, from detecting marker to enabling interacting hands after 3D object placement.

Figure 5.12 explains the interaction area of leapmotion device which 2 feet (60 cm) on each side and top.

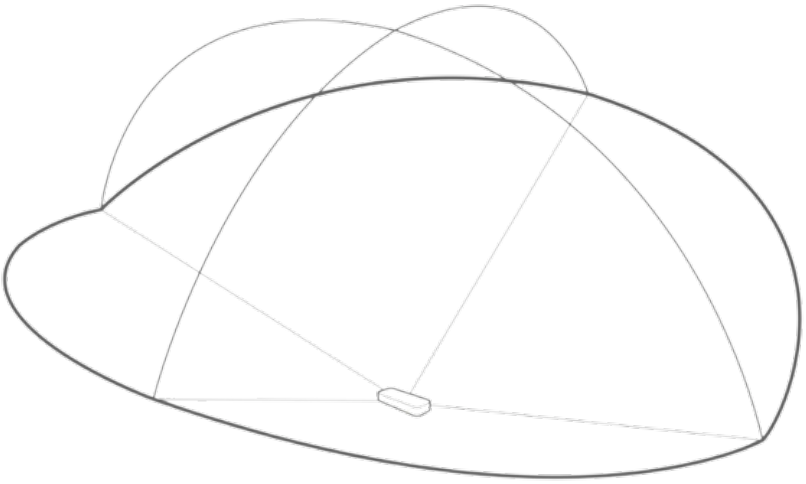


Figure 5.12: Leapmotion interaction area

The leapmotion was chosen for the initial application due to its proven high accuracy in tracking gestures [284] & allowing interaction via grasping, picking & place the virtual objects [11]. As

[2] https://unity.com/products/machine-learning-agents
[3] https://www.ultraleap.com/product/leap-motion-controller/

leapmotion offers limited device compatibility, a Windows OS machine was used. A laptop PC thus was used to conduct all the development and agent training for this project.

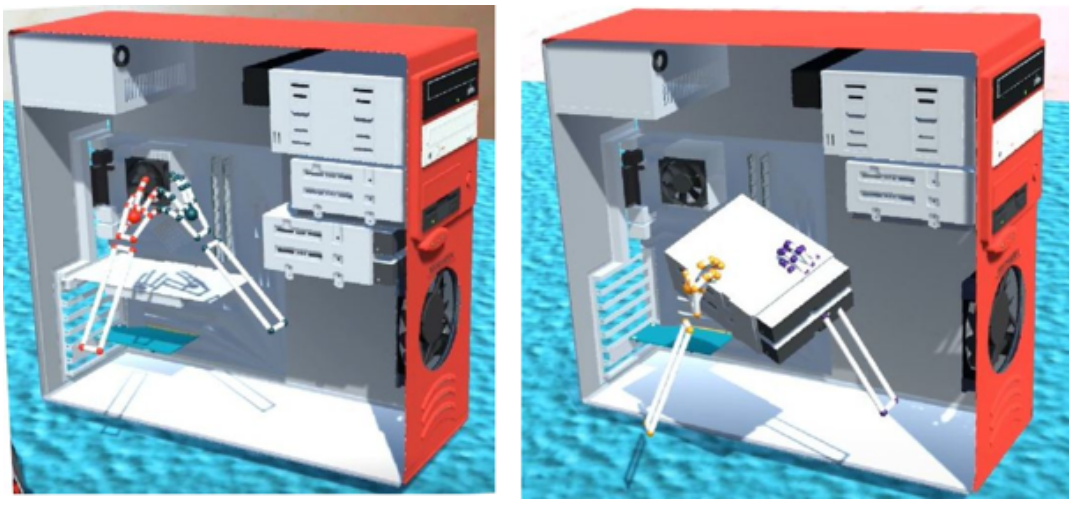


Figure 5.13: Touchless hand interaction for learning PC assembly using leapmotion hand tracking

A 3D PC model was used with all the necessary hardware to teach the interior architecture of a computer. The interaction hand helps users interact with the virtual PC's components, disassemble, and assemble it again.

Figure 5.13 shows hand interaction with the virtual PC components. It allows the user to touch, pick, grab, and place the 3D components virtually in the augmented environment. The time manager records the time taken to complete each episode which is used to assign rewards based on completed tasks. The role of the animated virtual robot is set to create engagement with the user by providing different gestures when completing a task and getting rewards. The process flow uses a self-guided learning approach in an edutainment way. In Figure 5.14, a demonstration is shown of how touchless hand interaction on the desktop PC using the leapmotion device is performed. This PC assembly learning case study has been taken as a kinesthetic learning approach by allowing the user to do PC assembling tasks with the 3D PC parts using the leapmotion hand tracking. The role of the virtual robot present in Figure 5.14 is defined as an engaging factor by providing different gestures to complete tasks by the user.

Figure 5.14: Using a different PC model, Touchless hand interaction for learning PC assembly using leapmotion hand tracking

Figure 5.15 explains the progress of getting cumulative rewards and episode length for different episodes. These graphs and different other aspects of training are explained more in Chapter 6.

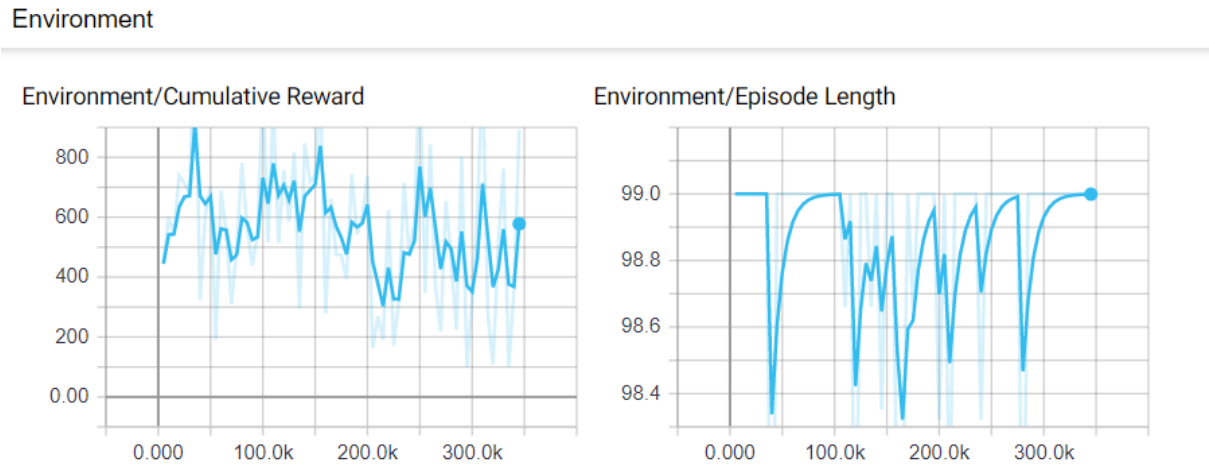


Figure 5.15: Tensor flow graphs of machine learning agents training (These graphs are taken from the Tensorflow dashboard after training the hand interaction data).

This design testing aimed to test the possibilities of integrating hand interaction for kinesthetic tasks and intelligent agents. Using real-time hand interaction and practicing the "learning by doing" approach, this study is developed for Windows desktop PC as the leapmotion device has no compatibility with android devices.

5.3 Conclusions

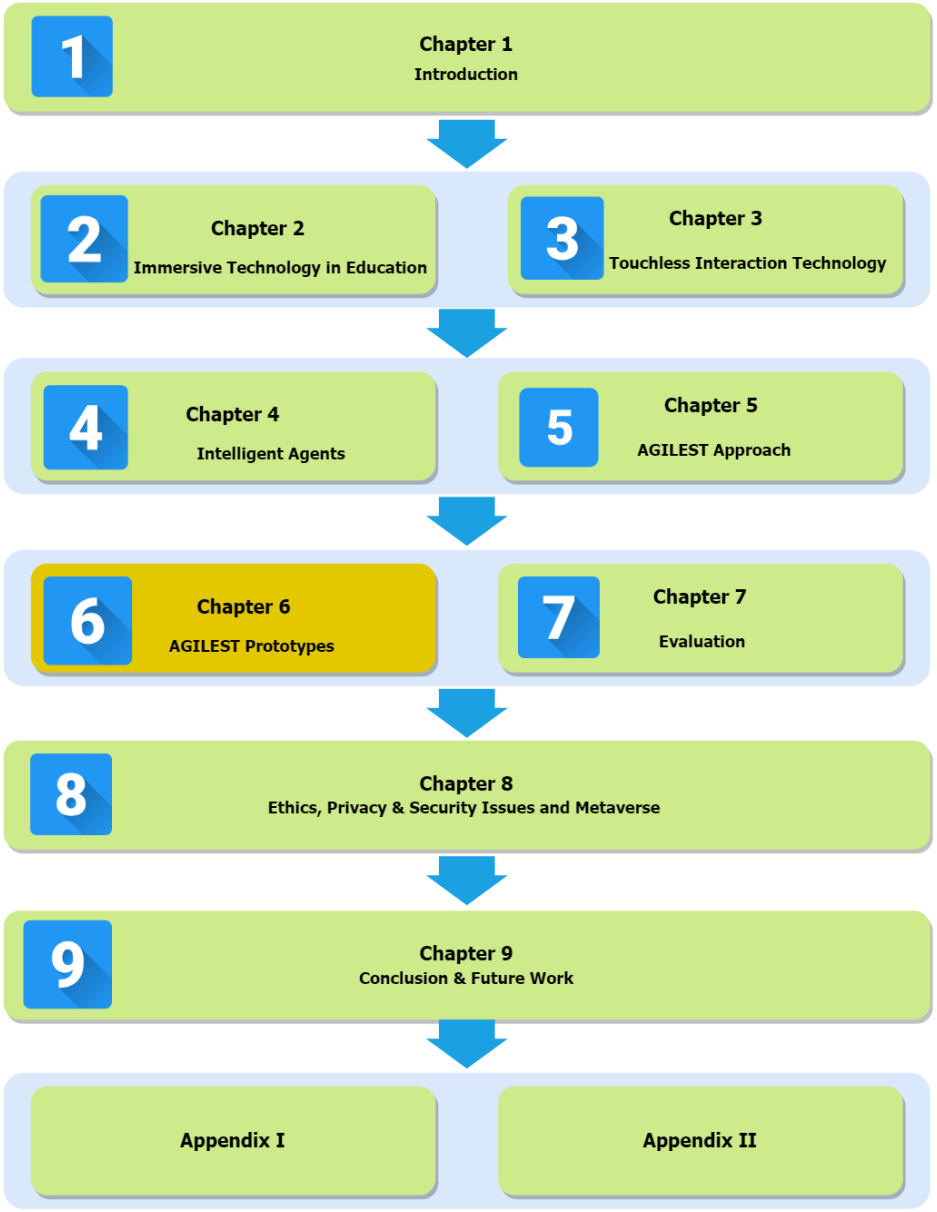
This chapter has proposed a methodology "AGILEST Approach" for implementing real-time hand interaction and intelligent agents in immersive learning systems. Based on the finding of Chapter 2, 3 and 4, this chapter has proposed four components to investigate further for developing learning environments that support interactive, kinesthetic, and self-guided learning pedagogy. This chapter also presented a design thinking process in the context of the thesis. Based on Chapter 3, different SDKs and devices are presented with details in the context of immersive environments that provide real-time hand interaction. Unity machine learning agents package has been proposed to integrate with a test case desktop application using leapmotion hand interaction SDK for self-guided learning.

This proposed methodology is further taken to implementation in Chapter 6 with STEM-related case studies and evaluation in Chapter 7 with expert reviewers. By integrating these components in immersive learning systems, XR can offer new possibilities for innovative learning in resource-constrained environments to save the learning material cost.

CHAPTER

SIX

AGILEST Prototypes Implementation



Following the concepts developed in Chapter 5, this chapter provides detail of prototypes developed combining real-time hand interaction and machine learning agents approach as tested in the section 5.2, for handheld devices (smartphones, tablets) and HMDs.

This chapter's principal contribution provides detail of two case studies developed using *AGents to facilitate Interactive kinesthetic LEarning in STEM education using a Touchless interaction* or AGILEST Approach. Two case studies are presented in this Chapter, Section 6.1 for handheld devices (smartphones and tablets) and Section 6.2 for HMDs (Oculus Quest 2). To focus the investigation on STEM education, these case studies use chemistry as a topic for creating learning content and concentrate on the secondary school curriculum where students are required to learn chemical reactions. The choice of case study is based on many factors;

- Traditional chemistry experiments can be expensive and AR/VR can provide a cost-effective alternative. AR/VR simulations can reduce the need for expensive equipment and supplies, making them more accessible to students and researchers with limited resources. These case studies provided a scenario where this learning pedagogy can be adopted using the self-guided learning approach and facilitating kinesthetic learning in the virtual environment.

- Chemical experiments can be dangerous, and AR/VR can provide a safer alternative to physical experimentation. AR/VR simulations allow students to experiment with chemicals and reactions without risking exposure to hazardous substances.

- AR/VR can be used to create 3D models of molecules and chemical processes, allowing users to explore and manipulate them in a more immersive and engaging manner.

Fundamentally, this approach does not replace the teacher but gives them more agility in their teaching as they can fit themselves into the process at any point. Using this approach, the teachers could act as the trainer and allow the agent to assess the student or vice versa. They could use the application to teach a complete lesson on this topic while focusing on another topic. This approach suggests that XR tools should be there to augment and enhance a person's abilities with productive learning experiences, not to replace the person. The system architecture

has been presented in Section 6.1 which explained the components of the system in detail. This architecture is developed using the learning of Section 5.2.

6.0.1 Hypothesis

1. Machine learning as an end-user trainer with previously trained neural networks can help in self-guided learning.
2. Real-time hand interaction in XR can help to increase productivity with kinesthetic (hands-on) learning tasks.
3. Virtual material in XR can help to replace the physical material in resource-constrained environments to produce a realism approach.

This hypothesis is further evaluated with a case study in Chapter 7.

6.1 AGILEST Approach - Handheld

In this section,s this approach focuses on handheld devices (smartphones and tablets) to reach a wider audience as smartphones are the most accessible device in the world right now. Figure 6.1 shows the growing number of smartphone users worldwide, which is growing very fast.

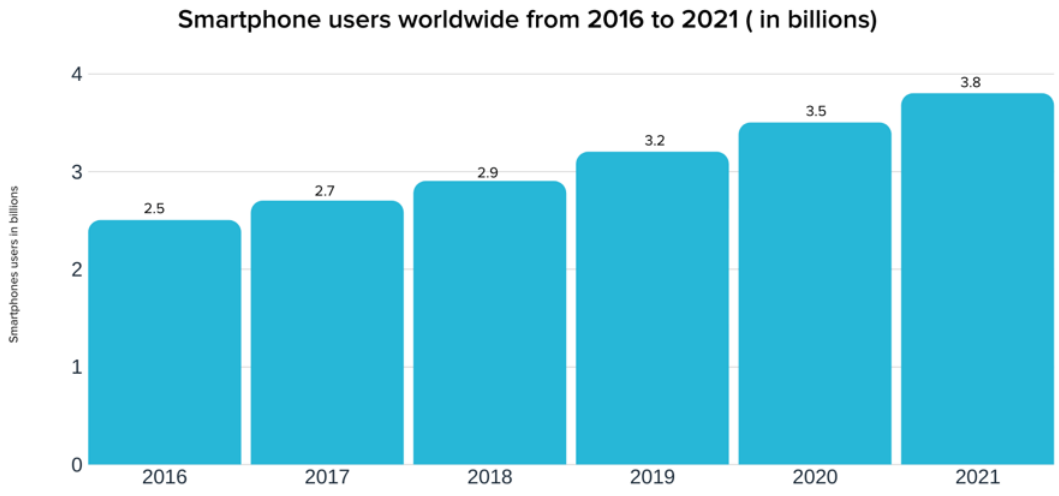


Figure 6.1: Increasing smartphones users in the world (Statista)

With the recent advancements in smartphone technology, these devices are becoming more powerful tools to facilitate immersive learning experiences. Smartphones in immersive learning can support interactive and engaging learning experiences with better accessibility and personalization; can help in easy data collection for feedback and improvement.

To implement the proposed concept, the AGILEST approach combines the use of Machine learning agents (using the Unity ML-agents plugin [1] [152]) as proposed in Section 5.1.1, hand tracking facilitated by deep learning Manomotion [2] and ARFoundation for Augmented Reality. Manomotion for hand tracking was chosen in this case study based on its compatibility with handheld devices. However, it is not working with a range of smartphones because of the particular requirement of APIs.

6.1.1 AGILEST Approach System Design

The overall system design architecture can be seen in Figure 6.2. The architecture diagram visually represents the AGILEST, making the system's design and structure more understandable. This architecture is further used in Section 6.2 for testing this approach with HMDs. The following subsections will detail this approach, first in machine learning in Section 6.1.2 and touchless hand interaction implementation in Section 6.1.3, and finally, outline the learning flow adopted in the AGILEST approach in Section 6.1.4. According to the sensorimotor embodied cognition theory [100], hand gestures or interaction in AR or VR influence how we understand and respond to them. If a user learns to perform certain gestures in a particular way in a virtual environment, he is more likely to perform the same gestures in the real-world for interaction in a similar way. Hand gestures are physical movements that users make with their hands to interact with a device or software, including swiping, tapping, pinching, rotating, shaking, or waving. User actions are inputs or interactions a user makes with a device or software. User actions can include input forms like typing, clicking, selecting, grabbing, or dragging.

[1] https://unity.com/products/machine-learning-agents
[2] https://www.manomotion.com/mobile-ar/

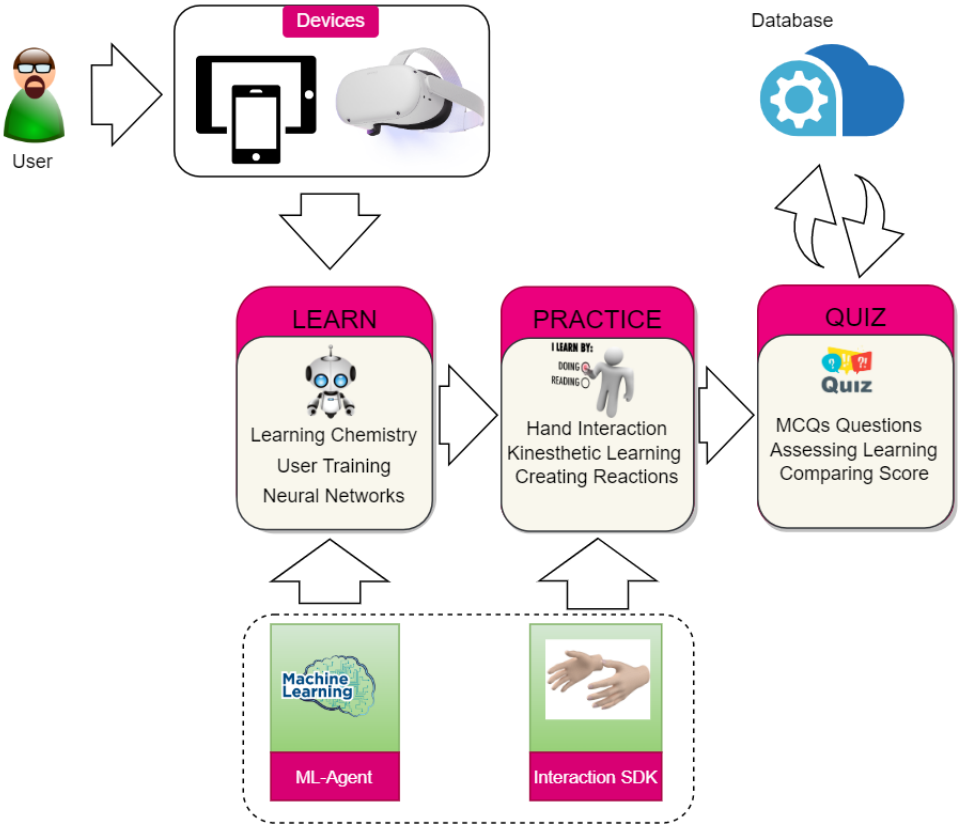


Figure 6.2: System Architecture Diagram for AGILEST Approach

Architecture diagrams have similar importance in immersive technology as in traditional software systems. The design process translates the concept of real-time touchless hand interaction and self-guided learning. Touchless (real hand interaction with virtual objects) technology in smartphones is the most recent advancement in smartphones, which creates more effective interaction with the virtual learning material using fewer resources. Moreover, touchless technology is a need of the post-covid world where avoiding touching digital devices is a health-centric approach to follow the hygiene concept [137]. To get a better field of view, tracking space, and getting more 3D objects into user interaction space; landscape screen orientation is used. It is true that some cameras can have a higher horizontal field of view as compared to what is displayed on the screen. This can happen due to factors like lens distortion and aspect ratio. Device screens play a crucial role in immersive learning experiences produced by smartphones.

6.1.2 Machine Learning Agents - LEARN Module

At the heart of the AGILEST approach is allowing the machine learning agent to train the user about the chemical interactions using already trained data. This RL-agent integration and training process are explained in Chapter 5.

The PC assembling/disassembling case study presented in Chapter 5 uses real-world scenarios where interacting with PC hardware is focusing on the real-world example, but at that time, ml-agents were not stable enough to accommodate the pouring actions in the chemical laboratory (however with recent advanced releases, it is becoming possible to deal with complex real-world scenarios). Therefore, these case studies use cubic elements, which is like a gamification concept for learning chemistry. The process of a chemical reaction is explained in Figure 6.3, which shows how two chemical elements react to make a new product(molecule). For example, copper in the form of crystals and copper oxide in the form of powder can be seen in the Figure, which helps users understand the elements' physical nature.

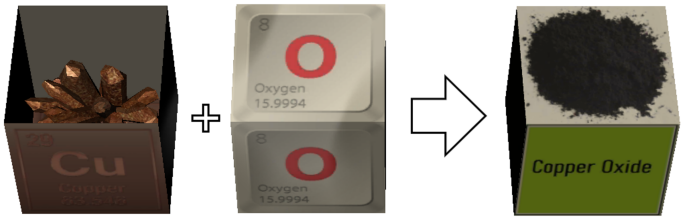


Figure 6.3: Chemical reaction explained

In a neural network, the training process records observations when different elements are combined to create reactions using the *pick, grab, and drop* functions. Then, it follows the reward-based assessment using the errors and time-based data of the user's actions. The graphs presented in Figure 6.4, 6.5, 6.6, show different parameters of the training. According to reinforcement learning, the learning rate should decrease with time, as seen in *Policy/Learning Rate*. As the number of episodes increases, the cumulative reward increases, which is shown in the Environment/Cumulative Reward (as shown in Figure 6.4). In a typical approach of using reinforcement learning, an agent should interact with the learning environment by perceiving

observations & performing actions, where the ultimate goal is to maximize the cumulative reward.

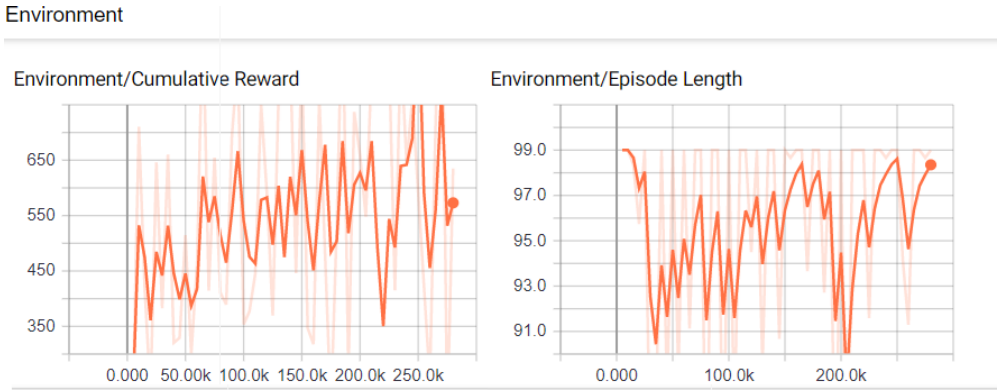


Figure 6.4: Tensorboard graphs showing the progress of the training agent.

The Losses/Value loss is calculated by finding the difference in the predicted value of the current state and the real accurate value of the next state, which needs to be discounted by the discount rate. The value loss helps select those actions that can lead to higher cumulative rewards. Value loss allows the agent to optimize its behavior with time.

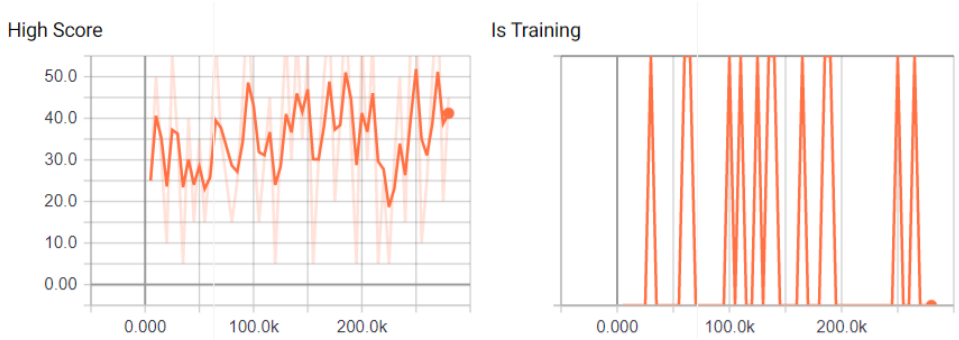


Figure 6.5: Tensorboard graphs showing the score and training process continuity.

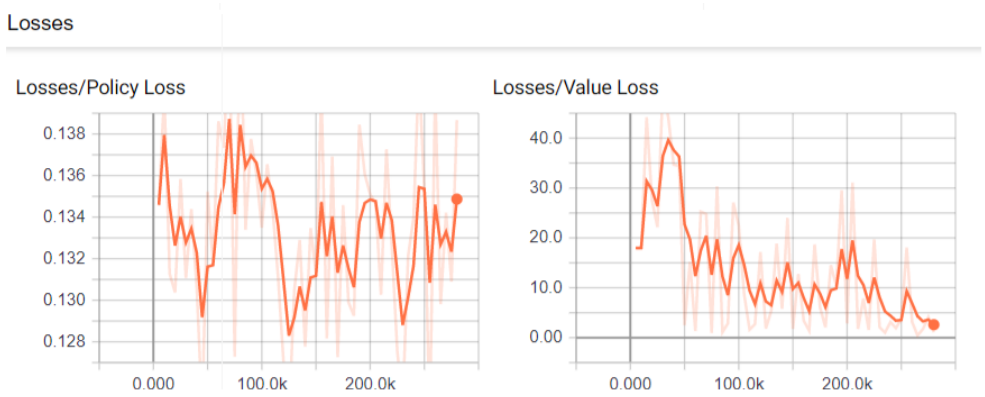


Figure 6.6: Tensorboard graphs showing Policy Loss and Value Loss in the training process.

Finally, the heuristic method trains the RL-agent on the same functions that the user will use in the next step (*PRACTICE*) through hand interaction. This module is designed with a self-guided learning approach. Figure 6.4 shows the graphs of TensorFlow after training the data. Figure 6.7 shows *LEARN* module on a smartphone display with a trained neural network model integrated as an agent.

Figure 6.7: Learn module, trained with Machine learning agent

A learner can access this module multiple times for better learning gain before entering the next module for practicing. As this application uses markerless tracking, it is independent of any specific target image.

Figure 6.8: User interaction with the application and machine learning module in Android Tablet

6.1.3 Hand Interaction - PRACTICE Module

As agent learning involves training the agent with interaction data using reinforcement learning, user learning involves different approaches such as experiential learning and reflective learning. In the context AGILEST approach, agent learning is action-based learning, learning through tracked interactions with the cubic chemicals (virtual contents) and training the agent, and user learning is content-based learning which is learning about chemical reactions. Compared to auditory and visual learning, kinesthetic learning is superior to improving learners' critical thinking and analytical skills because it gives hands-on learning opportunities. Research has shown kinesthetic learners can perform better in certain types of learning, such as those involving fine motor skills, technical topics, and physical coordination [14]. Kinesthetic learners can learn by doing, performing physical activities which include role-playing, hands-on learning and manipulation of objects. To enable hand tracking in the Unity application, Manomotion SDK with AR Foundation framework is used, which allows the user's hand to interact with the 3D objects through the smartphone camera using deep learning algorithms.

Figure 6.9: Learn by Doing "hands-on learning", adopted in PRACTICE module

To enable the AR elements in the scene, ARFoundation camera was integrated into the Manomotion event manager, as shown in Figure 6.10.

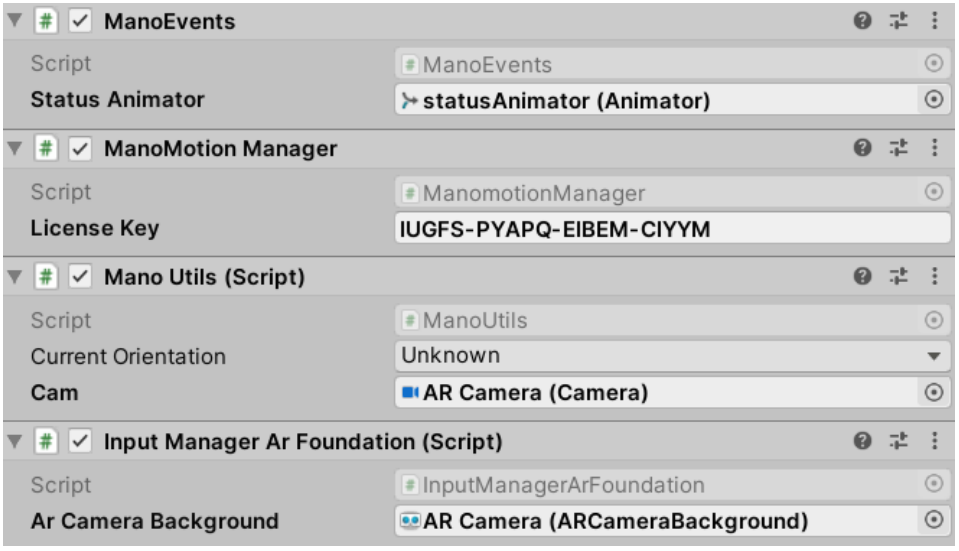


Figure 6.10: Adding ARFoundation components in Manomotion SDK in Unity

Manomotion Gizmo Canvas provides configuration for different gestures and enables hand interaction to perform grab, pick and drop functions. Figure 6.11 shows the Gizmo canvas configuration options. This hand interaction is achieved using Manomotion gestures with depth API within ARFoundation.

Figure 6.11: Hand Tracking Gizmo setting of Manomotion in Unity

To set up the tracking space for playing applications on handheld devices, AR Camera in ARFoundation provides options to choose XR device, focus mode, the option to use AR camera background, and tracking type. Figure 6.12 shows how a custom-made virtual hand can help users locate a hand in the virtual environment, interact with virtual cubic elements, and create chemical reactions, as previously learned in the *LEARN* module.

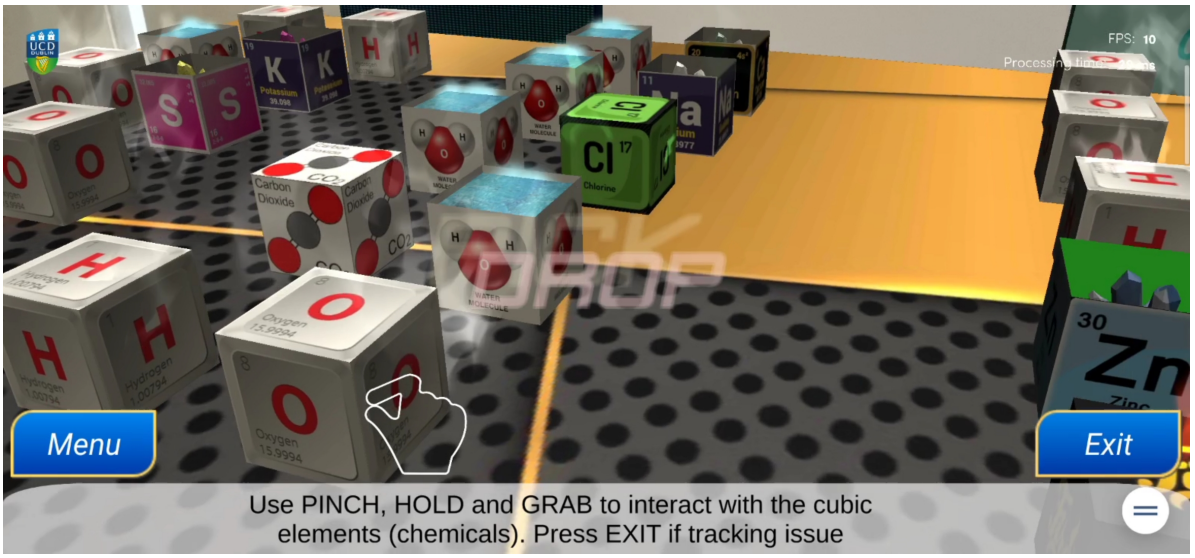


Figure 6.12: When the user's hand collides with any 3D cubic element, it allows grabbing and creating the chemical reactions

The custom-made hand is implemented by using the hand tracking info to help the user in locating the hand. When a user's tracked hand reaches any 3D object and collides, it activates a point light to notify the user that the interaction element is now interactable. Interaction allows the user to hold and move objects around to create a reaction of that chemical (element), as shown in Figure 6.12.

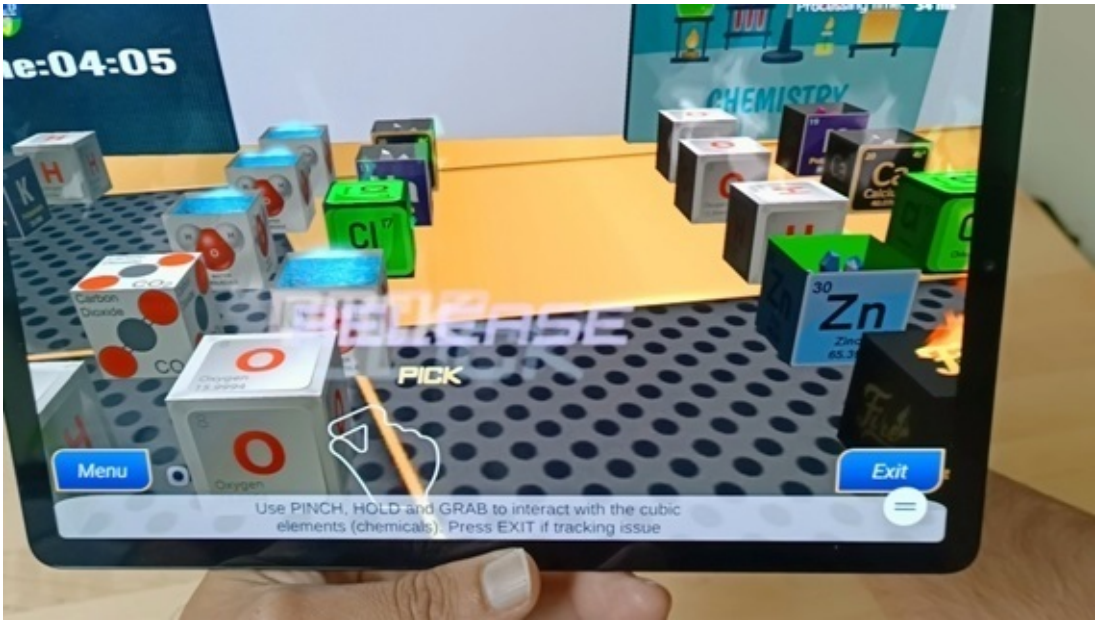


Figure 6.13: A user creating chemical reactions with real-time hand interaction using Android tablet (Samsung Tab S5e)

The application is also reporting the frame processing time and provides information about the different states of the user's hand *(Grab, Hold, Drop)* when hand tracking is enabled. The position of the holding device and the posing hand for interaction through the camera has been shown in Figure 6.13 in landscape mode. With the latest upgrade in Manomotion SDK, now the front camera can be used for hand tracking, and it provides more abilities for enhanced hand interaction. Visualizing the chemical elements in their real form helps students explore the physical structure of the elements, as shown in Figure 6.14. This concept if implemented further with haptic devices in future work, can make this approach more realistic because users will be able to feel the actual form of chemicals.

When a chemical reaction happens, the user receives audio feedback and vibrations telling what happens, like *"hydrogen reacts with fire, it creates an explosion"*, *"hydrogen reacts with oxygen to make water"*, *"nitrogen reacts with hydrogen to make Ammonia gas"* to make the process more effective.

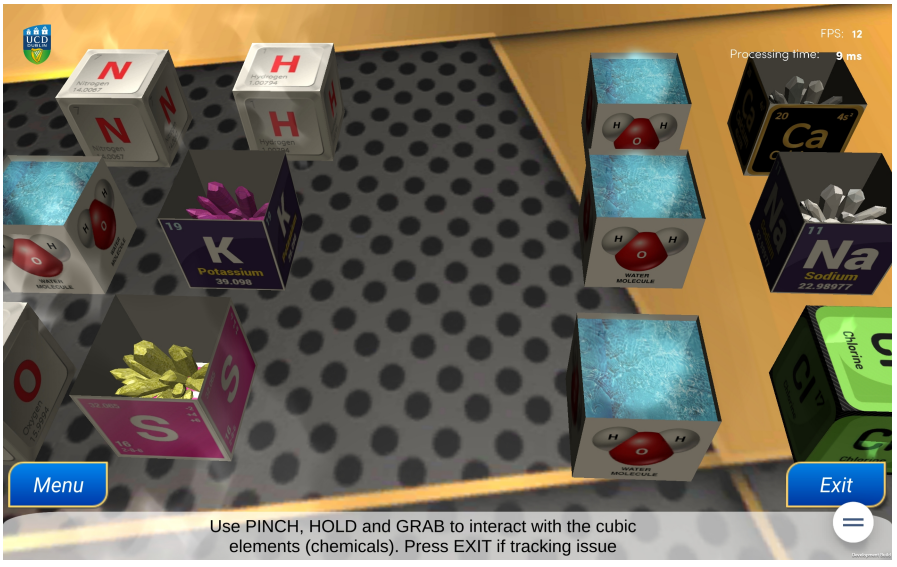


Figure 6.14: Visualization of elements with gas, fire, crystals, and liquid

The application records the time taken to achieve all the chemical reactions. It assigns a score based on correct reactions made and sends the user to *QUIZ* module after completing all reactions, where users can do self-assessments based on learning from these two modules.

6.1.4 Learning Flow

Learning flow in learning applications is defined as a sequence of activities learners must follow to acquire knowledge or learn a skill. There are different ways in which immersive learning applications can optimize learning flow. To understand how the machine learning agents and touchless interaction combine, the learning flow of the application needs to follow a focused approach, which must be student-centered.

This research has adopted Bloom's Taxonomy to explain the learning flow. Bloom's Taxonomy is a well knows classification of the different outcomes and skills a teacher or instructor can define for students (learning outcomes). The taxonomy was proposed in 1956 by Benjamin Bloom [35], an educational psychologist at the University of Chicago. The taxonomy has been updated over a period of time to include the six levels of learning. Figure 6.15 shows the six different components of Bloom's Taxonomy.

These six levels can be used to structure the course's learning outcomes, lessons, and assessments.

- Remembering (Knowledge): Retrieving, recognizing, and recalling relevant knowledge from long-term memory. In terms of AGILEST case studies, it is basic chemistry knowledge that a learner should have before learning these case studies.
- Understanding: Understanding from oral, written, and graphic through exemplifying, summarizing, comparing, and explaining. This step is about learning with a pre-trained module, where RL-agent can help learners to learn chemical reactions.
- Applying (Application): Using the learning and understanding for practical work where a learner can gain knowledge of chemical reactions in the PRACTICE module.
- Analyzing (Analysis): Analysing the visual models and different effects when chemical reactions happen.
- Creating (Synthesis): Hands-on learning practice, creating reactions; combining the application step.

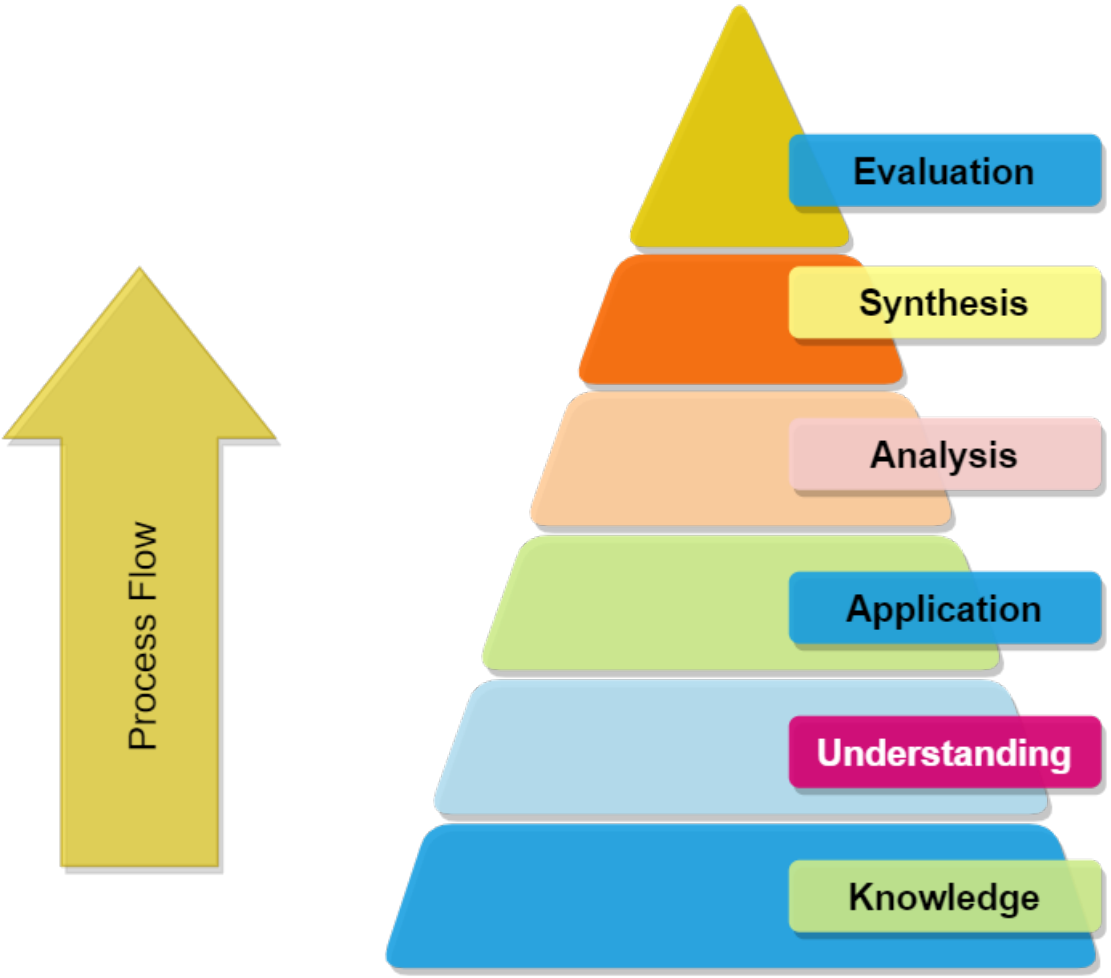


Figure 6.15: Explaination of Bloom Taxonomy, used for learning objectives.

- Evaluating: Evaluating the learning gained through the in-app QUIZ module.

Bloom's Taxonomy and its furthers revisions [164] are powerful tools that can help in developing learning outcomes because it explains the process of learning:

- Before understanding a concept, it is a must to know about it.
- To apply a concept, we must understand it first.
- To learn effectively throught the process, we must analyze it.
- To evaluate the learning gain, we must have an evaluation test.

To get the best out of the proposed approach, there is a need to apply a proper learning flow so

that students learn with agents before moving to hands-on learning in the virtual environment. This learning flow is explained in Figure 6.16.

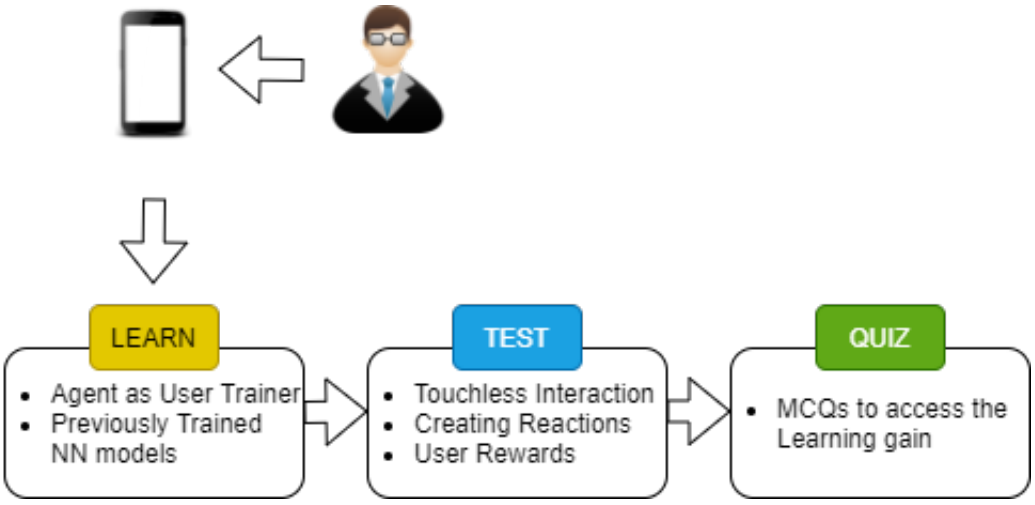


Figure 6.16: Concept of learning flow with ML agent, hand interaction and MCQs quiz

For machine learning agents, the learning concept follows the concept of *AI-Directed, learner-as-recipient* and *AI-empowered, learner-as-leader* [230]. As seen in Figure 6.16, the user starts with ***LEARN*** module, then goes to the ***PRACTICE*** module and ends with ***QUIZ*** based assessment which reports the score of student back to Firebase database which is following remote learning concept between teacher and students. In the ***LEARN*** module, the machine learning agent will take the previously trained Neural Network(NN) model to demonstrate to the user what possible chemical interactions are possible. Then, when the user feels they understand the possible interactions, they can move to the ***PRACTICE*** module. Figure 6.17 explains different steps users must follow when interacting with the application.

After completing the ***LEARN*** and ***PRACTICE*** sessions, the user will move to the ***QUIZ*** module. All the quiz questions are based on the chemical reactions users learned and tested in the previous two modules. The QUIZ interface is presented in Figure 6.18. After completing the quiz, the application shows the user's score and compares it with the highest score achieved previously recorded in the database. It completes the learning loop, starting with assisted learning, hands-on learning, and finally, learning gain assessment.

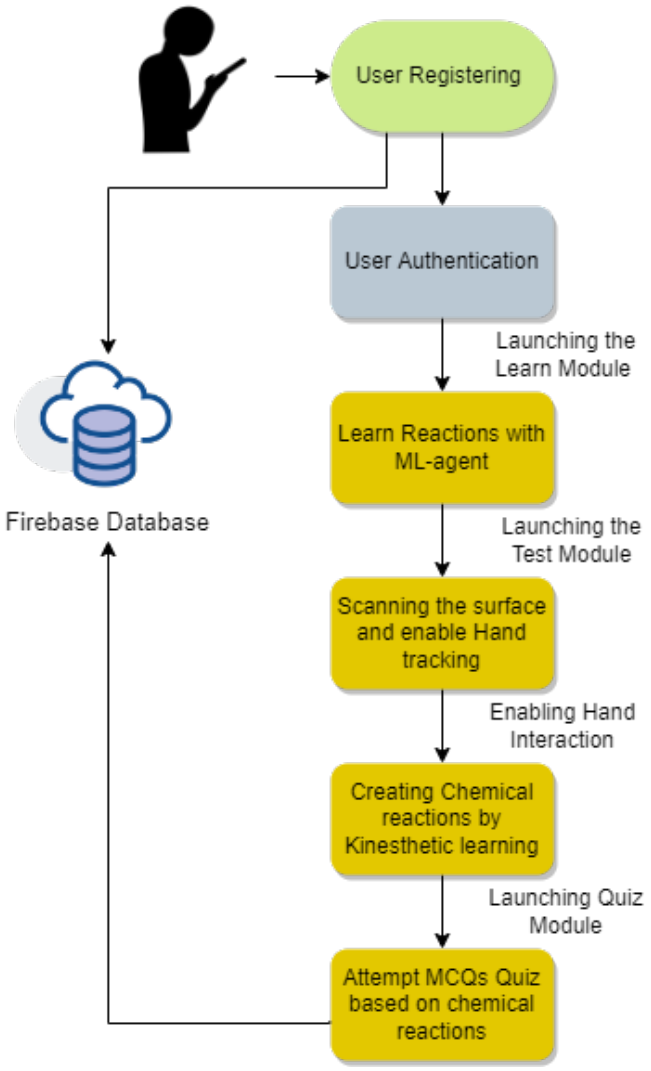


Figure 6.17: Different steps for the user to interact with the application

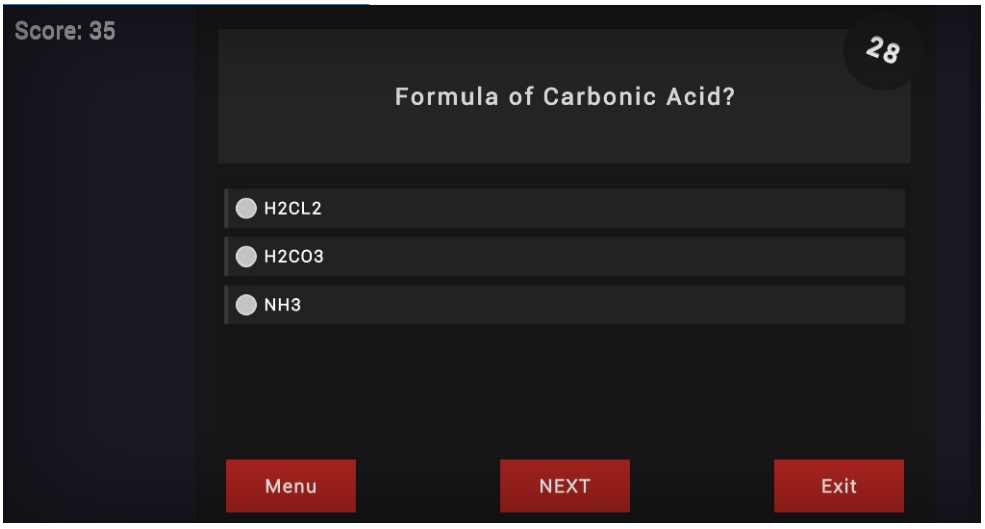


Figure 6.18: In-app multiple choice Quiz

These questions also include a negative score if the user fails to respond correct answer or cannot choose an option given within time.

As per the complexity of the questions, each question has a different score and a different time limit to respond. Every wrong answer leads to a negative score. The final gained score of the user is shown on the screen and also shows a comparison of its score with the highest score achieved by other users reported in the *Firebase* database. The limitations of this case study are discussed in Section 7.2.6, which includes both the design and usability test limitations.

6.1.4.1 Learning Gain Assessment

To measure the learning gain with actual end users, control group experiments are proposed for comparing the effects of intervention with traditional learning methods. The control group serves as a baseline using the traditional learning method (auditory, visual, and presentation), and the XR group (also called as experiment group) uses XR based learning approach. This method of learning gain assessment has been used in immersive learning with successful and supportive results [183, 287].

For conducting control group experiments in AR/VR, participants are typically assigned randomly to either an XR or a control group. The AR group is required to learn with XR intervention, while the control group participants do not. Assessment can be evaluated with task performance, learning outcomes, or user experience Results of these two groups, AR group results through an in-app Quiz and the control group through a paper-based quiz can be compared to measure the learning gain.

6.2 AGILEST Approach - HMDs

In XR, the use of HMDs and smart glasses is increasing with time due to more accessibility, decreasing costs, and increasing portability. The maturity of AR/VR/MR wearable devices has improved significantly during recent years and moving forward very fast. With the innovative

XR applications, the difference between learning in the classroom and outside is blurring with time. Moreover, the latest developments in XR technologies are making these environments more real, and high-quality XR technology in HMDs is becoming accessible in terms of affordability.

These recent developments and future opportunities push the need to test this approach with HMDs. Therefore, implementation of the AGILEST approach was considered for HMDs to evaluate it with more dynamic and portable devices with a better field of view. This section provides detail of the implementation of the AGILEST approach (as proposed in chapter 5) for HMDs, using real-time controller-free hand interaction and RL-agent, which is further evaluated in Chapter 7.

Figure 6.19: Different HMDs which are popular for XR experiences

Figure 6.19 shows different HMDs with different interaction abilities. In terms of hand tracking for real-time hand interaction as a standalone, Oculus Quest is most popular due to its accuracy in hand tracking and affordability. Microsoft Hololens 2 also provide full hand tracking for real-time hand interaction, but it is a comparatively costly device in terms of affordability. To

increase the safer duration of immersive experience, HMDs are now becoming more lightweight and very comfortable to wear. This development is very important for educational purposes because sometimes longer periods of use is required.

The aim of using hand interaction in the immersive environment is to facilitate the kinesthetic learning approach in science subjects providing higher interaction with 3D material; meanwhile, the RL-agent aims to develop self-guided learning, user training process, and facilitate assessment.

6.2.1 System Architecture

To implement the AGILEST approach for HMDs, a case study was developed for Oculus Quest 2 using controller-free hand interaction technology. The reason for preferring Oculus Quest over other VR handsets was the standalone feature of Oculus [129], and hand tracking functionality [43] as a major requirement of the study. Figure 6.2 explains the architecture of the system used in this case study.

Figure 6.20: Oculus Quest 2 which is used in this case study as a display device

Figure 6.2 explained the system architecture, which presents the role of RL-agent, *Interaction SDK* and the user's interaction with the application.

Influenced by Section 2.2.3 of using XR for STEM education for learning, this case study focuses on learning chemistry experiments with a resource-constrained learning scenario following the remote XR lab concept as discussed in section 5.1.3.

6.2.2 Training Module -LEARN

As discussed in Section 2.2.10, the agency has growing importance in empowering the user in the XR space. Therefore, higher user agency in an XR space could drive more empowerment for users.

Like previously used RL-agent as user trainer in Section 6.1.2, this case study uses machine learning agents to develop a training module and apply a self-guided learning approach in an immersive environment. To use intelligent agent, again Unity ML-Agents [153] are used as a package named as RL-agent in Unity. Full detail of installation, training, and embedding RL-agent is discussed in Chapter 4. which is used in this case study as well. The significant difference between the training agent for these case studies, in handheld devices, the input can be provided only through a single hand while holding the device in the second hand, and in HMD, input is possible with two hands.

This process consists of;

- Collecting required data of reinforcement learning; states, actions, rewards
- Training of reinforcement learning model
- Inputting trained model back to the unity application

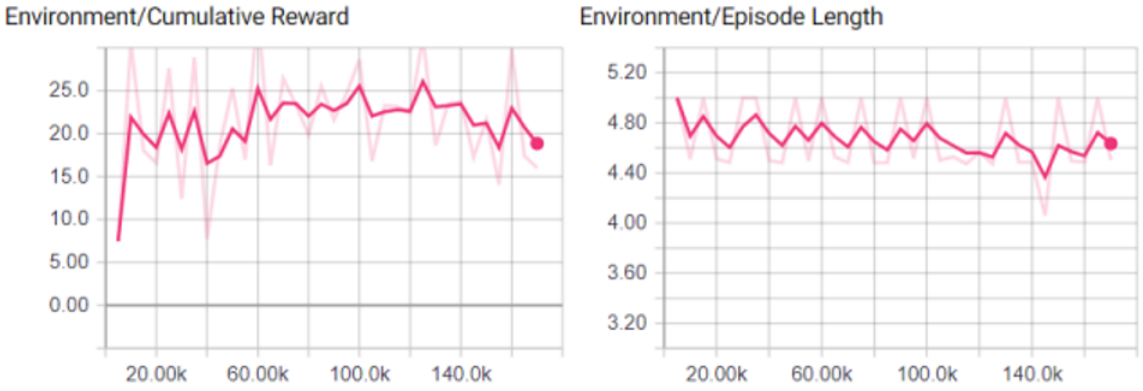


Figure 6.21: Tensorboard graph with Cumulative reward and episode length

To observe the training process, TensorBoard provides graphs in detail. The graphs presented in Figure 6.21, show the cumulative rewards and episode length. Each episode means a cycle

to complete all chemical reactions during the training process. A graph in Figure 6.22 shows the learning rate; according to the successful implementation of reinforcement learning, the learning rate should decrease with time.

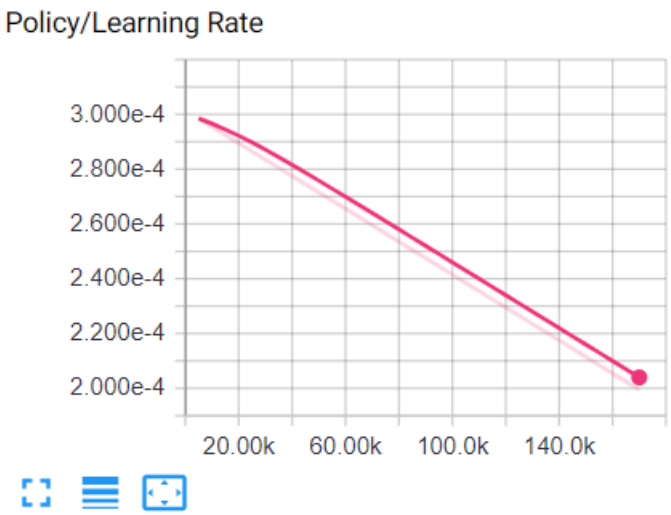


Figure 6.22: Learning Rate in Tensorboard; according to the successful implementation of reinforcement learning, the learning rate should decrease with time.

LEARN module trained as in Figure 6.23 using RL-agent to help users learn the kinesthetic tasks before going into the next module to interact in the virtual environment.

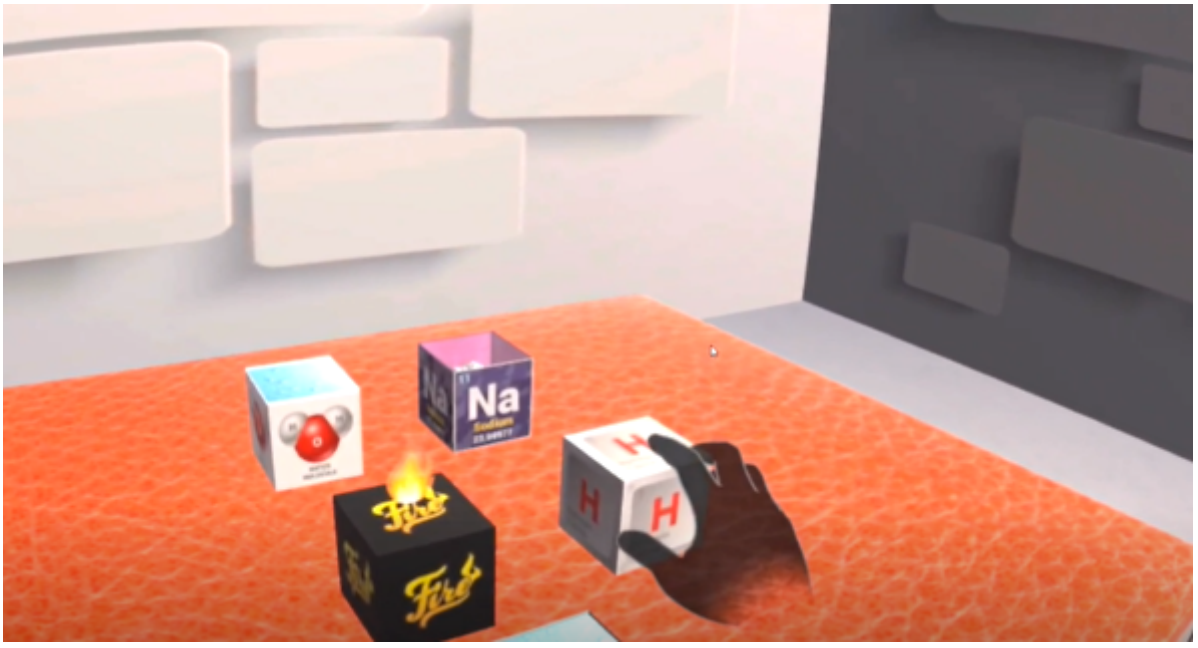


Figure 6.23: Training the Neural Network (NN) of RL-agent

Based on the user observation collections during kinesthetic tasks in the virtual environment, RL-agent is training for *Grab, Move, and Collide* actions. Like the handheld AGILEST approach, the HMDs version follows the same learning flow consisting of three different modules *LEARN*, *PRACTICE*, and QUIZ. The user can enter the module in the menu as part (a) of Figure 6.27.

The first module uses machine learning agent agents to guide the user in learning how to interact in the PRACTICE module. In this module, the user cannot interact with 3D cubic elements. In the case-specific scenario, this helps to learn how to create chemical reactions in the immersive environment.

6.2.3 Kinesthetic Learning Module - PRACTICE

The *PRACTICE* module allows users to interact with 3D chemical elements and, following the machine learning module create chemical reactions in an immersive environment. This module focuses on kinesthetic learning, "hands-on learning" pedagogy, a major requirement for STEM subjects, and technical training where "learning by doing" is necessary for learning gain. Using the hand-tracking SDK of Oculus Quest, this module provides real-time hand interaction in the virtual environment.

Enabling Hand Tracking in Oculus Quest;

- Press "Oculus" button on the right Touch controller to open the universal menu.
- Hover over the clock in the universal menu on the left-hand side. Select and open the "Quick Settings" panel.
- Select "Settings" from the top-right corner.
- From the left menu, select Device and then select "Hands".
- Turn on Hand tracking by selecting Toggle in front of "Hands Tracking".

Once this toggle button is turned on, Oculus Question automatically switches between controller to free-hand interaction. As a result, users can interact in the virtual environment without any controller. The Oculus headset detects hands with all fingers information through the cameras and uses this hand-tracking information as input to decide which activity to execute.

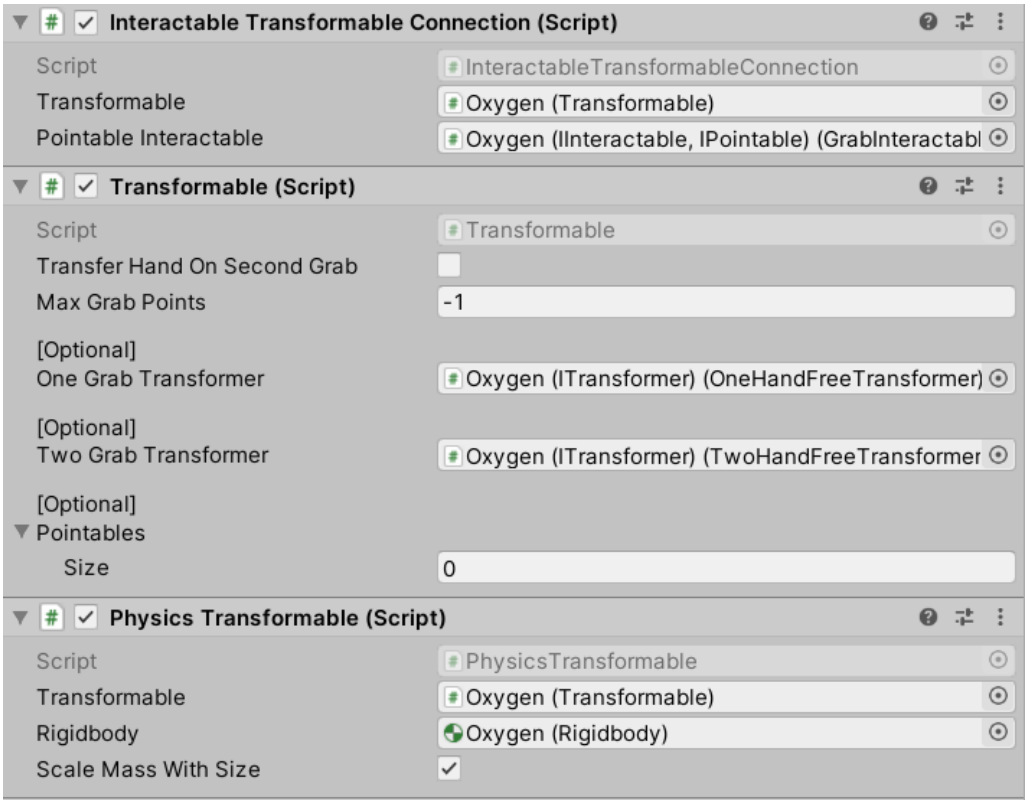


Figure 6.24: Making 3D objects interactable with Oculus Quest Hand Tracking SDK

In this module, reactions are followed by audio feedback to let the user know about chemical reactions. Figure 6.24 shows Unity inspector about making the 3D objects intractable with real-hand interaction without using a controller. It allows changing the point of interaction and setting the grabbing force needed to grab an object "translating the position of object". This script needed to apply every object which is supposed to be intractable with hands interaction. Unity Inspector elements, as shown in Figure 6.25 provide a setting to change the criteria for the hand grab feature for interacting with 3D objects. It can be set to all fingers role pinch or just one or two for interaction with 3D objects. Making the middle, ring, and pinky finger as optional means users will need less effort to grab objects. To make full hand compulsory for pick and grab, all fingers must be made "Required".

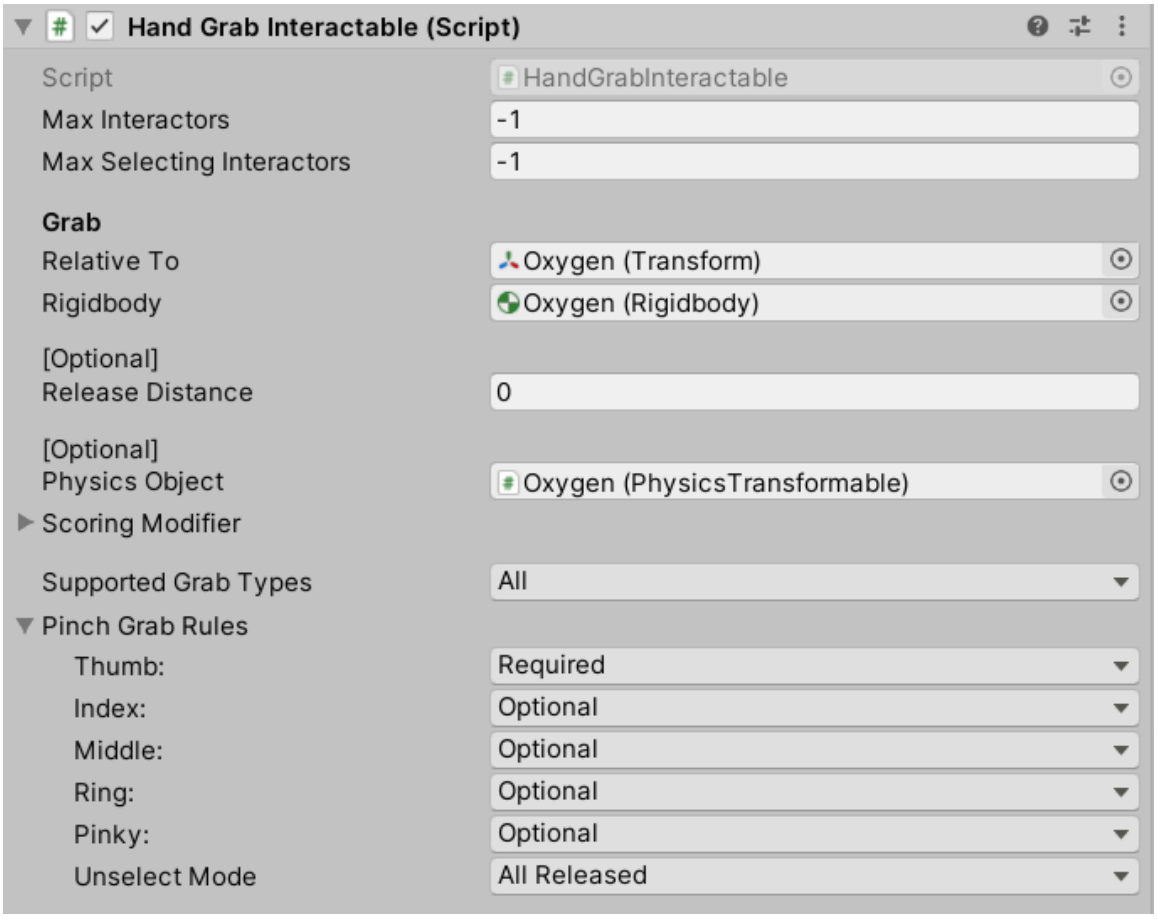


Figure 6.25: Setting hand grab feature in Oculus Quest Interaction SDK

Development view of Unity scene shown in Figure 6.26 for *PRACTICE* module; the user can move around the table in the configured tracking area.

Figure 6.26: Unity view of interaction scene

User interaction in the *PRACTICE* module is presented in Figure 6.27 with different views of

hand tracking.

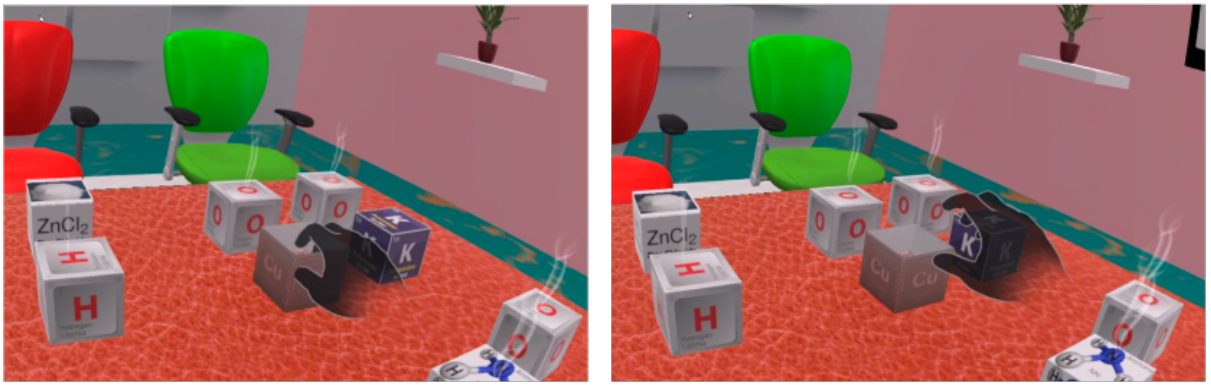


Figure 6.27: Different view of user interaction with Application in Oculus Quest

In the PRACTICE module, similar to Section 6.1.3, the user can understand the gas, crystals, and liquid forms of different elements and molecules, which adds a realistic concept to 3D chemicals and can be further extended to haptic feedback.

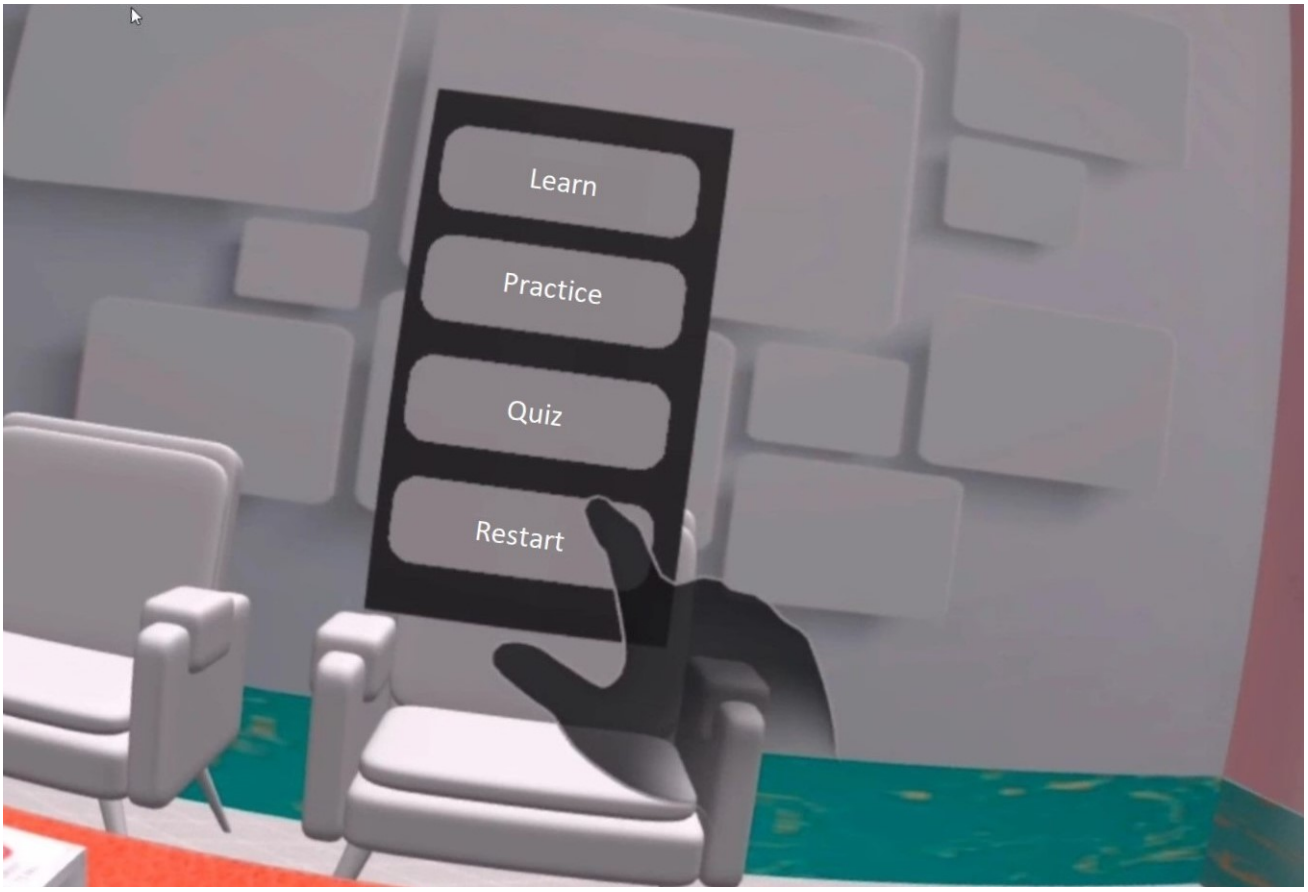


Figure 6.28: User Interaction with the menu in Oculus Quest

It can be extended to haptic feedback with hand gloves so users can actually feel the nature of the chemicals. This module allows users to move within the assigned tracking space, and create chemical reactions following the hands-on learning approach.

Figure 6.29: Process of creating a reaction in HMD virtual environment.

6.2.4 Assessment Module - QUIZ

After completing the LEARN & *PRACTICE* module to learn with hands-on practice, the user will enter to *QUIZ* module within the app. The QUIZ module overlays the PRACTICE module to provide MCQs-based assessment for users based on their learning in previous modules. To assess the learning gain in a better way, the QUIZ module has negative feedback if the user selects the wrong choice while answering the MCQs. The QUIZ module is linked to a database where instructors can review students' learning outcomes.

6.3 AGILEST Approach: HMD vs Handheld Prototype

Both AR and VR can potentially transform learning technology with digital information. As there are many similarities, some key differences are also reflected in the two above-presented

AGILEST prototypes.

- By wearing Oculus HMDs, the user can interact in the virtual environment with both hands, but in a smartphone, the user can only interact with one hand.
- Field of View (FoV) is smartphone is small compared to HMD, which allows a better exploration of the environment for the user.
- AR enhances the real world instead of putting the user in a completely virtual environment. The handheld case study can provide more comfort to the user by providing a virtual world without losing the real environment.
- Hand interaction technology of Oculus is much more advanced than Manomotion technology which is developing over time.
- From a user perspective, using HMD needs more training than using a smartphone which is the most common device.

In the future, user interaction in immersive experiences will improve significantly as XR hardware and software technology continues to evolve. Multi-user hand interaction can become more comfortable and realistic, enabling users to interact with each other in XR environments. These developments will create opportunities for more engaging and realistic immersive experiences, opening up new potential for using XR in education, skill training, and entertainment.

6.4 Conclusion

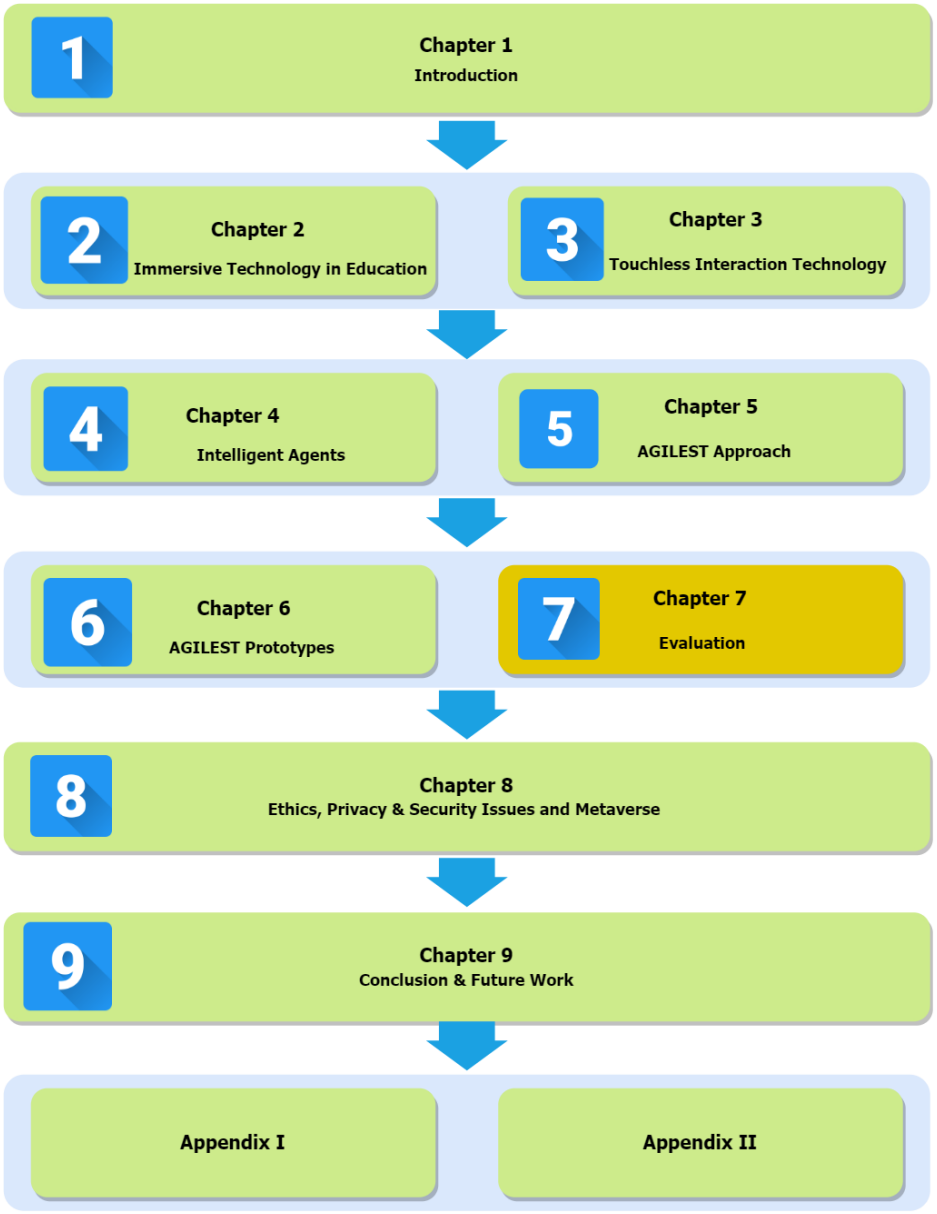
This chapter presented two case studies based on the proposed AGILEST approach presented in Chapter 5. The successful implementation of the real-time hand interaction capability with the virtual objects over the real environment and user training capability with machine learning agents proved the hypothesis presented in the section 6.0.1 to create possibilities for combining these components in an AR learning system. Detail of installation, environment configuration,

training, and the embedding process has been provided in section 6.1.2. Manomation and other hand-tracking APIs like Google Mediapipe for smartphones and tablets are continuously improving to provide better interaction in virtual environments. By extending the AGILEST approach to HMDs on Oculus Quest, this research has completed testing with three major display categories; desktops, handhelds, and HMDs. Considering the difference between different display devices, HMDs can be considered for higher expectations and graphics processing to produce more productive results. Progress towards wearable computing is swift, and HMDs are the major component of this race, either VR headsets like Oculus Quest, HTC Vive or see-through displays like Hololens and magic leap. Implementing the AGILEST approach in HMDs gives more accurate and comfortable interaction in the virtual environment, as Oculus Quest provides much better hand interaction capability than Manomotion for handheld. Secondly, HMDs have a much wider tracking field for interaction and allow interaction with two hands simultaneously instead of using one hand to hold the device in the case of handheld devices. Finally, the standalone HMDs are very portable devices and provide more flexibility to users in terms of walking in the tracking area, enjoying a wider gameplay area, and switching between different environments. Virtual laboratories for STEM subjects [242] are becoming a unique field in VR-enabled education tools. However, the additional requirement of tracking separate from the display device adds more complexity within AR. In terms of pure software engineering, using an agent-orientated abstraction could aid in creating much more modular systems [126] that allow the separation of the display and tracking, making XR tutor-based applications much easier to develop. Combining this with an agent-oriented approach can help to improve the evaluation process of large-scale assessments and automate the learning process for remote learning [325], and technological transformation of remote learning with AR/VR systems [219]. To evaluate the hypothesis discussed in Section 6.0.1 and the approach of using hand interaction with machine learning, an evaluation was conducted with the expert reviewers, which is presented in Chapter 7.

CHAPTER

SEVEN

Evaluation



Immersive learning applications depend on different factors, which include quality of rendering, responsiveness, interactiveness, and user interfaces. To consider human factors in technology adoption, evaluation and assessment are the most crucial components in XR systems for learning. This chapter discusses the evaluation of the AGILEST approach, which is presented in Chapter 6. For conducting evaluations, there were many ethical (further explained in Chapter 8), accessibility and hygiene issues emerged due to COVID-19, especially where end users are under 18 [281] as AGILEST case study is focusing on the high school students as end users. This situation in the EU region made it impossible to get ethics approval for conducting experiments with the actual end-users under 18 studying at high school level.

Studies involving human factors with machine interaction, especially those under 18, have adopted system evaluations with expert reviewers as an alternative evaluation methodology.

The purpose of the evaluation was to find the answers to these questions;

1. How can machine learning agents help in immersive learning as a self-guided learning approach based on previously trained neural networks?
2. How can real-time hand interaction help XR increase productivity with kinesthetic (hands-on) learning tasks with virtual material?
3. How can virtual material in XR help to replace the physical material in resource-constrained environments to produce a realistic interaction in an immersive environment?

7.1 Evaluating AGILEST approach for Handheld Devices

The experimental design of this research evaluation has adopted expert reviewers method influenced from different Human-Computer Interaction (HCI) studies for testing new applications involved with human factors [119, 270, 320]. This evaluation aimed to test the

usability of the interaction hand to perform a role for kinesthetic learning and efficiency of the machine learning agents in the augmented environment to support self-guided learning. The evaluation also aimed to get feedback from expert advice.

Along with assessing the adopted approach, this evaluation has also explored the ethics, privacy, and security challenges of using XR in remote environments. These issues are discussed in Chapter 8.

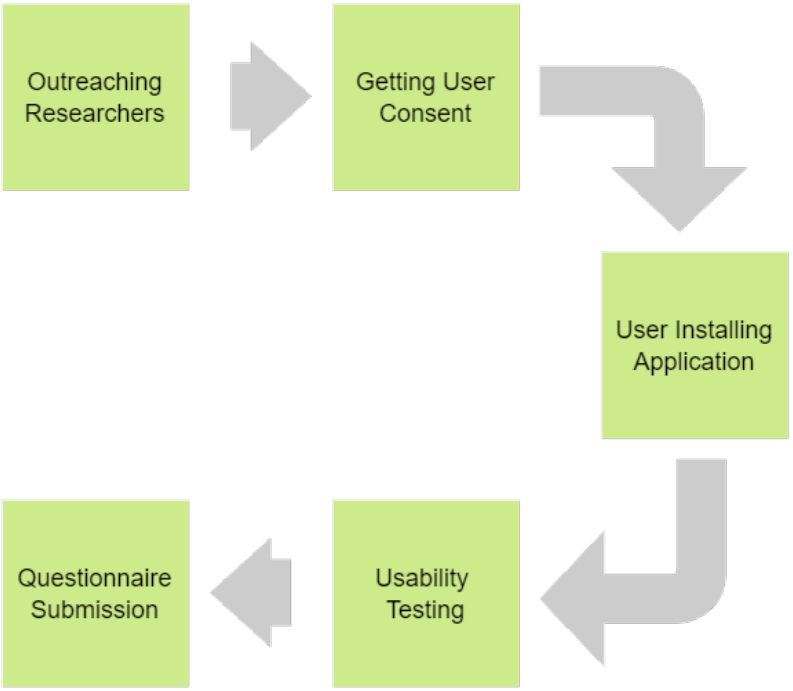


Figure 7.1: Steps followed in the evaluation

7.1.1 Participant Recruitment

For effective usability research in technology, recruiting the right participants is the foundation because research results are only good if the involved participants are good. The participants were recruited through direct outreach through email and the online platform of Connected Learning Summit (CLS21) [1] & International Conference of the Immersive Learning Research Network (iLRN 2021)[2].

[1] https://2021.connectedlearningsummit.org/
[2] https://immersivelrn.org/ilrn2021/

Figure 7.2: Connected Learning Summit & International Conference of the Immersive Learning Research Network

CLS is a home of learning technology researchers presenting the latest innovations in technology-enhanced learning using AI, XR, data analytics, and m-learning. iLRN is a gathering of educators, developers, and researchers developing immersive learning solutions for scientific, technical, and formal learning.

Initially, 46 expert reviewers were outreached based on their research interests. Out of these 46 potential experts outreached via formal invitation emails, a total of 19 signed consent to participate in the evaluation process. At the next stage, 4 withdrawn due to compatibility issues with their devices as API level of application higher for Manomotion compatibility and older smartphones are not working with ARFoundation. So finally, 15 participants participated in the evaluation procedure and submitted the final questionnaire.

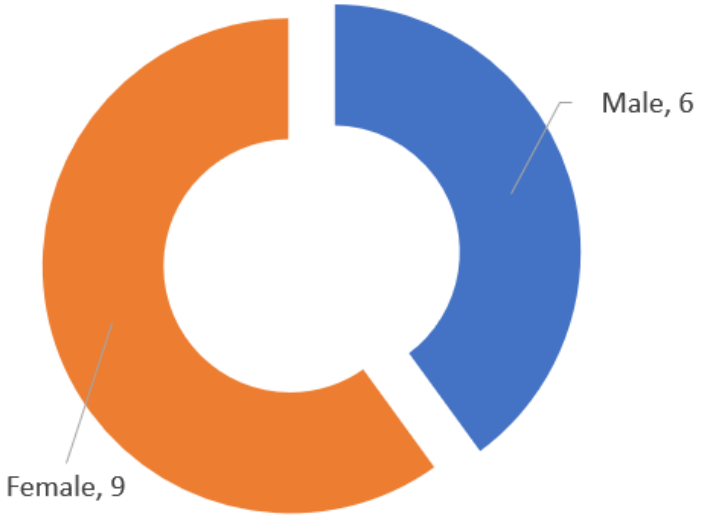
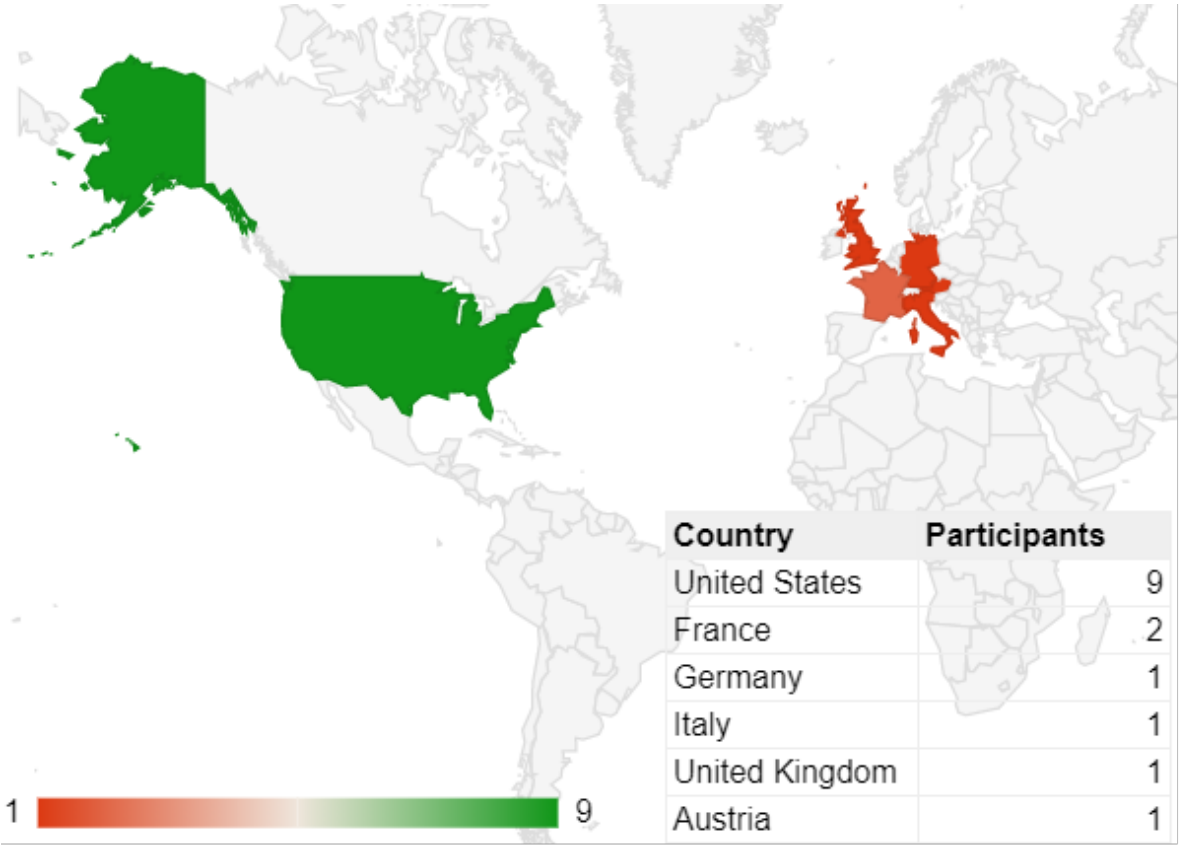


Figure 7.3: Gender-wise distribution of the expert reviewers

Gender diversity wise, among 15 final participating subjects, 6 were males, and 9 were females as visualized in the Figure 7.3. All participants had research-level experience in XR, HCI, interaction design, and learning technology with published peer-reviewed research papers in journals and conferences. The expert reviewers' demographics have been presented in Figure 7.4, which shows the diversity and inclusion of different regions in the evaluation process.



Country	Participants
United States	9
France	2
Germany	1
Italy	1
United Kingdom	1
Austria	1

Figure 7.4: Geographic mapping of the expert reviewers

Those participants who were outreached from Connected Learning Summit had more experience in educational pedagogies and different learning technologies; other participants who outreached from iLRN conference were fully engaged in immersive learning, which includes AR & VR. Along with NASA-TLX and TAM questionnaires for evaluation, qualitative feedback from these expert reviewers was collected, which is discussed in Section 7.1.5. The learning on this evaluation aimed to help in the AGILEST approach's concept development and interaction design for HMDs, which is presented in Chapter 6 and its evaluation in this Chapter.

7.1.2 Evaluation Procedure

After accepting the consent, these participants were provided with the APK file and for installation on their Android smartphones, instructions for installation and conducting experiments, Youtube video [3] explaining the application working and final questionnaire in Google form to fill after testing the application. The Google form can be seen in Appendix, Chapter 11.

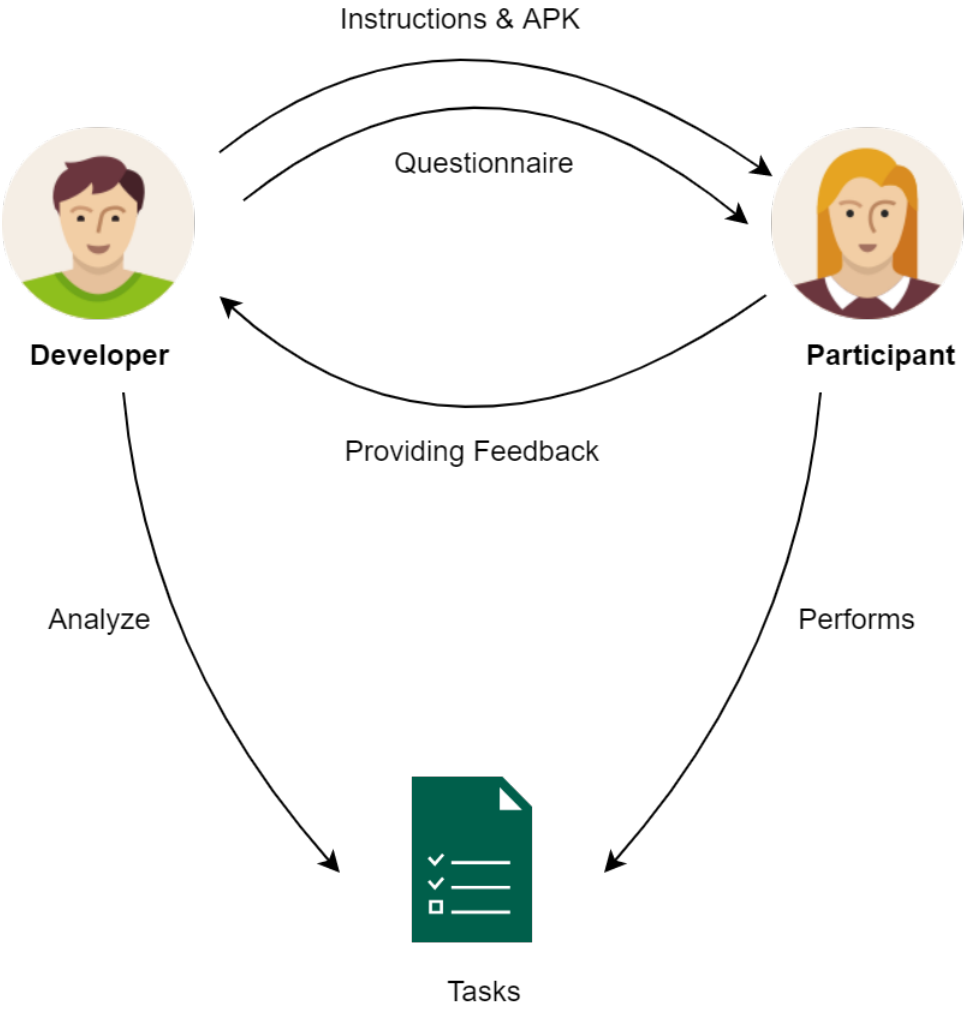


Figure 7.5: Process flow of evaluation tasks and questionnaire

The expert reviewers had to follow the instructions and perform the tasks necessary to complete the usability evaluation.

[3] https://www.youtube.com/watch?v=mQ6D6ItJaG8

7.1.3 Tasks

The evaluation process consisted of installing an AR application on compatible Android smartphones and testing the usability of the application, which includes the role of the machine learning agent as a trainer and real-time hand interaction to create chemical reactions with cubic elements. For the purpose of subjective and objective analysis, post-experiment task was to fill a questionnaire designed using NASA Task Load Index [122] known as one of the best tests to measure the cognitive load in XR [42] and Technology Acceptance Model(TAM) for Perceived Usefulness and Ease of Use [78] to examine the usability & subjective questionnaires to get qualitative feedback. The NASA Task Load Index (NASA-TLX) is an assessment tool that helps to assess the perceived task load for the assessment of kinesthetic learning tasks. It is divided into six categories as explained in Table 7.1.

Sub-dimensions of workload	Explanation
Mental Demand	Mental demand needed for task completion.
Physical Demand	Physical demand needed for task completion.
Temporal Demand	Time demand and pace of the task.
Performance	Success in accomplishing the task.
Effort	How hard to accomplish your level of performance?
Frustration	How irritated, stressed, and annoyed felt to complete the task?

Table 7.1: Sub-dimensions of workload NASA Task Load Index

NASA-TLX proved as a good tool for the assessment of workload in different XR studies [187, 312], which makes it a better choice for measuring workload in user contexts. NASA-TLX is can help XR researchers and instructors to understand the cognitive load level experienced by the learners when learning in the immersive environment. This collected information can help to adjust the instructional design and to optimize the immersive learning experience. It can also help to identify high-risk factors.

Following the Technology Acceptance Model(TAM), the Perceived Ease of Use(PUEU) and Perceived Usefulness(PU) questionnaire used to measure these human factors for acceptance of new technology;

- Perceived usefulness
- Perceived ease of use
- Behavioral intention

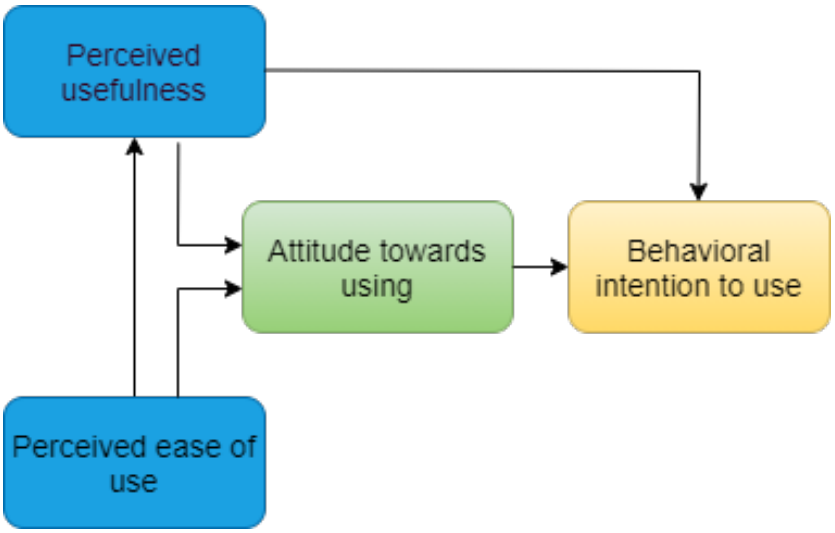


Figure 7.6: Technology acceptance model [204]

7.1.4 Results

After conducting an evaluation in the immersive learning experience, analyzing the results is very crucial to determine the effectiveness of the learning approach and improving the proposed design in the future. This also includes assessing the nature of the experience if it positively affected to participants' attitudes, beliefs, and behaviors. Analysis was performed based on questionnaire results filled by the participants after testing the application. Based on the data collected in the questionnaire, Table 7.7 & Table 7.3 provide information about the mean, median, and high to low scores on usability and efficiency of real-time hand interaction and machine learning agents.

Questions- NASA Task Load Index 5-point Likert scale	Average	Median	Min	Max
How much mental and perceptual activity was required? (Low - High)	2.5	3	1	3
How much physical activity was required for performing tasks?	2.5	2	1	4
How much time pressure did you feel due to the pace at which the tasks or task elements occurred?	1.8	1	1	5
How successful was you in performing the tasks in experiments?	2.75	3	2	5
How hard did you have to work (mentally and physically) to accomplish your level of performance?	2.3	2	1	4
How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?	2.6	3	1	4

Table 7.2: Analysis based on data of NASA Task Load Index questionnaire's responses with average, median, min and max

The graph in Figure 7.7 shows the visual representation of results from Table 7.2.

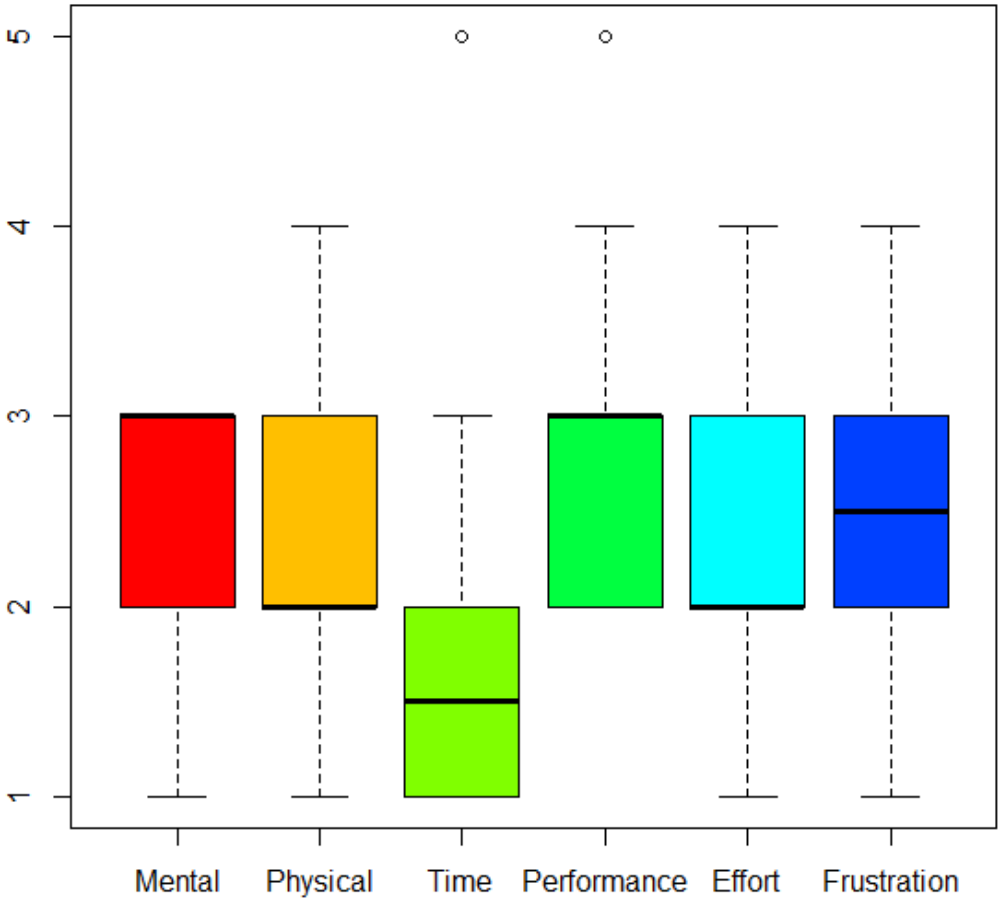


Figure 7.7: Ratings of NASA Task Load Index (TLX) on 5-point Likert scale

The physical task load and effort needed to complete the task are slightly lower than mental efforts. However, the time pressure to complete the task is definitely lower than all other factors which means users performed the tasks quickly. Performance indicators are higher and linked with the mental frustration factor to understand the system the first time is also a little higher, which is further explained in the section 7.1.5 with user follow-up interviews.

Table 7.3 shows the Perceived Usefulness and Ease of Use score on a scale of 1-7. The score for learning performance and learning effectiveness improvement with this approach was rated very high, 5.2 and 5.6 on average, respectively. The average score for the machine learning module is 4.78, which shows reasonable effectiveness of using the agent-oriented approach; however, it needs improvements as expert reviewers provided feedback in the qualitative questionnaire. Ease of Use for interacting with the application, creating reactions with virtual hand interaction, and following the LEARN module received very positive scores on average, which means expert reviewers appreciated the usability of the implemented AGILEST approach.

Questions - Perceived Usefulness and Ease of Use) 7-point Likert scale	Average	Median	Min	Max
Using touchless hand interaction with 3D learning material improves learning performance?	5.2	6	1	7
Using AR-based interaction method will enhance learning effectiveness?	5.6	6	2	7
Machine Learning module helps to learn creating chemical reactions?	4.78	5	2	7
It was easy to learn chemical reaction with AR Hand Interaction?	4.6	5	1	7
It was easy to interact with the Application during test?	4.66	5	1	7
It was easy to follow the Learn Module when creating reactions in the PRACTICE module?	4.35	4.5	2	6
It was easy to interact with the 3D chemicals with hand interaction?	4.06	4	2	6
How satisfied you are with the learning approach and interaction?	4.6	5	2	7
Will you recommend this approach to use with students ?	4.66	5	1	7
It was a pleasant experience to use the application?	5.06	5	2	7

Table 7.3: Data of Perceived Usefulness and Ease of Use questionnaire responses with average, median, min and max

In terms of having a pleasant experience, the average score 5.06 is very high, which shows encouragement to adopt this approach for creating enjoyable and engaging learning experiences in the classroom or outside the classroom as presented in focused review Figure 2.1.

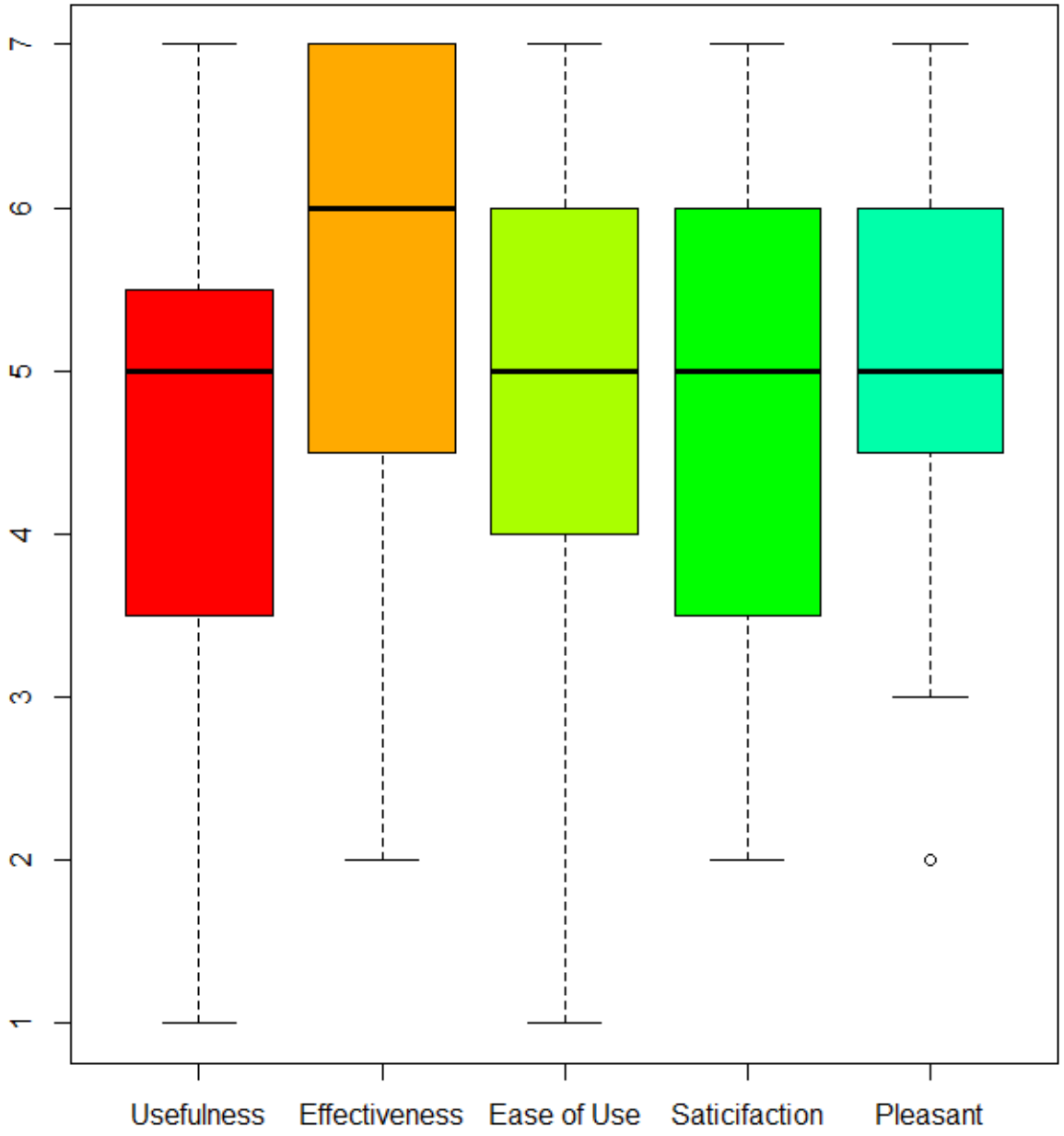


Figure 7.8: Ratings for Perceived Usefulness and Ease of Use on 7-point Likert scale

The PUEU graph in Figure 7.8 indicates the effectiveness of hand interaction and machine learning agent is higher as compared to all other factors. The satisfaction level of the experts

is very high regarding the general usability, and behavioral intentions of the user towards the system also indicate a higher score.

7.1.5 Follow-Up Interviews: User Experience

Along with NASA-TLX and PUEU, there was a subjective questionnaire to understand user experience and get more detailed answers as recommendations to extend the design concepts in the future. During the first usability test, feelings regarding hand interaction with the virtual chemicals and the use of machine learning agents to assist the learning process were reported positive overall. Furthermore, responses were very positive on the system's consistency, expected productiveness and ease of use. The common issues reported related to frame processing speed on different APIs like a user of *"Samsung S7"* because it is an old phone with lower API compatibility.

Responses of the experts on a general usability question were *"felt some troubles for initially following the LEARN section, but the general interaction with the app and with cubic elements is easy after a few tries"*. Another expert said; *"it was not working with my phone but I used a tablet. Previously, I played with gesture-based interaction with Hololens but this direct hand interaction is fantastic."*

As a response to recommendations for making the app more productive, participants responded as *"adding more learning material on different topics in the app can help to make the application more productive"*, *using spheres instead of cubes* and *improving the machine learning part to create more attention*.

A participant appreciated the visualization of effects "crystals, liquid and gas" relevant to the actual chemicals as, *"On top of the cubic elements, you can actually see the physical appearance of certain elements (e.g. gas flow, vapor, etc)"* which is supposed to create more realism in the virtual learning.

When it comes to the "most interesting part of the application", responses were *"the most interesting concept was the indication of the hand actions that appear to be highly responsive*

to the actual human hand action", *"provide it for iPhone"*, *hand interaction capability is my smartphone*, and *educational part of AR chemistry* which shows the potential of this proposed approach for create motivation in the learning process.

The participants responded differently to the machine learning module in terms of guiding users but it brings an overall conclusion that machine learning can help in AR learning when used as a pre-trained learning module *"this concept could be successful in this regard"* and another *"yes, I think this needs more of a built-in lesson or learning goal. How is the AR activity allowing people to apply newly learned knowledge, or are they discovering new knowledge which will be formalized in a reflection? You may want to look at Kolb's model of experiential learning. "*.

Overall, the experts showed very positive, constructive and interesting feedback for use of hand interaction for "hands-on learning" and proposed use of machine learning agents for training end-users.

7.2 Evaluating AGILEST Approach - HMDs

After designing and implementing the AGILEST approach for HMDs with Oculus Quest, the goal of the validation study was to evaluate the usability and psychological workload with expert reviewers.

Using ineffective or imperfect approaches in the learning systems can risk the successful acquisition of targeted learning goals and outcomes. It can also mislead the user experience with specific technologies creating negative perceptions. To achieve the proof-of-concept, this evaluation study aimed to investigate the effectiveness, interactiveness, and level of value creation in the learning process. Usability evaluation of XR systems allows the developers to assess different aspects of the system in a better way. In addition, the evaluation reveals how the users interact with the system and find the product or system easy to use, meeting the proposed goals and investigating design issues. This blended learning approach using the components of Section 6.2.1 in a VR application is supposed to provide a self-guided learning experience and user confidence in the immersive environment. This evaluation study aimed to investigate

whether integrating hand interaction in immersive learning and using machine learning as self-guided could improve concept learning in science subjects with hands-on practices. These experiments are conducted with expert reviewers where main focus is to assess the usability.

7.2.1 Recruiting Participants

For evaluating the AGILEST HMDs version, an in-person evaluation was conducted during ACM International Conference on Interactive Media Experiences (IMX) 2022[4] and 16th EATEL Summer School on Technology Enhanced Learning 2022. EATEL Summer School[5] is an annual gathering of researchers in Technology Enhanced Learning(TEL) who are working on immersive learning, learning analytics, and learning intelligence.

Figure 7.9: ACM IMX Conference and EATEL Summer School where the second evaluation was conducted.

ACM IMX is an international conference for researchers in interactive media experiences with major contributors from XR researchers. The main pre-requisite for reviewers participating in the research evaluation was a research-level experience in XR, HCI, and technology-enhanced learning with a history of publications. A direct outreach was performed based on identified research work in their contribution to the IMX and Summer School. Equal inclusion of both genders is necessary for conducting proper evaluation because it can ensure better representation of the target audience [210]. Although this evaluation is not based on end-users, it is still very important because different people have different needs, abilities, and specific preferences; a prototype that can work perfectly for one may not work for another. A total of 15 expert

[4]https://imx.acm.org/2022/
[5]https://ea-tel.eu/jtelss22

reviewers (plus two subject experts presented in section 7.2.2) participated in the evaluation process, which included 6 participants from Summer School and 9 from the IMX conference. Out of 6 in summer school, 2 were females and 4 males, while out of 9 in IMX conference, all 9 were males. Among these 15 participants, 6 participants who were from summer school had more background in technology-enhanced learning as general or learning pedagogy in XR. 9 other participants who participated from IMX conference had more experience in multimedia and interactive technologies in learning, which includes different types of immersive technologies.

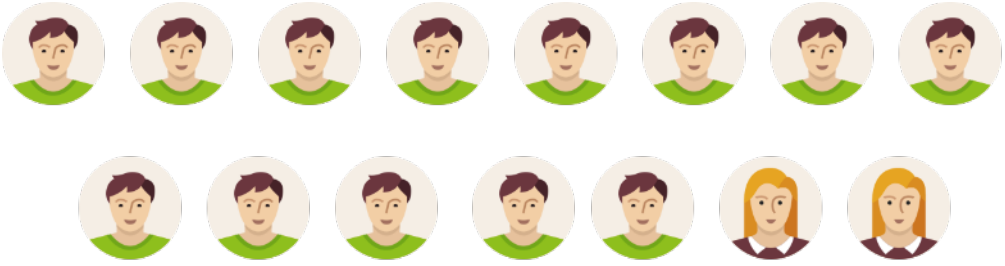


Figure 7.10: Participants' demographic details

All of the expert reviewers are at different levels of research with diverse ages, starting from 23 to 38 as the maximum one; Figure 7.11 shows a comparison of the ages of participants.

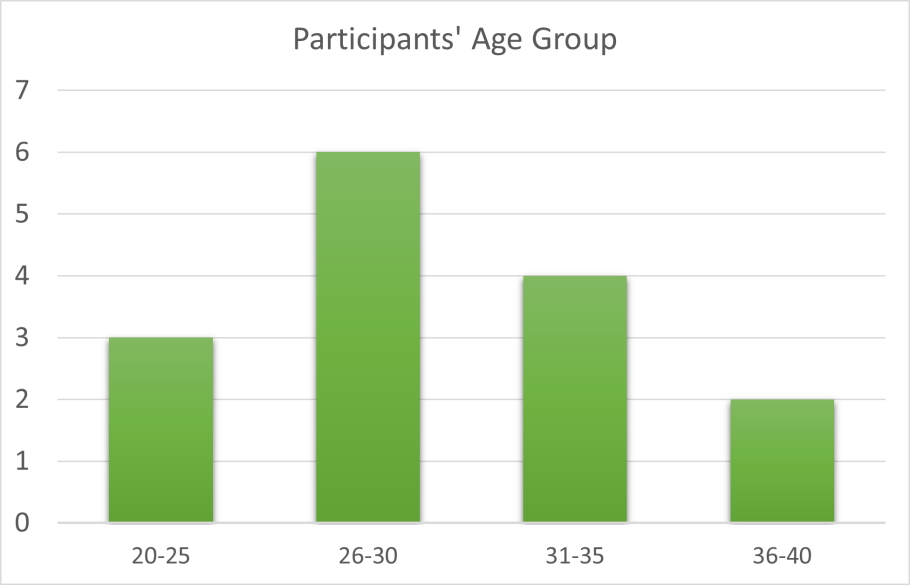


Figure 7.11: Participants Age Group

7.2.2 Subject Matters

Aside from the formal evaluation process by testing with expert XR users, two *two secondary school level instructors* were invited to provide their input in the adoption of using hand interaction, self-guided learning and introducing cubic elements for learning chemistry in the virtual environment. The aim of involving the chemistry-related instructors was to get subject-related help for usability recommendations for the system and help with the future work in TEL for STEM. Reviews of subject experts are discussed in Section 7.2.5.

7.2.3 Experiments Procedure

Experimental procedure in immersive learning can have different procedures which depend on the experiment's goal. As a first step, getting informed consent is a crucial part of immersive learning same as any other research involving human participants. Using the same evaluation methods when evaluating two prototypes can help in fair and unbiased comparison and a more accurate assessment of both prototypes to find differences.

Figure 7.12: Learning with LEARN module using self-guided learning: Evaluations with young researchers at ACM International Conference on Interactive Media Experiences 2022

It is essential to use the same evaluation method to ensure that collected results are compared and observed differences are due to the technical differences in the prototypes instead of evaluation method differences. Using different evaluation methods for two prototypes can make it difficult to conclude relative merits due to confounding variables used in the tests. After getting consent from participants, they were introduced to the technical aspects of the application and the learning goal of this approach. Further, they were guided about the learning flow in the application before starting actual experiments with Oculus Quest. With hand-tracking functionality enabled, Oculus Quest 2 was used in the experimentation process. It was a fully controller-free interaction process, allowing users to interact with virtual 3D objects with hand-tracking technology.

Figure 7.13: Hands-on learning with interaction hand: Evaluations with young researchers at ACM International Conference on Interactive Media Experiences 2022

Every expert reviewer was asked to jump into *LEARN* module after starting the experiment, where a pre-trained machine learning neural network can help to learn to create chemical reactions in the virtual environment (Figure 7.12). After learning through *LEARN* module, each participant switched to *PRACTICE* module to practice hands-on learning for creating chemical reactions. The tracking area, field view, and interaction space are set to a user sitting on a chair and can reach all elements at arm's length without the need to walk in the tracking area. Following the learning experience of *LEARN* module, participants created all chemical reactions using virtual hand interaction with 3D cubic elements. After completing both *LEARN* and *PRACTICE* modules, each participant was provided with a questionnaire based on two components;

- NASA Task Load Index (NASA TLX)
- Technology Acceptance Model (TAM) to measure Perceived usefulness (PU) and Perceived ease-of-use (PEOU)

As used in the evaluation of handheld case study, NASA Task Load Index (NASA TLX) is a tool used for conducting workload assessment [122]. In terms of user's workload, there are different contextual characteristics in AR and VR. In AR, cognitive processing to integrate virtual and real-world information is the main factor as the user's workload. In VR, the workload is mostly about the level of immersion, quality of graphics, sensory processing, and interaction with virtual objects. In expert evaluations, NASA-TLX can provide valuable feedback on the usability of the interface and interaction design. It can help in the development process to identify usability issues and making changes to improve the system's overall user experience. Also, it can help to investigate high workload areas happening due to poor usability, such as high mental or physical demand which can lead to user frustration and fatigue. There are six sub-scales in NASA-TLX which consists of Mental, Physical, and Temporal Demands, Frustration, Effort, and Performance are presented in Figure 7.14.

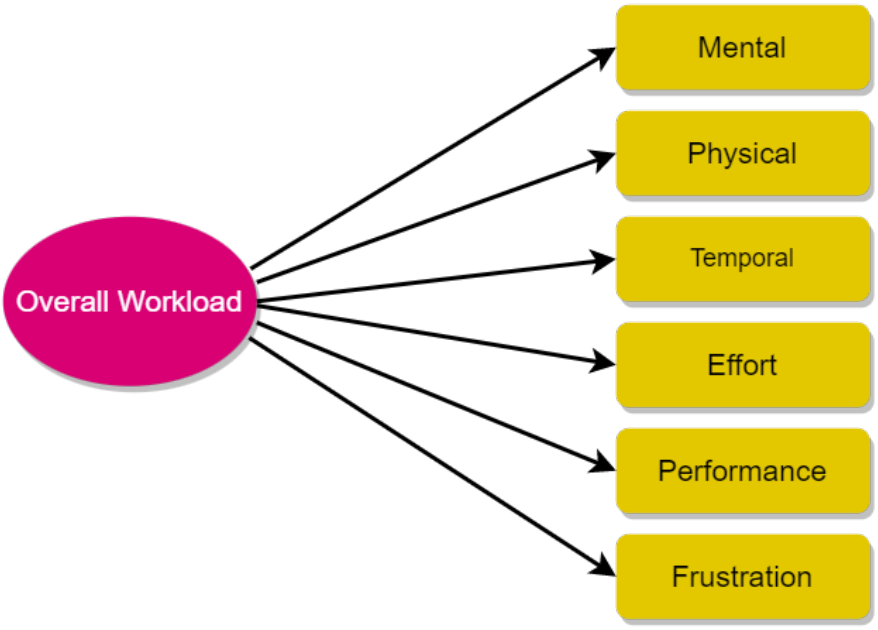


Figure 7.14: Six sub-scales in NASA-TLX

Similar to AR case study, applying TAM in VR, can help to get valuable insights about the factors which influence the acceptance of VR learning experiences by users. By understanding the perceived usefulness, perceived ease of use, attitude toward using, behavioral intention to use, and actual use of VR technologies; this evaluation has presented ways to optimize the proposed design of VR application for improving user acceptance.

It is crucial to consider user acceptance and level of confidence for new development in any technology or introduction of innovations. TAM in the actual form or with modifications has been successfully applied to many empirical studies for testing and explaining the acceptance and adoption of various technologies where human factors involve [86]. Perceived usefulness and perceived ease of use are fundamental determinants of TAM for user acceptance [125].

7.2.4 Results & Analysis

To measure the efficacy of immersive technology tools in education and the relevant learning outcomes, several factors are investigated through these post-experiment questionnaires.

The results of the questionnaires are presented in the Table 7.4 and Table 7.5 as well as

visualizations in graphs.

Questions- NASA Task Load Index (TLX) 5-point Likert scale	Average	Median	Min	Max
How much mental and perceptual activity was required? (Low - High)	1.8	2	1	4
How much physical activity was required for performing hands-on tasks?	1.6	2	1	3
How much time pressure did you feel when performing tasks?	1.93	2	1	3
How successful was you in performing the task of experiments?	3.93	4	3	5
How hard did you have to work (mentally and physically) to accomplish your level of performance?	1.86	2	1	3
How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?	1.73	2	1	3

Table 7.4: Analysis based on data of NASA Task Load Index questionnaire's responses with Average, Median, Min, and Max

The result of the NASA TLX in Table 7.4 shows the level of mental and physical workload required to complete the tasks in the application is 1.8 and 1.6, respectively, on average on a scale of 5. It shows that users felt a minimal workload physically to perform the kinesthetic tasks for creating chemical reactions.

Lowering the mental and physical workload actually means "freedom from difficulty," which is a major goal of use XR in education and new interaction technologies and giving confidence to users.

The Time pressure of completing tasks and work needed to accomplish performance is 1.93 and 1.86, respectively, which shows users efficiently perform the tasks in terms of time. Lower time means, the user felt quicker in performing assigned tasks. Figure 7.15 shows a visual explanation of the results for the NASA Task Load Index, representing the results of all six factors.

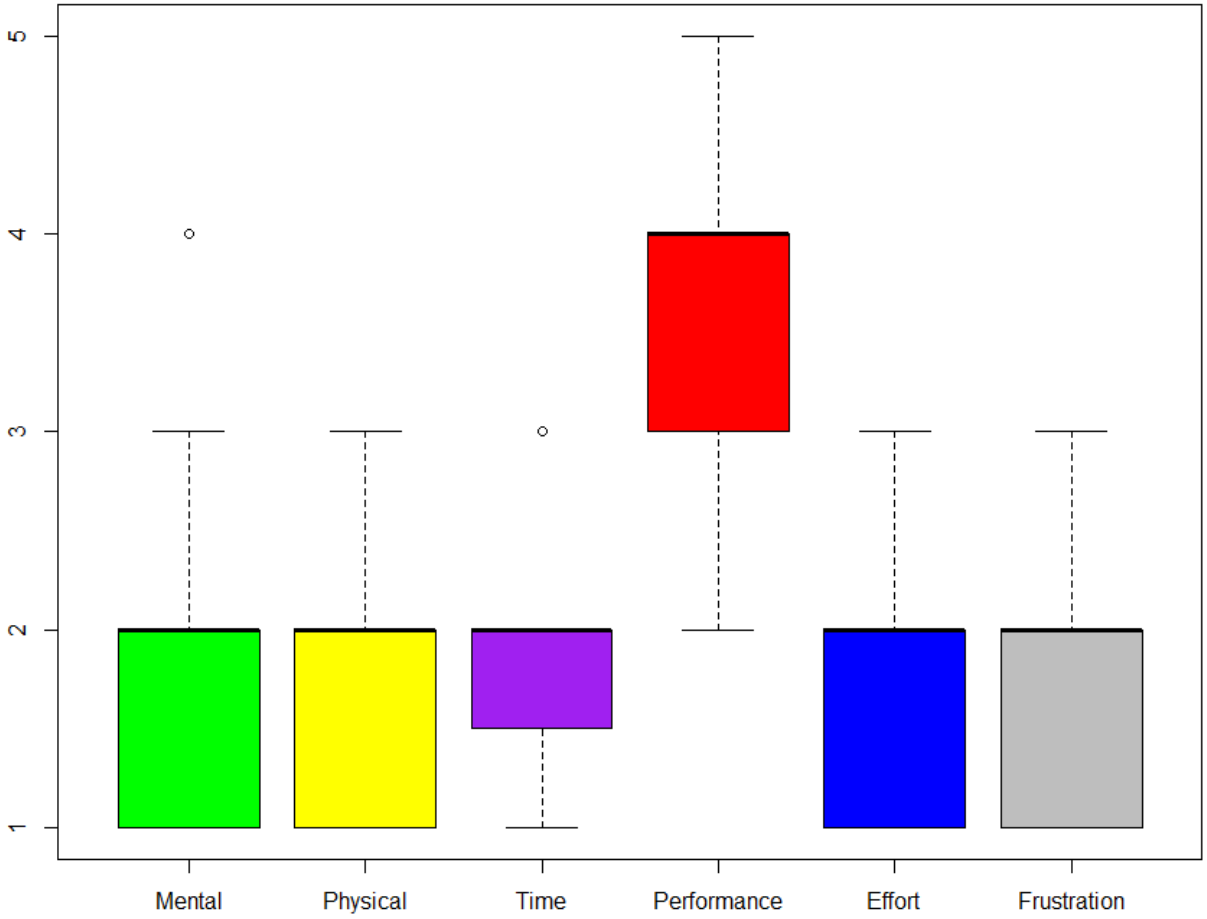


Figure 7.15: Visual Presentation of NASA Task Load Index Questionnaire

Graph of "Mental workload" is presented in Figure 7.16. There was one user who felt a little higher mental workload as compared to others.

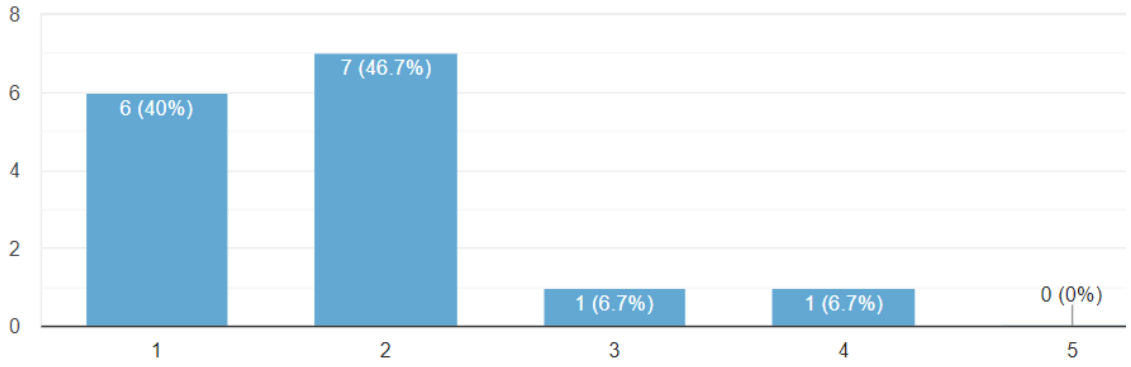


Figure 7.16: Responses of expert reviewers about "mental workload"

Responses of the participants about *time pressure* are shown in graph Figure 7.17 which shows how effectively users were able to perform the tasks.

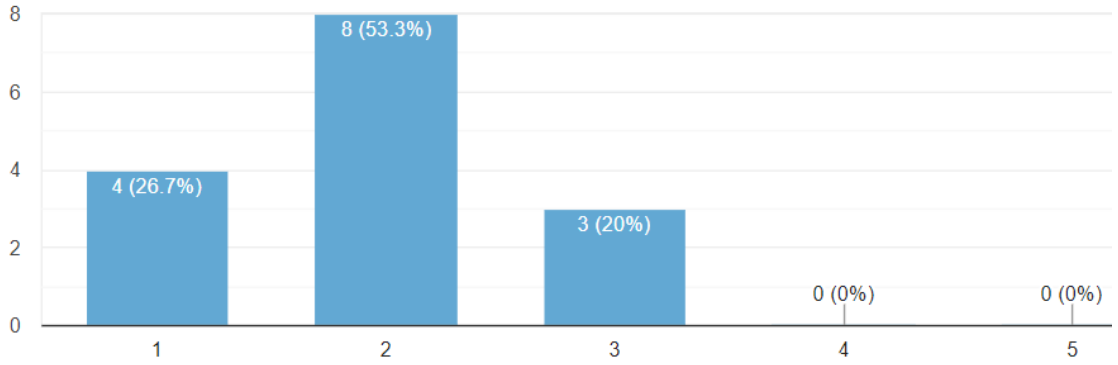


Figure 7.17: Responses to "How much time pressure did you feel due to the pace at which the tasks or task elements occurred?"

In getting success in performing the tasks successfully, the average score is 3.93, reasonably higher, which shows participants were very successful in performing the required task with hand interaction. It is also representing the efficiency of application in terms of involving human factors. Finally, the level of irritation, stress, and annoyance compared to the quality of content, level of relaxation, and self-satisfaction was low, with an average score of 1.73, showing participants were relaxed and satisfied compared to irritated. It proved that this XR learning activity was actively engaging for users without any risks and adverse effects in terms of their health.

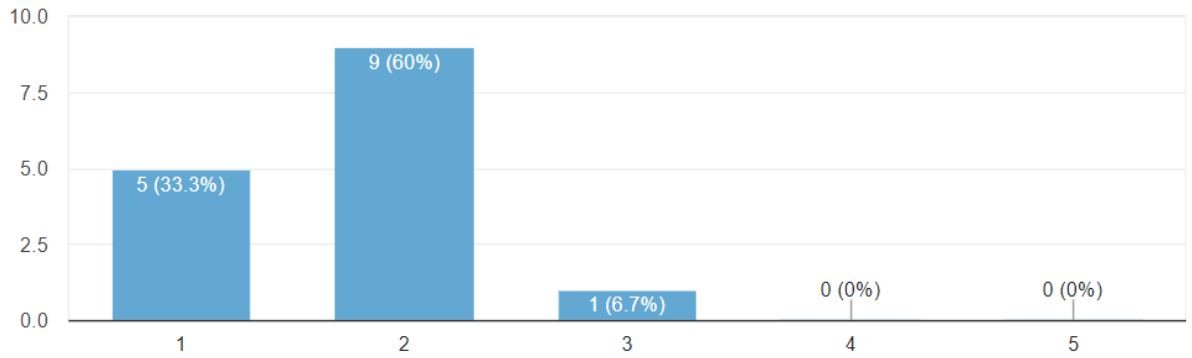


Figure 7.18: Responses to "How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?"

To reduce the cognitive load during learning, it is essential to minimize irritation, stress, and annoyance, which this study has achieved to a higher level. It builds the trust of the user in the proposed system.

Results based on TAM for Perceived Usefulness and Ease of Use questionnaire in Table 7.5 show use of hands-on "kinesthetic" learning in an immersive environment increases the learning performance with an average score of 6.07 on a scale of 7 and use hand interaction with an average of 6.40 for effectiveness. This higher score in performance and effectiveness shows the efficiency of development systems and adopted approaches. This develops confidence in this approach and can lead to increased engagement, flexibility, and competence in learning with XR technology.

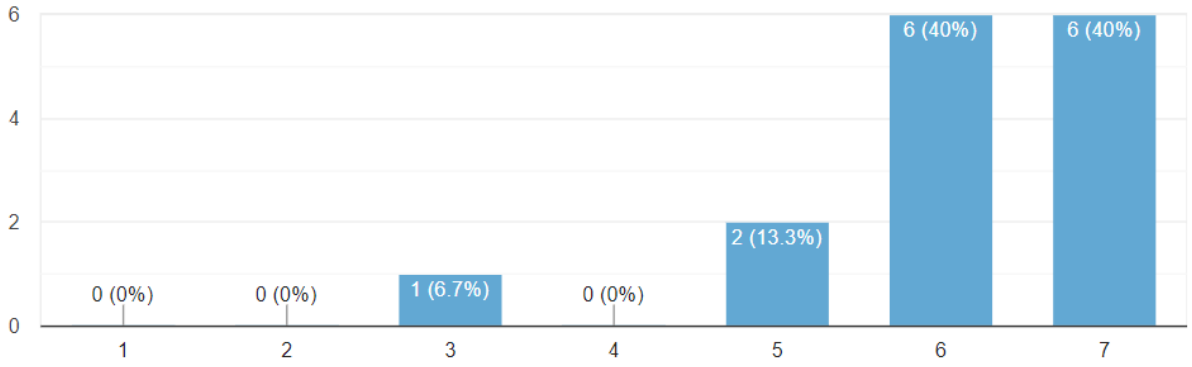


Figure 7.19: Responses to "Usefulness of real-time hand interaction with 3D objects"

Perceived usefulness and ease of use are key predictors to find if the users will adopt and use this learning technology with the proposed approach. With higher scores, expert reviewers perceived that this technology could be useful and easy to use, and it can be beneficial to real end users. Due to immersive, more natural, and intuitive interaction methods in the virtual environment, VR has shown higher user experience and increased engagement. The pleasantness of the learning experiment proved as significantly impact the learners' overall motivation and engagement.

Questions - Perceived Usefulness and Ease of Use) 7-point Likert scale	Average	Median	Min	Max
Using a hands-on learning approach in an immersive environment can improve learning performance?	6.07	6	3	7
Use of VR-based real-time hand interaction with 3D material will enhance learning effectiveness?	6.40	7	5	7
Machine Learning module helps to learn before the hands-on activity of creating chemical reactions?	5.33	5	4	7
It was easy to learn chemical reactions with hand interaction in MR?	6.33	6	2	7
It was easy to interact with the application and navigate in all modules?	6.33	7	3	7
It was easy to follow the steps in LEARN Module?	6.00	7	4	7
It was easy to interact with the 3D chemicals through hand interaction?	6.33	7	4	7
Are you satisfied with the learning approach and interaction?	5.93	6	4	7
Will you recommend it as XR learning approach?	6.33	6	5	7
How pleasant was this experimental experience overall for you?	6.40	6	6	7

Table 7.5: Data of Perceived Usefulness and Ease of Use Questionnaire Responses with Average, Median, Minimum and Maximum score.

The use of machine learning agents is the most crucial component of this study; with an average of 5.33, participants think machine learning can help in self-guided learning in immersive environments. This shows the potential of adding power of intelligent agents in immersive learning environments. By leveraging the power of these agents, immersive learning can become more engaging, efficient and productive. Figure 7.20 shows results of ”how pleasant

was experimental experience", which represents a higher trend.

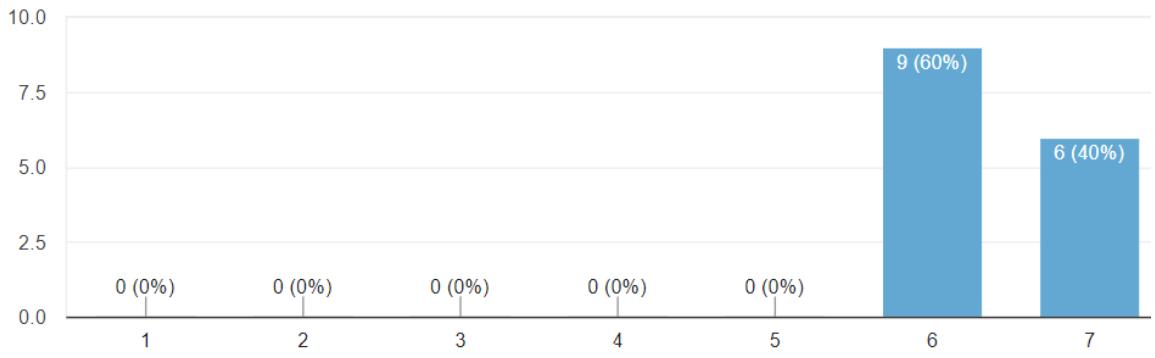


Figure 7.20: Responses of expert reviewers to questions " how pleasant was the experience?"

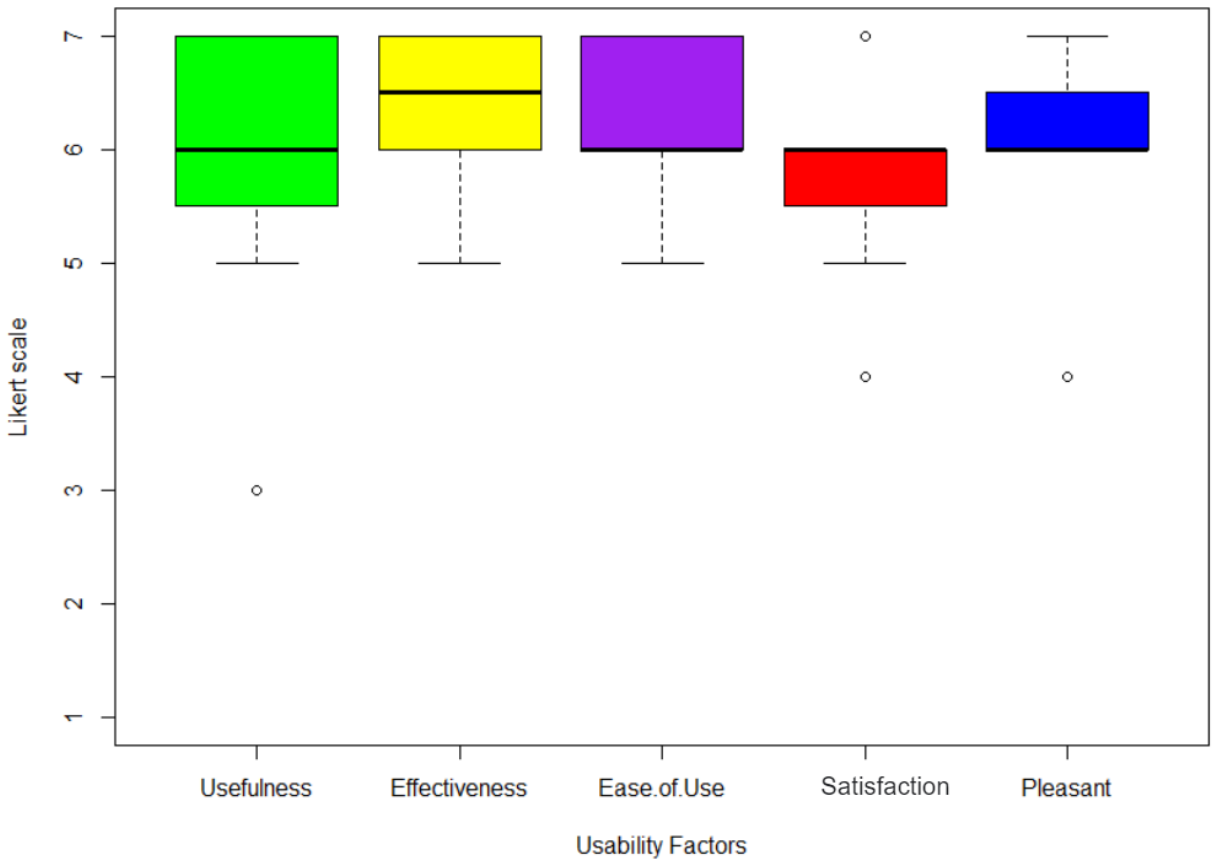


Figure 7.21: Visual presentation of Perceived Usefulness and Ease of Use

The average score of all other usability and ease of questions, including the nature of the experience, was very high, showing a higher engagement and satisfaction, leading to a higher recommendation score of 6.33. Figure 7.21 shows the visual representation of these results.

7.2.5 Subjective User Experience Questionnaire

Along with the NASA TLX and TAM questionnaire, expert reviewers were asked to provide subjective feedback about usability and further recommendation. About hand interaction to create chemical reactions, participants responded as;

"Hand interaction makes it more interactive as compared to other interaction approaches in XR",

"Easy to use and friendly" and *"interactive, accessible and very responsive"*.

A participant expressed his views about the adopted approach, *"I like the adopted approach of kinesthetic learning"*, which provides evidence of productiveness for real-time hand interaction.

Regarding using machine learning agents for self-guided learning, the responses of the expert reviewers were;

"It can help in personalization, more scalable and deliver accurate learning contents"

"Machine learning and intelligent agents can play a very big role in learning systems for training users"

"I like the self-guided learning approach before going to hands-on learning" and

"Yes, it can be improved more. It helps definitely before going to actual interaction-based experience".

These comments of the expert reviewers about using an agent-oriented approach provided highly positive feedback and a tendency of encouragement to make it more productive in the proposed context.

Answering the question of *most interesting thing about experiment*, expert reviewers responded;

"I liked the interaction and the immediate reaction"

"The visual effects that make for an immersive experience"

"To see visual reactions like fire really enhances the experience" and

"Simulated environment is pleasant with attractive textures."

These results show an exciting and interactiveness experience as a user prospect. An expert user appreciated the learning cycle,

"Learning flow of the app is interesting; taking the user from self-guided learning approach to hands-on learning and then integrated assessment".

Sharing experience about the use of RL-agent, an expert reviewer said;

"Use of agent guided learning can reduce cognitive overload and such suitable learning concepts can improve the learning gain" which is one of the core focus on using agents to support self-guided learning.

One expert reviewer appreciated the use of the kinesthetic learning approach,

"Use of kinesthetic learning encourages users to engage with 3D material and increasing the effectiveness" and another one acknowledged the approach, *This approach combines great thoughts of hands-on learning, agent-led and interactive learning*.

The kinesthetic learning approach has moved a broader scope in terms of adopting XR technology for STEM subjects. In expert reviewers' recommendations,

Figure 7.22: Word cloud for "Most interesting thing" from expert reviewers

"Increasing the overall visual quality (including special fusion effects) would improve the experience in general",

"The organization of the cubes should be optimized. Even though the Model explains in which "order" you must combine the elements, to give the user freedom of exploration regarding similar components, would be much appreciated" and

"Adding more relevant case studies to engage user within the app".

One expert reviewer recommended using user collaboration in an immersive environment,

"This approach can be enhanced to a collaborative approach, adding multiple users in the learning environment", this actually a great idea to develop a co-creation concept within this approach.

Another similar response was about collaboration,

"Try to develop user collaboration for interaction to create co-learning activities".

Moving towards realism approach, a response was *"You can use this approach with Multisensory experiences which will allow the user to actually play in an immersive environment with realism"*,

which is definitely the future of the XR and indeed, it will add much higher value in the current system.

7.2.6 Limitations

In the first evaluation for handheld devices, due to remote experimental design, metrics used, and device compatibility, this is acknowledged that results might have limited generalizability as compared to in-person evaluations or control group experiments with real end users. This matter is addressed in the second evaluation, which is in-person, conducted with HMDs case study of the AGILEST approach. Due to ethical issues because of the COVID-19 pandemic, evaluations were conducted with the expert reviewers instead of end-users (students), so this evaluation study is about assessing the system's performance and feedback of the expert users on the defined hypothesis and implementation. Furthermore, due to the lack of control group experiments, this evaluation does not compare with traditional learning, the use of hand

interaction in AR, and the use of machine learning agents with the AR system.

In the first evaluation, as the app was designed for Android only, there is also a limitation for iOS users. However, the most important technical limitation is the required API which is 24(Android 7) or later, which means Android phones were assembled after 2016. Hand interaction in smartphone AR enables direct interaction with virtual content, but as compared to the smartphone's field of view, human hands can ergonomically move in a broader range which requires users to be aware of the usable interaction region where interaction is possible. As a wider field of view is required for better hand interaction, the orientation of the application is set to landscape orientation by default. Similarly, there are limitations to the HMDs case study. The testing and feedback is collected with the expert users who already have a good level of using XR applications so that real end users might face other usability and interaction-related issues.

7.2.7 Comparing Virtual & Augmented Reality Case Studies

For most of the usability and cognitive load factors in HMDs evaluation, the average score is comparatively better compared to evaluations of the handheld version. It shows Oculus hand tracking and hand interaction functionality is much higher than Manomotion, but there was also a remote evaluation factor in handheld evaluation. However, it is acknowledged that hand tracking technology of Oculus much better and accurate which is increasing with time because of Meta's shift towards Metaverse and using hand tracking technology with haptic feedback. In the new HMDs of Meta, hand tracking will be more realistic due to the concept of social presence. More confidence and comfort in usability show that users feel more comfortable with HMDs because of a better XR experience. On the other side, superimposing the virtual content on top of the real environment is a an important property of AR, which keeps the user in the real world while interacting in a virtual environment. VR and AR can both be effective and useful, but there are specific strengths and weaknesses linked to both on the learning goals, hardware requirements and context. VR provides an immersive experience, while AR enhances learners' understanding by overlaying virtual contents on the real-world environments.

7.3 Conclusion

This chapter has provided a detailed procedure of evaluation and analysis for AGILEST prototypes presented in Chapter 6 for handheld devices and HMDs. The evaluation for handheld devices was done remotely and in-person for HMDs with expert reviewers, which provided detailed results about interaction design, working of touchless hand interaction technology for kinesthetic learning and machine learning agents to help in the learning process. The aim of the evaluation was to find the effectiveness of this approach for developing intelligent immersive learning environments for STEM education. The use of machine learning agents is a novel approach that would help to use applications for teaching any STEM subject. As discussed in Chapter 6, neural networks can be trained to mirror the trainer's hand movements, allowing the end-user to be trained without the intervention of a real-life teacher.

However the proposed approach does not aim to remove the teacher from the process but to give them more agility in their teaching hence the term AGILEST. The approach is complementary to existing constructivist approaches, which can be best summed up as "an approach to learning that holds that people actively construct or make their knowledge and that reality is determined by the experiences of the learner" [292]. The usability tests conducted with the expert reviewers have shown that hands-on learning using virtual hand interaction supported with an agent-based self-guided learning approach can help the learning process to create engagement with interactive content in the XR environment. The expert reviewers' feedback about the RL-agent for increasing the learning efficiency was positive, which supported the hypothesis behind implementing the machine learning agents. Furthermore, the realism approach by providing real-time hand interaction with learning material got positive reviews from reviewers. In a resource-constrained scenario where the teacher cannot present chemicals or any other specific material for learning or conducting experiments, an immersive learning experience can be a productive practice. Thus this approach of using agent-oriented approach in immersive environments, touchless interaction, and XR offers new possibilities in innovative learning, where the actual material in physical form is not possible due to cost or availability.

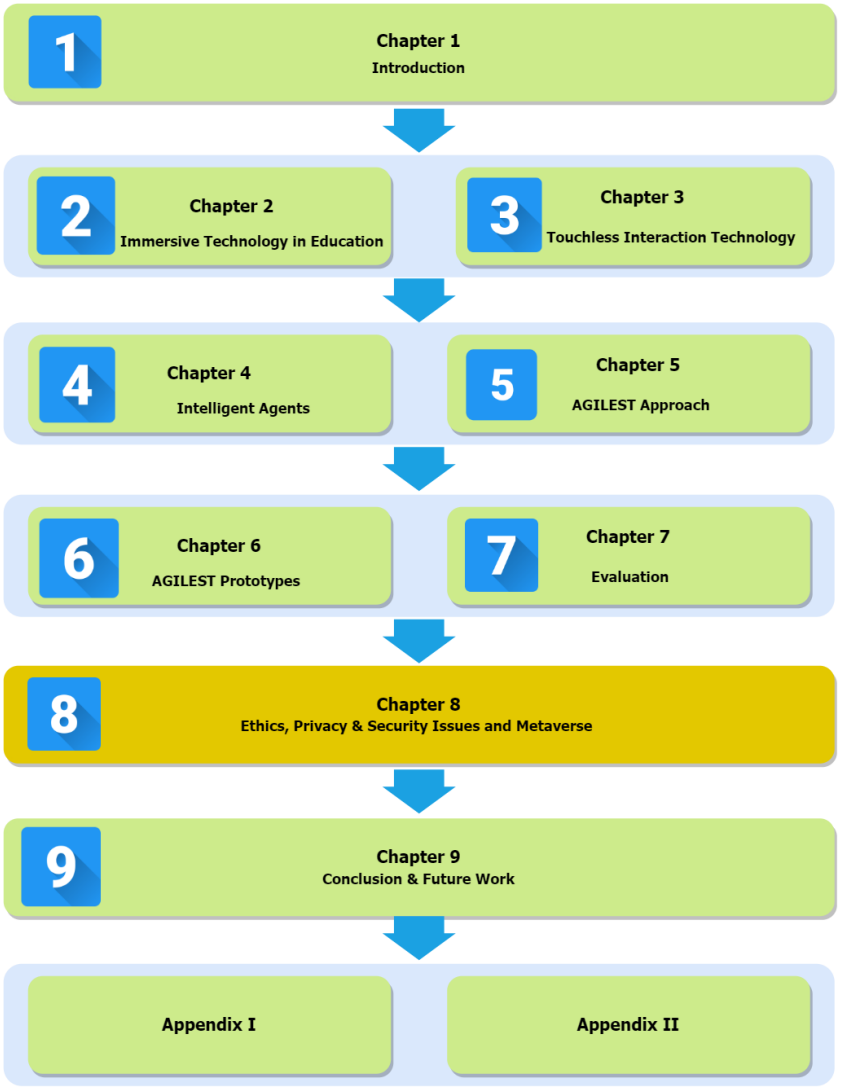
Kinesthetic learning in XR by hand interaction techniques is a new field of research and offers potential for remote learning. The detailed evaluation of the system, comparing students' knowledge gain and the effectiveness of the hypothesis, needs more structured control group experiments. Dealing with these ethical issues during evaluations and learning about privacy and security issues in remote use of XR have been explained in detail in Chapter 8.

Results of both evaluations with expert reviewers suggest that XR has a solid ability to work as a bridge between hands-on learning practices and learning technical topics in the resource constraint environments. Knowing that XR technologies are becoming a prominent trend for virtual laboratories for STEM subjects, this research can further enhance the capacity of XR with standalone devices, hand-free interaction, and self-guided learning approaches.

CHAPTER

EIGHT

Ethics, Privacy & Security Issues and Metaverse



This Chapter focuses on the ethics, privacy, and security issues as a general in XR and these issues faced during this research. Also, it discusses potential use cases and possible benefits of the Metaverse in education. By outlining the potential areas where a positive impact could occur and highlighting recent progress, it discusses the issues around trust, ethics, and cognitive load in Metaverse.

8.1 Ethics, Privacy & Security Issues in Extended Reality (XR) for Learning

The golden rule of reciprocity ("treat others as you would have them treat you") refers to traditional and religious norms. A vast majority of published research work focuses on display technology advancements, benefits in visualization, software, collaboration architectures, and applications. However, the potential privacy, ethical and security concerns that affect collaborative and remote platforms have not received enough research attention.

8.1.1 Existing XR Privacy Issues

Privacy concerns are not exclusive to extended reality but have long been associated with management information systems, human-computer interaction, robotics, and drone technology.

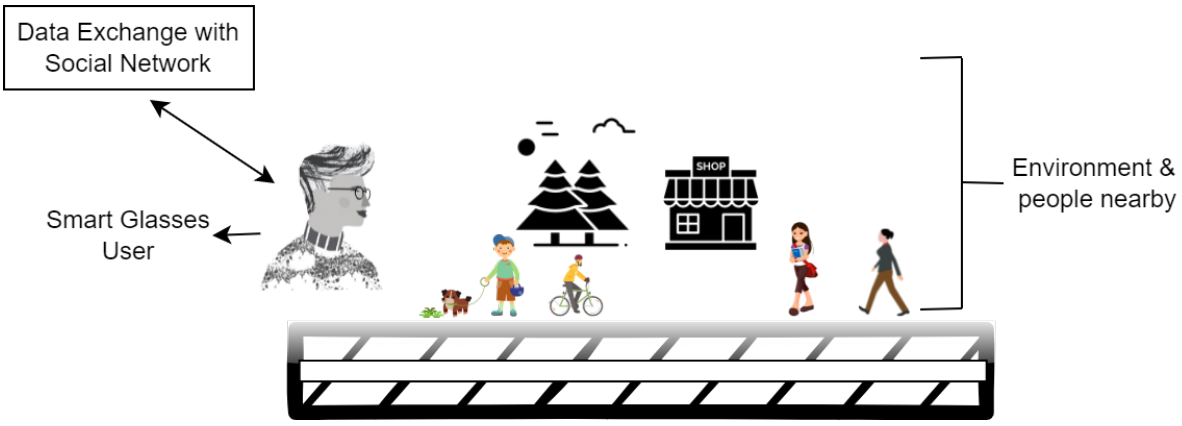


Figure 8.1: Data exchange and explanation of environment and third party (people nearby)'s privacy

As XR allows compelling utilities and games in the world mapped in 3D space, this could mean allowing a lot of personal information sharing over the network for a user. These concerns are slightly different when comparing AR, VR, and MR.

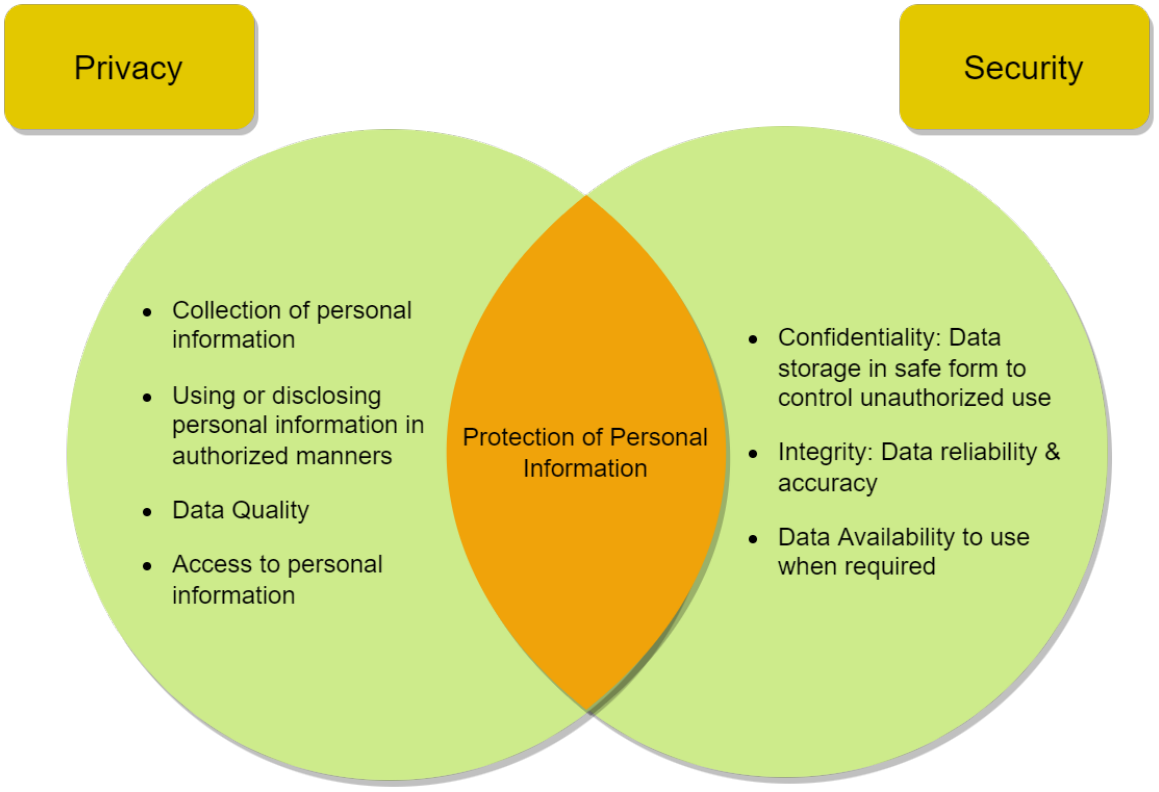


Figure 8.2: Differentiating Privacy and Security

XR devices use cameras, microphones, and sensors to allow users to interact with the real world. This means that information about our environment can also be collected, as explained in Figure 8.1. Adams et al. interviewed 20 VR users and found that most users were concerned about their devices' microphone and IR sensor data and information that can be gleaned about their physical and virtual environments [2]. A potential case of privacy-preserving with cloth try-on use of AR can be used as a privacy steal tool because it can collect enough data with a full-body scan [264].

The adoption of innovative wearable technologies is potentially increasing as a new trend. Jumping into the AR and Metaverse, Facebook (now known as Meta) launched smart glasses partnering with Ray-Ban sunglasses brandâs parent company EssilorLuxottica. Ray-Ban stories have several technical features for entertainment and socializing; more importantly, these

features can be adopted in the future for more advanced wearables. According to Meta, their product designers have considered user privacy issues when designing products and enabling the functionalities as per the commitments of Responsible Innovation Principles of Facebook. However, these smart glasses also came with many ethical and privacy concerns along with their potential benefits [143]. Furthermore, the unbridled deployment of these smart glasses brought several challenging questions for public social interaction when we will have more such devices in our lives. This short article has discussed the Ray-Ban stories' ethical and privacy issues for social interaction and public places.

There are models of XR headsets in development that would not only allow you to record your everyday life by taking pictures and videos using the headsets but also to live stream what you see and even to perform live analytics such as facial recognition on the footage you capture. And if the headsets integrate with third-party apps, this could even add new ways to violate the rights of bystanders. XR browsers facilitate the augmentation process in the virtual space, but the contents are delivered by third parties, which raises questions about the unreliability. There are various cyber threats like data manipulation and sniffing, which can create unreliability in the contents, even coming from authentic sources.

8.1.2 Existing XR Security Issues

As there is already an exorbitant number of privacy and personal data theft issues with the use of social networks [259], yet these issues would be minor compared with the level of personal data generated within a mixed reality device that could be exploited. As always, these risks are heavily dependent on the use cases [133]. Data flow across in XR is explained in Figure 8.3, which shows how raw input with untrusted apps is involved in creating XR experiences and where security filters are needed. It applied to all kinds of display devices used for XR experiences. Security issues in VR differ slightly from AR and MR because VR doesn't involve any interactions with the real environment and it is limited to closed environments where all depends on the simulated environment.

Privacy, security, and ethical concerns are emerging as these technologies are becoming more popular and accessible.

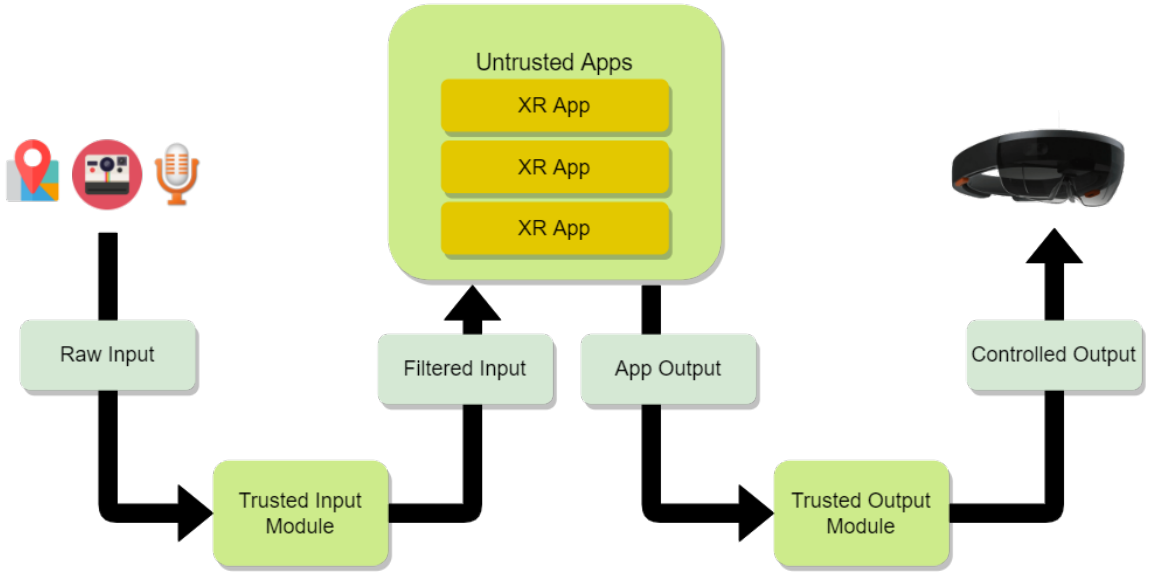


Figure 8.3: Flow of Information through an XR Platforms

8.1.3 Existing XR Ethics Issues

In the evaluation planning stage of this thesis during the COVID pandemic, ethics issues emerged as a big hurdle for all kinds of human-centered technologies usability testing. In a scientific context (such as universities and academic labs), the use of XR technology is governed by ethical guidelines and laws. These may vary across countries but tend to abide by some general principles, especially in the EU region; these laws differ from the rest of the world.

The designers and developers of XR technology often consider ethics-in-practice as a potential factor, which includes the cognitive, physiological, and behavioral impact. Therefore, ethics-in-practice has a role in XR design and instructional curriculum development.

XR technologies are considered future computing platforms; these headsets are the potential successors of ubiquitous technologies such as smartphones and desktops but with very high capability to get into our lives. With higher ergonomics and better design, these systems can offer personal, private, increased availability of sensing and augmented reality, allowing a near-constant flow of digital content delivery [113].

XR technologies are rapidly being adopted by consumers and are increasingly being used for work and for education. It is essential that guidelines are set to ensure privacy and safety while business models are being established. As AR smart glasses automatically screen and process a userâs environment, the privacy of users and those around them can also be affected. This is very unique to AR, since most existing technologies only collect information about the user. In decision-making, people often consider how other people perceive their behavior, so-called 'social norms. The term 'glassholes' [88] became a prototypical term for insulting Google Glass users.

For developers and designers of XR, there are many concerns regarding accountability for the ethical design of XR devices and applications in virtual remote learning environments [44]. In addition, ethical design considerations and privacy issues are things to consider for design research when integrating interactive media into learning content and placing the user in a virtual environment.

It might be surprising that in the XR landscape, the biggest security concerns are not about the virtual intrusion, they are about physical compromise. XR technology requires access to multiple sensors, data, and cameras (data flow explained in Figure 8.3). In fact, it has been proven that even the digital video cables themselves, such as HDMI, are vulnerable to remote video stream eavesdropping [260]. This poses a huge security risk when AR and VR devices/applications are hacked or breached.

When AR and VR devices and applications use authentication from social media accounts, it adds another layer of vulnerability for the data. Moreover, VR social networks themselves record a multitude of data about the user and their virtual interactions [315]. There are potential risks and threats to the data exchange using mixed reality for educational purposes. Security risks and vulnerabilities in devices, mobile apps, and web browsers used by XR will allow attackers to compromise information, steal highly valuable and sensitive intellectual property, send false information to XR headsets, and even prevent access to the XR systems themselves.

The privacy of a user can be easily compromised if hackers gain access to the device, and it can not be understated how much more critical a breach would be than a similar attack on other

computing devices. When a constant stream of data flows between the digital and physical worlds, with attacks on the digital world directly, it creates dire consequences for privacy and personal safety. Casey et al. explored the possibility of compromising a VR session and performing several attacks, including chaperone, disorientation, human joystick, overlay, and camera stream and tracking [52]. While some VR attacks may initially seem minor in their implications, XR systems are being employed in professional settings, e.g., industrial control systems [191].

Research practices in Human-Computer Interaction (HCI) have changed due to innovative modern interactive technologies. The new methodologies are shifting the diversity of contexts in which novel digital technology is being used. As a result, new ethical challenges emerge for the HCI community regarding research ethics and responsible research and innovation. In a scientific context (such as universities and academic labs), XR technology is governed by ethics guidelines and laws. These may vary across countries but tend to abide by some general principles.

The designers and developers of XR technology often consider ethics-in-practice as a potential factor, including the cognitive, physiological, and behavioral impact. The ethics-in-practice has a significant role in XR design and instructional curriculum development.

8.2 Issues using Remote XR in Terms of Teaching and Learning

Immersive technology for education in remote environments has a bright future due to its capacity for immersion with high-quality interactive content, which is impossible in any other way. However, with all of the incredible advantages of XR in remote learning, several issues need the attention of developers, designers, policymakers, and students.

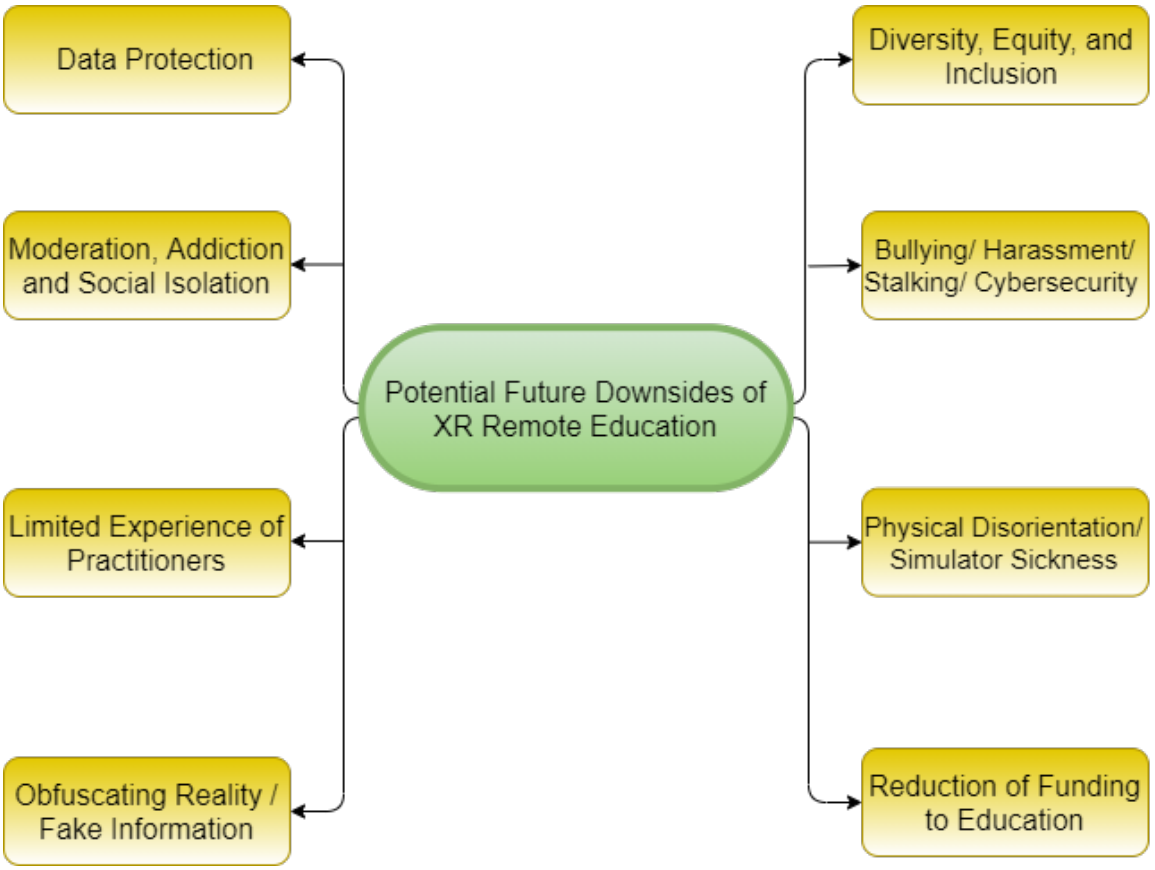


Figure 8.4: Downsides of using XR for Remote Education

During the first evaluation reported in Chapter 7, remote experiments were conducted to meet the social distancing guidelines. These experiments with expert reviewers helped to learn the issues with remote XR. Though XR technology is very innovative in bridging geographic distances between the learners and instructors with realism, it has several complex issues. Figure 8.4 has visualized some downsides of using XR in remote learning.

8.2.1 Inconsistent Quality of Learning - Equipment/Resources

To facilitate learning in the resource-constrained environment, XR technology provides virtual learning material and enables innovative interactive techniques like gestures, hand interaction as in Chapter 6, and haptic feedback. However, the quality of learning with such approaches fully depends on the devices used, the application, and the strength of the network connection. In a remote XR education, unlike an XR lesson in a classroom, most of the students will be using

their own devices, with a massive difference in the processing power of devices; this could create inconsistency in the frame processing, which leads to a different learning experience between users.

8.2.2 Privacy Issues

As the availability of XR technology is increasing very fast, privacy issues are also emerging at the same pace. Findings of the evaluations presented in Chapter 7 show fundamentally this involves three forms of privacy concerns; keeping a user's behavior private when recording their actions in the real world, keeping users' actions and data in the virtual world confidential, and finally, other people's privacy who are around when using their device. When interacting with digital devices, many people are aware of the privacy risks but paradoxically do not behave in a manner that acknowledges this fact [24]. In the context of XR, the findings are similar and even more.

8.2.2.1 Privacy of Environment

The use of XR remote for education creates an additional burden on maintaining privacy within their environment. For example, in an immersive VR use case, a user may be unaware of users entering the room in which they are conducting a lesson through virtual reality. Due to the use of headphones and the natural privacy of the VR HMD, the external party would only be aware of the user's physical actions and speech with others in the virtual world. It is explained in Figure 8.5.

There have been innovations in improving existing boundary systems like the Oculus Guardian system, such as from O'Hagan and Williamson [228], which allowed a user to be made aware of a bystander through multiple techniques such as an avatar represented, text notification, silhouette, and even a sonar radar approach.

Without such systems in place, users have been documented to reveal personal information. One experiment conducted by Campbell et al. [46] found that during the testing of a Tele-presence

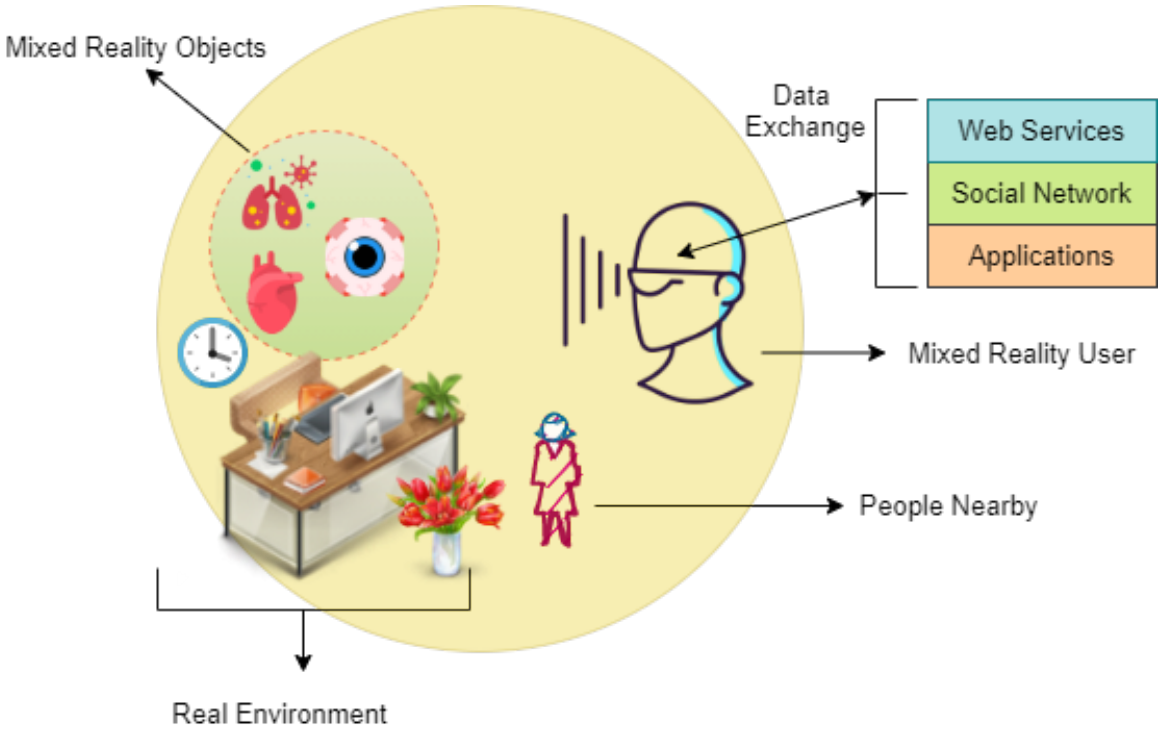


Figure 8.5: Privacy of environment and nearby people explained

VR system, users would openly discuss personal issues, as they were so immersive in their communications that they forgot that in reality, they were both standing in a bank lobby with dozens of people around them. The experimenter needed to briefly stop the experiment to remind the participants that they were not alone.

8.2.2.2 Third-party Privacy

Third-party privacy means the privacy of the people nearby who are being captured in your virtual environment setting. Remote XR education, by its very definition, is remote from traditional classroom environments, and thus, third-party privacy needs to be considered in any remote XR education application.

8.2.2.3 Forcing students to sign EULAs

One area of deep concern is users' need to log into the service to use an HMD unnecessarily. Understandably, a user may need to login into a service such as an online world, but it seems

unnecessary when the user is simply using an education service. This always-connected and login approach has become common in many devices in the mobile market, and its introduction into the XR space is logical but comes with even more challenges. This login inevitably comes with the user needing to agree to an End-user license agreement (EULA). A major example of this is the Facebook EULA that needs to be signed by a user if they use the consumer-grade version of their Quest series. This EULA is not required if the user purchases the more expensive business edition. Some have accused these requirements and the EULA [82] of creating a "Wild West" where users can have "missing rights". For instance, users' basic property rights are in danger if their access to applications bought on the Quest is not accessible if they violate Facebook's EULA while posting something on their social media accounts. This lack of access to a device based on social media activity is completely unacceptable from an educational perspective. It can result in the suppression of the freedom of speech of a user, knowing that the provider can, at any given time, could remove access to their device. This constraint on education could infringe on a student's basic fundamental rights. In the classroom, XR allows the school to potentially bypass this requirement if the institution sets up the devices themselves, but in remote XR education, where users are using personal devices in general, this issue is a major one.

8.2.3 Security Issues

Security issues are the byproduct of any technology; it is the same with all types of immersive technology. Looking into Chapter 6, security issues are real in both handheld and HMDs because both XR applications collect lots of data through hand tracking. As XR users, we generate data about our behavior and movements in virtual environments. We often share this data over the cloud or social network, which could be used to steal our virtual assets or virtual identities [114]

8.2.3.1 Data Collected by Sensors

An immersive experience is based on high-level sensor accuracy and precise data processing. For high performance, XR headsets require extremely sensitive and responsive motion sensors. These devices collect lots of data about the user with these multiple types of sensors. With the new advances in the sensors used in the XR applications, a large amount of data is needed from the real world.

8.2.3.2 Location Data

There is a significant amount of augmented and mixed reality applications in education that are designed for localized learning. These applications use the location of the users with GPS sensors and collect location data [235]. Adams et al. found that the majority of VR users they interviewed were concerned about the data collected from cameras and sensors commonly found on XR devices, where it is being sent, and what it could be used for [2].

8.2.3.3 Biometric Data

Biometric data can be generated in multiple ways through interaction with an XR device. Eye tracking has a long history to use for assessing user behavior. This technology is becoming efficient, cheap, and compact with increasing use in gaming, marketing, education, military, and healthcare. This rapidly expanding technology coming up with serious privacy issues. Research has evidence for the possibilities of inferring personality traits automatically from eye tracking data [132]. For educational purposes in XR, eye tracking technology has been used for emotional learning, accessing reading patterns, and student behaviours [241]. Devices that have the capability of eye tracking can potentially capture more information than the user expects to reveal. Some of this personal data protection is prescribed in European General Data Protection Regulation (Art. 9 GDPR) [165]. According to Bloomberg's Privacy and Security Law Report, eye tracking is not just a tool for interaction; it is possible to approximate the

identity by utilizing the attributes from gaze patterns [1].

XR devices provide hand tracking abilities which are collecting gesture data as shown in a case study in Figure 8.6, real-time hand interaction in augmented reality. Hand tracking technology has gained more attention recently as touchless interaction technology in the post-COVID world [137] provided with leap motion or other devices for hands-on (kinesthetic) learning in education [142].

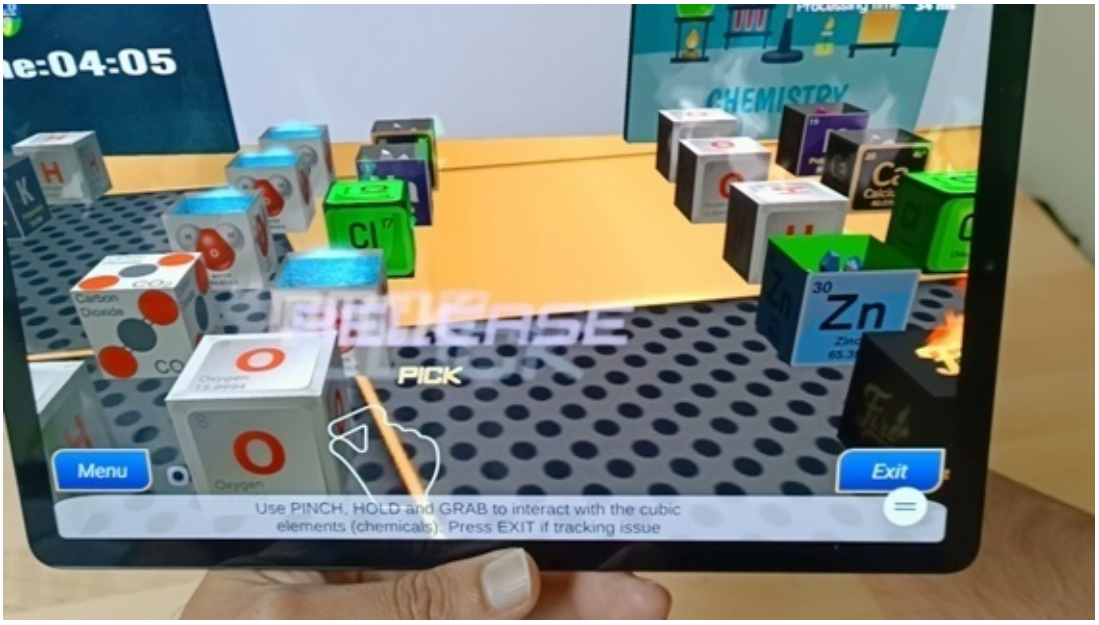


Figure 8.6: Use of Real-time Hand Interaction in the Augmented Reality for Learning Chemistry

Speech data includes very sensitive and personal characteristics which can be used for a plethora of diverse range of applications, from medical profiling to digital biometric recognition [217]. Speech command data can be a security threat for users as speech commands are also used as identification data in numerous applications. Voice recognition technology marketing is surging as touchless technology is emerging in the world with the ”avoid touching” concept. The privacy and security risks associated with voice recognition technology cannot be overlooked.

[1] https://news.bloomberglaw.com/us-law-week/privacy-issues-in-virtual-reality-eye-tracking-technology-1

8.2.3.4 Software/Hardware Vulnerabilities

The security and privacy issues associated with XR are strongly linked with the system architecture and flow of the data. For example, some applications are designed to render, process, and store data in the device, while others are cloud resources integrated. On the other hand, the provision of software applications by the platform and third parties creates a difference in cyber threats in the virtual world. One of the solutions to prevent inconsistency in the quality of learning is to make sure that all students use the same device or a small subset of approved devices. This can aid in software development as testing becomes far easier on a narrow range of devices or simply one device. Security-wise, this can result in a homogeneous environment, where a single exploit could allow a hacker access to the system. This situation also results in a lack of choice for the student on what devices they can use to access their education.

To adopt XR in remote education, students are sent software to access their classes and to aid in their learning. In main cases, due to rapid prototypes in this space, there can be a lack of content signing leading to students bringing used to ignoring warnings of unsigned content, even going as far as asking students to allow content onto their devices, by turning off existing security settings. This allows for multiple ways for hackers to embed malicious content into XR applications to trap the users from collecting data. There needs to be more tailored content signing mechanisms in place, where once-off permissions are given without having to set the entire device into developer mode. Also, XR HMD manufacturers create walled gardens that force developers into requiring end-users to use side-loading applications, so it's not simply a case where developers ignore the best practices.

8.2.4 Ethical Issues with XR in Teaching and Learning

During the evaluation of the AGILEST approach, both in HMDs and handheld devices, this research has faced many ethical issues in terms of remote use of XR, using XR in public, and considering under 18 end-users.

There are many important ethical questions linked with the use of XR in remote learning.

These ethics-related issues will increase with the development of learning systems with more collaboration capabilities in remote learning for the users, as the data involved in a collaboration can also create new, more sensitive problems. There are issues of consent when children use XR for distance learning and issues of *depersonalization* and *derealization* when they operate such devices in an unsupervised environment. Designing applications from an ethical perspective where they give maximum benefit to the learners while attempting to minimize any potential harms [276]. Acknowledgment of the potential ethical issues of using XR within remote learning applications is critical.

8.2.4.1 Bullying

Bullying has been identified as a group process, where children subconsciously take on various roles for social acceptance [257]. It has also been shown that peer pressure can also affect behavior in XR situations [220]. This indicates the potential for "behavior without consequences" to be perpetuated in the virtual world and even transferred to the physical world. That is, there are not only likely to be situations where bullying takes place in remote XR environments, but also that since there is no physical harm done, little (or less) is done to control it.

The remote XR education will require new policies for schools, similar to the development of cyberbullying [40] or it could become the perfect tool for a bully. This has two implications, the first on the mental health of the bullied, and second on all the students co-present in that situation who learn that bullying is without consequences.

8.2.4.2 Erosion of Physical World Feedback

Linked to the lack of behavioral restraints that operate in the real world, is the lack of physical consequences that also serve an important role in the development of children. As every parent knows, children from a very young age learn a lot about their environment through spatial exploration and construct highly useful models of causation, and qualitative physics, that enable

them to navigate the world. While XR offers the opportunity to scale up certain kinds of learning (e.g., larger class sizes can experiment with chemistry kits without having to fear breakage), it also disconnects the students from the real-world consequences of their actions.

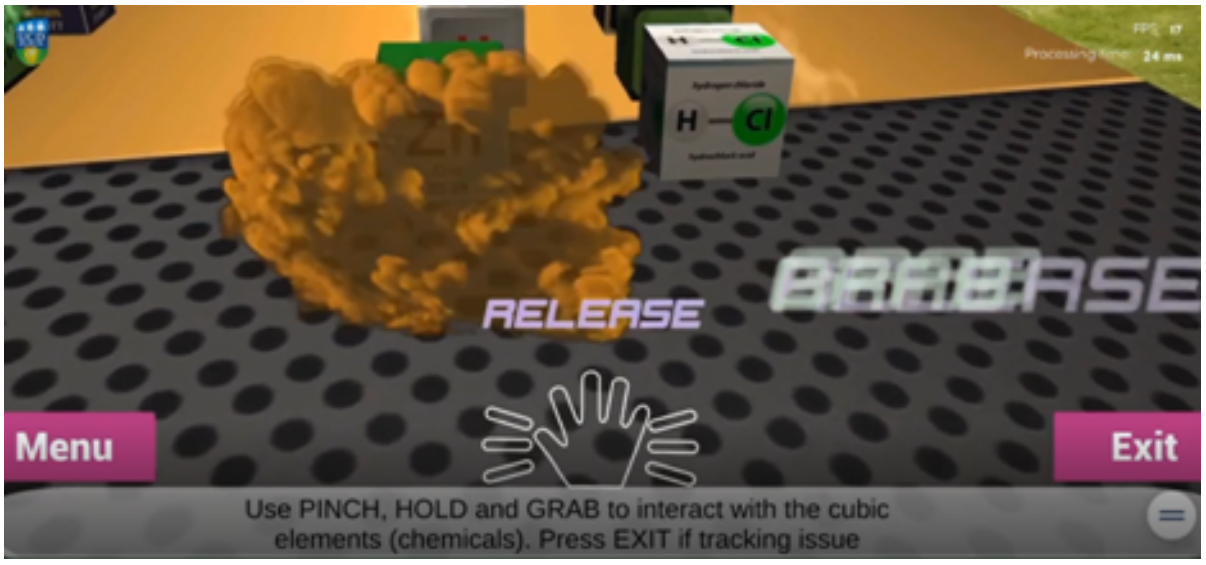


Figure 8.7: Blast in the virtual environment when hydrogen reacts with fire

For example, a mistake or carelessness in handling chemicals in the virtual world may lead to a predictable virtual explosion or burns, but given the absence of a physical counterpart, it may not result in the correct lessons being learned by students. As Figure 8.7 shows a case of virtual explosion from AGILEST handheld application Chapter 6.

The decoupling of sensory experience may lead to incomplete (and even dangerously wrong) physical and spatial models of the world.

8.2.4.3 Lack of Common Environments and Social Isolation

Sociologists tell us that social interaction due to a situated environment acts as a grounding force in our conception of the world, and interaction norms. XR creates a situation where people can start to prefer a virtual world, and not learn how to interact with unpleasant people/events in the physical world. An extreme case would be an inability of children to interact with peers and other social groups [240]. **Note:** It does not mean that extreme versions of this condition (such as *Hikikomori* [283]) will inevitably result, however, even mild versions in large classroom

cohorts could have a significant impact on society. Furthermore, in remote XR education environments, the typical start points and end points of the classroom are removed, which could further erode the connection between their peers.

8.2.4.4 Re-entry and Disembodiment

Immersive experiences, whether positive or negative, inside an artificial world, can cause problems with adjusting to the real, physical world. The same cues, environments, and effects are not present, and behavior that is valid or learned within the augmented world, may not be appropriate in the physical world. These are labeled as re-entry problems. Not only has it been shown that children are particularly susceptible to not distinguishing the virtual from the real, but also that the practical experience lasts longer than the actual immersion experience. That is, any emotions that are generated during the immersive phase are carried over into the re-entry process [27]. This is not necessarily a bad thing; students that are excited about experimentation will have their curiosity about the real world. However, students who experience intense emotions (e.g., during depictions of extreme events in geography or frightening events in history/ literature) may carry these into the real world. Therefore, the teacher must be aware of the potential emotional impact of their immersive educational experience, this could prove to be more difficult in a remote XR environment, and thus, this issue may be more pronounced.

8.3 Learning from AGILEST Case Studies

Learning during this thesis research, COVID effects on the learning landscape and an emerging need for technological solutions to consider personalized and remote learning have created the need to think about several ethics, privacy, and security issues. The evaluation process which is discussed in Chapter 7 raised many questions when using XR in a remote setting, engaging with the end-users under 18 during the pandemic, and health safety measures when using the same device with multiple users. First, ethics issues placed limits on this research in terms of conducting evaluations with the right end-users, which later moved to expert

reviewers. This has created limits on the number of subjects because outreaching a large number of expert reviewers is difficult as compared to real end-users (a group/class of students). This limitation moved evaluations more towards usability and ease of use aspects instead of learning gain measurement, which is only possible with students. Conducting evaluations with expert reviewers can also be a biased and unequal representation of certain groups of people. Addiction and compulsive behavior are common issues with XR adoption [21] [246]. This is also the same in the case of immersive learning. This has been noticed because its highly engaging nature can lead to addictive behavior and compulsive use when dealing with vulnerable children with mental health issues. In the evaluation of AGILEST prototypes, due to no end-user experiments, discussion about such behaviors is lacking. This research focuses on hand interaction technologies that collect data related to hand tracking, so privacy and security are the major factors to consider regarding collected human data. As a learning flow is proposed in the AGILEST Approach to help with remote assessment. It aims to allow user authentication, so this data needs its own security measures. It is the same as with authoring toolkits or any other XR application where user authentication is needed. Growing trends of XR authoring toolkits and integrating assessment capability in the XR learning application have raised concerns over privacy issues.

As discussed in Section 8.2.4.2, physical and psychological harm is possible during immersive learning when trying to simulate real-world scenarios. Chemical reactions and this kind of other immersive learning experiences can cause physical discomforts, such as motion sickness, psychological harm, anxiety, or stress.

These highlighted ethical issues are raising the importance of developing guidelines and regulations for the use of immersive learning, which can ensure the usage of these technologies responsibly and ethically. The evaluation studies presented in Chapter 7 have suggested that privacy, ethics, and security issues in XR are real issues and need the attention of policymakers. It should be considered an essential human moral requirement in technology adoption. As with the growing use of sensors and tracking technologies, XR is advancing towards more advanced environments which will heavily focus on the data. If extending the AGILEST approach to an

authoring tool and allowing instructors to develop content, there will be more data that require security measures. Along with countless benefits in different domains, XR technology raises critical ethical, security, and privacy-related questions. As these case studies use hand tracking and gestures data, which is very private, it creates privacy issues and needs effective protection measures in terms of security. When using XR devices in a remote or public environment, especially in the case of see-through HMDs, it creates privacy issues for the environment and people around in the tracking area. With the portability and compatibility of XR devices, it has been noticed during this research that remote use of XR is growing and creating new opportunities in learning technology. In this scenario, data encryption is very important when collecting personal information. It can help to protect private and sensitive data by increasing the security of information transmitted between clients and servers. It also includes the use of cloud services in the XR for data storage.

8.4 Metaverse & Educational Technology

The recent surge in the adoption of new technologies and innovations in connectivity, interaction technology, and artificial realities can fundamentally change the digital world. The core contribution of this thesis has provided proof of concept for integrating real-time hand interaction, which is a step toward realistic haptic feedback and the use of intelligence to empower learning in immersive environments. The Metaverse concept is the most recent trend to encapsulate and define the potential new digital landscape by combining high-speed internet, graphic power, blockchain, and immersion technology. With the introduction of 5G with high speed and low latency moving to 6G, advancements in the hardware & software with the graphics power to display millions of polygons in 3D, and blockchain technology, Metaverse is no longer a fiction.

This transition of today's Internet to a spatially embodied Internet is at its core a transition from 2D interactions to 3D interactions, taking place in multiple virtual universes. In recent years, augmented virtual reality has created possibilities in the private and professional spheres. The

new VR headsets and AR glasses can provide immersion in the physical sense. To turn this concept into reality, technology must offer a realistic experience for users.

8.4.1 WHAT IS THE METAVERSE?

The concept of the Metaverse refers to a shared virtual world environment where people can interact just like in the real world. This concept of the Metaverse is not new; it is a term acquired from the science-fiction novel Snowcrash [282], and has now become a byword for a future version of the Internet using VR and AR technology to interact instead of using desktops, laptops and mobile phones [279]. One of the most prominent examples of developers attempting to create such a virtual world was Second Life [106]. However, its implementation is entirely for the gamer community. It is one of the first Massive multiplayer online games to have shown us the potential and effects of these shared worlds. *Metaverse refers to shared digital spaces with a realism approach using AR or VR.*

The word Metaverse is also being used to describe gaming worlds where every user can have a virtual character to interact with other players' virtual characters. Taking the VR from gaming to this virtual world for practically everything, Metaverse will be for work, education, healthcare, conferences, play, concerts, or just hanging out [225]. Today, we care about using different apps and websites for connection through the Internet. The concept behind the Metaverse is to create new online spaces for more multidimensional interactions for people by enabling an immersive experience instead of just viewing. We are starting to think about the Metaverse as the place for all possible resources to come together, but not something whose final form exists yet; it will take a few more years. However, technological limitations will decrease with time as Internet speed, and hardware resources will grow more advanced.

The Metaverse requires many innovations in current technologies, protocols, innovative enterprises, and discoveries to function. In the market, there are several competitors in the development of hardware for virtual, augmented, and mixed reality, including Apple,

Facebook(Meta), Google, HTC, and Microsoft[2]. Therefore, there is a need for strong computing power to be embedded in a frame of glasses to create possibilities for making the technology convenient. It is possible by focusing on the decreasing size by including the computer and networking chips [12], holographic waveguides [95], sensors, batteries, and speakers in the tiny space.

8.4.2 How did we get here?

This journey started with the Internet simply allowing people to send emails and chat on BBS(Bulletin Board System) message boards [171]. In 1989, Tim Berners-Lee created the World Wide Web to connect the Internet through a web browser [28], which allowed for the creation of millions of different websites and is still growing every day. It further created things like Yahoo and Google, leading to the advent of web 2.0 for user-generated content like blogging, which eventually morphed into social media. These innovations are being invented on the original foundation of the Internet. Living today, we use an app-based layer that allows us to engage through apps on smartphones like Facebook, Twitter, Snapchat, Zoom, Instagram, and so on. The upcoming layer for connectivity is the Metaverse. With the haptic feedback using wearables [4], sensory experiences like touch can bring more realism with a wider adoption [121].

8.4.3 Why Now?

An ideal immersive experience needs an Internet connection which was not possible before. Recently COVID has increased the race of virtual technologies (just like it increased the need for touchless interaction technologies [140]), which are becoming possible due to the availability of 5G Internet [90], fast computer processing powers and strong chips [6]. So realistically, technology is moving very fast towards a Super Smart Society named "Society 5.0" by the Japanese Government [253]. Figure 8.8 explains our journey from Society 1.0 to

[2]https://www.cbinsights.com/research/ar-vr-corporate-activity/

Society 5.0. Society 5.0 concept is mapped based on the progress of humans through Society 1.0 (hunter-gatherer), Society 2.0 (agricultural), Society 3.0 (industrialized), and Society 4.0 (information) [102].

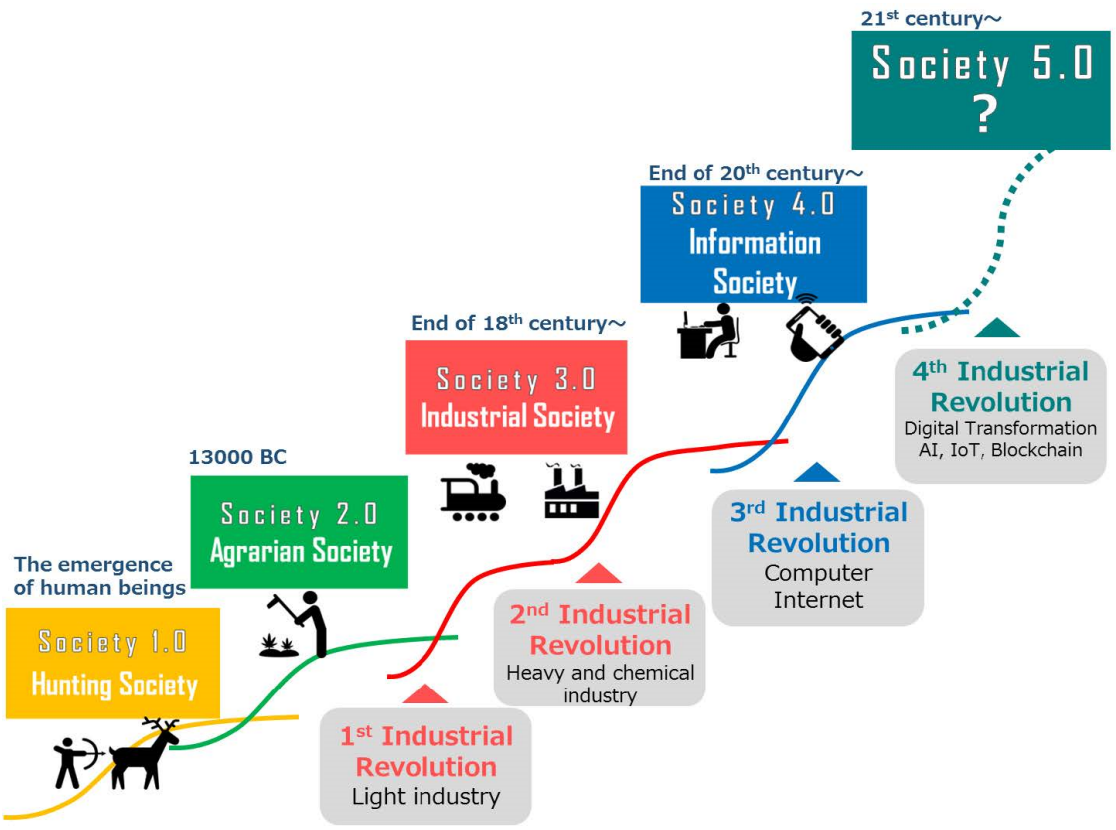


Figure 8.8: Society 5.0 as described by the Japanese government, ”Super Smart Society” [253]

The idea behind Society 5.0 is using technologies like AI, ML, AR/VR [192], Blockchain, Web 3.0 and the use of 5G & 6G to make the 21st century more connected, liberated from various constraints and free for diverse lifestyles.

The most crucial factor in these interactions is if a user feels a sense of presence. This can be achieved by producing a sufficiently realistic user interaction to feel psychologically and emotionally immersed [84]? The Metaverse can fundamentally change how we interact with technology, social experience, and online collaborations. Digitizing the actual surroundings in reality as its best version will enable human interaction with cartoonish resembling avatars (*avatar is a virtual character to represent humans in the virtual world*) in pre-built virtual worlds.

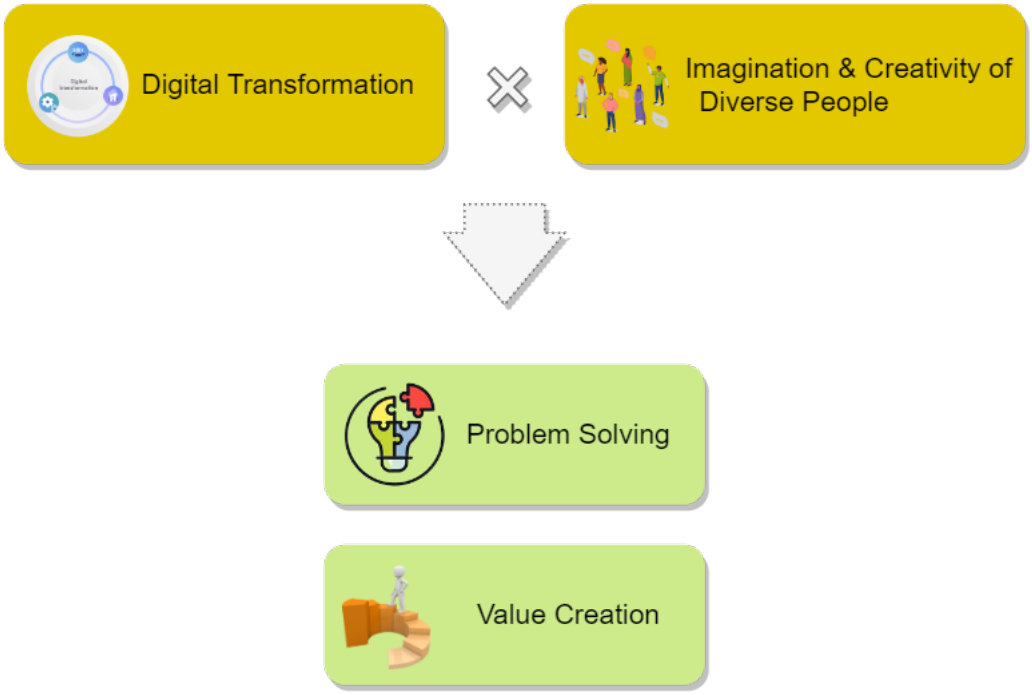


Figure 8.9: Digital transformation and creativity to solve problems and creating value in the system

8.4.4 What is Next?

With an immeasurable potential, the concept of the Metaverse is the biggest thing when it comes to immersive digital workplaces, health services, gaming, and customer experience for the growing contingent of brands with the adoption of the technology [262]. Moreover, modern digital devices need the support of considerable advancements to provide latency-free experiences through virtual and augmented reality using 5G and upcoming technologies [224]. The metaverse generally looks like a souped-up version of VR, but it can be the future Internet. Instead of sitting in front of a computer and working, the metaverse can use a headset to enter the virtual world connecting digital environments. Most of our digital interactions are based on 2D imagery, which is changing rapidly, like virtual tours of places where users can interact and explore in a 3D environment.

Niantic, the creator of Pokemon Go, raised $300 million in funding to create its Metaverse[3]. In addition, Niantic is developing an AR platform for 3D models of the planet, which can play a significant role in the upcoming computing revolution.

[3]https://www.forbes.com/sites/charliefink/2021/11/24/this-week-in-xr-niantics-300-million-raise-nfts-as-tickets-dent-reality-

8.4.5 Potential of Metaverse in Education

As Chapter 2 discussed, the background of using XR as learning technology and learning from the implementation of the AGILEST Approach provides a lot of evidence for using XR in different domains of education. Across the globe, XR is becoming an integral part of the educational systems which will move forward to the Metaverse. Education has rich traditional practices of classrooms, curriculum structures, grading systems, etc., but so far in the digital transformation, it is not possible to completely turn it into virtual spaces. This need emerged during the COVID pandemic when the world felt the need for virtual classrooms [5].

Figure 8.10: Metaverse's Applications in Education

The metaverse concept as an immersive virtual space can bring the campus activities class lectures with 3D simulations to enable a more realistic classroom learning experience where everyone presents virtually in an immersive form. With the involvement of activity-oriented and enhanced gamification, it can increase classroom participation [205]. Metaverse's applications in education are included but not limited to virtual 3D classrooms, simulated real-life situations, digital learning in a remote setting, interdisciplinary learning, virtual campus tours, events, and collaborative activities. It can help to create powerful immersive learning experiences, gamification, hands-on learning practices, and improve learning speed. By bringing the concept of social presence, Metaverse can help students to meet and interact virtually with other students and teachers in 3D virtual classrooms. Metaverse's ability to replicate real-life situations where students can conduct scientific experiments can revolutionize STEM learning, especially in resource-constrained environments.

A prototype of a campus Metaverse at the Chinese University of Hong Kong, Shenzhen (CUHKSZ) presented with a blockchain-driven system (as shown in Figure 8.11). The system aims to provide an on-campus interactive metaverse for students with a mixed environment where students' real-world actions reflect in the virtual world [87].

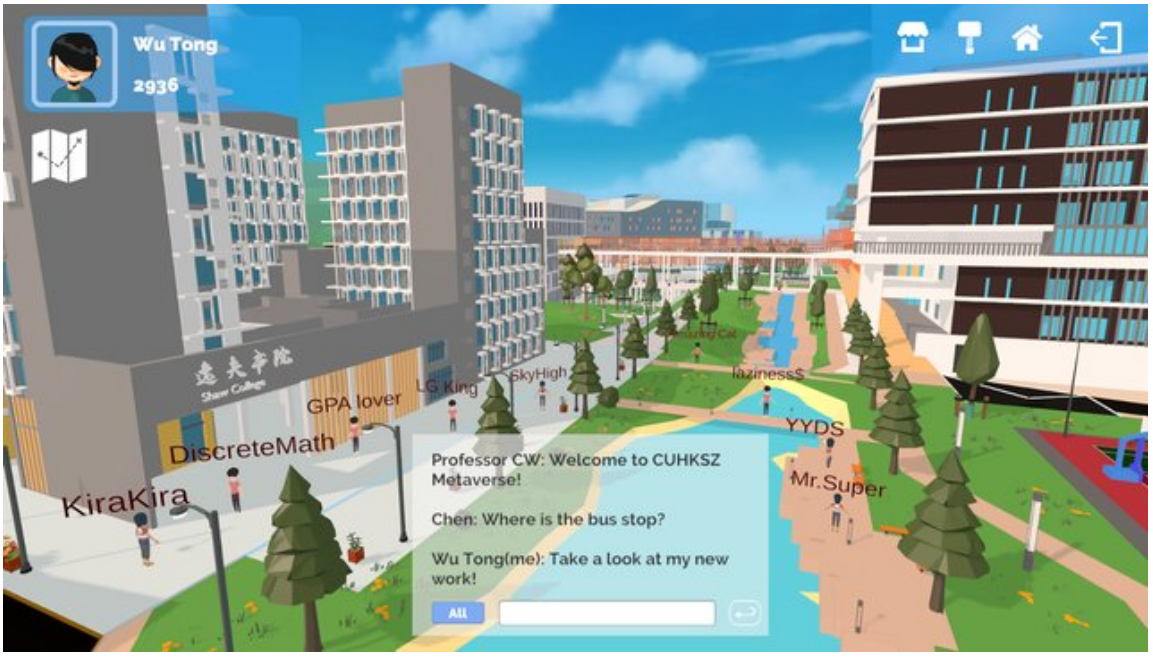


Figure 8.11: A corner of Chinese University of Hong Kong, Shenzhen (CUHKSZ) as Metaverse [87]

The exciting thing about the Metaverse in the context of education is that learning seems to be a perfect fit as it will empower *learning by doing* "kinesthetic learning" [141] at its best with simulated activities about experiential learning. In 2021, Stanford University started its course COMM 166/266: "Virtual People" entirely based on VR [4]. The evaluation of a collaborative e-learning Metaverse platform, VoRtex showed positive results in overcoming the learning boundaries [150]. In a recent study, a bottom-up approach adopted for real case studies to use Metaverse-based Education has been shown to create sustainable learning experiences [234]. As presented in evaluations, Chapter 7 focused on assessing the workload; mental and physical workload will be an essential topic when using Metaverse for education. Following the concept *"From University to Metaversity"*, immersive learning environments in the future with intuitive interactions will enable much more focused, personalized, and engaging learning experiences. It is further discussed in future work, Section 9.2.2.

8.4.6 Potential of Metaverse for Practical Training

Practical training is always essential to human resource development in all sectors. Learning technical topics and training in remote and resource-constrained environments is possible using artificial technologies, and the concept of haptic feedback has the power to take this approach to the next level.

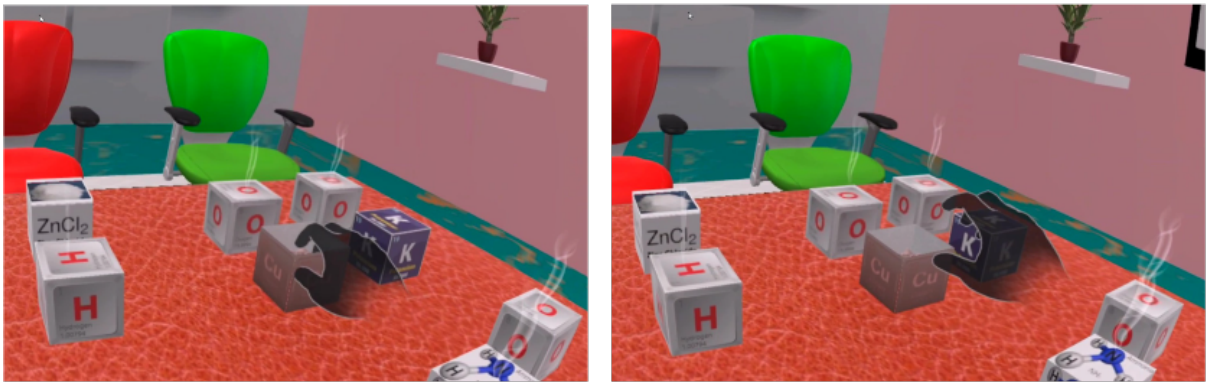


Figure 8.12: Different view of user interaction with Application in Oculus Quest

The kinesthetic learning approach proposed as part of methodology in Chapter 5 and further

[4]https://stanforddaily.com/2021/12/01/stanford-launches-first-class-taught-completely-in-virtual-reality/

implemented in Chapter 6 is a major component of the practical training in immersive environments. As Figure 8.12 shows the kinesthetic learning approach with virtual hand interaction in an immersive environment as one of the significant contributions of this thesis. It supports the concept of practical training and virtual laboratories in the Metaverse.

Figure 8.13: Haptic feedback gloves revealed by Facebook Reality Labs [Meta Reality Lab]

Using haptic sensing gloves would allow interaction with the virtual world and experience it the same way as we do in the real world. In artificial reality, the goal of haptic technology is comfortable and lightweight gloves to convey tactile information such as pressure, heat, and weight. Suzuki et at. used the concept for the learning system in Metaverse [286]. XR for training has been successfully adopted in various practical learning scenarios like retail, firefighting, aviation, police, military, chemical, mechanical, tourism, and gaming. Now it is time to move with haptic XR with a realistic approach to move forward with this technology in the practical field.

8.5 Conclusion

This chapter focuses on the challenges of ethics, security, and privacy faced during this research, the relation of these issues with the larger landscape of XR in education, and the future of XR in learning as Metaverse. With the advancements in computer vision, sensor fusion, and realistic displays, XR technology is gaining momentum in every field of life. The potential for XR in remote learning is substantial and will improve over time. Using HMDs with high-fidelity graphics and immersive content can allow students to explore and learn complex technical topics in a way impossible with traditional teaching. Planning in a rapidly evolving technology environment is a constant challenge. Making XR technology more accessible and safe is the right way to accommodate this pace of change. It is the right time for organizations, policymakers, and curriculum designers to consider XR for remote education.

Learning from the different steps of this research, it is found that these concerns of privacy, ethics, and security attached to XR technology are real and have increased over time. Therefore, there is a need to stress notions like ethics, responsibility, safety, and trust in XR technologies, mainly when used in a remote environment. Continued discussion in this area has stressed the need for a code of conduct [195] for using XR technologies similar to the codes of conduct emerging in artificial intelligence, such as the IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems in 2019. The IEEE Global Initiative on Ethics of Extended Reality is the first worldwide effort to achieve this goal. This process is ongoing, and it is crucially important that the use of XR in remote education is highlighted within this process, as its needs differ from in-person XR education.

This chapter emphasizes the need to ensure that any XR technology designed for educational purposes should be as affordable as possible. In addition, users must be informed about the type of data the system is collecting and allow them to opt-out. For the collection of personal data, data security measures must be considered to be a top priority. Finally, to protect XR users, most corporate solutions like *Responsible Innovation Principles* by Facebook will need to collaborate with international regulatory authorities, government policies, and the users

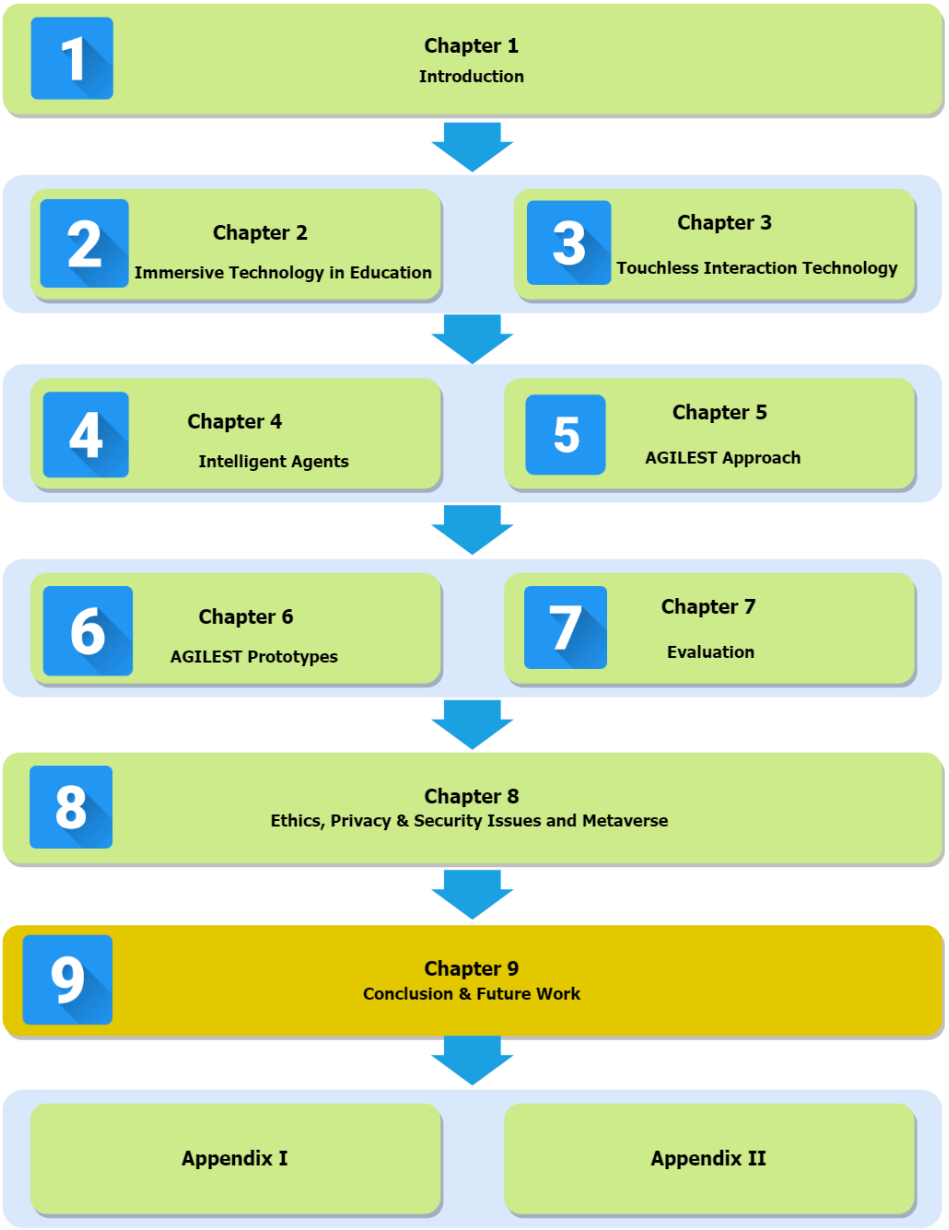
themselves. Defining the Metaverse is just like defining the Internet in the early 1990s. The resulting combination of all emerging technologies forms an entirely new virtual universe that may offer tangible and meaningful experiences that could be compared to real life.

That Metaverse is years away from a point where it is genuinely pervasive and accessible to all. Once it becomes possible, AR and VR will become ubiquitous in everyday life. Our current Internet communities and online spaces form a beta Metaverse. However, these changes will not happen overnight because it will take time to complete this transition for accessible, interactive, immersive real-world experiences to become a reality. Control of such worlds should not be controlled by one group or well-meaning regulation that results only in nation-states or large corporations controlling and running such a world. Due to the low cost of entry as long restrictions by the government are not put in place, worries about who controls the Metaverse are probably misplaced, as any attempts to holistically create a managed Ecosystem will falter, as we have seen by the rapid growth of internet communities of all shapes and sizes. In the past, there was a lack of resources for creating 3D content, which has been removed effectively by creating the ability for high-definition content and virtual representations. The Metaverse is reliant upon the power of 3D capture and virtualization technologies. From virtual gaming, world workplaces, fashion or entertainment, and even public services, Metaverse can bring tremendous opportunities to form an entirely new way of living, the same as the Internet has done in the last 30 years. We would need 3D capturing and advanced virtualization technologies for developing digital twins to provide a virtual realm.

CHAPTER

NINE

Conclusion & Future Work



9.1 Summary of Contributions

XR is rapidly becoming ubiquitous and vital in TEL due to its benefits for active participation and an engaging environment. In this tech-savvy generation, immersive learning has professed advantages that encourage embracing technologies like MR as a pedagogical tool in STEM education. Despite the fact that the MR technology learning design in different studies has shown very positive and encouraging results [131] [314], this study has mainly focused on the controller-free hand interaction, use of machine learning as self-guided learning using agents and implementation of kinesthetic learning approach. The fundamental contribution of this thesis is providing new directions of research in immersive learning technology using the real-time hand interaction approach for kinesthetic learning pedagogy and ML-agents for self-guided learning in immersive environments. Based on a critical review, an analysis proposed that previous research in XR lacks the use of hands-on learning practices and intelligent agents to provide self-guided learning pedagogy for students. Considering this research gap, this thesis has proposed using real-time virtual hand interaction and an agent-oriented approach to use machine learning in XR educational applications.

The proposed AGILEST approach has been tested with case studies with desktop, handheld, and head-mounted displays to provide proof of concept. Furthermore, it has been evaluated by expert reviewers in remote and in-person experimental designs. The design assessments and evaluation results provides evidence that AI and ML would be two major components of the future learning systems in immersive technology to facilitate personalized and agent-guided learning. The role of real-time hand interaction will be crucial in future immersive learning environments, as it will be empowered with real haptic sense in future research. Background knowledge about the domain is provided in Chapter 2. Chapter 3 has provided detail about the recent emergence, need, and benefits of touchless and contactless technologies, which is a major component of the thesis in subsequent chapters. Chapter 5 has provided detail about the methodology of the proposed approach of combining real-time hand interaction and machine learning agents. Chapter 6 has presented two case studies as proof of concept developed for handheld and HMDs, respectively. Chapter 7 has presented evaluations of handheld and HMDs

case studies with expert reviewers. Matters of ethics, privacy, & security, and further move of immersive technology towards Metaverse are discussed in Chapter 8. This research concluded that using immersive technology in education gives more autonomy, giving individuals space for highly interactive, self-motivated, and self-guided learning. Chapter 2 addressed RQ 1, which analyzes current challenges and new research opportunities in XR and concludes that the use of agency and higher user interaction is a research gap in the previous research studies. It is further extended by investigating higher-level interaction and the use of intelligent agents in XR. RQ2 about finding the opportunities of touchless hand interaction and exploring its productivity has been addressed in Chapters 3 and 5 & 6. This research question is addressed in terms of desktop, handheld devices, and HMDs. Using hand interaction for kinesthetic learning in AGILEST case studies provided evidence of increasing productivity in evaluation with expert reviewers. RQ3 is addressed in detail in Chapter 4 and further investigated in terms of immersive technologies. AGILEST case studies used an intelligent agent for self-guided learning, which proved helpful in expert reviewers' evaluation. RQ4 focuses on using virtual learning material in resource-constrained environments where the provision of actual physical material is impossible. According to the expert reviewers, the hand interaction approach helps to effectively interact with the virtual learning material, which is closely relevant to physical learning tasks and interaction with physical learning material.

9.2 Future Work

XR is a versatile technology representing a significant evolutionary transformation in educational content delivery, increasing learning gain and reducing cognitive load. Furthermore, as technological progress is moving the world toward a smart society, XR will create more opportunities by collaborating with technologies like AI, ML, Blockchain, and the Internet of Things (IoT). This research has opened many new opportunities for the future and will be taken further with new explorations into:

9.2.1 Intelligent Agents in Immersive Learning

Artificial intelligence and machine learning are increasingly used as learning technology to develop self-directed and self-assisted learning applications. The advancements in learning games technology and simulated learning applications have increased the use of intelligence to create productivity in independent learning. In the context of immersive learning environments, the agency can play a supportive role in simulated experiences and further move toward Metaverse. As technology continues to evolve with time, we can expect more innovative and advanced uses of intelligent agents in education in the near future. The use of Intelligent Pedagogical Agents (IPA) [278] will get more attractive in immersive technology in the future. The proposed ML-agents in this research can enhance the immersive learning experiences when implemented effectively. This can help to develop personalized, adaptive, and intelligent learning systems to learners in the future. However, designing and implementing these agents ethically and responsibly is important to avoid potential biases in the learning process.

9.2.2 Learning Technology in Metaverse

As Section 8.4 has presented the detail of Metaverse as a learning technology. The enhanced capability of immersive technology and progress towards Metaverse will create more opportunities for learning technology. As this thesis concluded that "Learning-by-Doing" or kinesthetic learning is the best way to learn complex tasks and technical topics. In the immersive Metaverse, learners will be embedded using haptic devices to accelerate learning further.

Metaverse sets to become a reality, paving the way for new opportunities in learning and interaction. There is no doubt that Metaverse can be a turning point for EdTech, and the immersive learning experience will surely stay with us for a long time [138]. Looking into potential, Metaverse can bring breakthroughs in active learner participation in the learning process. In the future, Metaverse will provide immersive learning experiences for students that ignite inspiration, cognitive development, and collaboration through interactive virtual learning with peers and mentors.

9.2.3 Multi-sensory Haptic Feedback for Kinesthetic Learning in XR

Using haptic sensing gloves would allow interaction with the virtual world and experience it in the same way as we do in the real world. In artificial reality, the goal of haptic technology is comfortable and lightweight gloves to convey tactile information such as pressure, heat, and weight.

Haptic feedback is getting more important in the learning and training process because it provides better learning gain and adds extra value to the virtual learning material by providing force or tactile feedback. SenseGlove technology provides haptic feedback about shapes, textures, stiffness, and resistance of any virtual object, which adds a realistic approach to the interaction [70]. Virtual laboratories for STEM subjects are becoming a unique field in VR-enabled education tools. AR & VR with hand interaction, intelligent agents, and haptic feedback concepts can create more productive learning environments for resource-constrained spaces where providing actual learning material is impossible due to the cost issues.

Haptic feedback provides better simulation and opportunity for hands-on learning [211], which feels like touching or interacting with something in real life. In addition, it allows superior precision, which supports faster task completion. The convergence of virtual and physical space in the Metaverse could help to advance healthcare and medical training. Replacing conventional technology with Metaverse can expand the user experience of medical education [168]. Applying Metaverse in medical training will provide more effectiveness when hands-on learning and advanced interactions are required for surgical procedures. In addition, it will move the concept of Metaverse from just a virtual space to haptic feedback with more realism. Collaborative design platforms like NVIDIA Omniverse [1] for creating virtual worlds offer creative design possibilities for creators, developers, and large enterprises. Such developments are not just to accelerate complex 3D world designs but also enable ground-breaking new methods of visualizing and simulating because of powerful multi-GPUs. The ability to

[1] https://www.nvidia.com/en-us/omniverse/

create digital twins in Omniverse and other platforms will open doors for developers and designers to develop accurate virtual replicas of unique physical objects, processes, or working environments. As Meta is moving very fast in the development of XR HMDs like the Meta Quest Pro VR headset, the world is moving towards extraordinarily incredible and realistic XR experiences. The concept of social presence and eye contact in virtual reality, translating behaviors into avatars in real-time, is becoming a reality soon.

9.2.4 XR with Web 3.0 as Learning Technology

The next iteration of the world wide web is Web 3.0, which will transform the current web technology by introducing a fully decentralized and democratized internet, which will not be under the control of a single or few entities. Web 3.0 technology and Metaverse are interlinked and are part of an in-progress revolution in our interaction with digital technology [94, 115]. Based on the decentralized nature of Web 3.0 technology, it will empower remote XR in the future. Furthermore, adopting Web 3.0 in immersive learning will also provide new doors for integrating collaborative agent-oriented approaches. Web 3.0 will be media-centric, and search research will give access to 3D multi-media objects. It will empower the concept of 3D Wikis and virtual labs in immersive technology.

9.2.5 Novel Contributions

This thesis has made several contributions to immersive learning technology and immersive technology in a broader view concerning other domains where this technology is applicable. First, it has investigated the current challenges and future opportunities in immersive learning. Based on these findings, given new developments and the need of a learner in the modern world, a novel immersive learning approach called AGILEST Approach *AGents to facilitate Interactive kinesthetic LEarning in STEM education using a Touchless interaction* is introduced. This approach combined the potential of real-time hand interaction for kinesthetic learning pedagogy and machine learning agents for self-guided learning in immersive learning environments. This

proposed approach has been developed for desktop, handheld, and head-mounted displays to provide proof of concept by involving the design thinking process. The evaluations of the proposed approach are conducted with remote and in-person experiments with expert reviewers. Learning from the development cycle, usability, and design evaluations, this thesis has provided a detailed discussion about ethics, privacy, and security issues with immersive learning environments. Furthermore, Metaverse as the future of immersive learning has been discussed with its benefits, challenges, and importance of digital twins, which will soon become a reality.

The contributions of this thesis to the future of immersive learning technology can open new opportunities for creating more user-centered immersive learning environments combining the power of highly responsive interaction technologies, artificial intelligence, and machine learning. This thesis has provided a framework that can be further advanced to the next level with content authoring capability, haptic multi-sensory technology and the integration of agents with advanced capabilities.

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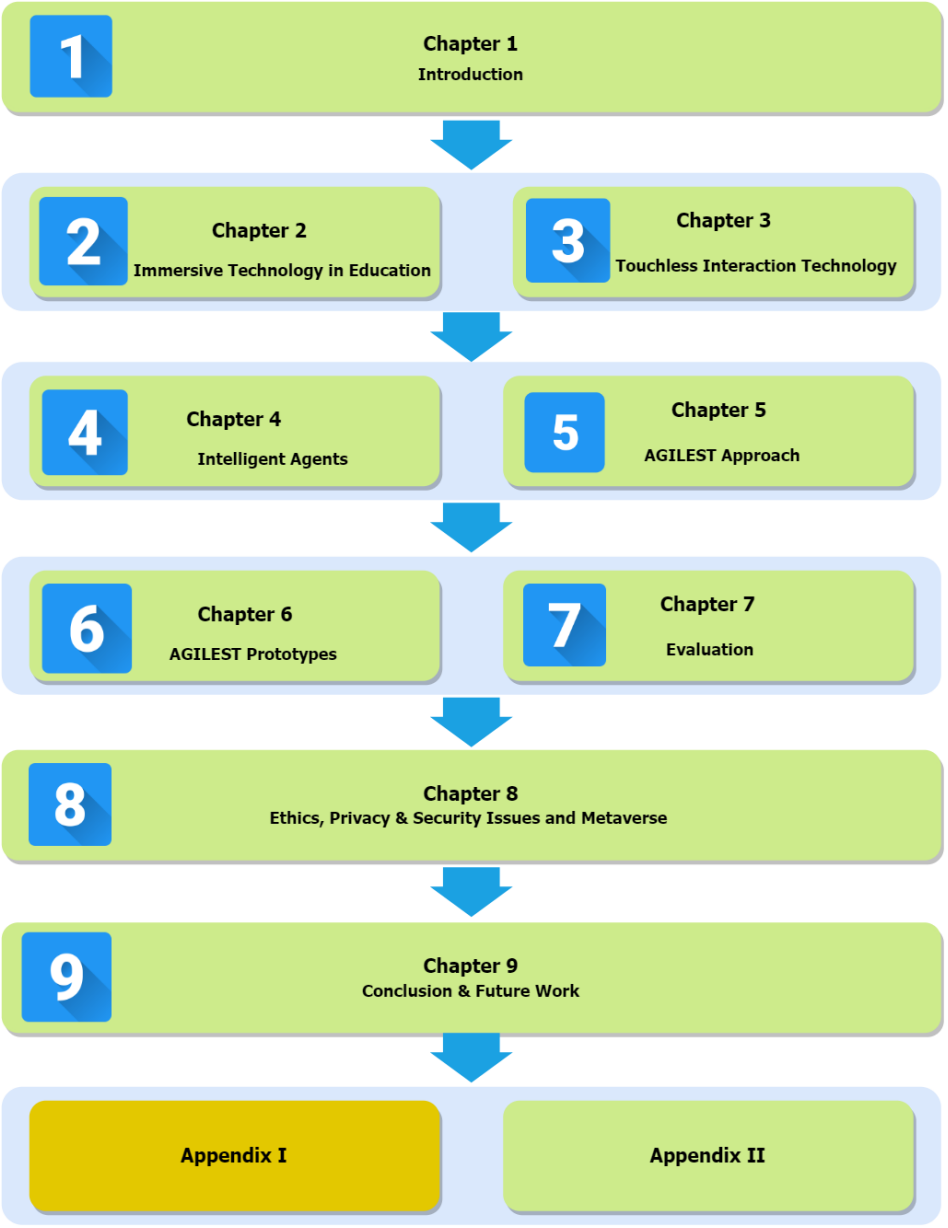
CHAPTER

TEN

Appendix I



10.1 Acronyms

Abbreviation	Words
AR	Augmented Reality
VR	Virtual Reality
MR	Mixed Reality
XR	eXtended Reality
UI	User Interface
HCI	Human-Computer Interaction
STEM	Science, Technology, Engineering and Mathematics
IoT	Internet of Things
GPS	Global Positioning System
NFC	Near-Field Communication
RFID	Radio-Frequency IDentification
HMDs	Head-Mounted Displays
API	Application Programming Interface
AI	Artificial Intelligence
ML	Machine Learning
EULA	End-User License Agreement
EdTech	Education Technology
NFT	Non-Fungible Token
TEL	Technology Enhanced Learning
SDK	Software Development Kit
NASA-TLX	NASA Task Load Index
TAM	Technology Acceptance Model
CAVE	Cave Automatic Virtual Environment
ARCS	Attention, Relevance, Confidence, Satisfaction
NPL	Natural Language Processing
ARTP	Augmented Reality Teaching Platform
ARiSE	Augmented Reality in School Environments

Table 10.1: Abbreviations Used in Thesis

10.2 Code for Implementing ML-Agent

Collecting observations to take decision. First step is to install the ml-agents on the system and integrating in the Unity platform. It needs python installation as pre-requisite.

- Install the `com.unity.ml-agents` Unity package
- Install the `com.unity.ml-agents.extensions` Unity package (Optional)
- Install the `mlagents` Python package

To Install the `mlagents` Python package, there is need of installing other Python packages that `mlagents` depends on. As this application is developed on Windows OS, there is need to install the `PyTorch` package before `ml-agents`.

Activating virtual environment and run this command from the command line:

`pip3 install torch =1.7.1 https://download.pytorch.org/whl/torch_stable.html` After installing `PyTorch` package, activated the virtual environment to install the `mlagents` Python package from command line:

```
python -m pip install mlagents==0.26.0
```

```
public override void CollectObservations(VectorSensor sensor)
{
sensor.AddObservation(hydrogen.transform.localPosition);
sensor.AddObservation(hydrogen1.transform.localPosition);
sensor.AddObservation(oxygen.transform.localPosition);
sensor.AddObservation(carbon.transform.localPosition);
sensor.AddObservation(nitrogen.transform.localPosition);
sensor.AddObservation(fire.transform.localPosition);
sensor.AddObservation(fire1.transform.localPosition);
sensor.AddObservation(water.transform.localPosition);
sensor.AddObservation(co2.transform.localPosition);
sensor.AddObservation(hydrogen2.transform.localPosition);
sensor.AddObservation(hydrogen3.transform.localPosition);
 }
```

`TrainChemistry` is the Unity scene name. When all the molecules (products) are present in the scene after all reactions are done, the `TrainChemistry` scene needs to restart for another episode.

```
void Update()
 {
 if (carbonic.activeInHierarchy && explosion.activeInHierarchy
 && carbon.activeInHierarchy && ammonia.activeInHierarchy
 && zncl.activeInHierarchy && water.activeInHierarchy
 && HCL.activeInHierarchy)
       {
```

```
            SceneManager.LoadScene("TrainChemistry");
        }

 }
```

Using *BrainParameters* for training purpose.

```
        public BrainParameters BrainParameters
        {
            get { return m_BrainParameters; }
            internal set { m_BrainParameters = value; }
        }
        [HideInInspector, SerializeField]
        NNModel m_Model;
```

The neural network model used in inference mode.

```
public NNModel Model
  {
   get { return m_Model; }
   set { m_Model = value; UpdateAgentPolicy(); }
  }
  [HideInInspector, SerializeField]
        InferenceDevice m_InferenceDevice;
```

How inference is performed for this Agent's model.

```
 public InferenceDevice InferenceDevice
  {
   get { return m_InferenceDevice; }
   set { m_InferenceDevice = value; UpdateAgentPolicy();}
   }
```

The *Behavior Type* for the Agent.

```
        [HideInInspector, SerializeField]
        BehaviorType m_BehaviorType;

        public BehaviorType BehaviorType
        {
            get { return m_BehaviorType; }
            set { m_BehaviorType = value; UpdateAgentPolicy(); }
        }
```

The name of this behavior, which is used as a base name.

```
[HideInInspector, SerializeField]
   string m_BehaviorName = "My Behavior";
   public string BehaviorName
    {
      get {
      return m_BehaviorName;
      }
      set { m_BehaviorName = value; UpdateAgentPolicy(); }
    }
```

Setting the ID of behavior of ml-agent.

```
[HideInInspector, SerializeField,
FormerlySerializedAs("m_TeamID")]
public int TeamId;
// TODO properties here instead of Agent
[FormerlySerializedAs("m_useChildSensors")]
[HideInInspector]
[SerializeField]
bool m_UseChildSensors = true;
```

Whether or not to use all the sensor components attached to child GameObjects of the agent. This code segment helps choose whether to use all sensors or not.

```
public bool UseChildSensors
 {
  get { return m_UseChildSensors; }
  set { m_UseChildSensors = value; }
 }
```

The code below is used to define grab and pinch gestures for real-time interaction. It can be customized if changes need different gestures and actions performed.

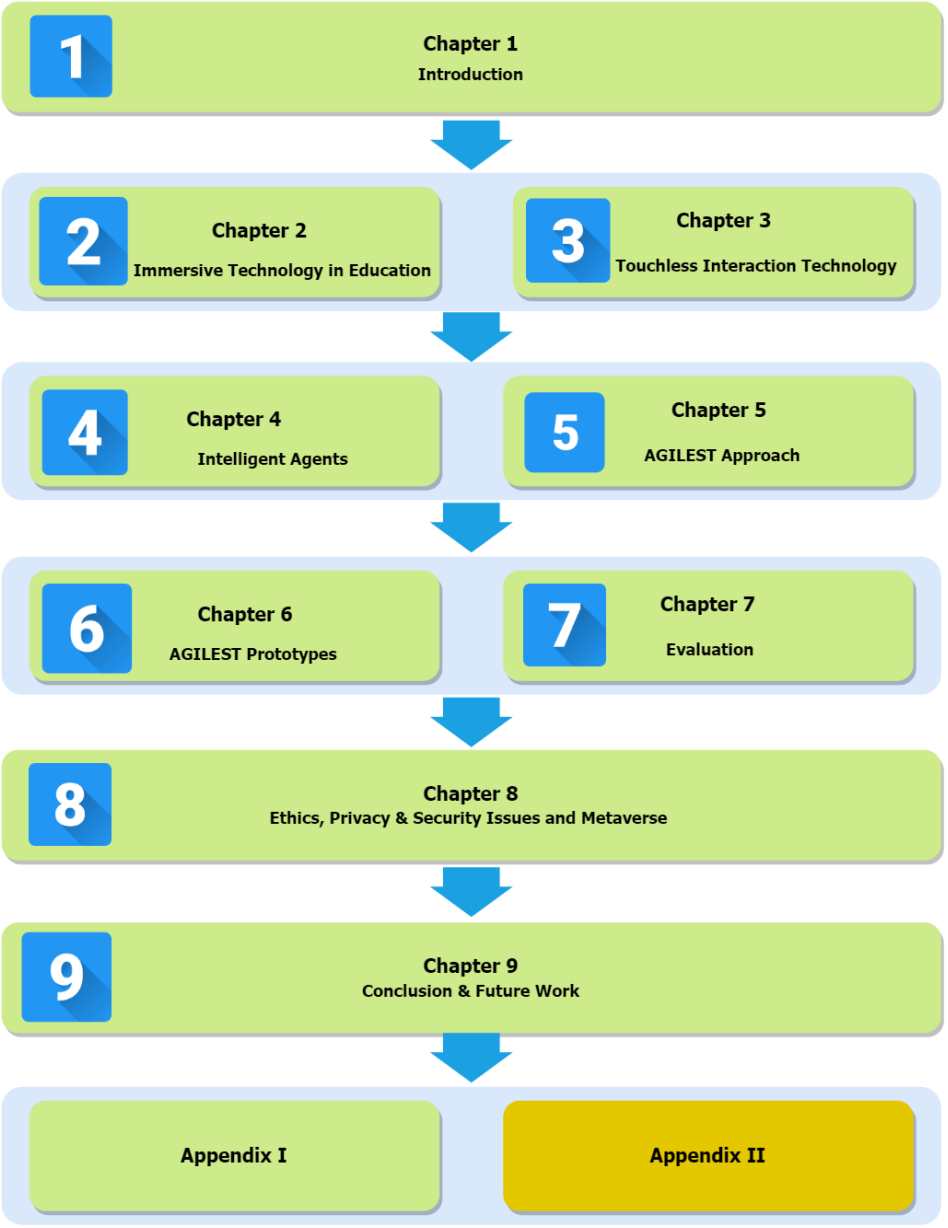
```
grab = ManoGestureContinuous.CLOSED_HAND_GESTURE;
pinch = ManoGestureContinuous.HOLD_GESTURE;

private void MoveWhenGrab(Collider other)
{
 if (ManomotionManager.Instance.Hand_infos[0].hand_info.
 gesture_info.mano_gesture_continuous == pinch)
  {
    transform.parent = other.gameObject.transform;
    }
        else
        {
            transform.parent = null;
        }
 }
```

CHAPTER

ELEVEN

Appendix II



Consent Form for Expert Reviewers (for Handheld Devices)

I am a PhD student at University College Dublin, conducting a research experiment with Augmented Reality experience in smartphones for learning chemistry. You will need to participate in the hands-on chemistry learning experiments by installation application on your smartphone. I appreciate your participation in my study. For assessment, there will be questionnaire and usability test after the learning exercise. Please be noted that participating in my study is voluntary basis and you have the right to withdraw at any time you wish without any consequences, in case you like to withdraw be assured that any information related to you will be destroyed. I will ensure your anonymity in publication results and your data will be securely stored. You can contact me if you have any questions about my study through my email. If you agree to participate, please fill the consent form, many thanks to you in advance for your contribution.

- Everything in this experiment has been explained to me, and I have been given a chance to ask questions.
- I have knowledge about what I am going through in case I agree to participate in this experiment.
- I am aware that my participation is voluntary and that I may withdraw at any stage without any consequences.
- I understand that any information or opinions I provide will be kept confidential to the researcher and only for the publication purpose.
- I am aware of the risks that I may go through during the experiment.

By signing below, I agree to participate in this research project.

Name : ..... Experience in Research (years) : .....

Organization/University : ..... Age : .....

Date : ..... Signature : .....

Consent Form for Expert Reviewers (for HMDs)

I am a PhD student at University College Dublin, conducting a research experiment with Mixed Reality in Oculus Quest for learning chemistry. You will need to participate in the hands-on chemistry learning experiments in immersive environment using controller-free hand interaction. I appreciate your participation in my study. For assessment, there will be questionnaire and usability test after the learning exercise. Please be noted that participating in my study is voluntary basis and you have the right to withdraw at any time you wish without any consequences, in case you like to withdraw be assured that any information related to you will be destroyed. I will ensure your anonymity in publication results and your data will be securely stored. You can contact me if you have any questions about my study through my email. If you agree to participate, please fill the consent form, many thanks to you in advance for your contribution.

- Everything in this experiment has been explained to me, and I have been given a chance to ask questions.
- I have knowledge about what I am going through in case I agree to participate in this experiment.
- I am aware that my participation is voluntary and that I may withdraw at any stage without any consequences.
- I understand that any information or opinions I provide will be kept confidential to the researcher and only for the publication purpose.
- I am aware of the risks that I may go through during the experiment.

By signing below, I agree to participate in this research project.

Name : ..... Experience in Research (years) : .....

Organization/University : ..... Age : .....

Date : ..... Signature : .....

11.1 Experts Reviewers' Questionnaire (Augmented Reality with Real-time Hand Interaction & ML Agents)

How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

How much physical activity was required? Was the task easy or demanding, slack or strenuous?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

How much time pressure did you feel due to the pace at which the tasks or task elements occurred?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

How successful were you in performing the task? How satisfied were you with your performance?

	1	2	3	4	5	
Perfect	○	○	○	○	○	Failure

How hard did you have to work (mentally and physically) to accomplish your level of performance?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

Figure 11.1: Part 1: Questionnaire with NASA Task Load Index questions for evaluation with handheld devices

Perceived Usefulness and Ease of Use

Description (optional)

1). Usefulness

Description (optional)

Using touchless hand interaction with 3D learning material improves learning performance *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

Using AR-based interaction method will enhance learning effectiveness *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

Machine Learning module helps to learn creating chemical reactions

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

Figure 11.2: Part 2:Questionnaire for Perceived Usefulness questions for evaluation with handheld devices

B). Ease of Use

Description (optional)

It was easy to learn chemical reaction with AR Hand Interaction *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

It was easy to interact with the App *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

It was easy to follow the Learn Module

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

It was easy to interact with the 3D chemicals with hand interaction *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

Figure 11.3: Part 3: Questionnaire for Perceived Ease of Use questions for evaluation with handheld devices

C). Satisfaction

Description (optional)

I am satisfied with learning approach and interaction *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

I will recommend it to my students or friends *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

It is pleasant to use it *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

Figure 11.4: Part 4:Questionnaire for Perceived Satisfaction questions for evaluation with handheld devices

Please write your comments

Description (optional)

Did you find it easy to interaction with cubic elements and create reactions? *

Long-answer text

Do you think pre-trained module can help students to learn before actual interaction?

Long-answer text

What was the most interesting thing you found during playing with application? *

Long-answer text

Provide your recommendation to improve the application *

Long-answer text

Figure 11.5: Part 5: Qualitative feedback Questionnaire for evaluation with handheld devices

11.2 Experts Reviewers' Questionnaire (Mixed Reality with Real-time Hand Interaction & ML Agents)

How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

How much physical activity was required? Was the task easy or demanding, slack or strenuous?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

How much time pressure did you feel due to the pace at which the tasks or task elements occurred?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

How successful were you in performing the task? How satisfied were you with your performance?

	1	2	3	4	5	
Perfect	○	○	○	○	○	Failure

How hard did you have to work (mentally and physically) to accomplish your level of performance?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?

	1	2	3	4	5	
Very Low	○	○	○	○	○	Very High

Figure 11.6: Part 1: Questionnaire with NASA Task Load Index questions for evaluation with HMDs

Perceived Usefulness and Ease of Use

1). Usefulness

Using real-time hand interaction with 3D learning material improves learning performance *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

Using MR-based interaction method will enhance learning effectiveness *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

Machine Learning module helps to learn creating chemical reactions

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

B). Ease of Use

It was easy to learn chemical reactions with real-time hand interaction in immersive environment *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

It was easy to interact with the App *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

Figure 11.7: Part 2:Questionnaire for Perceived Usefulness and Ease of Use questions for evaluation with HMDs

It was easy to follow the Learn Module

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

It was easy to interact with the 3D virtual chemicals using hand interaction *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

C). Satisfaction

I am satisfied with learning approach and interaction *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

I will recommend it to my students or friends *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

It is pleasant to use it *

	1	2	3	4	5	6	7	
Strongly Disagree	○	○	○	○	○	○	○	Strongly Agree

Figure 11.8: Part 3:Questionnaire for Perceived Satisfaction questions for evaluation with HMDs

Please write your comments

Did you find it easy to interaction with cubic elements and create reactions? *

Your answer

Do you think pre-trained module can help students to learn before actual interaction?

Your answer

What was the most interesting thing you found during playing with application? *

Your answer

Provide your recommendation to improve the application *

Your answer

Back Submit Clear form

Figure 11.9: Part 4:Qualitative feedback Questionnaire for evaluation with HMDs