

Article

# Current Challenges and Future Research Directions in Augmented Reality for Education

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**Abstract:** The progression and adoption of innovative learning methodologies signify that a respective part of society is open to new technologies and ideas and thus is advancing. The latest innovation in teaching is the use of Augmented Reality (AR). Applications using this technology have been deployed successfully in STEM (Science, Technology, Engineering, and Mathematics) education for delivering the practical and creative parts of teaching. Since AR technology already has a large volume of published studies about education that reports advantages, limitations, effectiveness, and challenges, classifying these projects will allow for a review of the success in the different educational settings and discover current challenges and future research areas. Due to COVID-19, the landscape of technology-enhanced learning has shifted more toward blended learning, personalized learning spaces and user-centered approach with safety measures. The main findings of this paper include a review of the current literature, investigating the challenges, identifying future research areas, and finally, reporting on the development of two case studies that can highlight the first steps needed to address these research areas. The result of this research ultimately details the research gap required to facilitate real-time touchless hand interaction, kinesthetic learning, and machine learning agents with a remote learning pedagogy.

**Keywords:** Augmented Reality; AR learning; AR technology; STEM; blended learning; collaborative learning; kinesthetic learning; e-learning



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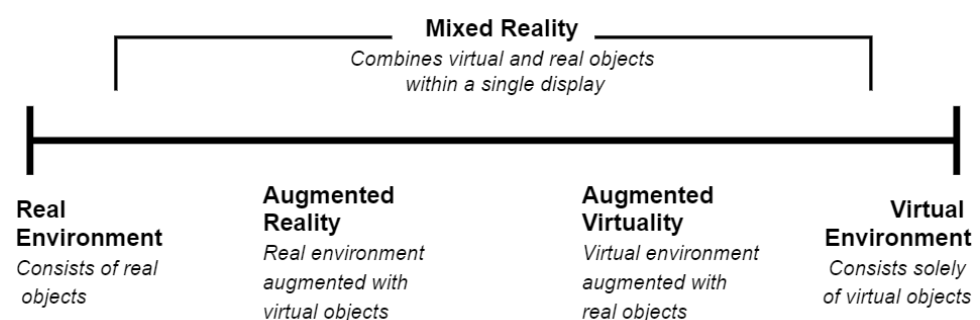
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## 1. Introduction

Augmented Reality (AR) allows for the superimposing of computer-generated virtual 3D objects on top of a real environment in real time [1] as explained in Figure 1. Learning assisted with AR technology enables ubiquitous [2], collaborative [3], and localized learning [4]. It facilitates the magic manifestation of a virtual object displayed in real time in a real-world space that can engage a user in the learning process like no other medium has been able to before. AR is an emerging technology with high potential for learning, teaching, and creative training [5].



**Figure 1.** Milgram's Continuum about Physical reality, Augmented Reality, Augmented Virtuality and Virtual Reality [6].

The fundamental research question this paper seeks to address is that *since AR technology has a large volume of published studies about education that reports advantages, limitations and effectiveness, what are the major challenges and emerging opportunities that can help to adopt new pedagogies such as kinesthetic and self-directed learning in the resource- constrained environments in AR?*

## 2. Background

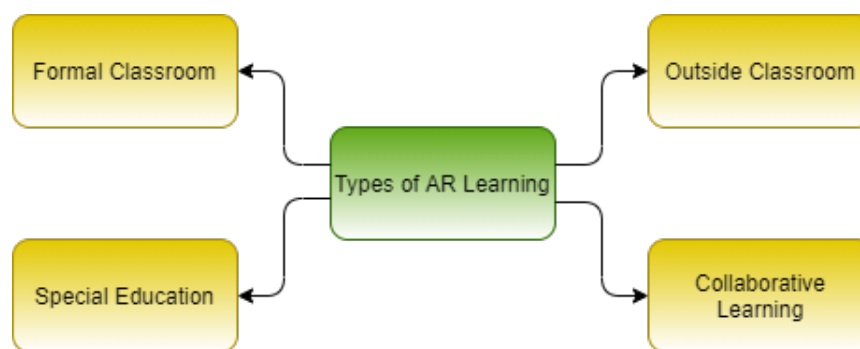
AR-based training has advantages over Virtual Reality (VR) approaches, as training takes place in the real world and can have access to real tactile feedback when performing a training task. Other advantages include the instructions and location-dependent information being directly linked and/or attached to physical objects [7].

AR due to both its novelty and potential to create innovate and attractive interfaces can bring a natural enticement to the learning process [8,9]. It can be used with desktops, tablets, smartphones, or Head-Mounted Displays (HMDs). Moreover, it is portable and adaptable in different scenarios to enhance the learning process in the traditional classroom, special education classroom, and outside the classroom [10]. The large-scale study of Ecosystems Augmented Reality Learning System (EARLS) reported the highest ratings on “Usefulness of learning Ecosystems” [11]. However, previous research presented results of reviewing different methods of augmenting educational content, testing at different education levels and subject domains [12], game-based learning [13], AR in remote learning [14] and systematic review of AR in Science, Technology, Engineering, and Mathematics (STEM) [15], but it lacks focus on new interaction techniques, the involvement of intelligent agents and collaboration capabilities [3] in the AR application.

Given recent moves worldwide to explore the use of remote learning, it is now the perfect time to explore the current challenges of this field and its potential future research directions of using AR for education to meet this need. Advancements in machine learning combined with agent-oriented approaches allow for developing rich conversational embodied agents to aid in remote learning. It has long been known that a co-learner agent can greatly help a participant in a learning task [16] and collaborative learning approaches with enhanced emotional abilities have relatively recently been also shown to increase this effect [17]. Research in 3D Augmented Reality Agents (AURAs) [18] is more limited though. Thus, this review includes examining the different uses of agents within some of the projects surveyed. To capture the current state of the art related work for this research, five types of AR applications are considered based on the definition of the five directions of AR education explored by [19] in the field. These categories are as follows:

- AR books;
- AR educational games;
- AR discovery-based learning applications;
- AR projects that model real-world objects for interaction;
- AR projects exploring skill-based training.

The survey has a narrow focus on AR-specific learning scenarios outlined in Figure 2, and this search did not have sufficient papers to justify taking a typical systematic review approach, as all papers that met the criteria were included, giving a perfect snapshot of the current state of the art in these areas.



**Figure 2.** Types of AR learning included in this study.

### 2.1. AR Learning in Formal Classrooms

In the classroom setting, AR allows students to learn through the combination of both real and computer-generated images [20]. It helps to understand the different topics with different scenarios.

### 2.2. AR Learning in Special Education

AR has the capability to create a learning opportunity for special children by overcoming the physical barriers; it can bring a high-quality educational experience to students with learning and physical disabilities as well as the special education classroom, as explained in Section 4.11.

### 2.3. AR Learning Outside the Classroom

Using AR smartphone application, the AR learning experience can be extended outside the formal classroom, including self-assisted learning. AR can create immersive learning opportunities by overlaying digital content from field trips to learning in personalized space.

### 2.4. AR for Collaborative Learning

If an educator is looking to model scientific practice, AR provides the opportunity to support the multifaceted world of scientific exploration. The need for collaborative learning has increased recently due to the growing demand for remote and independent learning where students need to connect with other mates and teachers.

In Section 4, current research studies are presented in different subsections according to domains and then educational level, which resulted from surveying and documenting projects in this field discovered through an exhaustive search. These research projects will be further examined in a table listing research objectives, educational levels, subjects they trialed the study with, how they have created their AR applications, and what devices and tracking technologies they used.

This review gives a high-level overview of the different user interface complexity with the corresponding level of possible collaboration with either a human or some form of Artificial Intelligence (AI) construct. This construct can take the form of a simple script, an agent-based system, or a machine learning algorithm.

In Section 5, based on the review from Section 4, this section will identify future research areas. This is followed by Section 6, where the exploration of these research gaps is presented with the implementation of two case studies, which can better illustrate the proposed research directions and highlight the current state of the art in AR. Finally, Section 7 will outline the conclusions of this paper.

## 3. Methodology

The search aimed to cover all the reputed AR studies in education found through IEEE Xplore, ACM digital library, and Google Scholar with the keywords “Augmented Reality” and “Learning” in the title after 2000. Considering the results found by IEEE Xplore 395 and ACM Digital Library 546 and 3389 on Google Scholar, this study is moving away from

the systematic review approach to explore more technical aspects of the AR learning applications. The goal of this study is to explore only those studies which are presenting new and productive applications for learning with different APIs, interaction capacity, libraries, agents, and display devices. The studies conducted at the early level up to 5th grade are considered Primary School and from 6th to 8th grade are considered Elementary School. Both Primary and 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 as university (Tertiary Education).

Finally, this research only included papers that focus on these four AR learning scenarios mentioned in Figure 2.

#### 4. Results and Discussion

This section will provide detail discussion on AR learning studies in different domains and different educational levels. Furthermore, this discussion is presented in Table 1 with a short objective, number of participants (subjects), display devices (desktop, handheld (smartphones/tablets), WebAR, HMDs), UI level, collaboration capacity and agency. Below is the detailed discussion.

##### 4.1. Interactive ARBooks for Early Classes

AR books are the most adopted learning pedagogy in the field of AR learning [21]. This concept involves converting the traditional books into interactive AR books by overlaying 3D contents. Nguyen et al. reported that the use of AR, regardless of grade level or subject area, allows students to be actively engaged in the learning process [22]. The concept of Augmented Instructions [23] can convert a physical book to virtuality and ARGarden [24] is an interactive flower gardening AR system, creating a positive learning engagement by adding visualization in the learning process.

Similarly, study findings about AR for teaching basic concepts of transportation [25], Toys++ [26] and an AR magical playbook to digitize the traditional storytelling by [27] shows the role of AR as an engaging factor in the learning process.

Adding more to interaction, an inquiry-based AR learning environment AIBLE [28] manipulates the virtual representations of the Sun, the Moon, and the Earth, which helped to prove the concept of tasks mobilization and active learning in AR.

The use of AR to enhance the learner's interest in the Chinese library classification scheme was supported by using a physical presentation agent [29]. To learn the role of parents in child learning, the concept of an AR picture [30] identified four behavioral patterns: parent as dominator, child as dominator, communicative child–parent pair, and low communicative child–parent pair.

##### 4.2. Interactive Books for Higher Classes

For high school, Liarokapis, Fotis et al. [31] developed 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, enabling the user to interact with the VMC composed of three-dimensional objects and animations.

To convert the 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 [32]. This idea of virtual interpretation showed an impact on learning outcomes by adding up visualization to a regular textbook. In a similar approach, the ARIES system [33] showed the physical markers as significant impact creators in usability and perceived enjoyment proved as a much more important factor than perceived usefulness.

To find the effectiveness of AR, the ARCS model (Attention, Relevance, Confidence, Satisfaction) of motivation was applied by Wei et al. [34] using “AR Creative-Classroom” and “AR Creative-Builder”. A pilot study proved that the proposed teaching scheme significantly improved learning motivation and student creativity in creative design courses.

To enhance the reading and writing of physical books, SESIL combines book pages and handwriting recognition using the AR camera [35]. It is considered robust and reliable for practical use in education as it yielded positive results. In addition, Jeonghye Han conducted an exploratory study to empirically examine children's observations toward the computer- and robot-mediated AR systems which reported positive dramatic play and interactive engagement [36]. By mixing the interactive concept maps with AR technology, the support of a good instructional technique and scaffolds improved the learning outcomes when mixed in to develop a new learning pedagogy [37].

#### 4.3. STEM (Science, Technology, Engineering, and Mathematics) Education

One of the first use cases of AR learning in secondary education is for STEM subjects. AR allows teachers to incorporate new technology and techniques in the classroom, which is one of the primary scenarios outlined in Section 2.1. STEM is taught in secondary and tertiary level education, which will be discussed in the overview of Education Level given in Section 5.1. Given the link between the technologies that enable AR and STEM, it naturally has become one of the primary domains where AR learning is present, as discussed in Section 5.2. Some of the best examples of AR learning come from looking into the possible use cases in Chemistry. Chen et al. [38] investigated how students interact with AR models as compared to physical models to learn amino acids structure in the 3D environment. Learning chemistry with ARChemist [39] and through gestures tested in CHEMOTION [40] provide a virtual interaction with chemicals using hand-tracking technology.

Similarly to Chemistry, one of the first topics to be covered using AR learning is Astronomy. The use of the AR to learn the Earth–Sun relationship [41], Earth–Moon System [42] and Live Solar System (LSS) [43] helped to enhance meaningful engagement in learning astronomy concepts and conceptual thinking. AR can assist in learning gravity and planetary motion with an interactive simulation, which increased the learning gain significantly and increased the positive attitudes of the students [44].

Visualization techniques of biology processes within AR allow students to understand better processes that are impossible in real time. Nickels et al. [45] developed an AR framework ProteinScanAR as an assistive tool for engaging lessons on molecular biology topics using AR. Science Center To Go (SCeTGo) [46] 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 university level for learning anatomy. For example, refs. [47–52] developed AR anatomy learning systems to learn the exterior to interior of the body by introducing an innovative, hands-on study of the human musculoskeletal system. In addition, the use of leapmotion for 3D body anatomy learning was tested to use hand tracking for interacting with 3D models [53,54].

The teaching of engineering subjects is a cornerstone of STEM, and as such, there are multiple examples of AR learning in this area. One summary to view these innovations used 3D web tools in technical and engineering education to help the multidimensional augmentation of teaching materials [55,56] used in technology and design engineering. Learning Physics through Play Project (LPP) helps to learn concepts of physics about force and motion [57] and LightUp [58] is used for learning concepts of electronics such as circuit boards, magnets, and plastic sheets.

By combining modern mobile AR technology and pedagogical inquiry activities, Chang et al. [59] used AR for teaching Nuclear Power Plant activities with more productive digital visualization. Adding more to learning electronics concepts, ElectARmanual [60] and an AR-based flipped learning system [61] helped to achieve better learning outcomes by using the AR guiding mechanism.

Collaboration within an AR environment is an important AR learning scenario as outlined in Section 5.8. In keeping with the Chemistry theme, one example of a tangible interaction study that focused on chemistry was conducted using a Tangible User Interface (TUI) called Augmented Chemistry (AC) which reported higher user acceptance by interacting with the 3D models in the lab [62]. The tangible user interface could be one area that helps collaborative

learning, but the nature of tangible interaction can require additional resources, and in the current COVID crises, alternative touchless interaction approaches could be a better solution to this, which will be discussed in Section 6.1 and further in Section 6.5 with a Chemistry-related case study. Other prominent examples of collaboration using Situated Multimedia Arts Learning Lab (SMALLab) found extensive evidence as a powerful approach to learn in a design experiment with secondary earth science students [63]. There is also the collaboration ability of AR and Internet of Things (IoTs) to create productivity in Engineering education with different scenarios [64]. Finally, AR as a learning tool in the mathematics tested with Construct 3D [65] and GeoAR [66] to support learning the geometry showed a highly positive impact concerning its educational potential.

Field trips are one example of STEM scenarios that require leaving the formal learning environment to suit the outdoor AR use case mentioned in Section 2.3. Embodied experiences at the field trips for the science classrooms with situated simulations obtained valuable and effective results about student engagement and their connection with the experiential learning from the curriculum [67].

This potential for kinesthetic learning or hands-on learning by performing tasks (discussed more in Section 6.2) has been adopted for AR technical training for people to learn new maintenance and assembly skills for various industries [68]. For a trainee, interaction with real-world objects and machinery parts while obtaining the virtual information for learning is the actual advantage of using AR for training.

#### 4.4. Language and Vocabulary Learning

The use of AR for learning languages is concerned with the formal classroom learning in Section 2.1, which has been tested successfully in different studies. The use of AR flashcards for learning about the English alphabet and animals [69] and an AR-based game for Kanji learning [70] reported AR as a tool of motivation and visual presentation to learning languages. To test the ubiquitous games in the learning approach for language learning, HELLO (Handheld English Language Learning Organization) [71] and another handheld language learning approach [72] showed improved retention of words, which increased student satisfaction and attention [73]. Similarly, TeachAR using kinect [74] is used for teaching basic English words (colors, shapes, and prepositions) and game-based foreign language learning [75]. The use of Microsoft HoloLens for vocabulary learning, as compared with traditional flashcard-based learning, produced higher productivity and effectiveness in learning outcomes [76].

For language learning at higher classes, a mobile learning tool Explorez [77] used interacting with objects to improve their French language skills which received acceptance as “useful” and “motivating for students”.

#### 4.5. Collaborative Learning

The collaborative learning approach, as defined in Section 2.4, provides an opportunity of collaboration: either teacher-to-student or student-to-student. AR as collaborative learning [78] with SMALLab, which is a Student-Centered Learning Environment (SCLE) that uses interactive digital media in a multimodal sensing framework, reported promising results in social and collaboration aspects. Furthermore, in the collaborative learning approach, ref. [79] used 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 communicate between instructors and students by sharing written class materials.

An AR game concept, “Locatory”, was introduced by combining a game logic with collaborative gameplay and personalized mobile AR visualization, which provides different perspectives of the interactive 3D visualization to learn the content with AR and identify positive experiences [80]. LookingGlass and HoloLens between students and teachers to collaborate is adopted in METAL [81] where users can share 3D content between devices. Further identified collaboration opportunities are discussed in Section 5.8, and there is a recommended approach in Section 6.6.

#### 4.6. Environment and History Learning

Taking AR to location-based learning for environment and history as outlined in Section 2.3 has proved many successful results. A study of learning environment [82] and location-based experiments [83] reported the use of an AR learning engagement factor by providing virtual media over the top of the physical environment. Gurjot Singh et al. developed an inquiry-based learning application CI-Spy that seeks to engage the students in history using an AR environment [84]. 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 an interactive game-based test [85]. 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 [86]. Once it recognizes an image, the related scene is rendered over the video frame as a learning object. By considering the goals of learning achievement and attitude, EARLS promotes a positive learning attitude among students over Keyboard/Mouse-based Computer-Assisted Instruction (KMCAI) approach [11].

#### 4.7. Special Education

AR learning in special education, as defined in the Section 2.2, can increase the learning gain by enhancing the representation of content. To explore AR learning in special education, Luna et al. [87] created 3D Learning Objects using AR for an online learning program that is working for ADHD (Attention Deficit Hyperactivity Disorder)-affected students. It was further developed as an AHA project in the extended study as a Web-based AR learning system [88]. Their evaluation study highlighted the potential of AR for interactive learning and allowing users to become more engaged with learning content [89]. In addition, it provides opportunities for educational engagement and process reiteration for learners.

#### 4.8. MOOC (Massive Open Online Courses)

MOOC (Massive Open Online Courses), as shown in Section 2.3, facilitate learning outside the classrooms. Its importance has been increased recently due to the remote learning adoption throughout the world in the emergency due to the pandemic. The use of AR in the MOOC has been taken into account to generate interactive and extra appealing online content, which helped to create more productivity by improving visualization, supporting individualism, and enlightening the interest factor [90,91]. MOOC as a remote learning environment can lack the hands-on approach of other learning approaches.

#### 4.9. Technical Training

AR has been taken as a learning tool in skill-based training. In general, technical training, the concept of kinesthetic learning is important for hands-on learning. For example, the integration of Intelligent Tutoring Systems (ITS) involves training users about how to assemble components on a computer motherboard, including identifying individual components and installing them on the motherboard [92]. This approach of adaptive guidance helped an intelligent AR system show faster performance than an AR training system without intelligent support.

Joanne Yip et al. [93] used AR for a technical training workshop to perform the threading task, which facilitated better learning and helped to improve students' learning experience and understanding of the complex concepts. In Section 6.2, this concept was taken into account along with a focus on adding intelligence in the technical skills learning and doing more with a hands-on approach in a resource-constrained environment. These training experiences also require the introduction of Authoring Tools to allow for the rapid development of customized experiences, which are further discussed in Section 6.

#### 4.10. Authoring Tools

The need for authoring tools is the more important work in AR learning, which still has open opportunities. There is very little work on authoring tools in AR [94]. In an immersive AR authoring tool, allowing users to create AR content was an excellent approach to addressing the need for authoring tools [95]. It reduces the workload for the teacher in creating and managing AR learning experiences. This can be directly aided by the introduction of different forms of artificial intelligence; one such approach is discussed in Section 6.3, and the background to this work will be discussed in the next section.

#### 4.11. Multi-Agent Systems

In both use cases, Sections 2.1 and 2.3, incorporating the agents can play a significant role. The concept of using interacting intelligent agents in AR can bring more productive results. The use of self-directed animated agents in the AR such as AR Puppet [96], validated in AR Lego, helped in the autonomous decisions based on their perception of the real environment. A multi-agent system (SRA agent) approach helped to increase the motivation, using the principle of “learn by doing” or kinesthetic learning [97].

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 with learning by playing [98]. The initial study showed that children were involved actively with the projected character during a math exercise.

FenAR is an AR system following the Problem-Based Learning (PBL) approach [99]. 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 [100] examined the aspects of perceived enjoyment in the students’ acceptance of an Augmented Reality Teaching Platform (ARTP) developed using Augmented Reality in School Environments (ARiSE) [101] with test cases in biology and chemistry. This research found perceived usefulness and ease of use as extrinsic and perceived enjoyment as intrinsic for this news learning environment. This paper has recommendation an implementation of machine learning agents in Section 6.3.

Table 1 shows details of AR learning studies according to their research objectives, educational levels, interaction capacity, collaboration capacity, and agency. Subs. means subjects, participants of the specific study. Studies those have no evaluations are mentioned as (-). Collab. means collaboration capacity. The user interaction (UI) is categorized as Low, Medium, and High; Low means only placing the 3D objects in the real environment, and High means a higher interaction such as a hand interaction or gestures. It has been divided based on simple marker-based interaction to real-time touchless hand interaction. These findings are further visualized in Figure 3.



**Table 1.** AR studies with their status of domain, education level, libraries, display devices, user interaction, collaboration capacity and agents.

Project	Research Objective	Education Level	Subs.	Display Devices	UI Level	Collab.	Agent
EARLS (2012) [11]	Kinesthetic learning activities guided by AR gestures	University	1211	Desktop	Medium	Yes	No
ARGarden (2008) [24]	Learning about environment using ARToolKit	Primary	-	Smartphone	Medium	No	Yes
Magical- Playbook (2013) [27]	Storybook with AR book	Secondary	3	Smartphone	Low	No	No
Toys++ (2010) [26]	Physical object tracking and labeling	Primary	-	Laptop	Low	No	No
ARLIS (2012) [29]	Use of agent for library instructions in AR	Elementary	116	Desktop	Medium	No	Yes
AIBLE (2014) [28]	Astronomy concepts learning using AR markers	Elementary	69	Laptop	Medium	No	No
AR picture book (2014) [30]	Picture book for learning behavioral patterns and cognitive attainment	Secondary	33	Smartphone	Low	No	No
MARIE (2002) [31]	AR for engineering concepts with 3D object placement on trained markers	University	-	HMDs	Medium	No	Yes
miBook (2009) [32]	AR storytelling using markers and audios	Primary	5	Desktop	Medium	No	Yes
ARIES (2013) [33]	Learning chemistry with 3D model placement on markers	Secondary	42	Desktop	Medium	No	No
AR Creative- builder (2015) [34]	Enabling students with adding three models for chemistry learning	Secondary	33	Desktop	Low	No	No
SESL (2011) [35]	AR books for learning in early classes	Primary	-	Desktop	Low	No	No
AR-infused robot (2015) [36]	AR robotic interaction using markers attached to body	Primary	81	Desktop	Low	Yes	No
CMAR (2016) [37]	Learning science topics using AR animation	Elementary	71	Tablets	Medium	No	No
ARChemist (2020) [39]	Chemistry learning using markers	University	2	Tablets	Medium	No	No
CHE- MOTION (2017) [40]	Leapmotion hand tracking for Chemistry learning	Secondary	16	Desktop	Medium	No	No
AR Solar System (2002) [41]	Sun–Earth relationship learning in solar system	University	30	HMDs	Low	No	No
Earth-Moon System (2019) [42]	Learning astronomy using three-dimensional models	Secondary	35	Tablet	Medium	No	No

Table 1. Cont.

Project	Research Objective	Education Level	Subs.	Display Devices	UI Level	Collab.	Agent
LSS (2010) [43]	Learning about solar system by rotating multi-target markers	Secondary	30	HMDs	Medium	No	No
MEteor (2016) [44]	Astronomy learning with motion tracking system	Elementary	113	CAVE	High	Yes	No
Protein ScanAR (2012) [45]	Use of AR marker with FLARToolkitfor for Biology learning with object placement	Secondary	16	Web AR	Low	No	Yes
SCeTGo (2010) [46]	Marker-based 3D object placement for learning science	Secondary	-	Desktop	Low	No	No
Carmen's Anatomy Learning (2008) [47]	Learning interior of human body Anatomy using ARToolkit	Primary	40	Desktop, HMDs	Medium	No	No
Barrow, John (2019) [48]	Learning human anatomy with vuforia marker-based tracking	University	90	Tablets	low	No	No
MIRRACLE (2012) [49]	Human anatomy learning with Kinect gestures	Secondary	-	Desktop	High	No	No
Ma, Meng et al. (2016) [50]	Anatomy learning using Kinect body Tracking	University	72	Desktop	Medium	No	No
REFLECT (2019) [52]	Using Microsoft Kinect gestures to learn human anatomy	University	288	Desktop	Medium	No	No
Nainggolan et al. (2016) [53]	Learning human skeleton models using leapmotion hand tracking	University	30	Desktop	High	No	No
Umeda, Ryosuke et al. (2017) [54]	Using Leapmotion hand tracking for interactive anatomy learning	University	2	Desktop	Medium	No	No
ARIFLite (2004) [55]	Using Web3D for learning mechanical parts in AR	University	-	Web AR	Medium	No	No
LPP (2012) [57]	Learning Physics with simulated experiments using markers & Kinect	University	43	Desktop	Medium	Yes	No
LightUp (2013) [58]	Simple electronic kits learning using AR	University	12	Smartphone, Tablets	Medium	No	No
SSI on Nuclear Energy 2013 [59]	Learning about nuclear reactor phenomenon using AR simulation	Secondary	22	Tablets	Medium	No	No
Elect ARmanual (2015) [60]	Use of AR for practical manual for electronics using remote instructions	University	50	Web AR	Medium	No	No
AR-Flipped Learning (2018) [61]	Physics learning activities at early school	Primary	111	Smartphone, Tablet	Medium	No	No

Table 1. Cont.

Project	Research Objective	Education Level	Subs.	Display Devices	UI Level	Collab.	Agent
Augmented Chem. (2002) [62]	Learning chemistry with simple markers	Secondary	0	Desktop	Medium	No	No
GeoAR (2012) [66]	Geometry learning with marker-based object placement and virtual buttons	Elementary	6	Desktop	Low	No	No
Opera2222 (2015) [67]	Using simulations for teaching about historical places	Secondary	2	Smartphone	Low	No	No
AR Flashcards (2017) [69]	Use of AR Flashcards for language learning	Primary	42	Tablets/ iPads	Low	No	No
Kanji learning (2003) [70]	Collaborative Kanji Learning using ARToolKit	Secondary	-	PDA	Low	Yes	No
HELLO (2010) [71]	Using agents in AR for language learning	Elementary	64	Smartphone	Medium	Yes	Yes
Handheld AR system (2016) [72]	Vocabulary learning using markers placement on physical objects	University	45	Tablets	Low	No	No
Scaravetti et al. (2019) [102]	Mechanical design	University	59	Tablet	Medium	No	No
TeachAR (2016) [74]	English learning using object placement and speech recognition with Kinect	Primary	4	Desktop	Low	No	No
Erman et al. (2018) [75]	Use of Kinect tracking for language learning	University	62	Desktop	Medium	No	No
ARbis Pictus (2018) [76]	AR for tracking objects and labeling physical objects to learn vocabulary	University	52	HMDs	Low	No	No
Explorez (2015) [77]	Language learning using situated gaming with GPS	University	11	Smartphone	Medium	No	No
SMALLab (2006) [78]	Student–instructor interactive learning using audio sensing	Secondary	-	Desktop	Medium	Yes	No
ARClass- Note (2017) [79]	Collaborate between students and teachers using notes	Secondary	-	HMDs	Low	Yes	No
Locatory (2011) [80]	Location-based educational gaming using GPS	Secondary	3	Smartphone	Low	No	No
METAL (2021) [81]	Anatomy learning using LookingGlass with Azure Kinect and Hololens	University	10	Looking Glass,HMD	High	Yes	No
Inquiry-based learning (2014) [82]	Environmental learning using GPS situation learning scenarios	Elementary	57	Smartphone	Low	No	No
EcoMOBILE (2013) [83]	Situated learning about environment using GPS and FreshAir App	Elementary	71	Smartphone	Medium	Yes	No

Table 1. Cont.

Project	Research Objective	Education Level	Subs.	Display Devices	UI Level	Collab.	Agent
CI-Spy (2015) [84]	Learning about Historical places using AR labels and GPS	Primary	16	Tablet/Smartphone	Medium	No	No
AR marine learning (2015) [85]	Marine science topics learning using AR projector	Secondary	51	Laptop	Medium	No	No
iARBook (2014) [86]	Immersive learning using audio instructions and object placement	University	30	Tablets/Smartphone	Low	No	No
AHA (2018) [88]	Vocabulary learning for ADHD affected students with audio and animated object placement	Primary	117	Web AR	Low	No	No
MAT (2015) [92]	Learning motherboard assembly using marker-based intelligent Agent	University	16	HMDs	High	No	Yes
AR Sewing Video (2019) [93]	Providing AR tutorial for sewing as workshop	Technical	46	Smartphone	Low	No	No
Immersive Authoring (2014) [95]	Authoring tool for storytelling	University	142	Desktop	Low	No	No
AR Lego (2004) [96]	Use of a virtual agent as guider in AR for assembling tasks	Primary	-	Desktop	Medium	No	Yes
SaCI (2017) [97]	Discovery-based learning using SRA agent, GPS and AR marker	University	100	Smartphone	High	No	Yes
Kid Space (2018) [98]	Early age math learning with an external agent	Primary	16	Desktop	Medium	No	Yes
FenAR (2019) [99]	Use of virtual buttons and markers for teaching science subjects	Elementary	91	Smartphone, Tablet	Medium	No	No
ARTP (2010) [100]	Teacher student collaborative concept in AR	Elementary	7	Desktop	Low	Yes	No
ARiSE (2006) [101]	Learning cultural history with remote collaborations between players	Secondary	-	PC, PDA	Low	Yes	No
ALE (2010) [103]	AR game-based learning	Secondary	188	Desktop	Medium	Yes	No
LearnHeart (2015) [104]	Learning heart anatomy with ARToolkit with Flex SDK	University	3	Web AR	Low	No	No
ARVR Microscope (2020) [105]	Virtual microscope for Biology experiments using marker tracking	Secondary	-	Smartphone	Medium	No	No
HoloYolo (2021) [106]	Use of machine learning algorithms for markerless navigation in surgery	University	-	HMD	Low	No	Yes

Table 1. Cont.

Project	Research Objective	Education Level	Subs.	Display Devices	UI Level	Collab.	Agent
IWB (2022) [107]	Leapmotion hand gestures with interactive white-board	Primary	20	Desktop	High	No	No
IVALA (2021) [108]	Learning cardiac anatomy	University	36	Tablets	Medium	No	No
Save the planet (2021) [109]	Minigames for storytelling	Primary	50	Smartphone	Medium	No	No
Daineko et al. (2019) [110]	Using hand tracking with leapmotion for learning Physics	University	-	Desktop	Medium	No	No
ARBOOK (2015) [111]	Basic anatomy learning using 3D model placement on markers	Secondary	211	Desktop	Low	No	No
Construct 3D (2000) [112]	Collaborative learning geometry with 3D models	Secondary	14	HMDs	Medium	Yes	No
AR English Learning (2014) [113]	Learning English vocabulary using pictures as markers	Secondary	122	Smartphone	Low	No	No
Hong-Quan et al. (2017) [114]	Geometry learning with leapmotion hand tracking	Secondary	27	Desktop	Medium	No	No
GeoGebra 3-D (2021) [115]	Geometry learning with GeoGebra 3-D	Secondary	72	Desktop	Low	No	No

	User Interaction Level			Collaboration	Agents	Educational Level
	Low	Medium	High			
FenAR 2019		+		No	No	Early Education
AHA 2018	+					
AIBLE 2014		+				
AR English Learning 2014	+					
AR Flashcards 2017	+					
AR picture book 2014	+					
ARTP 2006	+					
Carmen's Anatomy Lear.. 2008		+				
CI-Spy 2015		+				
CMAR 2016		+				
GeoAR 2012	+					
Inquirey based Learning 2014	+					
Magical Playbook 2013	+					
SESL 2011	+					
SMART 2008	+					
Toys++ 2010	+					
AR-infused robot system 2015	+			Yes		
EcoMOBILE 2013		+		No	Yes	Secondary Education
SMALLab 2006		+				
AR Lego 2004		+				
ARGarden 2008		+				
ARLIS 2012		+				
Kid Space 2018		+				
MEteor 2016			+			
miBook 2009		+				
HELLO 2010		+				
AR Creative-builder 2015	+					
AR marine learning 2015			+			
ARBOOK 2015	+					
ARIES 2013		+				
Augmented Chemistry 2002		+				
Live Solar System (LSS) 2010		+				
Locatory 2011	+					
MIRRACLE 2012			+			
Opera2222 2015	+					
Science Center To Go (S.. 2010	+					
SSI on nuclear energy 2013		+				
STEM Lessons 2012		+				
ALE framework 2010		+				
AR based Kanji learning 2003	+			Yes		
ARClassNote 2017	+					
Construct 3D 2000		+				
ARISE 2006	+			No	Yes	University
ProteinScanAR 2012	+					
AR Sewing Video 2019	+					
AR Solar System 2002	+					
ARbis Pictus 2018	+					
ARIFLite 2004		+				
Augmented Instructions 2005	+					
ElectARmanual 2015	+					
Explorez 2015		+				
Handheld AR system 2016	+					
iARBook 2014	+					
Immersive AR authoring.. 2014	+					
LearnHeart 2015		+				
LightUp 2013		+				
REFLECT 2019		+				
EARLS 2012		+		Yes		
LPP 2012		+				
MARIE 2002		+				
Motherboard Assembly .. 2015			+	No	Yes	
SaCI 2017			+			

Figure 3. Graphics representation of different AR applications according to their user interaction capacity, collaboration capacity, agents and educational level.

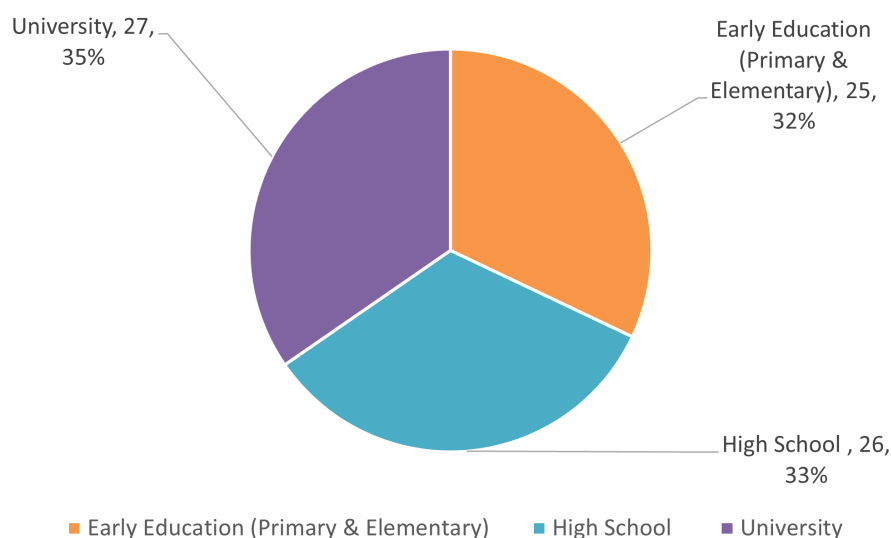
## 5. Main Insights and Future Research Agenda

Examining current and past projects based on educational level, domain, tracking, collaboration capacity, agents, and interaction level leads naturally to identifying specific future research areas. The AR application design requirements suggested in [116] include being flexible of the content that the teacher can adapt according to the children's needs, guiding in the exploration to maximize the learning opportunities, in a limited time, and attention to curriculum needs.

This analysis involves 25 studies from primary and elementary levels, 26 from secondary school levels, and 27 from university levels. In devices-based analysis, a desktop is used in 49% and tablets/smartphones, HMDs, laptops, and WebAR are used in 25%, 18%, and 8%, respectively.

### 5.1. Education Level

The analysis shows that AR has been tested and proved equally effective at three educational levels: early (Primary and Elementary School), secondary (High School) and tertiary education (University) presented in Section 4. Furthermore, there is a trend toward AR use in medical education [117]; however, there is a lack of focus on technical or vocational evaluation [93]) of its use in teaching. Figure 4 explains distribution based on educational level.



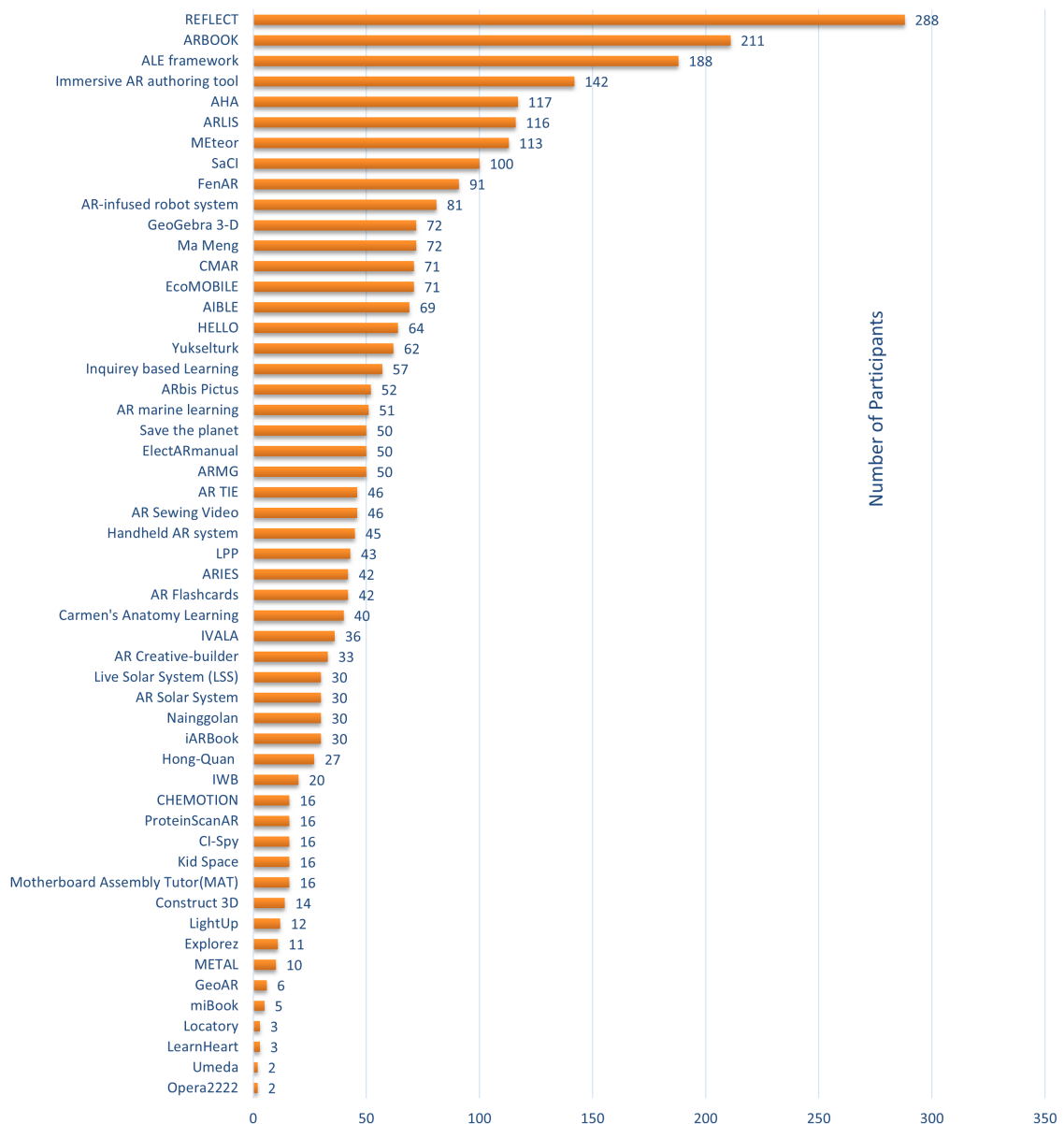
**Figure 4.** AR studies distribution according to educational level.

### 5.2. Domain

At early level education (Primary and Elementary schools), most of the studies are using AR for alphabet learning such as [69], vocabulary learning, or early level science topics as [28]. At the secondary level (High School) and tertiary level (University), it has been used as a learning enhancement source for STEM subjects, as discussed in Section 4.3. STEM has emerging future opportunities in the immersive learning technology. To teach those topics or skill training where actual material is not affordable or not possible in the class setting, the use of AR technology can be an effective resource for students.

### 5.3. Experiments Conducted to Evaluate AR Education

Most of the large-scale studies have conducted experiments using the control group and experiment group. The focus of the studies is to seek to increase students' attention, become more relevant to the study topics, and gain confidence and satisfaction compared to the traditional learning resources. Some studies are evaluated at a large scale just like EARLS [11]. Figure 5 shows the visual explanation of the scale of the experiments used in the evaluation of different studies (excluding EARLS in the graph as an outlier).



**Figure 5.** AR studies analysis according to the scale of experiments (Participants).

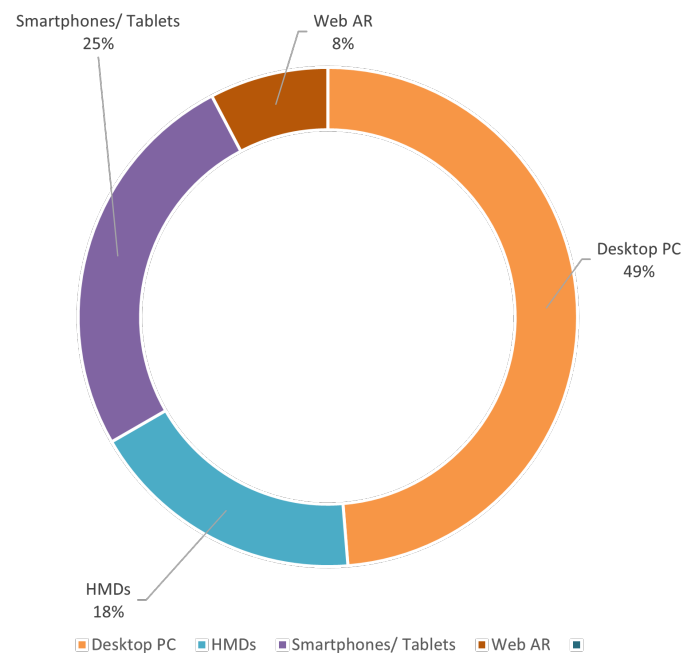
#### 5.4. Libraries Used

GPS has been used in location-based learning applications. Vuforia is used as tracking SDK for most of the studies just like [86]. ARKit, ARCore, ARFoundation, MRTK, and AR.js are the other main libraries used for tracking. These are compatible with a new series of high-end devices. There are lots of custom-made solutions used as well.

#### 5.5. Devices

In the previous studies, desktop PCs have been used as a major device for AR applications followed by smartphones and HMDs [92]. With the saturation, now, tablets and smartphones are achieving higher adoption rates due to their portability. Specifically, in Section 4.3, there is a higher possibility of using a smartphone due to the availability of personal devices. Figure 6 explain distribution based on devices.





**Figure 6.** Distribution of display devices used in AR educational applications.

Smartphones and tablets are the most reliable devices for AR in education due to affordability, as the cost of good HMDs is much higher versus smartphones. The legacy desktop is moving more toward smartphones and HMDs such as Magic Leap and Hololens. In Section 6, recommendations will be presented using two exemplar case studies; one using a desktop and the other using a smartphone.

### 5.6. Tracking

Most of the studies have used markers for tracking, which are implemented with Vuforia such as in [86], and recent studies started using markerless tracking with ARCore or ARKit (moved to plane tracking) in AR application, which allows the users to use the application without a specified marker. However, the use of markers is still important in situations that require high accuracy and some form of tangible interaction with virtual objects. Studies involving location-based learning are using GPS-like field trips study [67]. For devices not supported by ARCore, ARFoundation with ARCore XR Plugin is adopted to achieve a similar experience. This is important, as AR conducted in the classroom (Section 2.1 requires good lightning conditions, which are not always possible. Some studies focused on the hand-tracking technology to use gestures with Leapmotion and full body with Kinect; these are presented further with recommendations in the Section 6.

### 5.7. User Interaction

There are very few studies in AR learning which are using hand tracking and gesture control functionality. User interaction has a vast opportunity for applications in the future. The use of Kinect for anatomy learning is a great example of it [51]. There are opportunities to discover new forms of interaction, gesture versus real-time hand interaction (adopted in Section 6), and possibilities of tactile learning. Leapmotion technology is not widely explored yet in AR learning applications. Recent innovation in the machine vision-based hand tracking technology in smartphones [118,119] is also a very recent opportunity to explore, which is still going through testing stages to achieve stability.

### 5.8. Collaboration

There is still no significant focus on collaboration between students and teachers in an AR learning setting in the previous studies. However, it is a crucial aspect of AR learning,

as outlined in Section 2.4. Furthermore, both formal and outside classroom environments can be enhanced by collaborative learning.

Few studies have attempted collaborative learning, such as interactive simulation for learning astronomy [44], HELLO [71], EARLS by [11], ARClassNote [79] and METAL [81]. This area will be a critical future research area and will be discussed in the future research direction section, as collaboration is an important need for remote learning. There is a need for collaborative learning in the remote learning setup where the teacher can have access to students and students can collaborate in between. This approach is further addressed in Section 6.6.

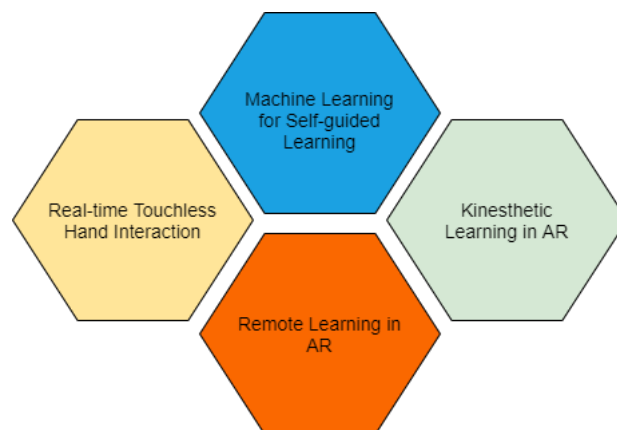
### 5.9. Agents

From all of the above studies discussed, there are only a few that have considered agents (as shown in Figure 3); these are presented in Section 4.11 such as Kid Space [98,99] for problem-based learning. Machine Learning Unity Agents are pretty new and have not been effectively implemented in any AR studies for education, as discussed in detail in Section 6.3. Experiments are required to demonstrate this logical next step in developing AR learning applications where agents can enhance the learning process and hence outcomes.

## 6. Highlighting Future Directions Using Prototype Case Studies

Based on the visual presentation in Figure 3, which shows an evident lack of “High” level interaction and “Agency”, this section will focus on highlighting future directions by the creation of prototype case study applications that can illustrate the research gaps that need to be addressed. These research gaps derived from Section 5.3 though to Section 5.9 include how to approach real-time touchless hand interaction, kinesthetic learning, machine learning agents, and remote learning components in the AR for learning applications.

The recent health crisis influences the choice to illustrate these research gaps due to the COVID-19 pandemic, which has caused educational disruption and forced people to re-think traditional e-learning approaches and innovate new ways. This research has taken four components into further investigation as presented in Figure 7.



**Figure 7.** Four core components of a future research approach in this area.







The worldwide adoption of the *Suspending Classroom without Suspending Learning* policy [120] has created a rush toward the learning technologies and mainly focuses on learning within the personal space. Furthermore, the virus spread through touching created demand for touchless or contactless technologies, which is essential in digital transformation, including AR educational applications. Therefore, the future of this research tends more toward finding new types of user interfaces, integration of agents to create more productive learning contexts, and new formats of learning pedagogies.

### 6.1. Real-Time Touchless Hand Interaction (Avoid Touching Devices)

In previous studies, the interaction in AR has been tested such as tracking markers, voice and gestures [74] and some other case studies presented in the Section 4.3, but there is no research about real-time hand interaction, which can help to implement the practical kinesthetic learning approach. These research gaps tie into our Section 5.8 discussions of the future direction of tracking and Section 5.9 on user interaction. In touchless hand interaction, there is nothing to hold in your hands, no buttons to push, no need for a mouse, keyboard, or touch on the display screen. It is all with the help of a depth sensor camera, motion sensor camera, infrared technology, and machine learning algorithms that help to interact with the digital elements.

Research studies use Kinect 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 the vocabulary learning approach [76]. Kinect and Leapmotion are working only with desktop systems, and HoloLens is too costly to afford as a personalized learning solution. The current shift of the learning spaces is moving toward more personalized, affordable, and portable, so smartphones can be the topmost priority for learning technology. The recent development of the Google Mediapipe by [121] and Manomotion for hand tracking in smartphones has opened new opportunities for touchless interaction technologies on affordable devices. Touchless interaction by hand-tracking technology is of two types: interacting with gestures and real-time hand interaction with virtual objects.

Figure 8 shows the different options of touchless interaction APIs and devices, which are providing the gesture-based interaction ability to the user for interaction in an augmented environment. This demonstrates the current state of the art about devices which was discussed previously in Section 5.7.

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

**Figure 8.** Devices/APIs used in AR for interaction to allow hand tracking and gestures.

### 6.2. Kinesthetic Learning

Kinesthetic learning is a form of learning which allows the user to “learn by doing the task” [122] instead of reading, listening, or watching. Specifically, in the STEM subjects, this learning approach is required to help students with learning the concepts, as the distance learning mode has many challenges for both learners and instructors. This is especially for learners during COVID, where access to hands-on experiences is sometimes not possible

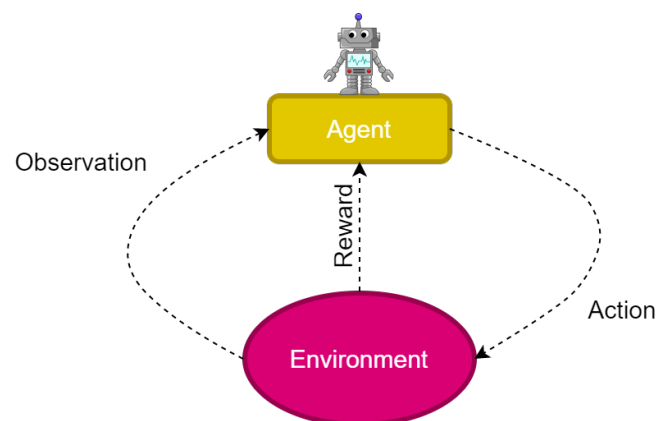
due to social distancing requirements. When considering remote learning for technical and scientific topics, the use of hands-on work is preferred for acquiring better knowledge; a kinesthetic learning approach with touchless hand interaction can bring this power in AR learning. It can add a positive impact on learning and skills acquisition when integrated effectively. To proceed with the kinesthetic learning approach, there is a need of real-time hand interaction with the 3D objects.

### 6.3. Machine Learning Agents for Self-Guided Learning

The changing imperative of the current learning state is moving toward independent learning or self-guided learning. Machine learning and artificial intelligence play a significant role in achieving this goal in e-learning solutions by taking a new role as a frontier. As discussed in Section 5.9, machine learning agents can transform the future of learning if implemented in the AR application intelligently. In addition, artificial intelligence and human interaction can play a role by utilizing the collected data. To integrate the machine learning agents in the proposed research, there are two possible use cases which are taken into account:

- End User Trainer
- Self-Assessment

This research has taken machine learning agents to work in unity, which is following the reinforcement learning concept as explained in Figure 9.



**Figure 9.** Process flow of machine learning agent in the AR application, following the reinforcement learning.

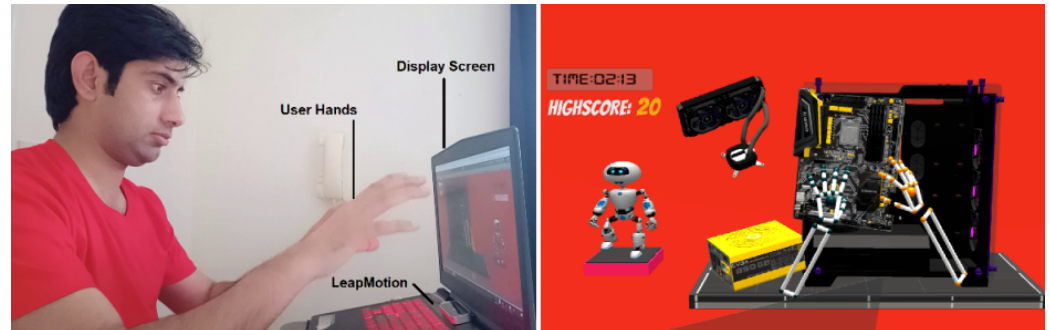
### 6.4. First Case Study—Learning PC Assembling

By considering the recommendations made in Section 6, a practical approach is adopted for the implementation of this concept. This first case study focuses on learning PC assembling for high school students as a part of necessary computer science education. A motherboard assembly learning case study [92] is presented in Section 4, which added an interaction hand to interact with the virtual PC, thus allowing hands-on learning in the virtual environment). The technical components are the unity 3D Engine, Unity machine learning agents (ML-agents), Leapmotion hand-tracking SDK, Leapmotion device, hand interaction SDK, and 3D models.

In Figure 10, a demonstration shows touchless hand interaction on the desktop PC using the Leapmotion device. It is a PC assembly learning case study using a kinesthetic learning approach by allowing the user to do PC assembling tasks with the 3D PC parts using the Leapmotion hand tracking.

Using real-time hand interaction and practicing the “learning by doing” approach, this study is developed for a Windows desktop PC, as the Leapmotion device is incompatible with android devices. The role of the virtual robot present in Figure 10 is defined as an engaging factor by providing different gestures to complete tasks by the user. The ML-agents are used to train the Neural Network (NN) model, which is integrated into the

application later as a user trainer based on the pre-trainer models; secondly, it helps in the self-assessment in the testing phase when the user himself is interacting with the system to virtually disassemble the PC.



**Figure 10.** Touchless hand interaction for learning PC assembly using Leapmotion hand tracking.

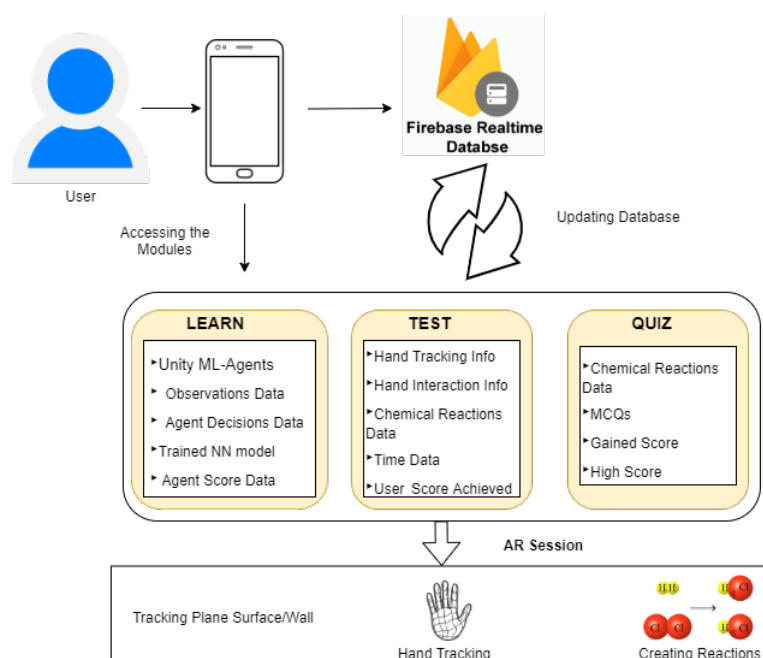
### 6.5. Second Case Study—Learning Chemical Reactions

Moving away from the desktop environment and HMDs with hand tracking in smartphones is a long-awaited technology that is now possible with Google Mediapipe and Manomotion using the neural network and machine learning algorithms. This concept from the virtual chemistry lab is influenced by the second case study, which is influenced by [62] and the STEM-related case studies presented in Section 4.7. Moving the display device from a desktop to a smartphone, this case study was implemented using the latest interventions in the vision-based SDK *Manomotion* with ARFoundation and ARCore XR Plugin. Manomotion provides real-time 2D and 3D hand tracking without using any external hardware with the smartphone with minimal computing power. The architecture diagram and process of learning flow have been explained in Figure 11.

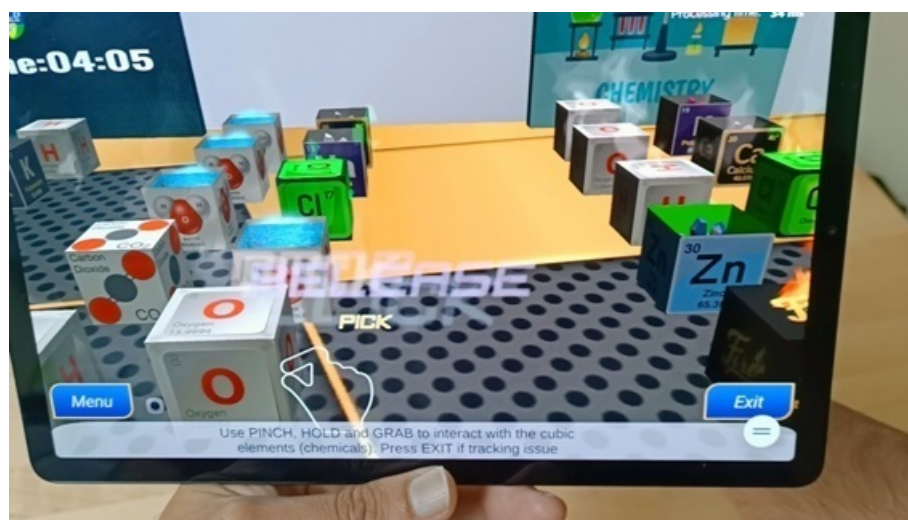
Figure 12 shows the hand tracking in smartphones and touchless hand interaction, which allows the user to create chemical reactions by interacting with cubic elements. Using the depth camera, custom-made hand, and collaborating with defined gestures of Manomation, it allows the implementation real-time hand interaction with the virtual objects (chemicals/elements). Real-time hand interaction is natural and is a great solution for a health-centric digital interaction. In this case study, machine learning agents are used to implement the user trainer and self-assessment learning scenarios following the flow explained in Figure 9.

The ML agent has been taken as a trainer for users by following previously trained models that help users learn the chemical reactions and then create the same reactions in the next module, where agents help in self-assessment. For training agents, data of user hand interaction with the models and success in creating reactions have been taken as behavior collections and rewards assigning. The trained Neural Network (NN) models are integrated into the AR application in Unity, which works as a trainer module for users before learning by interacting with 3D objects.

As explained in Figure 11, users will start with the LEARN module, where machine learning agents will help users learn to create chemical reactions using the previously trained NN model. In the next step, the process moves into the TEST module, where hand tracking is enabled using Manomotion technology and allows users to create chemical reactions using hand interaction. After completing the TEST module, the user enters the QUIZ module, which has all assessment-related MCQs that complete a learning cycle from assisted learning to hands-on learning and assessment.



**Figure 11.** Architecture diagram and working flow of recommended approach in second case study.



**Figure 12.** Touchless hand interaction for learning chemical reactions using hand tracking (real-time hand interaction) in smartphones.

### 6.6. Empowering Remote Learning in AR

The landscape of education has dramatically changed since the COVID-19 pandemic started, which provided a directional shift toward blended learning. Through AR applications, learning becomes dynamic and user-centered. All of the previous studies in AR were implemented in the context of the classroom environment. Still, it has not been explored in the personal devices outside the classroom with an organized system such as ARETE [123]. The shift of the current learning scenario has created a need to implement new types of learning pedagogies using the collaboration factor, as mentioned in Section 6.7. In addition, the concept of remote learning has been adopted by integrating the Firebase database. In Section 6.5, it is developed for smartphones and involves remote user authentication and post-test learning assessment integrated with a Google Firebase database which helps to control and access the learning outcome of the users.

This approach allows for the conducting of a remote evaluation, as explained in [124] in VR applications for skill training. This design would start to address the research

gap highlighted in Section 5.3. This application can be extended as a collaboration and authoring tool between the students and instructor, and it further allows for large-scale remote evaluation with 100s if not 1000s 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' [125].

#### 6.7. Limitations

The main limitations of the study are that it is not following a systematic review approach because intelligent agents and kinesthetic learning using hand-tracking technology is not widely adopted yet. Hence, this study aims to consider only those AR studies presenting some new ideas in interaction and enhancing learning capacity. Secondly, we are not using "Mixed Reality" (Only "Augmented Reality") as a keyword to find the research items because this study is specifically planned for AR only.

AR 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, which is needed for personalized and hands-on learning in resource-constraint environments for learning STEM subjects. There are very few studies that have performed evaluations at a large scale [11]. Despite the listed advantages, certain drawbacks should be considered when building educational solutions with AR: Some teachers may not be able to put these new technologies into practice due to a lack of necessary skills. There is a need for instructors willing to engage with new technologies and educational institutions to adapt their infrastructure with applications of AR in the classroom. Hardware availability is a limitation to consider for the uptake of AR in schools. Still, it is time for governments and policymakers to consider the investment in AR devices, given their long-term impact on knowledge retention and students' enhanced engagement with educational content and activities.

### 7. Conclusions

From STEM to foreign language learning, immersive technologies have proven to be effective and result-oriented tools in creating more interactive learning environments. In particular, AR 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 AR contents with the same quality on all devices.

The next logical step in AR-based learning discovered from reviewing the current literature is the development of applications that can enable personalized learning materials for both students and teachers. Future technology challenges are user acceptance, proving its educational effect, and further development of the frameworks to develop these innovative applications. As the cost of hardware and software decreases, AR technology will become more affordable, thus allowing it to be widespread at all educational levels. Based on the previous studies and current progress in technology, it can be said that AR can produce supportive results in the education of STEM subjects to reduce the cognitive load in learning. Virtual lab-based practical learning, where augmented objects can fill the need for physical material, allows the user to "learn by doing" where learning material in physical shape is unavailable.

The investigated future research areas have been further demonstrated in two STEM-related case studies, which will be further advanced in future work and evaluated in terms of usability. The use of hand interaction technology combined with kinesthetic learning pedagogy can be integrated with multi-sensory haptic feedback to facilitate our effects for realism and enter into the metaverse as a collaborative learning approach.

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