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Universidad del País Vasco
Euskal Herriko Unibertsitatea

Computer Languages and Systems Department

A Novel Architecture for Collaborative Augmented Reality Experiences for Education

by:
Stefano Masneri

Supervised by:
Dr. Ana Arruarte
&
Dr. Mikel Zorrilla

Donostia – San Sebastián, Sunday 17th December, 2023

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A papà, che è andato avanti troppo presto

Abstract

In recent years, thanks to the availability of powerful mobile devices, the release of specialized libraries and the shrinking cost of head mounted displays, the number of Augmented Reality applications has grown exponentially. Initially deployed for manufacturing applications, Augmented Reality is now used in many other fields, among others gaming and entertainment, cultural heritage, customer engagement, and education.

Focusing on education, Augmented Reality has a huge potential to revolutionise the sector. Even though learning applications based on Augmented Reality already exist, their creation is complex and they are mainly intended for individual usage. The lack of tools for synchronizing Augmented Reality experiences across several users, the issues related to the adaptation of the augmented content on different devices, the difficulty of incorporating applications into the learning management systems used in schools have, so far, limited the adoption of Augmented Reality in classroom settings.

To address these issues, this research presents *cleAR* (Collaborative Learning Environment for Augmented Reality), a novel architecture that enables the development of interoperable and collaborative Augmented Reality applications. The architecture has been designed taking into accounts both technical and educational aspects. In fact, several teachers from Basque primary and secondary schools helped in the definition of the architecture requirements. *cleAR* is a modular architecture which also provides teachers tools for analysing the data about usage of Augmented Reality applications as well as the students results. Furthermore, since *cleAR* relies on open standards, it can in principle be easily integrated with the schools data collection systems.

To evaluate the architecture design, a multiplatform, collaborative Augmented Reality application has been developed and tested in three educational institutions. The evaluation included collecting survey responses from the students who participated in the trials, interviewing their teachers and performing a quantitative analysis of the data collected through the application.

This work has been done in the context of the ARETE project - Augmented Reality Interactive Educational System, a H2020 EU-funded research project which aimed to investigate and define novel tools for collaborative Augmented Reality applications.

Acknowledgements

While the cover lists only my name as author, this work would not have been possible without the contributions of many people who helped a lot over the last four years.

First and foremost, many thanks to Ana Arruarte and Mikel Zorrilla, my Ph.D. supervisors, for their support, guidance and involvement. Mikel Larrañaga did not have an official role, but he has been acting since the start as the third supervisor and has greatly helped me.

I would also like to thank my former Vicomtech colleagues, who contributed to this work even after I left the company and without any obligation to do so. Ana Domínguez has been invaluable in this sense and my Ph.D. would not have been half as good without her contributions and support. She mentioned once that she hoped to help me as much as I helped her during her Ph.D, but she went far beyond that. Iñigo Tamayo and Guillermo Pacho developed most of the code and helped greatly in the validation of the architecture. Without their help *cleAR* and *ARoundTheWorld* would probably exist only in my head. The rest of the Vicomtech team helped and supported a lot, especially Roberto Viola, Dorleta García, Álvaro Gabilondo and Miguel Sanz.

The Ikastolen Elkartea association played a key role by helping me get in touch with many teachers. The teachers filled in the survey and their answer enabled us to define the requirements of the architecture. Furthermore, they provided important feedback in many phases of the development process. Later, Nahia Ugarte, Pello Bereziartua and Ana Domínguez (again!) allowed testing and validating the application with their students. This work would not have been possible without the input from the teachers, so I am especially grateful for their willingness to help.

The ARETE consortium, after a rough start, was invaluable in providing many interesting discussions and even better social events. The project gave me the opportunity to start working in the field of Augmented Reality applied to education, to learn many new things and to meet amazing professionals.

Many colleagues at NTT DATA, especially Julián González and Diego Rodríguez, gave me their feedback for all the data analysis tasks and they were willing to help whenever I pestered them.

Last but not least, I want to thank Itxaso. She helped and encouraged me throughout the ups and downs of this journey, and she offered her unwavering support during the many evenings and weekends I spent working on my Ph.D. I would not have been able to accomplish this feat without her by my side.

Thank you all.

Stefano Masneri

December 2023

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List of Acronyms

ADHD Attention-Deficit/hyperactivity Disorder

AI Artificial Intelligence

API Application Programming Interface

AR Augmented Reality

ARGBL Augmented Reality Game-Based Learning

ASD Autism Spectrum Disorder

CV Computer Vision

DBMS Database Management System

DL Deep Learning

DO Design Objective

EAI Edge Artificial Intelligence

HMD Head-Mounted Display

IMU Inertial Measurement Unit

ITS Intelligent Tutoring System

LAD Learning Analytics Dashboard

LMS Learning Management System

LRS Learning Record Store

ML Machine Learning

OLM Open Learner Model

PBIS Positive Behaviour Intervention And Support

PoC Proof-Of-Concept

PoV Point Of View

RQ Research Question

SDK Standard Development Kit

SLR Systematic Literature Review

SME Small And Medium-Sized Enterprise

STEM Science, Technology, Engineering And Mathematics

TEL Technology Enhanced Learning

UI User Interface

UX User EXperience

VLA Visual Learning Analytics

VR Virtual Reality

xAPI EXperience API

XR Extended Reality

Part I

Introduction

CHAPTER 1

Scope of the Research

This initial Chapter introduces the dissertation by providing an introduction of the research work. It provides an initial overview and presents the motivation behind the work, as well as the defined objectives, hypotheses, and the methodology employed. The purpose is to set the stage for an in-depth exploration in the subsequent Chapters. It also includes a Section detailing the structure of this document.

1.1 Overview

Augmented Reality (AR) is a technology which overlays virtual 3D objects or other content in the real world, with the aim of providing a sense of Mixed Reality (Azuma 1997). Another widely used definition is from Milgram and Kishino (1994) where, in a continuum ranging from a purely virtual environment to a completely real one, AR is positioned close to the real environment and the users perceive the real world with an additional layer of virtuality. This technology was originally used as an aid tool for assembly workers at Boeing by showing them virtual labels through the use of custom made glasses (Caudell and Mizell 1992). Since then, AR has quickly attracted research and industry attention in many different areas such as gaming and entertainment (Das et al. 2017), cultural heritage (Vlachos et al. 2022), customer engagement (McLean and Wilson 2019), manufacturing (Ong et al. 2008) or education (Garzón et al. 2019).

Despite the appeal and clear advantages provided by AR, the widespread adoption of devices that support the technology, and the availability of software libraries such as ARKit[1] or ARCore[2] which simplify the development process; AR adoption rate is still low (Jalo et al. 2022). In most cases, AR applications must be created ad-hoc and cannot be used in different settings. It is not uncommon that technologies considered mature do not achieve widespread usage or, once commercialised, fail to attract interest for the public. One example is that of 3D TV, which suffered from the lack of content and has disappeared from the market. Other technologies, such as artificial neural networks, where initially deployed in commercial application more than 30 years ago (LeCun et al. 1989) but only in the last decade have reached ubiquitous diffusion. It happened thanks to improvements in hardware and software as well as the availability of massive amount of data. This led to the possibility of training models which surpassed the state of the art.

AR is currently at a turning point: the technology has already reached maturity and is actively being promoted both by hardware producers (Apple is the latest big player who released its AR headset[3]) and software companies. This seems to suggest that the low adoption of AR is not due to a lack of software solutions enabling the creation of apps, nor to the availability of hardware devices supporting such solutions. The lack of widely accepted standards for the technology and the difficulties of creating portable solutions may be factors affecting the diffusion and acceptance of AR for the general public, but it is of interest to investigate if there are deeper reasons behind the limited availability of AR applications, especially for education (Commission et al. 2023).

Unfortunately, AR has not yet seen widespread usage in education, and most studies evaluating AR in schools so far are based on small experiments. Despite this, AR applications have found a valuable role in training and education: several companies offer educational AR apps and many scientific publications have shown that AR can enhance and improve the learning experience (Akçayır and Akçayır 2017, Buchner et al. 2022, Christopoulos et al. 2022, Garzón et al. 2019, Garzón and Acevedo 2019, Garzón et al. 2020, Huang et al. 2016, Khan et al. 2019, Kristoffer B. Borgen and Weldon 2021, Sahin and Yilmaz 2020, Theodoropoulos and Lepouras 2021). The ability to attach virtual

[1] `https://developers.google.com/ar/`
[2] `https://developer.apple.com/documentation/arkit/`
[3] `https://www.apple.com/apple-vision-pro/`

content to any physical surface (through the usage of markers, by performing plane detection or using geographical information) makes AR applications a valuable tool for training and education. In the context of this research work the focus is on the area of education, specifically on the use of AR in schools, in particular for primary and secondary education.

The main reasons behind the lack of real integration of AR in education, described in more detail in Chapter 3, can be summarised as the difficulty developers and educators have in creating content that can be used by every student and that integrates well with the existing school curricula. The majority of AR applications available for education provide single-user experiences and they are more apt to be consumed at home rather than at school. In addition, since most of the existing AR applications are not multi-user, they do not allow students to cooperate. Cooperative learning, defined as the instructional use of small groups to promote students working together to maximise their own and each other's learning (Johnson 1991), has long been used as an educational approach to improve students' learning and performance (Johnson and Johnson 2019, Kuh et al. 2011).

AR applications for education, and Technology Enhanced Learning (TEL) in general, can also collect data related to usage statistics and students performance. The data should be leveraged by the teachers (through dashboards and visualization, for example) to easily assess the work of the students and their progress. In most cases, though, the data is not accessible. Additionally, the data collected could be used to train Artificial Intelligence (AI) models that could help predict which students are at risk of failing, or cluster them into different groups.

Another issue limiting the adoption of AR in schools is the integration of AR applications within existing school programs. Existing applications cannot be easily adapted to specific school curricula, and the data generated inside the apps (*e.g.*, test results or lesson progress) are not automatically added to a Learning Management System (LMS), thus creating additional workload for teachers. Educational AR applications should ideally use open standard for data collection and storage, to simplify their integration into the school LMS.

This research work therefore aims to investigate how to promote the usage of AR in the classroom through the creation of interactive, multi-user and collaborative mechanisms for AR solutions. This is achieved by closely collaborating with teachers and schools associations, that provided the background information about what is required to successfully adopt this technology in educational environment. The proposed solution should offer a software framework, and it must also consider various factors to encourage the development of an ecosystem. This ecosystem should simplify content personalization and facilitate integration with other applications used in education, allowing adoption regardless of the available hardware in schools.

1.2 Motivation

The work presented in this dissertation has been performed in the context of the project ARETE[4] (Masneri et al. 2020), which aimed to develop, integrate and disseminate interactive technology via AR tools. The project involved academic partners (universities and technological research institutions), small and medium-sized enterprises (SMEs) developing AR solutions for schools and children with learning disabilities, psychologists, educators and institutions connecting schools across all Europe. The consortium thus supported fast dissemination of AR content to a wide audience and allowed the participants to collect feedback from teachers, students and industrial partners. The overall scope of the ARETE project is defined around four main pillars:

- Develop and evaluate the effectiveness of an interactive AR content toolkit.
- Pilot and evaluate the effectiveness of AR interactive technologies.
- Apply human-centred interaction design for ARETE ecosystem.
- Communicate, disseminate and exploit the project result.

The author of this thesis contributed to this project while working at Vicomtech, whose role in the consortium was to contribute in the definition of the system, provide a set of libraries that can simplify and streamline the development of AR applications with a particular focus on interactivity and ease of use, and enable the collection of data that allows statistical analysis of how the applications developed were used during each pilot. In particular, Vicomtech led the development of *Orkestra*, a software library that offers multi-user support across different platforms, which in turn enables user to share

[4] `areteproject.eu`

their current state and send messages and updates with the low latency required in AR environments.

In addition to working with Vicomtech, this Ph.D. work was possible thanks to the affiliation with the GaLan group of the University of the Basque Country, UPV/EHU, a research group integrated into the consolidated ADIAN group. The group works in the field of educational informatics, and its objective is to enhance learning support systems from the perspectives of both teachers and students. For teachers, the group develops tools to aid and simplify course design processes, as well as tools for analyzing the learning process. For students, the group creates tools equipped with adaptation and visualization mechanisms to assist them in learning, reflecting, understanding, and improving their learning processes. The development of such tools involves various technologies derived from the fields of Artificial Intelligence and Information Systems, in addition to agile methodologies and experimental testing and evaluation mechanisms.

Finally, Ikastolen Elkartea and three educational institutions in San Sebastian (IES Xabier Zubiri Manteo, Salesianos Donostia Basque School and University of Deusto) also collaborated in this work. Ikastolen Elkartea, one of the primary and secondary schools association in the Basque Country, helped by organising a series of interviews with teachers as well as with the diffusion of a survey. This allowed the collection of the information that drove the development of the Ph.D. work. The educational institutions participated in the evaluation of the proposed solution. The help of the teachers and of the school association has been invaluable as it allowed bridging the gap between the developers and educators community. They helped in the definition of the architecture described in Chapter 3 as well as in the evaluation of the application presented in Chapter 4.

1.3 Objectives

The main objective of this work is to explore and propose innovative solutions which use AR in the educational sector, with a strong focus on collaborative, multi-user interactions. This can in turn provide researchers, educators and software developers with tools that simplify the creation and adoption of AR solutions in the classroom, without the need to modify existing school curricula or requiring specific hardware or software setups. Furthermore, the main objective can be decomposed into four more specific objectives:

- Objective 1: Identify the main causes behind the lack of adoption of AR solutions in schools, through the analysis of current research and by interviewing teachers who are familiar with information technology.
- Objective 2: Develop a software library which enables the creation of multi-user AR applications, where the users can share their experiences across different hardware – PCs, laptops, smartphones or Head-mounted Displays (HMDs) – and software – web browsers, iOS, Unity or Android apps –.
- Objective 3: Define a modular architecture that fulfills the requirements and design objectives for AR in education, as identified by working with primary and secondary school teachers as well as researchers with education and computer science background.
- Objective 4: Validate such architecture by creating a collaborative multi-platform AR application and testing it in a real world scenario, to demonstrate that it fulfills all the design objectives.

1.4 Hypothesis

The working hypothesis is constructed as a statement of the following expectations:

1. It is possible to enable low-latency communication and state sharing functionalities to AR-based applications across a variety of devices and operating systems.
2. AR applications supporting all the identified capabilities should be developed just once and compiled for all the required platforms.
3. AR applications may include data collection capabilities that can be used to perform advanced visualization or for training machine learning models, as well as being integrated into existing LMSs.
4. Existing AR standards can be leveraged to enhance portability and enable easy customisation of the applications.

These mentioned expectations involve different stakeholders:

1. **Students**: They are the end users and the ones who will spend the most time using the applications. In an educational context, it is paramount to provide them with the capabilities to collaborate and interact with their peers or their teachers, either in a face-to-face or remote scenario.

2. **Teachers**: Teachers have the role of introducing students to the usage of AR and, in order to use AR beyond short-lived experiments, they need to be able to incorporate it into other existing TEL systems used at school, as well as keep track of the progress of each student and identify potential learning problems.

3. **Software developers**: The creation of AR applications is often a very time-consuming task and usually requires developers knowledge of different fields such as 3D geometry, computer vision and User Interface (UI) design and User eXperience (UX) requirements in 3D environments. Simplifying and streamlining the development process is extremely important in every project involving AR content.

4. **Researchers**: Since there is limited data available about the analysis and effects of AR applications in education with large amount of students, it is important to provide researchers with all the data collected during the study, as well as open source all the software developed to enable replication and the possibility to extend the current work.

1.5 Methodology

The research performed in this Ph.D. has followed a methodology consisting of two converging lines, whose work culminated in the definition of the *cleAR* architecture and the evaluation in schools of *ARoundTheWorld*, the application used to validated the design objectives defined.

The first line of work relates to the understanding of the problem domain. This involved an in-depth analysis of the literature and, more importantly, discussing with teachers the limitations of current AR solutions and what was needed to encourage its use in their schools. The interactions with teachers were performed several times across the duration of the Ph.D. work. The initial contact was with Ikastolen Elkartea, a Basque association of primary and secondary school teachers. Through the association it was possible to set-up interviews with teachers. The association also helped in the preparation and diffusion of a questionnaire that was filled by more than 40 teachers. Their answers helped greatly in the definition of the requirements and design objectives of *cleAR*.

The other line of work is related to the software developed throughout the Ph.D. work. Since the focus was on research rather than in the creation of a product, the methodology followed in this case was that of fast prototyping development. Each new iteration of the software produced was tested via the creation of simple prototypes, which could be more easily validated and could provide early feedback about strengths and weaknesses of the solution proposed. This approach allowed first the creation of *Orkestra*, a JavaScript library for collaborative web-based applications, and then to extend it to other platforms, improve its performance and use it in AR scenarios.

Finally, the two work lines converged once the development of *ARoundTheWorld* was completed. The application was evaluated in three different schools, thanks to the participation of both teachers and students. Each student filled a questionnaire after testing the application, while the teachers provided feedback through post-study interviews.

1.6 Document structure

This dissertation is structured as follows. Part I is composed by this chapter and presents an introduction to the research scope, focusing on the motivation for the research, the main objectives, the hypothesis, the methodology and the main contributions of the Ph.D. work.

Part II, composed of Chapter 2, describes the literature related to AR applications used in education, with a special focus on publications describing interactive, multi-user and collaborative applications.

In Part III the research results are described in two main chapters:

- Chapter 3 describes *Orkestra*, the library that allows to easily implement multiplatform and multi-user capabilities in AR applications. It also includes the definition of *cleAR*, the architecture that enables the creation of collaborative AR applications and the usage of the collected information for data analysis and predictive modelling.

- Chapter 4 describes the application implemented using the aforementioned architecture, and its evaluation and validation in three educational institutions. The evaluation was done by analysing the data collected from the app in the form of xAPI statements, as well as through user questionnaires filled by the students and post-intervention interviews with the teachers.

Part IV contains Chapter 5, which describes the main conclusions of the research, the contributions of this work and its related publications, as well as a discussion about future work.

Finally, Part V contains the bibliography while Part VI provides additional information in the form of an Appendix.

Part II

State of the Art

CHAPTER

2

Related Work

This Chapter presents a systematic review of the literature on the use of AR applications in primary and secondary schools, with a specific focus on collaborative, multi-user and interactive applications. It is based on a paper that included information up to the end of 2020 (Masneri et al. 2022b). The work is now updated with papers published as of September 2023. This study synthesises a set of 131 publications since 2015 and performs a qualitative analysis of their content. The review describes the current state-of-the-art of research in AR and presents the trends for the future of AR applications in educational settings, analysing the relevance of the multi-user interaction challenge within the augmented reality ecosystem.

2.1 Overview

Digital transformation is profoundly impacting and disrupting every facet of society, and education is no exception. In recent decades, AR has broken into the educational area. Nowadays, thanks to the widespread adoption of devices that support AR applications, as well as the availability of software libraries such as ARKit or ARCore which greatly simplify and speed-up the development process, AR has become a technology which is being more and more used in educational settings. Given its surge in popularity, AR has become an active research topic and several systematic studies have been performed to analyse how this technology has been used in educational contexts.

Some studies presented an analysis of the advantages and drawbacks of AR in generic educational settings (Akçayır and Akçayır 2017, Diegmann et al. 2015, Radu 2014) or have provided insights on the status of the technology, the availability of authoring tools as well as suggestions for future research (Arici et al. 2019, Bacca et al. 2014, Cheng and Tsai 2013, Dengel et al. 2022, Pellas et al. 2019). Other reviews have focused on specific subjects, such as Science, Technology, Engineering and Mathematics (STEM) (Ahmad and Junaini 2020, Ibáñez and Delgado-Kloos 2018, Nielsen et al. 2016, Sırakaya and Alsancak Sırakaya 2022) or language learning (Khoshnevisan and Le 2018, Majid and Salam 2021); on specific topics such as AR-based serious games (Bartolomé et al. 2011, Laine 2018, Li et al. 2017), the evaluation of the usage of AR in schools (Chen et al. 2017b, da Silva et al. 2019) or the impact of AR applications in learning effectiveness (Chang et al. 2022b, Garzón et al. 2019). Table 2.1 summarises the content of some of the most recent and comprehensive Systematic literature reviews (SLRs) about AR in educational settings.

Since the publication of the seminal paper on collaborative AR by Billinghurst and Kato (2002), which first discussed how AR could be used to enhance online and offline collaboration, much progress has been made in providing collaborative tools for AR applications. So far, the only study which explicitly evaluates the usage of collaborative AR applications for education is (Phon et al. 2014), which reviews publications on the subject from 2000 to 2013. In light of the numerous advancements in AR technology over the past few years, it is relevant to analyse the current literature about collaborative AR applications in education. This Chapter examines how AR apps function as tools for enhancing collaboration among students, as well as between students and teachers. Additionally, the review aims to explore how multi-user interfaces contribute to facilitate cooperation and learning.

Cooperative learning, defined as the instructional use of small groups to promote students working together to maximise their own and each other's learning (Johnson 1991), has long been used as an educational approach to improve the learning and performance of the students (Johnson and Johnson 2008, Kuh et al. 2011). Technology can help foster collaboration among students, but their engagement depends on how much they can interact with the different tools. AR *per se* is not a collaborative tool:

Table 2.1: *Summary of SLRs about usage of AR in education.*

Study	Purpose	Papers	Findings
Chang et al. (2022b)	Investigate the impact of using AR apps in education	134	AR showed a medium effect to promote students' positive responses to the learning experience, a medium to large effect to enhance students' knowledge and skill, and a nearly large effect to facilitate students' authentic performance
Avila-Garzon et al. (2021)	Bibliometric analysis of studies of AR in education from 1995 to 2020	3475	The number of publications on AR in education is increasing, and the field is gaining momentum; the current emerging and trending research topics in AR in education are special educational needs, Industry 4.0, storytelling, 3D printing, mobile applications, and higher education
Law and Heintz (2021b)	Analyse AR apps for education from a usability and UX perspective	49	There is a disconnect between HCI and TEL communities; there are no AR-specific UX evaluation methods; the learner age seems not a significant factor in determining the perceived usability and UX or the learning effect of AR apps
Sırakaya and Alsancak Sırakaya (2022)	Advantages and challenges of using AR for STEM education	42	Use of AR in STEM education supports the learning and teaching process; there are not enough studies to test the effect of AR according to individual students characteristics

it is up to researchers and developers to provide such functionalities in an AR-based educational application. The objective of this Chapter is to evaluate which publications described AR applications providing the following features:

- *Levels of interactivity*: The app should respond to the user input and let the student modify the app content using different interaction methods (which will be described in detail in Section 2.3.2.
- *Multi-user functionalities*: More than one user at the same time can use the app and the actions of one user are directly reflected in the device of other users.
- *Collaboration*: Besides being multi-user, a collaborative app engages its users to collaborate or compete to reach a goal or complete a task.

Furthermore, how the usage of these applications affected the engagement of the students and their academic performance is described.

This Chapter provides an SLR of the AR applications deployed in primary and secondary schools, with a particular focus on the collaborative, multi-user and interactive characteristics of such applications. Only the articles published from 2015 to 2023 are considered, since in 2015 the number of publications related to the application of AR in education has seen a huge increase (as shown in Figure 2.1). Furthermore, only works with an audience comprised of primary or secondary students are included, since there are already several works which review the usage of AR in higher education, and because this study was conducted in the context of the ARETE H2020 European project, studying multi-user AR applications for primary and secondary schools.

The Research Questions (RQs) addressed are the following:

RQ1: What collaborative, multi-user, interactive AR applications have been used in an educational environment in primary or secondary schools?

RQ2: Is there a motivation for using these AR applications as an educational tool? If so, what is it?

RQ3: How effective are these AR applications at improving the knowledge of the students? How is this evaluated?

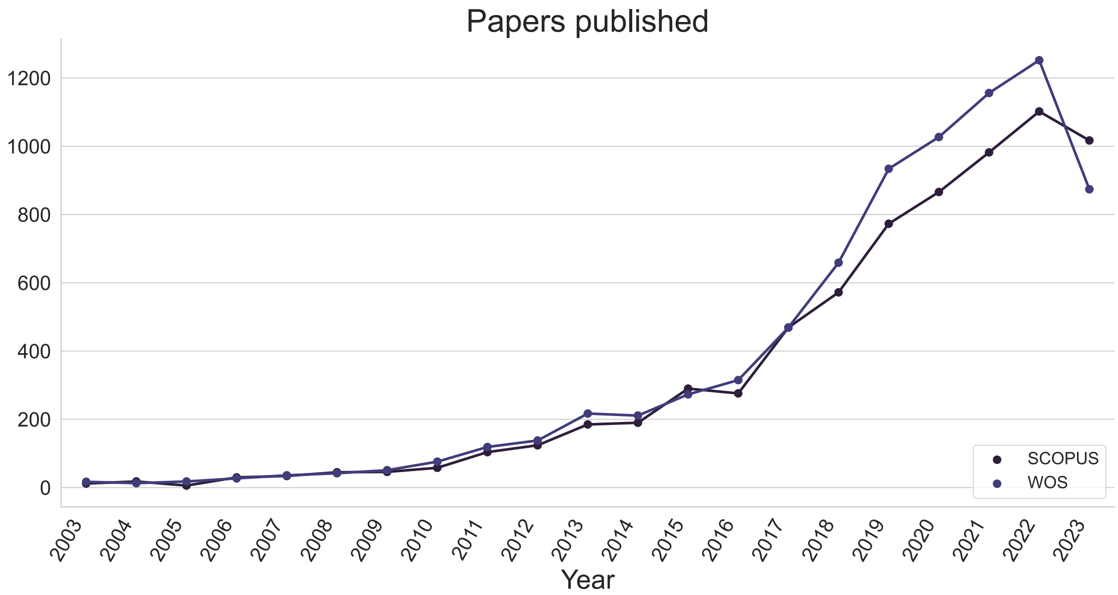

Figure 2.1: *Numbers of papers published per year with topic "augmented reality" and "education" from 2003 to 2023.*

The answers to these RQs will hopefully provide researchers information about the current landscape of how AR applications are used in primary and secondary schools, what the motivation is for it and what effects AR has on the learning and retention skills. Understanding the potential of interactive and collaborative AR, as well as its limitations and the factors limiting its usage in schools, can hopefully provide information on how future applications should be designed and developed.

Besides answering these research questions, the different technologies used by such applications will also be discussed. For example, the hardware required (HMD, tablet or smartphone), the way the system tracks information from the real world (marker-based, markerless, location-based), whether the application augments other senses beyond vision, and which design strategies (if any) have been used to make the applications accessible.

2.2 Methods

For this review, the guidelines proposed by Kitchenham et al. (2009) were followed and the search was framed using the PICOC criteria (Petticrew and Roberts 2008):

- **Population**: Applications, Developers.
- **Intervention**: Collaborative, multi-user and interactive AR applications.
- **Comparison**: The results of the students in classes which use AR applications with classes that do not.
- **Outcome**: Effectiveness in increasing understanding of a topic.
- **Context**: Education, primary or secondary schools.

Once the research questions have been defined, the literature review is split into three steps: planning, conducting and reporting. The Parsifal[1] online tool was used to conduct the first two steps of the review while the third was performed using Google Forms[2], to collect the results in a spreadsheet. The results of the data collection, as well as the code used to generate the figures in this document, are available on Github[3].

2.2.1 Study selection

The aim of this phase is to select the papers which are relevant for the systematic review, define the inclusion and exclusion criteria, and to provide the categories for the analysis. Publications were selected from IEEExplore, Scopus, Springer and ISI Web of Science, as these four digital libraries collect most of the research that is published in the area of technology enhanced learning. The search terms *Augmented Reality*, *Education* ∨ *Learning*, *Collaborative* ∨ *Interactive* ∨ *Multi-user*, *Application* ∨ *Evaluation* were used, with the aim to include only papers that could help address RQ1 and RQ3. For this work, only papers which appeared online from 2015 to the end of August 2023 were considered. The search returned 3070 results, of which 395 were marked as duplicates. The abstract of the remaining 2675 articles were read and, applying the inclusion and

[1] `parsif.al`
[2] `https://forms.gle/D7NHktgfaRmAeWTS8`
[3] `github.com/Stocastico/AR_SLR_Paper`

exclusion criteria specified below, 359 articles were left to read. Finally, after reading these articles 228 further documents were discarded, thus 131 studies were selected for the literature review. Table 2.2 summarises the selection process, specifying the search string used for each digital library as well as the number of papers returned, marked as duplicated and selected for the systematic review.

As inclusion criteria, the studies have the following requirements:

- Were published from 01/01/2015 to 31/08/2023.
- Describe an AR application which has actually been implemented.
- Have a target audience of primary and/or secondary school students.

The focus for selection is only on applications that were fully developed (and could then be evaluated). This decision was taken to limit the amount of studies to analyse, but led to the exclusion of other interesting articles such as the one from Osypova and Tatochenko (2021), which studies the AR features of GeoGebra[4], or (Tümler et al. 2022), which describes an approach to research on multi-user and multiplatform XR experiences.

The studies selected should also present interactive, multi-user or collaborative applications. This is because there is a broad amount of literature showing that students learn better when engaged with other children, or being involved in interactive activities compared with purely passive ones. Finally, the decision to limit the literature search to papers published after 2015 is to avoid including older publications, often using obsolete hardware with setups that cannot be reproduced easily. The exclusion criteria are the following:

- The application described is not interactive, multi-user or collaborative.
- The paper does not describe an AR application.
- The paper describes an unrelated application (e.g. for museums or clinical training).
- The paper is not peer reviewed.
- The paper is not written in English.

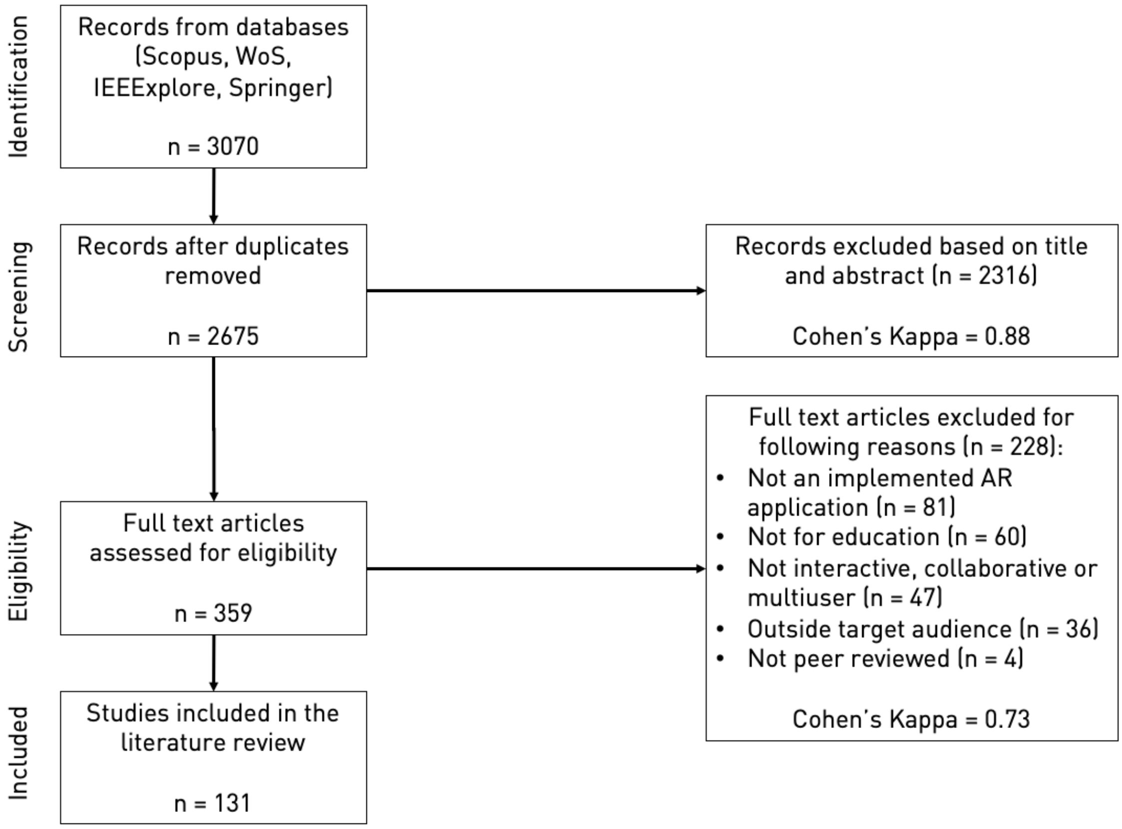

Figure 2.2: *Prisma flowchart of the search protocol.*

Figure 2.2 shows a flowchart depicting the systematic review process. The 359 papers were reviewed by 3 researchers. To compute the interrater agreement, two researchers read a set of 50 abstracts randomly selected from all the studies (excluding duplicates) and 10 papers (among the 359 eligible papers). The interrater agreement, as defined in Cohen (1960) was 0.88 for the abstracts and 0.73 for the papers. The values represent(McHugh 2012) an almost perfect agreement when selecting papers based on the abstract and a substancial agreement in the selection based on the whole text of the article. This indicates that the exclusion and selection criteria were defined in a clear, objective and replicable manner.

[4] `https://www.geogebra.org/`

Table 2.2: *Query strings and number of papers returned.*

Digital Library	Query string	Papers	Duplicates	Selected
IEEExplore	(“All Metadata”: “Augmented reality” AND (“Education” OR “Learning”) AND (“Collaborative” OR “Interactive” OR “multi-user” OR “multi-user”) AND (“Application” OR “Evaluation”)) Filters Applied: 2015 - 2023	286	52	**65**
Scopus	TITLE-ABS-KEY (“Augmented reality” AND (“Education” OR “Learning”) AND (“Interactive” OR “multi-user” OR “multiuser” OR “collaborative”) AND (“Application” OR “Evaluation”)) AND (PUBYEAR > 2014)	963	196	**118**
Springer	(collaborative OR interactive OR multiuser OR multi-user) AND “augmented reality” AND (education OR learning) AND (primary OR secondary) AND (application OR evaluation) within Chapter - Conference Paper 2015 - 2023	1289	88	**99**
Web of Science	“Augmented reality” AND (“Education” OR “Learning”) AND (“Collaborative” OR “Interactive” OR “multi-user” OR “multiuser”) AND (“Application” OR “Evaluation”) Filters Applied: 2015 - 2023	574	57	**77**

2.3 Results

In this Section, the results of the three RQs introduced in Section 2.1 are presented, focusing on the adoption of collaborative and multi-user tools, the advantages and disadvantages of using AR solutions in the classroom and the evaluation of the interventions. The Section briefly analyses and summarises the main characteristics of the AR applications described in the selected studies.

2.3.1 Overview of reviewed studies

Of 131 studies reviewed, most of them (104 articles) were published in 2018 or afterwards. The vast majority of the AR apps analysed (88) cover STEM subjects, while 24 studies cover Humanities and Foreign language subjects. The remaining articles cover specific subtopics such as sustainability, creativity and social interactions or do not specify the subject. Figure 2.3 summarises the subjects covered by the AR apps analysed in this SLR.

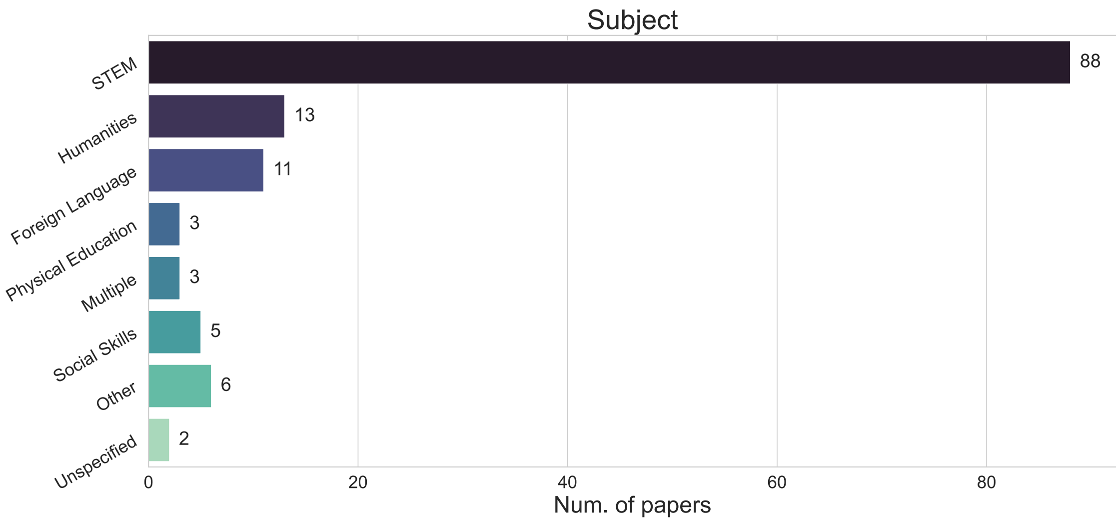

Figure 2.3: *Subjects covered in the studies analysed.*

Regarding which AR type is used in the classroom, marker-based solutions (either image or QR-code based) are the most used, as two thirds of the studies described apps using markers as the exclusive source of the augmentations. Some studies describe applications using multiple types of AR, usually a combination of markers and object detection based methods. Other types of AR such as markerless or location based are seldom implemented, as they were used only in 10 and 3 articles, respectively. Figure 2.4 summarises the types of AR used by the articles analysed in this SLR.

With reference to the hardware required to experience the AR apps and the software used to develop them a similar pattern can be inferred. Most of the studies describe apps which have been developed for smartphones or tablets using the Unity[5] framework,

[5] `unity.com/`

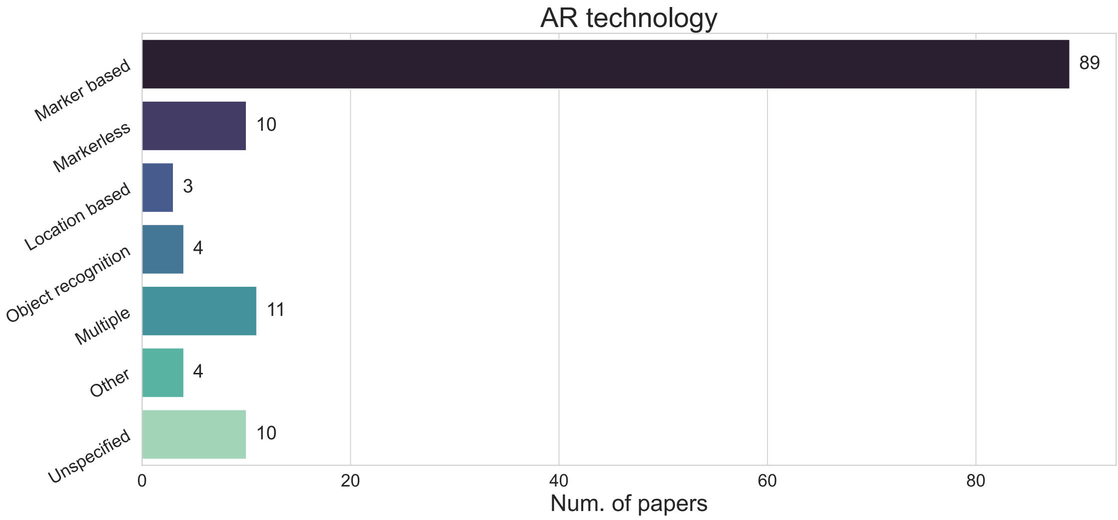

Figure 2.4: *Different types of AR used in the studies analysed.*

often in conjunction with the Vuforia[6] Standard Development Kit (SDK). Some studies, usually the oldest ones, describe systems using projectors or PCs with depth sensor cameras such as Microsoft Kinect[7]. Only 8 articles describe apps which require HMDs or smart glasses (Khan et al. 2018, Kum-Biocca et al. 2019, Matsutomo et al. 2017, Oh et al. 2016; 2017, Radu and Schneider 2022, Resnyansky et al. 2022, Wei et al. 2018). This might be due to the higher cost of such devices and their consequent limited adoption compared to smartphones or tablets.

Using web technologies for the creation of AR application is still the exception rather than the norm: despite the availability of a javascript library such as Three.js[8] and frameworks such as A-Frame[9], only Abriata (2020), Protopsaltis et al. (2016), Rodríguez et al. (2021) provide augmented content that can be consumed through the browser. Somewhat surprisingly, very few studies rely on the libraries produced by Google and Apple (ARCore and ARKit), which were developed to provide advanced AR functionalities for smartphone and tablets. A few studies (Acosta et al. 2020, Carlos-Chullo et al. 2021, Costa et al. 2021) have used ARCore in conjunction with Unity, but the current

[6]`developer.vuforia.com/`
[7]`developer.microsoft.com/en-us/windows/kinect/`
[8]`threejs.org`
[9]`a-frame.io`

trend still favours less powerful but easier to use libraries such as Vuforia. Usage of specialised Computer Vision (CV) libraries or Deep Learning (DL) frameworks is also very low, which probably means that researchers prefer to use the functionalities provided by Unity. Statistics about software usage may be skewed, though, as about one fourth of the studies did not provide information about it.

Figures 2.5 and 2.6 summarise the hardware required and the software used by the apps analysed in this SLR. The total in this case does not sum up to 131 since the same application could support more than one device and likewise it may have been developed using several software libraries.

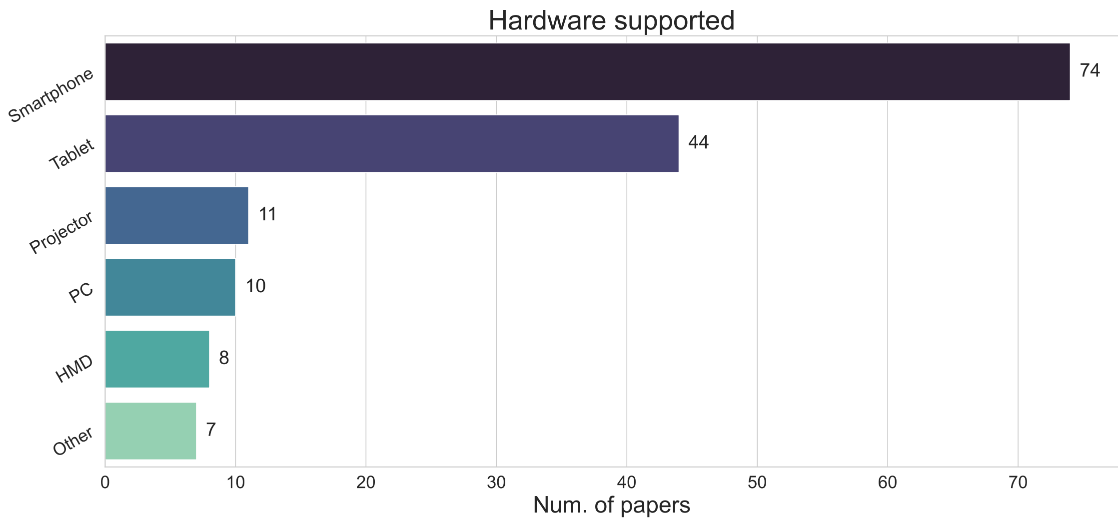

Figure 2.5: *Device types supported by the AR applications.*

Unfortunately, researchers very rarely publish their code alongside their peer reviewed publication. Of all the studies analysed, only Abriata (2020), Domínguez et al. (2022), Farella et al. (2022), Laviole et al. (2018), Manrique-Juan et al. (2017), Mylonas et al. (2019), Wellmann et al. (2022) publicly released the source code of their applications. In some cases, the researchers published the application for free on Google Play or the App Store. Although, in principle, this allows other researchers to test the application, without releasing the source code this is impractical, as very rarely the application can be used without some form of adaptation (for example, translation of the content, inclusion of new multimedia elements or adjustments to the school curricula).

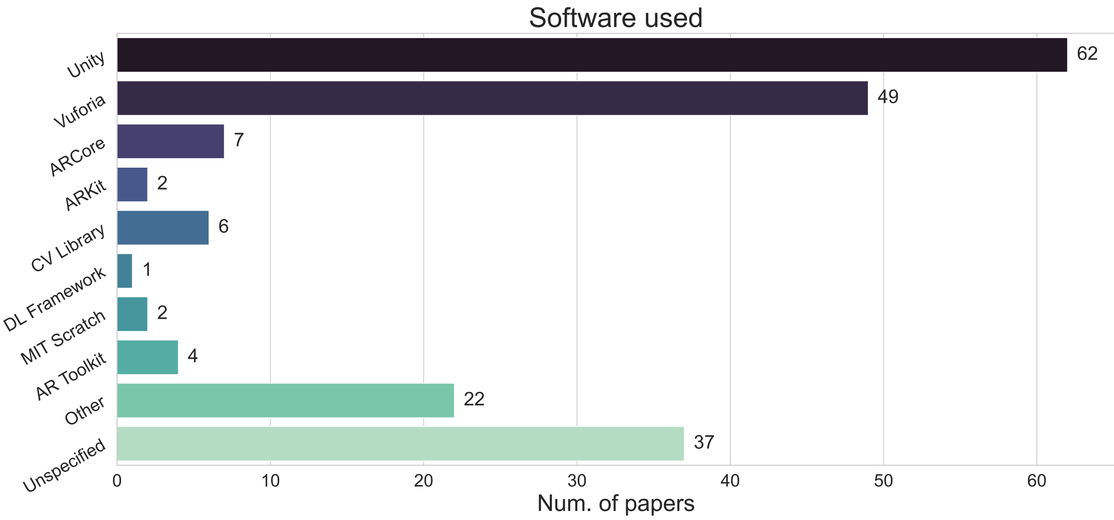

Figure 2.6: *Software used to develop AR applications.*

2.3.2 Interactive and collaborative capabilities of AR applications

This subsection addresses the first research question. Interactive, multi-user and collaborative capabilities of the AR apps described in the selected studies were analysed. The studies were categorized into five different clusters, based on how the applications provide interactive functionalities. The categories were chosen by analysing the common traits of each study, as well as considering the characteristics of interactive applications in the context of education (assessment, feedback to the teacher, quizzes) and of user interface elements that enable the interaction. The five interactivity levels were defined as follows:

- *Basic interactivity*: The student can interact with the app through UI elements such as menus and buttons directly in the augmented space.
- *Object interaction*: the student can interact directly with the augmented content, without having to use UI elements.
- *Quiz*: The application provides quizzes (or allows teachers to add new ones) to test the understanding of a topic directly within the app, or it includes gamification concepts.

- *Behaviour tracking*: The application keeps track of student behaviour and, using this information, the teacher can modify the content shown to the user. Both the active interactions (questions answered, buttons clicked) as well as passive usage of the app (time spent on each activity, for example) are logged and made available to the teacher so that the lecture can be modified accordingly.

- *Augmented interactions*: The augmented content shown to the user may change depending on the interactions of the user with the environment, for example when changing the relative positions of different markers, or by varying the distance of the device from the markers.

In addition to these, *multi-user* AR experiences were considered. In these applications multiple students can view the same augmented content from different devices and any change, for example caused by the interactions of one of the students, is visible to all the other students as well. Finally, *collaborative* AR applications are also of interest, that is applications where the students share a common goal and work together (or compete against each other) to reach it.

These applications are of particular interest because interactive learning environments have been shown to have a positive impact on the education of the students (Johnson et al. 2000). At the same time, collaborative learning offers the students several benefits at the social, psychological, academic and assessment level (Laal and Ghodsi 2012). In Table 2.3, the 131 articles reviewed were classified into the categories described above. Some of the studies can appear on multiple rows in the table, meaning that they may offer multiple interaction types as well as provide multi-user or collaboration functionalities. The works of Tscholl and Lindgren (2016) and Manrique-Juan et al. (2017) present collaborative application that were not categorised as multi-user, since only one device is shared by multiple students.

As it is impractical to provide a description of all the selected articles, a short description of the most interesting ones will be presented here. In Khan et al. (2018), the authors implemented a mixed reality system based on HoloLens[10] smart glasses and several stretch and Inertial Measurement Unit (IMU) sensors, where the users can control and move augmented objects using their arms or an ad-hoc controller. The

[10] `https://www.microsoft.com/en-us/hololens`

multi-user application is used to teach the students physics concepts such as force fields or velocity vectors, without needing to set up a laboratory. Some studies use multiple markers to increase interactivity. The work of Wang et al. (2018) uses AR to teach the double-slit experiment (a physics experiment demonstrating the characteristic of light being both a wave and a particle). In the application each marker is related to one part of the experimental apparatus. By modifying the distance of each marker from the next one, the augmented animation generated by the app changes its behaviour, visually showing the dual nature of light. A similar idea is implemented by Boonbrahm et al. (2015). In the app, which was created to facilitate learning English as a foreign language, each marker by itself only shows a letter in 3D. When multiple markers are combined to create an English word (from a predefined set), the app will show a 3D model of the corresponding word.

Table 2.3: *Articles classified according to interactivity and collaboration capabilities.*

Interaction type	Papers
Basic interactivity	Acosta et al. (2020), Adi Badiozaman et al. (2022), Ang and Lim (2019), Arcos et al. (2016), Buchner et al. (2021), Cao and Hou (2018), Carlos-Chullo et al. (2021), Cerqueira et al. (2018), Chang et al. (2019), Chang and Hwang (2018), Chao et al. (2018), Chen et al. (2016; 2019), Chen and Wang (2015), Costa et al. (2019), Cruzado et al. (2020), Debnath et al. (2021), Dobrovská and Vaněček (2021), El Kouzi et al. (2019), Estudante and Dietrich (2020), Hossain and Ahmed (2021), Hrishikesh and Nair (2016), Hsieh and Chen (2019), Hsu (2017), Huang et al. (2016; 2019), Khan et al. (2018), Klautke et al. (2018), Korosidou and Bratitsis (2019; 2021), Lai et al. (2015), Lee et al. (2018), Lin et al. (2019), Liou et al. (2017), Liu et al. (2020), Luna et al. (2018), Macariu et al. (2020), Mikułowski and Brzostek-Pawłowska (2020), Mylonas et al. (2019), Pasalidou and Fachantidis (2021), Pérez-Muñóz et al. (2020), Pombo and Marques (2017; 2018; 2019), Protopsaltis et al. (2016), Ramos and Comendador (2019), Resnyansky et al. (2022), Sarkar et al. (2018), Seel et al. (2022), Sharma et al. (2022), Sorrentino et al. (2015), Suzuki et al. (2020), Syahidi et al. (2020), Syamsudin et al. (2022), Tang et al. (2015), Theodoropoulou et al. (2020), Uriarte-Portillo et al. (2023), Wang (2017), Wei et al. (2019), Xia et al. (2022), Yilmaz and Goktas (2017), Yin et al. (2020), Yuhana et al. (2020), Yusof et al. (2020), Zhao et al. (2018)

Table 2.3: *Articles classified according to interactivity and collaboration capabilities.*

Interaction type	Papers
Object interaction	Amrit et al. (2015), Antoniou et al. (2017), Arcos et al. (2016), Boonbrahm et al. (2016), Cao and Liu (2019), Cárdenas-Delgado et al. (2021), Carlos-Chullo et al. (2020), Cen et al. (2019), Chen (2018), Costa et al. (2019; 2021), Domínguez et al. (2022), Farella et al. (2021; 2022), Ferrer et al. (2017), Gargrish et al. (2022), Giasiranis and Sofos (2017), Hsu et al. (2018), Ibáñez et al. (2020), Iqbal et al. (2019), Kenoui and Mehdi (2020), Kum-Biocca et al. (2019), Kurniawan et al. (2018), Laine and Suk (2016), Lee et al. (2019), Li et al. (2018), Logothetis et al. (2021), López-Faican and Jaen (2020), Lytridis et al. (2018), Mahmoudi et al. (2018), Manrique-Juan et al. (2017), Matsutomo et al. (2017), Nabila and Junaini (2021), Oh et al. (2016), Ortiz et al. (2018), Radu and Schneider (2022), Rammos and Bratitsis (2019), Rodríguez et al. (2021), Rusiñol et al. (2018), Suzuki et al. (2020), Swearingen and Swearingen (2021), Syahidi et al. (2020), Takahashi et al. (2018), Thamrongrat and Lai-Chong Law (2020), Thamrongrat and Law (2019), Theodoropoulou et al. (2020), Tscholl and Lindgren (2016), Wei et al. (2018), Wellmann et al. (2022), Zhong and Cui (2021)
Quiz or gamification	Bakar et al. (2021), Chang and Hwang (2018), Costa et al. (2019; 2021), Cruzado et al. (2020), Daineko et al. (2018), Dave et al. (2020), Domínguez et al. (2022), El Kouzi and McArthur (2021), Jumat and Su (2022), Lai et al. (2015), Laviole et al. (2018), Lee et al. (2019), Li et al. (2018), Limsukhawat et al. (2016), Lin et al. (2016), Macariu et al. (2020), Oh et al. (2017), Ortiz et al. (2018), Pombo and Marques (2019), Protopsaltis et al. (2016), Ramos and Comendador (2019), Thamrongrat and Lai-Chong Law (2020), Wei et al. (2018), Xefteris and Palaigeorgiou (2019)
Behaviour tracking	Cao and Hou (2018), Chang and Hwang (2018), Chen et al. (2016), Hsu et al. (2018), Mylonas et al. (2019), Protopsaltis et al. (2016)
Augmented interaction	Abriata (2020), Boonbrahm et al. (2015), Cai et al. (2017), Cárdenas-Delgado et al. (2021), Cen et al. (2019), Chao et al. (2018), Dave et al. (2020), El Kouzi and McArthur (2021), Ferrer et al. (2017), Gardeli and Vosinakis (2018), Gargrish et al. (2022), Kalpakis et al. (2018), Lam et al. (2020), Laviole et al. (2018), Logothetis et al. (2021), Macariu et al. (2020), Nasongkhla et al. (2019), Rodríguez et al. (2021), Theodoropoulou et al. (2020), Wang et al. (2018), Wellmann et al. (2022), Xefteris et al. (2018), Yilmaz and Goktas (2017)
Multi-user	Boonbrahm et al. (2016), Cai et al. (2017), Dave et al. (2020), Domínguez et al. (2022), Farella et al. (2022), Gardeli and Vosinakis (2018), Kum-Biocca et al. (2019), Laviole et al. (2018), Lee et al. (2018; 2019), López-Faican and Jaen (2020), Oh et al. (2016; 2017), Ortiz et al. (2018), Palaigeorgiou et al. (2018), Radu and Schneider (2022), Swearingen and Swearingen (2021), Takahashi et al. (2018), Triantafyllidou et al. (2017), Xefteris and Palaigeorgiou (2019), Xefteris et al. (2018)
Collaborative	Boonbrahm et al. (2016), Cai et al. (2017), Domínguez et al. (2022), Farella et al. (2022), Gardeli and Vosinakis (2018), Laviole et al. (2018), Lee et al. (2019), López-Faican and Jaen (2020), Manrique-Juan et al. (2017), Oh et al. (2016; 2017), Ortiz et al. (2018), Swearingen and Swearingen (2021), Takahashi et al. (2018), Tscholl and Lindgren (2016), Xefteris and Palaigeorgiou (2019)

In Gardeli and Vosinakis (2018), the students learn the basics of computer science by visually implementing algorithms. Each marker, besides showing augmented content, represents an instruction in ALGO, a specially developed programming language, and sequences of different markers generate different behaviour from the augmented content. Macariu et al. (2020), implemented an app for learning Chemistry that includes a text recognition module to provide information on specific Chemistry-related words, as well as 3D animations that show the molecule created when combining different atoms, with each atom using a specific marker. In Logothetis et al. (2021), the application implements hand-tracking technology that allows the students to directly modify the objects in the augmented space.

Only a few studies experiment with other senses beyond sight. The work of Kenoui and Mehdi (2020) uses the IBM Watson SDK[11] to allow the user to interact by asking questions in English, while the answer is shown both as text above the augmented content and as computer-generated audio. Mikułowski and Brzostek-Pawłowska (2020) designed a system for visually impaired students that detects mathematical formulas and generates both an audio description as well as a Braille representation on the Braille display.

In the context of multi-user applications, different studies employed different strategies to foster collaboration. Boonbrahm et al. (2016) describe an application where the users aim to solve a jigsaw puzzle. Since students cannot move two pieces in a row but are forced to alternate their moves, the puzzle can only be solved with a joint collaboration. In the work of Ortiz et al. (2018), the app is an Augmented Reality Game-based Learning (ARGBL) where the user learns about different regions of Colombia while competing for resources. In this case, competition with others stimulate the students to learn about the subject. Another form of collaboration is described by Oh et al. (2016): the authors created a HMD-based AR application where the user can study properties of light such as reflection and refraction. Each user acts as a light source and sees what happens when light hits a wall or passes through different materials. At the same time, two or more users can generate multiple light rays and see how they interact with each other. Using a projector system, users without smart glasses are able to share the same experience, although not as actively as users wearing them. Another multi-user application for learning about electromagnetism is presented in Radu and Schneider (2022), where multiple students can share the same experience in the augmented space.

[11] `www.ibm.com/cloud/watson-speech-to-text`

Some applications incorporate functionalities to enable users to add new content. In Costa et al. (2021), the AR application comes with a web application that allows to easily add new AR experiences, by specifying markers and their associate 3D objects. In Wellmann et al. (2022), the authors prepared a repository with detailed instructions for creating new AR content, even though this is done in the form of Jupyter notebooks and thus require Python knowledge from the content creators.

2.3.3 Motivation for using AR as an educational tool

This subsection addresses the second research question. While the studies reviewed do not usually motivate the choice of the particular application presented in the articles, they do present however, several advantages provided by AR in the classroom. The main advantage provided by AR is that it can integrate seamlessly with the real world, especially for markerless applications that can interact with objects or printed material already available in the classroom. This encourages student engagement and minimises the time required to learn how to use the technology, allowing the students to spend more time learning the subject, as shown by Thamrongrat and Law (2019). Another work by the same authors (Thamrongrat and Lai-Chong Law 2020) shows that using gamification concepts in AR significantly impacts the students results.

Another advantage provided by AR is that this technology does not require the existing curriculum to be remodeled, rather it can be used as a tool to stimulate interest or to supplement existing pedagogical materials by simply adding more contextual experiences. Pombo and Marques (2018) mention that using an AR app improves the engagement and interest of the students visiting an urban park by providing information that would otherwise be available only on textbooks.

AR is also a powerful tool for visualisation and animation, especially for STEM subjects, as it offers several advantages for displaying 3D or 3D+t information (i.e., three-dimensional data changing over time) in comparison to books, blackboards or videos. Cao and Liu (2019) describe an application for learning 3D geometry where the user can interact with 3D objects with their hands. The fingers are tracked with a Leap Motion Controller[12] while a set of markers are used to generate the augmented content. Suzuki et al. (2020) use advanced features provided by ARKit (such as joint detection) together with object tracking technologies to provide interactions and visualizations

[12] www.ultraleap.com/product/leap-motion-controller/

through sketches drawn on the device. In the context of collaborative and multi-user applications, AR similarly helps providing new opportunities for students to learn how to communicate and collaborate with one another, as well as to inspire empathy and to teach the importance of teamwork (Hill and Miller 2013).

Some of the reviewed studies used AR applications as radically new tools that could improve skills and grades of children with mental or developmental disabilities: Luna et al. (2018) describe an application that helps students with Attention-deficit/hyperactivity disorder (ADHD) improve their English literacy skills. Similarly, Chen et al. (2019) uses AR together with concepts maps to teach kids with Autism Spectrum Disorder (ASD) different types of social cues designed to help them when meeting people. Takahashi et al. (2018) designed a large scale AR and projection system, modifying the gymnasium of the school, to create a learning game for children with ASD, which intends to keep their attention focused on the content provided. Other studies, such as Domínguez et al. (2022), Farella et al. (2021; 2022) describe applications used in the context of Positive Behaviour Intervention and Support (PBIS), where the applications shows through examples and quizzes how to establish a positive student culture.

Beyoglu et al. (2020) check the effects of using mixed reality applications and how they impact the motivation of the students. They show that while such apps do not significantly impact the motivation to learn, they increase the motivation of the students for collaborative working, and the results are more significant for AR than for Virtual Reality (VR) apps. More in general, AR also compares favourably with respect to VR not only because it allows users to perform tasks faster (Krichenbauer et al. 2018), but also because its requirements (namely a stable internet connection and one or more mobile devices), can be provided at a lower cost and the system does not need as much time to set up. Cost is often seen as one of the most important factors limiting the access of newer technologies, so in this sense AR is often seen as a better tool in comparison with VR or expensive hardware such as laptops and projectors.

2.3.4 **Effectiveness of collaborative AR applications**

This subsection addresses the third research question. Of the 131 studies selected for this SLR, only 103 provided information about the number of students who tested the AR application. The number of students participating ranged from 2 to 290. Around 60%

of the studies were carried out with fewer than 40 participants and another 30% were carried out with a number of participants between 41 and 80 students. Only 12 studies employed 100 or more students for the evaluation. Figure 2.7 shows the histogram representing the distribution of users who tested the AR application across the studies selected for review.

The analysis of the studies shows three main ways for evaluating how effective a AR application can be in helping students improve their understanding of a subject: performing pre- and post- tests, comparing with a control group, and asking the teachers and/or the students to fill out surveys after the experiment.

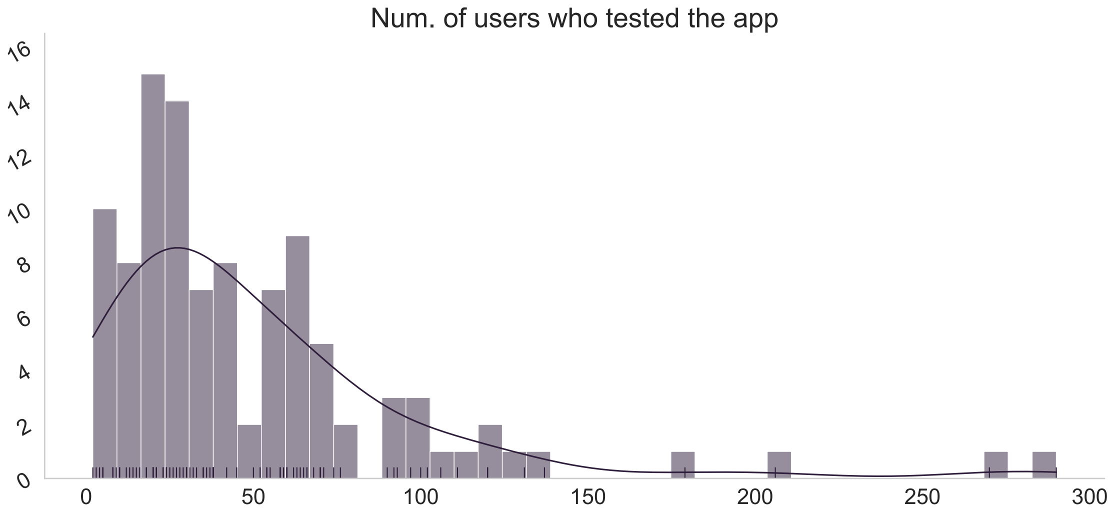

Figure 2.7: *Histogram of the participant in user tests across different studies (grey) and its smooth density estimate (black).*

While the first two options try to objectively measure the impact of using AR, by analysing the grade of the students, the third option relies on the personal judgement of the teachers and students and can, in principle, be subject to bias. In Table 2.4, the 131 reviewed articles are classified into the categories described above. Some of the studies can appear on multiple rows in the table, meaning that they evaluate results of the students in more than one way. The table does not include studies in which no evaluation was performed, or in which surveys only asked about the app usability and ease of use.

It is worth mentioning the work described in (Chang and Hwang 2018). The researchers developed a system which, apart from the AR application, included a Database

Table 2.4: *Classification of studies according to the method used to evaluate the effectiveness of AR in the classroom.*

Evaluation type	**Papers**
Pre- and post-tests	Cao and Liu (2019), Cárdenas-Delgado et al. (2021), Carlos-Chullo et al. (2020; 2021), Cen et al. (2019), Chang et al. (2019), Chang and Hwang (2018), Chao et al. (2018), Chen et al. (2019), Chen (2018), Cruzado et al. (2020), El Kouzi et al. (2019), Gargrish et al. (2022), Huang et al. (2016; 2019), Ibáñez et al. (2020), Korosidou and Bratitsis (2019), Lai et al. (2015), Laine and Suk (2016), Lee et al. (2018), Li et al. (2018), Limsukhawat et al. (2016), Lin et al. (2016; 2019), Liou et al. (2017), Liu et al. (2020), Macariu et al. (2020), Nabila and Junaini (2021), Nasongkhla et al. (2019), Oh et al. (2017), Ortiz et al. (2018), Pombo and Marques (2019), Radu and Schneider (2022), Syahidi et al. (2020), Thamrongrat and Lai-Chong Law (2020), Thamrongrat and Law (2019), Uriarte-Portillo et al. (2023), Xefteris and Palaigeorgiou (2019), Xefteris et al. (2018), Yuhana et al. (2020)
Control group	Arcos et al. (2016), Cai et al. (2017), Carlos-Chullo et al. (2020; 2021), Cen et al. (2019), Chang and Hwang (2018), Cruzado et al. (2020), Giasiranis and Sofos (2017), Hossain and Ahmed (2021), Hrishikesh and Nair (2016), Hsieh and Chen (2019), Hsu (2017), Huang et al. (2016), Korosidou and Bratitsis (2021), Ortiz et al. (2018), Sarkar et al. (2018), Takahashi et al. (2018), Thamrongrat and Lai-Chong Law (2020), Thamrongrat and Law (2019), Uriarte-Portillo et al. (2023), Yilmaz and Goktas (2017), Yuhana et al. (2020)
Survey or interviews	Adi Badiozaman et al. (2022), Buchner et al. (2021), Carlos-Chullo et al. (2021), Cen et al. (2019), Chang and Hwang (2018), Chen et al. (2016; 2019), Chen and Wang (2015), Chen (2018), Costa et al. (2019; 2021), Dobrovská and Vaněček (2021), El Kouzi and McArthur (2021), El Kouzi et al. (2019), Farella et al. (2021), Ferrer et al. (2017), Gardeli and Vosinakis (2018), Hsieh and Chen (2019), Hsu et al. (2018), Huang et al. (2019), Jumat and Su (2022), Kalpakis et al. (2018), Li et al. (2018), Luna et al. (2018), Macariu et al. (2020), Mahmoudi et al. (2018), Manrique-Juan et al. (2017), Mylonas et al. (2019), Nabila and Junaini (2021), Oh et al. (2016; 2017), Ortiz et al. (2018), Palaigeorgiou et al. (2018), Pasalidou and Fachantidis (2021), Pombo and Marques (2017; 2018; 2019), Ramos and Comendador (2019), Rodríguez et al. (2021), Seel et al. (2022), Suzuki et al. (2020), Syamsudin et al. (2022), Triantafyllidou et al. (2017), Tscholl and Lindgren (2016), Wang et al. (2018), Wang (2017), Xefteris et al. (2018), Xia et al. (2022), Yusof et al. (2020)

Management System (DBMS), a teacher interface and an e-learning platform. The evaluation of the system includes a statistical analysis of the performance of the students and their learning achievements, as well as an analysis of the ease of use of the system for teachers and students. The application described in Thamrongrat and Law (2019) uses AR to teach children about 3D geometry. Pre- and post- tests were used along with quizzes to evaluate the system. The results showed that students who used the AR applications consistently had better grades than the control group, but such results were not statistically significant. Analysing the results for different tasks, however, the data showed that the group who used AR performed worse on the easiest task, while performing much better (with statistically significant results) than the control group in more complex tasks. From this, the authors concluded that AR can be a valuable tool for learning difficult geometric concepts. The same study also conducted tests about the user experience, and the results showed that the AR application could engage its users in extremely worthwhile, highly attractive and interesting learning activities with good usability.

The app described in Cen et al. (2019) is used to teach Chemistry to 45 high school students and behaves differently depending on the distance of the device from the markers. The authors performed a quantitative evaluation of the system, analysing the grades and the distribution of mistakes in the different quizzes. They concluded that there is a statistically significant improvement in the performances of the students, and that the greater the difficulty level of the question, the bigger the performance improvement is over the control group. The authors concluded that their Augmented Immersive Reality (AIR) system is most likely responsible for the bulk of learning improvements and the knowledge retention gains demonstrated in their case study, since that is the critical component differentiating their system from other applications available on the market.

Of the 65 studies presenting a quantitative evaluation of the results, none of them concluded that using AR in the classroom has a negative impact on the results of the students and their level of engagement in the classroom. Even though, in many cases, the improvement over traditional teaching methods is limited, only Carlos-Chullo et al. (2020) do not detect any positive impact. This consensus on the effectiveness of AR applications is unexpected: besides the commonplace explication (AR is indeed a successful medium with a positive impact on the results of the students) two other possible explanations are the novelty effect (Pisapia et al. 1993), which explains the performance improvements introduced by a new technology such as AR as being due to an increased interest of the user, and the positive publication bias (Begg 1994), which makes it harder for researchers to publish studies with negative results.

Only Gargrish et al. (2022), Lin et al. (2016) present an analysis of the retention of the topics learned through AR over a time span of more than two months. As most of the students who participated in the tests had not previously used AR applications, there is a specific risk that the novelty effect introduced a recency bias, by increasing user engagement and knowledge acquisition, indirectly leading to better test scores.

2.4 **Discussion**

The research community is very active in investigating how AR applications can improve education and facilitate understanding of difficult concepts. Even though collaboration and participation by students is often seen as a key towards improving knowledge retention, there is still a lack of support for cooperation mechanisms in AR applications for education: of the 131 studies analysed, only 23 described multi-user application and only 16 employ some sort of collaboration between users. ARGBL is also quite uncommon, as only 17 articles describe applications which implement gamification concepts.

By reviewing the existing literature, several issues that are preventing the widespread adoption of collaborative AR in the classroom were identified:

- *Lack of authoring tools*: With the exception of Farella et al. (2021; 2022), Lytridis et al. (2018), Whitlock et al. (2020), the applications described do not make use of an authoring tool that simplifies the creation of an AR experience. All the authoring tools presented in the aforementioned SLR from Dengel et al. (2022) are very limited and none of them offers a no-code solution. Other authoring tools presented in the literature (Blattgerste et al. 2023, Rajaram and Nebeling 2022) have not been used in other studies. The lack of widespread, easy-to-use authoring tools requires every AR application to be developed from scratch. This leads to longer development times and more work required from the developers.

- *Lack of standardisation for the description of AR experiences*: Of all the papers analysed, only Farella et al. (2022) mentioned using a standard for the description of how AR is used in the application. This is mainly due to a lack of specific standards, as the IEEE ARLEM standard (Wild et al. 2020) for AR-based learning experiences was only released in February 2020, while the ETSI Augmented Reality Framework[13] document with AR authoring functions was published in August 2021. The adoption of these standards will drive and simplify the development of AR applications for education, as well as foster interoperability.

- *Availability of 3D content for education*: A few repositories where users can freely download 3D objects already exist, but there is a lack of 3D content specialised for education purposes. Although efforts have been made to solve the issue (Deitke et al. 2023, Masneri et al. 2020), this currently hinders the possibility of quickly and cheaply creating new AR apps for primary and secondary schools.

- *Code publication*: Out of all the studies reviewed, only 7 provided the code of the AR application, and only one (Wellmann et al. 2022) provides detailed information on how to replicate and extend the work of the researchers. Not releasing the code as open source means that researchers cannot build upon the results of previous studies: even for the more interesting and highly cited articles there will be no follow up work, with the exception of that from the original authors.

Studies claiming to have a stronger positive impact on educational achievements are the ones where the AR application is part of bigger learning environments. Providing automatic logging functionalities – for example through xAPI (Kevan and Ryan 2016) –, a teacher dashboard where the educator can track the progress or the grades of each student and a set of tools for improving communication capabilities could go a long way to better integrate AR applications in standard schools curricula. Using xAPI could simplify the application of techniques for the analysis and improvement of learning. This is especially the case for distance learning, in which the students are not in the same physical space as the teacher or other students but are following their classes remotely.

On the technical side, researchers are slowly adopting the latest advancements in technology, but the majority of the studies analysed are still focusing on more limited AR functionalities, for example marker-based systems. The implementation of AR applications that make use of Edge Artificial Intelligence (EAI) or which are based on web technologies such as WebXR[14] is currently limited because only the most recent devices

[13] `www.etsi.org/committee/1420-arf`

[14] `www.w3.org/TR/webxr/`

have hardware capable of supporting them. Nonetheless, these are key technologies that enable more immersive experiences and facilitate collaboration.

Most of the studies reviewed, with the exception of the works described in Chen (2018), Kenoui and Mehdi (2020), Mikułowski and Brzostek-Pawłowska (2020), focus on vision-based augmentations. Although it is clear that students rely predominantly on sight to collect and process information, providing other types of augmentations such as haptic or audio is worth investigating, since these could make the user experience more immersive as well as improve accessibility of AR applications for students with sight impairment.

None of the studies explored the possibility of using multi-user AR application for distance learning. The apps described by Oh et al. (2017) and López-Faican and Jaen (2020) use PUN[15], a network library that enables communication across different devices. Unfortunately, the applications require that the users share the same physical space. Especially after the prolonged lockdown due to the Covid-19 pandemic, newer technologies should provide AR apps with capabilities for the students to share the same experience even though they are not in the same room. This would be useful for teachers, who could make remote lessons more engaging, and for students, who would have the chance to work together with other schoolmates, even when they are at home.

Regarding the effectiveness of AR applications in the classroom, the majority of the studies present an evaluation of the AR solution described. There are great differences between the questions for teachers and students in the user surveys, but in general users find AR a successful educational tool which is both useful and engaging. The most common critiques identified refer to the user friendliness of the application and the errors in identifying the markers. More specifically, the users complained about the difficulty of navigating through the UI, due to its lack of consistency and about the difficulty of identifying and tracking the markers in poor lighting conditions or when the camera was not close enough.

Based on the review of the selected publications, a set of recommendations were identified. They should help increase the engagement of students while using AR applications as well as improving their learning and retention of new concepts. When creating the applications, developers should work closely with teachers to guarantee that the AR app can be easily integrated with existing school curricula, and that it can be used without requiring extensive training. Developers should also take care of simplify-

[15] www.photonengine.com/pun

ing the UX for the students, as this was one of the main sources of user dissatisfaction in the studies reviewed. While using the AR application in school, the teachers should try using collaborative features both when the students learn (to maximize their engagement) and when they are doing tests (to increase retention). After evaluating the AR applications, the teachers should also provide feedback to the developers on how to improve the application, while developers should provide educators the means to easily add new content to the app (teaching material, quizzes, 3D models, etc.), allowing them to keep using it for future lessons.

2.5 Final remarks

In this Chapter, a systematic review of the literature relative to applications of immersive, collaborative and multi-user AR in primary and secondary education was presented. 131 studies were analysed, to evaluate their technical characteristics and their advantages compared to traditional teaching tools as well as the impact they had on knowledge retention. The findings described in Sections 2.3 and 2.4 can be useful for researchers designing the next generation of AR applications.

The first research question aimed to identify which studies described interactive, multi-user and collaborative AR experiences. For this, the characteristics of the applications described in the studies have been compared. Every paper presented AR-based interactions, but only a few applications provided multi-user and collaborative capabilities. The analysis showed that Unity and Vuforia, the de-facto standard tools for creating AR applications, do not provide researchers and developers the tools to easily include collaboration mechanisms in AR applications.

The second research question aimed to understand the motivation behind the usage of AR as an educational tool. In this case both the motivations presented by the researchers and the results of surveys conducted on students were analysed. Even though few papers provided information in this sense, it appears that the main motivation for using AR in schools is to facilitate understanding of abstract concepts and to increase the engagement of the students.

Finally, the objective of the third research question was to measure, as objectively as possible, the impact of using AR in the classroom. The studies analysed pre-/post- tests or comparisons with control groups to assess the usefulness of AR and, in general, they showed that making use of AR applications leads to a small but statistically significant improvement compared to the scores obtained by the test group.

Part III

Research Results

CHAPTER

3

Interoperable Architecture for Collaborative Augmented Reality

In this Chapter the *cleAR* architecture is presented. *cleAR* is an interoperable architecture that simplifies the creation of collaborative AR applications, enables multi-user functionalities and provides advanced mechanisms for data analysis and visualisation. The architecture aims to answer the research gaps identified in Chapter 2 as well as the design objectives identified analysing the answers to a survey completed by 47 primary and secondary school teachers. The architecture has been validated through the development of 3 proofs of concept. *cleAR* provides a more mature technological ecosystem that fosters the emergence of AR applications for education and their inclusion in existing school programs.

3.1 Overview

In recent years, AR technology is being used more and more, thanks to an ever-increasing number of devices supporting it, as well as a more mature software ecosystem that allows developers to speed-up the creation of AR-based applications. With their ability to attach virtual content to any physical surface, either through the usage of markers or by using plane detection or geographical information, AR applications have found a valuable role in training and education. Several companies offer educational AR apps and, as detailed in Chapter 2, many scientific publications have shown that AR can enhance and improve the learning experience.

Unfortunately though, AR has not yet seen widespread usage in education, and most of the experiences carried out so far are based on small experiments. This is due to several causes (presented in Section 3.3.2), which can be summarised with the difficulty for developers and educators to create content that can be used by every student and that integrates well with the existing school curricula. One of the main issues, for example, is that the majority of AR applications available for education provide single-user experiences and they are more apt to be consumed at home rather than at school. Cooperative learning has long been used as an educational approach to improve the learning and performance of the students (Johnson and Johnson 2019, Kuh et al. 2011), but since the majority of existing AR applications are not multi-user, they do not allow students to cooperate. Another issue limiting the adoption of AR in schools is the integration of AR applications within existing school programs. Existing applications cannot be easily adapted to specific school curricula, and the data generated inside the apps (e.g., test results or lesson progress) is not automatically added to a LMS, thus creating additional workload for teachers.

To solve these problems, a new architecture has been designed. It is called *cleAR* (Collaborative Learning Environment for Augmented Reality), and it is an interoperable architecture that enables the creation of multi-user AR applications while providing advanced mechanisms for data analysis and visualisation. This Chapter presents the following contributions:

- Definition of multi-user AR requirements and their translation into Design Objectives (DOs). The requirements which an AR-based educational application should satisfy were identified with the help of teachers from an association of Basque primary and secondary schools (Ikastolen Elkartea). They were contacted to complete an online survey. The answers and the feedback provided led to the definition of the requirements and the DOs.

- The description of *Orkestra*, a library to support multi-device applications, whose main function is to facilitate the development of this type of apps. *Orkestra* abstracts the communication complexities that arise when trying to develop multi-device applications, and it is the main component of *cleAR*.

- An interoperable architecture for multi-user AR-based apps. *cleAR* is an architecture that allows educators and developers to design multi-user and collaborative learning experiences. Multi-users interaction allows sharing the same AR experience across users as well as transmission of information of any kind (textual, audio, video or 3D). This information could be, for example, interactions of a student in the augmented space, data gathered by the sensors in the devices, information provided by the professor from his laptop or a live video grabbed by a user with their mobile phone. *cleAR* also includes libraries for data analysis and data modeling. As it has been designed with ease of use as one of the core DOs, the architecture offers the user several web-based tools for data visualisation, reporting and information sharing. As the availability of hardware and software is extremely heterogeneous across different schools, the architecture supports several platforms, both web and native.

- Validation of the DOs within the proposed architecture. Three Proof-of-Concept (PoC) applications were developed to perform an initial validation of the architecture (which is further validated with end-users as described in Chapter 4). Such PoCs are released as open-source software[1] and can be used and combined by developers to create their own AR applications. These PoCs do not include all functionalities required by full-fledged applications: for example, privacy considerations such as compliance to GDPR (or other national or local regulations), user handling or access right management are not included in the PoCs, as such functionalities are application dependent and can vary greatly depending on the scope of the app.

The rest of this Chapter is organised as follows: Section 3.2 presents the related work. Section 3.3 describes the requirements of a multi-user AR architecture, how they were collected and how they are translated into design objectives, while Section 3.4 introduces *cleAR*. Section 3.5 presents the PoCs implemented to validate *cleAR* and, finally, Section 3.6 summarises the Chapter.

[1] `https://github.com/Stocastico/ARchitecture_paper`

3.2 Related work

In the last few years, a massive amount of publications presented implementations of AR applications for education (see Chapter 2). The review of Phon et al. (2014) is of special interest as it describes ten collaborative AR applications used in education. Of the ten studies, only four include collaborative features in the AR experience, while the others only use the collaborative approach as a learning strategy, which is not reflected in the application.

As the support of AR technology in modern browsers is relatively recent, there is a scarcity of publications presenting web-based AR applications. The work of Abriata (2020) describes a web application based on a client-server architecture. It enables the creation of AR experiences for molecular visualisation, while Coma-Tatay et al. (2019) present a solution for the creation and visualisation of generic AR applications in browsers which uses the FIWARE open-source software framework.

Even though most educational AR applications described in the literature are intended to be single-user, researchers have been investigating collaborative AR experiences since the seminal publication of Billinghurst et al. (2002). In López-Faican and Jaen (2020), the authors present a markerless AR application for improving socialization and communication skills of primary school children, and note that the collaborative game version of the app has a greater impact on emotional affection and social interaction. Oh et al. (2017) describe a collaborative AR app where the user, through the use of smart glasses, can study properties of light such as reflection and refraction.

Besides AR, the revolution of Information and Communication Technologies (ICT) has affected education in many other ways, providing means to enhance both the teaching and learning processes. Nowadays, TEL, such as Intelligent Tutoring Systems (ITSs), Adaptive Hypermedia Systems (AHSs), and Learning Management Systems (LMSs), are being widely used in many schools and becoming essential for education. An ITS is a system which aims to replicate with digital tools the effectiveness of human tutoring. Even though the first ITS was created over 50 years ago (Carbonell 1970), recent advances in AI translated into the development of newer systems for both education and professional settings (Mousavinasab et al. 2021) that have an effectiveness comparable to that of human tutoring (VanLehn 2011). The architecture of an ITS is typically composed of four components: a Domain model, a Student model, a Tutoring model and a User Interface (Nkambou et al. 2010). AI tools can be applied to each model but are especially relevant for Student models, as they represent the current state of knowledge of the students and are used to provide optimal teaching interventions (Sedlmeier 2001). Student models can then be characterized by what kind of information they model and how this information is stored and used (Chrysafiadi and Virvou 2013). There are only a few studies examining the combination of ITSs architectures and AR: in Westerfield et al. (2015) the authors present an AR application for motherboard assembly, where the usage of an ITS allows personalized training, while the work of Sanchez-Sobrino et al. (2020) uses AR to create 3D graphical representations of computer programs, helping students learn new programming concepts.

Visual Learning Analytics (VLA) is the research area at the intersection of Visual Analytics and Learning Analytics (Therón 2020). A recent survey of studies applying VLA to educational settings shows that so far there are very few examples of bringing VLA tools into the classroom and they generally use only very simple visualisations and do not consider background student information as data source (Vieira et al. 2018). Another review study (Bodily et al. 2018) analyses similarities and differences between Open Learner Models (OLMs) and Learning Analytics Dashboards (LADs) and concludes that there is a strong overlap in the two fields, and that applying the lessons learned in OLM research can drive the next generation of learning analytics tools.

Despite the huge amount of literature describing AR applications for education, there are currently no works describing systems and architectures that use AR technology, provide multi-user and collaborative functionalities and make use of VLA tools and/or ITSs.

3.3 Requirements and design objectives

To better understand the requirements of an architecture that enables educators to easily incorporate collaborative AR applications in their curricula, a questionnaire for teachers of primary and secondary education level was prepared. In the questionnaire, the teachers were asked a set of questions related to the usage of technology, and AR in particular, in their schools. The survey followed the methodology recommended in (Lazar et al. 2017, Chapter 5), and it was later modified following the recommendations of the teachers who revised the document. They suggested to reduce the amount of open-ended questions and to prepare a survey which would not take more than 20 minutes to fill. Based on the answers to the survey, a set of requirements was extracted, which in turn defined the DOs of the proposed architecture.

3.3.1 Teacher survey

The teacher survey, presented in Appendix A, is composed of 45 questions, split across 3 sections. 19 of the questions are open-ended and in many cases optional, while the remaining questions are multiple choice. The respondents did not have to answer all the questions, since the survey presented different branching paths based on the answers provided. For example, there is a set of questions asking about the teachers experience with AR applications, which are presented only to the respondents who answered positively in the question about the previous usage of AR in the classroom.

The first section of the survey contains 16 questions about the teachers (which subjects they are teaching, their years of experience, whether they teach in primary or secondary schools, etc.) and about the generic usage of technology in the classroom (how many laptops, tablets or smartphones are available at school, what applications they use besides office-related or videoconferencing solutions) and what advantages are provided by such technologies.

The second section contains 14 questions specific to the usage of AR applications at school. The section starts with a brief description of what AR is, as well as a few examples of how AR applications can be used in schools. These paragraphs were introduced so that even lecturers not familiar with the technology would be able to answer the questions related to AR. If the teachers had already used AR, the survey asked how often they used it, what they needed to use it, on which devices and whether they were satisfied with the experience. If the teachers did not have any previous experience using AR at school, the survey asked them whether they thought that AR could be a valuable tool to facilitate learning. Furthermore, the questionnaire asked the teachers what changes would be required in order to improve the experience of using AR and whether they think that an AR-based application would improve the learning experience of the students.

The final section includes 15 questions about the technological tools the teachers would like to use in their daily activities and when and where they would like to use them. Some questions focused specifically on AR, its advantages and disadvantages, what the teachers consider as the most interesting functionalities of AR apps, what kind of content they would show in the app and their willingness to create such applications, if they were given adequate authoring tools. The final questions were about the usage of AR in a collaborative learning environment and about the inclusion of AI as a support tool for analysing student data and creating automatic reports.

3.3.2 Survey results

The survey was answered by 47 teachers belonging to Ikastolen Elkartea, a Basque association of primary and secondary schools. In this subsection, the results of the survey are briefly summarised. The answers from the teachers were used to define the architecture requirements. The collection of anonymised answers, together with an exploratory data analysis, is available online[2].

With respect to demographic information, the majority of the respondents (53%) teaches STEM subjects in secondary schools (82%), in classes with 25 students on average. 43% of the teachers who answered the survey are *facilitators*, i.e., teachers in charge of helping colleagues to use technical tools in the classroom, and they are usually the most tech-savvy among the school personnel.

Schools are usually provided with many computers: although there is a lot of variance across the answers provided, on average each school has 68 desktop PCs available as well as 398 laptops. Tablets are seldom used (42% of the teachers said they have no tablets in school, but others mentioned an availability of up to 75 tablets). Every teacher mentions they have mobile devices available, but in most cases only their personal device. Teachers also mentioned that most of the students have a personal device, depending on their age (which was not asked in the survey). Apart from this, the teachers mentioned that they often use devices such as Chromebooks or Ultrabooks, digital blackboards, projectors or Apple TVs. From this, a solution that will work on top of different platforms and devices is extracted as a requirement (Requirement 1 - **R1**).

Regarding software, 77% of the respondents use software tools (besides Office applications) every school day. The most used applications are Moodle, the Google suite (Classroom, Drive, YouTube, Earth, Maps), SketchUp, Scratch, GeoGebra, Prezi and Lucidpress. The teachers use these applications because they help motivate the students and achieve teaching objectives. The most appreciated aspects of these applications are (in descending order):

[2] `https://anon.to/3vzfK4`

- They provide services which are accessible from different devices (86% of the respondents) (**R1**).
- Foster the interaction between the teacher and the students (86%) (**R2**).
- Foster the interaction between multiple students (75%) (**R3**).
- Provide customisation options (language, content, etc.) (69%) (**R4**).
- Gather data on how the application was used (53%) (**R5**).

Apart from these aspects, the teachers underlined as relevant aspects the possibility to update and maintain the tools (both hardware and software), providing the tools for free and using hardware with enough storage capacity (**R6**).

Regarding AR, the vast majority of the respondents (88%) never used it at school, and only about 3% used it more than once and very seldom. The question specifically mentions the usage of AR in school, and the high percentage does not reflect the familiarity of the teachers with the technology or their usage of AR in other contexts. Among those who used it, 75% of the teachers think that AR improved the learning process of the students. Despite the low usage of AR technology, 78% of the teachers think that AR can be a very useful tool. When asked what could help in increasing AR adoption in schools, about 75% of the teachers emphasized they would need to know the existing AR ecosystem better, what apps are available and their capabilities. Half of the teachers said that they would need more time and to have better hardware and software available for the students (**R7**). Other answers mentioned the necessity of technical support, better localization of the content and the ability to support multi-user interactions (**R8**), as the students get bored fairly soon doing individual activities. In general, teachers are dissatisfied with AR for education, rating it 2.2 on a Likert scale (where 1 means *very low satisfaction* and 5 means *very high*). The reasons for this is because most of the AR apps are very limited in terms of interactivity and user experience, and there is nearly no content in the Basque language. Despite this, 70% of the respondents think that AR can be of added value in learning, and the remaining 30% think that it may be. The main advantages of AR, as identified by the teachers, are:

- Improvement of the motivation of the students (82%).
- Better assimilation of concepts (78%).

- Better way to transfer knowledge (69%).
- Improvement of spatial orientation (58%).
- Improvement of interactivity (49%).

On the other hand, the teachers identified several key limitations of AR, as it requires an effort to learn how to use the technology and the school curricula must be adapted to include it. Furthermore, teachers often lack the time to get familiar with the technology and the experience is often not engaging enough, either because the devices used are too old or because the apps lack content. Ideally, the teachers would like to use AR applications that:

- Enable collaboration between multiple students as well as with the teacher.
- Are highly interactive and with plenty of quality content.
- Can work with a broad range of devices.
- Can be used both in the classroom and remotely.
- Collect data about how the students used the app.

The teachers also expressed interest in having the possibility to create their own AR content, if they were provided an authoring tool and training on how to use it. More than half of the respondents (53%) expressed their interest and that they would like to create simulations, quiz activities, immersive videos and 3D visualisations. Some of them mentioned that they routinely use tools such as Kahoot[3] for creating interactive web quizzes and they could use something similar for the creation of AR experiences.

Finally, regarding the usage of AI in education, 40 teachers identified the following use cases:

- Analysis of usage data and usage patterns (63%) (**R9**).
- Automatic analysis of the difficulty of the questions in a test-type activity (60%) (**R10**).
- Identification of students with difficulties at an early stage (58%) (**R11**).

Table 3.1 recapitulates all the architecture requirements identified after analysing the answers to the survey.

[3] `https://kahoot.com/`

Table 3.1: *Summary of the requirements identified from the results of the teacher survey.*

Code	Requirement
R1	Apps should work on different platforms and devices
R2	Foster teacher-student interactivity
R3	Foster student-student interactivity
R4	Enable several customisation options
R5	Collect data on how the applications are used
R6	Enable easy development as well as installing and updating
R7	Apps should work smoothly even on older hardware
R8	Apps should allow collaborative work
R9	Provide tools for analysis of data and usage patterns
R10	Enable automatic analysis test difficulty
R11	Detect students with learning difficulties

3.3.3 Design objectives

Based on the answers of the teachers collected in the survey and the identified requirements, six DOs (summarised in Figure 3.1) were derived. They guide the definition of an architecture for AR-based applications which can be used in schools.

The architecture must be **interoperable** (**DO1**). It should run on different devices such as HMDs, tablets, laptops or smartphones, with reasonable support for older models. At the software level, the architecture should provide Application Programming Interfaces (APIs) for development on native platforms (Android and iOS), for cross-platform engines like Unity and support Web standards for Extended Reality (XR) experiences (Goregaokar et al. 2022) and real time communication (Holmberg et al. 2015). An interoperable architecture has two advantages: it eases the dependence on specific hardware, thus reaching a wider user base, and it allows the development of hybrid solutions where users can connect either using an app or their browser.

The architecture should support **multi-user interactions** (**DO2**), both face-to-face and remote. Collaboration is a key requirement identified by teachers to increase the engagement of the students and keep them interested, so the architecture should enable user communication (via voice or chat) and also provide a way to exchange any kind of data in real-time, for example the interactions of the users with the application, the position of the AR camera, the answers to the questions in the app, etc.

The architecture should enable **long-term storage** (**DO3**) of the data collected, to guarantee that the teachers can track the progress of the students over time and to let them create **data visualisations** or automatic reports (**DO4**). The data will enable the implementation of **AI techniques** (**DO5**). The architecture gathers information about how the students are using the applications (both the interactions with the software as well as with other users) and store it in the appropriate format. The architecture should be agnostic to the AI models built on top of it (depending on the application, teachers may be interested in using recommender systems, anomaly detection systems or clustering algorithms, for example) but it should provide support for training a model from scratch, fine-tuning a previously trained model or using an existing model for inference tasks.

Finally, it should be **easy to develop** content using the specified architecture (**DO6**). Simplifying the development process would hopefully encourage developers to create applications based on the architecture, thus solving the problem of the lack of quality content identified by the teachers. The architecture should also be **easy to use**, simplifying the deployment and maintaining of the apps: in the ideal case the teacher using the AR application would be able to install and update the software for himself and the students without the need of external help. It should be noted though, that this design objective is not geared toward the creation of an authoring tool but rather on the definition of a set of libraries and APIs that allow software developers to speed up the app creation process. There is a lack of teacher-oriented authoring tools: most of them have been developed for computing literate users or software engineers and, therefore, they become too complicated for teachers, who may give up the development of their own applications. Brusilovsky et al. (2003) claim that teachers should focus on Domain Module authoring while the development of the core of technology support learning systems should be carried out by expert developers.

3.4 Architecture definition

In this section *cleAR* is presented. *cleAR* is the architecture that fulfils all the design objectives described in Section 3.3. It is a client-server architecture composed of several modules, each of which is in charge of a specific task. Two design objectives, namely interoperability (**DO1**) and ease of development (**DO6**), are not satisfied by specific modules but are rather fulfilled thanks to how the architecture has been designed. For

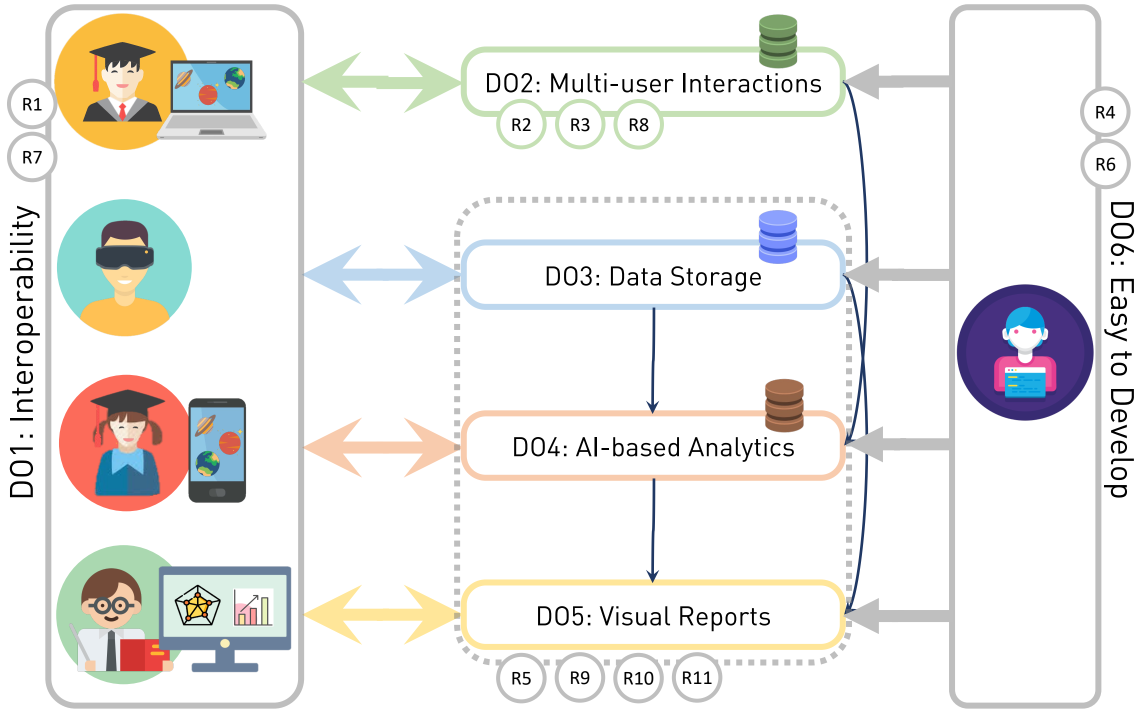

Figure 3.1: *A diagram representation of the architecture design objectives.*

interoperability, the definition of a web architecture and the development of multi-platform libraries ensures that developers can create applications working on different hardware (PCs, HMDs, tablets or mobile phones) and across multiple software tools, as the architecture has been tested on multiple browsers, desktop applications as well as native iOS and Android apps. While *cleAR* does not provide authoring tools that would allow AR applications to be created without requiring coding experience, extreme care was taken in developing a set of libraries and APIs that enables developers to easily create interoperable multi-user AR applications, as shown in Section 3.5.

In the following subsections, the four main blocks of the proposed architecture, summarised in Figure 3.2, will be described in detail. While part of the architecture has been developed from scratch, some components rely on existing libraries to provide the required functionalities. All the components have been integrated in a cohesive system that can be used to create collaborative AR applications.

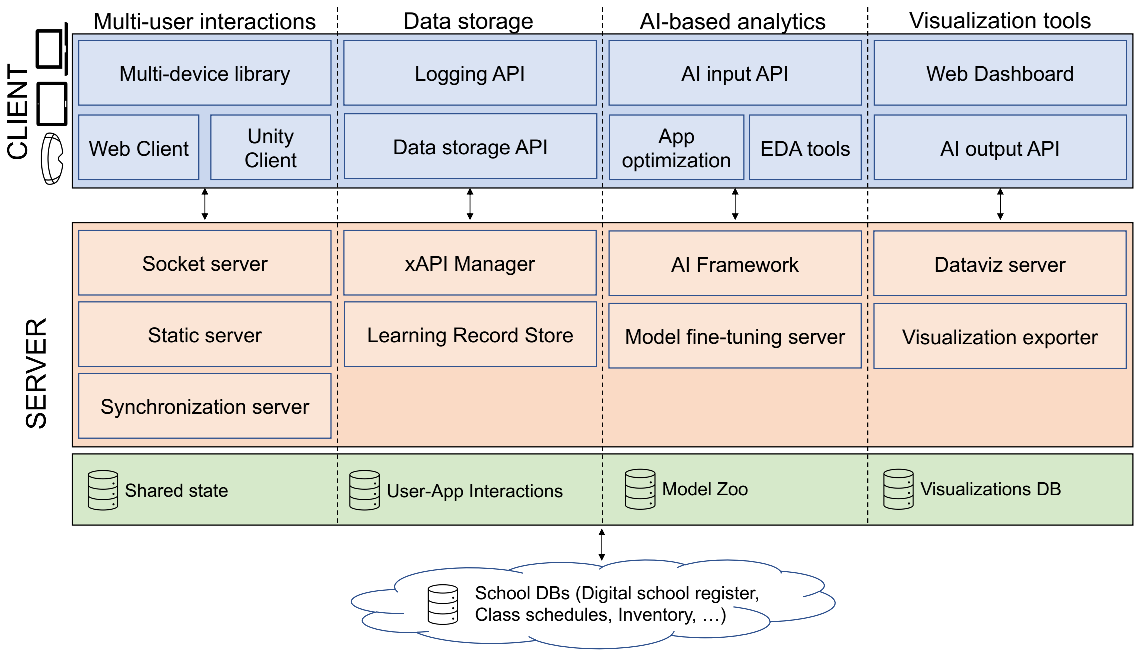

Figure 3.2: *A visual description of the proposed architecture*

3.4.1 **Mechanisms for multi-user interactions**

This objective is satisfied by *Orkestra* (Masneri et al. 2022a), a library for the synchronisation and management of heterogeneous devices in multi-user applications. It is the module enabling real-time communication between multiple users. The library was initially developed in JavaScript but it also includes bindings that allow its usage in different software environments. *Orkestra* simplifies the creation of multi-device applications that share state and stay in sync. To do so, the library provides functionalities such as: multi-device state synchronisation (being able to share any kind of information and have all devices in sync), video synchronisation from a centralised clock, video sharing between different devices and a service functionality where one device can publish any kind of service (e.g., authentication service) and this can be consumed by other devices.

Applications can store data of any kind and then share it with other devices. These data are the states, which will be synchronised between the different devices. When one device changes its state, it is replicated to all other connected devices.

There are two types of state:

- Agent state: corresponds to the state of each device (*e.g.*, the position of the device in a common reference frame relative to an AR marker).

- Application state: corresponds to a global state that is shared between the different devices (for example, the number of users currently connected to the application).

Through this functionality, the devices can send information to each other and keep the states synchronised. The library also allows maintaining video synchronisation across different devices. This way it is possible to create a multi-user environment, where different users can watch the same video sequence at the same time.

The library allows creating services between different devices so that others can consume them. For example, as shown in Figure 3.3, if a device has a model for detecting objects in images and wants other devices to be able to use such model, it can create an *Orkestra* service so that other devices can communicate with it and run the service.

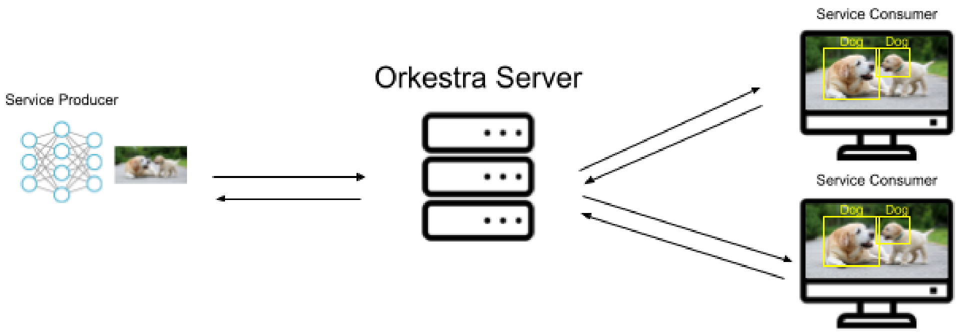

Figure 3.3: *Orkestra allows creating services that can then be consumed by any devices connected to the application.*

One of the main features of *Orkestra* is context maintenance in a multi-device environment. This is useful in multi-user applications, where all applications must have a synchronised context regardless of where they are running. The *Orkestra* library is in charge of:

- Communication with the other devices that are also using the library and are connected to the same session.

- Synchronisation of the contexts with the other applications.

- Storage of the context of the different devices.

In order to communicate with the other devices, the library connects to a server, which will redirect each event it receives from a device to all the other connected devices and will store the different events it receives. The context variables are stored on the server and then redirected to the other connected devices. Each client stores the context of the application and of the other devices. Each change made by a device in its context will be notified to the other devices (through the server), and they will then update their respective context.

Synchronisation of media content is achieved through the usage of a shared timeline, implemented with Motion (Boronat et al. 2017, Montagud et al. 2018). Motion is a service that allows multi-device applications to be synchronised from a central timer, allowing content to be adapted to a common time. It is based on the time-based multi-device synchronisation mechanism specified in the W3C draft Timing Object[4]. The service works as follows: a timing object is instantiated on each of the devices and each of these instances is connected to a single shared timeline. If one of the objects pauses, all local components are notified to act accordingly. In addition, if they are connected to the shared timeline by the server, that pause is relayed through the server to all other connected clients. This allows synchronisation of different content according to two different types of timers:

- *Sequencer*: Used to synchronise content that is not media, such as different data that needs to be displayed at the same time. This can be useful in a scene-based timeline, where each scene is associated with a set of data that has to be displayed at the same time.

- *MediaSynch*: Used to synchronise multimedia content such as video or audio. It consists of adjusting the playback speed with high precision, so that the contents are synchronised without time jumps.

Orkestra also allows connected users to send or receive video streams between all connected users. In this way, if a user wants to retransmit a video from a camera, or share a screen as a stream, they can share it via the platform and the connected users will be able to consume it. For this, the platform uses a WebRTC Janus server that is in charge of centralising the WebRTC streams, managing the sessions and forwarding the RTP/RTCP traffic between the browsers. To perform this communication with the WebRTC server by the browsers, the library provides an API that allows the user to abstain

[4] `https://webtiming.github.io/timingobject/`

from all communication with the WebRTC server. Internally, *Orkestra* uses the Janus library[5]. This library is used in the x-media, screen-share and webrtc-publisher web components. The library also exports a method called JanusClient which uses the Janus library and allows to handle events in the communication with the WebRTC server.

Finally, *Orkestra* uses web components as the minimum unit of the user interface. Web components are elements that encapsulate customisable and reusable functionalities avoiding code collisions. They are based on the following principles:

- *Custom elements*: A set of JavaScript APIs that allow you to define custom elements and their behaviour, which can then be used as desired in the user interface.
- *Shadow DOM*: A set of JavaScript APIs for attaching an encapsulated *shadow* DOM tree to an element - which is rendered separately from the main DOM document - and controlling associated functionality. In this way, features of an element can be kept private, so it can be styled and scripted without fear of collisions with other parts of the document.
- *HTML templates*: The template and slot elements allow you to write markup templates that are not displayed on the rendered page. These can be reused multiple times as the basis for the structure of a custom element.

3.4.2 Data storage

Besides sharing data and messages in real time, users may be interested in permanently storing other types of data. It can be data related to the user progress in specific tasks, like the answers to a test or the completion of a chapter, or other data linked to the interactions of the user within the application, for example the number of clicks, selections in a menu, or the interactions with 3D content in the augmented space.

In this case *cleAR* allows storage of data that can be serialized and stored in a database or on a local disk, and it provides means for easily querying and filtering the data when needed, either directly in the application or through a script. The architecture provides an API to store and access the data through a Learning Record Store (LRS), thus simplifying its integration into LMSs which are already in use at school. By enabling storage of the data on an external database, applications developed with this architecture can

[5] https://janus.conf.meetecho.com/

then be integrated into the school curricula, as they can fetch data from the LMS (for example, a set of questions and answers for a test) as well as writing new data to it (*e.g.*, the results of the in-app quizzes).

Finally, logging and storing usage data and activity can enable user monitoring practices. In the case of AR experiences, the teachers would be able to know how much time each student spends on different modules of an application, giving her insights on which concepts are harder to grasp. Furthermore, the teacher would be able to check if any of the students is falling behind, as the application can raise automatic flags if the student has not accessed an app in a while, or is performing consistently bad on the assessment questions. The amount of data that is stored is fully customisable at the application level, and there are options for anonymisation, adding user profiles (*e.g.*, admin, teacher and student) and for changing the frequency of data collection.

3.4.3 **AI-based analytics**

Given the amount of data that are made available by the module described in subsection 3.4.2, AI techniques, especially Machine learning (ML) algorithms, can be used to build learner and group models that can improve the learning processes. The models trained using this module are meant to be a support for the teachers, helping them gain new insights on the progress of the students or by simplifying their work, by automating some of the most time-consuming tasks.

As *cleAR* is used to create AR applications, the data collected are typically of three types: *natural text data*, for example all the data collected from chats or from answers to in-app questions; *structured data* such as all the logs collected from the applications, organized in tables where each data point represents a student interaction; and *image data*, which is data collected through interactions with the augmented content or directly from the mobile device camera. The analytics module is able to work with all these different data sources, and create models using both the supervised and unsupervised learning paradigm.

The ML algorithms are trained and stored on the server side. *cleAR* allows both training of a model from scratch, or fine-tuning an existing model when new data is available. As *cleAR* provides a standardised API for data input, it can work with any AI framework such as PyTorch or scikit-learn, and it supports a wide range of ML algorithms such as deep neural networks or random forests. Nonetheless, in the survey the teachers expressed the desire to understand how and why a model outputs its decisions, so the recommendation for developers is to rely on more explainable AI models (Khosravi et al. 2022) such as decision trees or linear regression models.

As the training and deployment of the models is done on the server, the client is responsible for sending the data collected to the server, and for this *cleAR* provides a specific API. The client also includes tools for exploratory data analysis that allows cleaning and filtering the data in order to generate insights that can then be displayed using the visualisation module described in subsection 3.4.4. Finally, the client also includes a set of functions for the optimisation of app parameters. These functions allow, for example, the adaptation of the application to the hardware available or the network conditions, so that the developers do not have to take care of this beforehand. An example of optimisation is described in Section 3.5.

Not every teacher who answered the survey was interested in applying automatic analysis of the data (and some of them were skeptical about the usefulness of it), but about 85% of the respondents identified the most important insights the AI-based analytics module should provide. First of all, the teachers would like to retrieve information which would be hard to come by: they are interested in finding patterns in the way the students perform so that they can plan the structure of the lessons better. For example, teachers would like to have a model that, given the results to some in-app quizzes and the time when the tests were taken, predicts the time of the day the students are more focused. This could help teachers plan their daily activities.

The architecture is AI-agnostic, as it supports any algorithm – supervised or unsupervised – that can be implemented using standard ML libraries. An example of a model that can be created using the functionalities provided by *cleAR* is a model that predicts an average score of a student on the test on a specific subject. In this case, the AR application should collect data –which is sent in the form of eXperience API (xAPI) statements (Clarke et al. 2020) – about how the student has been using the app. Data such as time spent on each lesson, number of interactions with the app, how quick the student was answering questions during the AR experience and so on will represent the predictor variables, while the results of the test at the end of each lesson would represent the target variables. Once the data from every student has been collected, it is then possible to train a classification model which, when given as input the predictor variables from a new student, will predict his test results on the lessons the model has been trained on.

Another category of models that is relevant for the teacher is that of unsupervised learning algorithms, especially outlier detection and clustering models. In the first case, detection of outliers can enable teachers to flag specific content (daily activity, test results or others) as outside of the standard data distribution and then decide what to do about it. In the second case, the teacher may be interested in grouping the students into different clusters, based on the metrics she consider relevant. By tracking the structure of the clusters over time, they can keep track of how the students are progressing. Finally, AI models can also help detecting which students are *falling behind* and are having learning difficulties. Being able to identify these students at an early stage allows teachers to tackle the situation better and in a more effective way. In this case, the AI model will use metrics from both the logging data and the application usage data to train a classification model. As both the input data and the model parameters are stored on the server-side of the architecture, the models could be continuously improved using online model learning, while the data could even be combined to extract insights at classroom or at school level.

The tools developed in this module are not meant to replace the insights from the teachers and their experience based on daily interactions with the students. They are meant to be used as a support tool, helping teachers make decisions based on more data evidence and simplifying their work for more time-consuming tasks such as test grading.

3.4.4 Visualisation tools

The final module provides visualisation and reporting functionalities. Through this module, the user can access a web interface where data can be displayed either as text or via interactive plots. This module allows teachers and students, who may not have the required expertise, to visually display the data collected and to help them draw insights from it.

This module relies on existing libraries for data visualisation such as D3 (Bostock et al. 2011) or Seaborn (Waskom 2021), but it simplifies the process of creating plots by providing an API for importing the output of the ML models, as well as a dashboard for generating interactive charts without code. The visualisations are generated on the client side. They can later be stored on the server or exported to a database, to a local storage or to the school LMS.

The visual reporting module is not meant to replace existing dataviz libraries, but rather provide teachers with a web interface that allows them to create, modify and export visualisations without requiring coding experience or directly manipulating the input data.

3.5 Implementation and Validation

Three PoC applications based on *cleAR* were created in order to validate that the software developed using this architecture satisfies the design objectives defined in Section 3.3: *AR Cube*, *xAPI Data Analysis* and *AR Geography Quiz*.

3.5.1 AR Cube

When starting the application, the users join a room and all the interactions with the virtual object are broadcast to all the users connected to the same room. The user is also able to select how often data is shared between users by selecting the time interval between the messages to the server. While simple, this application demonstrates how the architecture is able to fulfil the design objectives. The application is interoperable as it has been compiled for iOS, Android, Windows and Linux platforms and the users are able to share their AR experience when using devices running any of these operating systems. The application supports multi-user interactions in an AR environment, as the interactions with the augmented content are the same for all users. The application has been tested for up to four users, both sharing the same WIFI network and using 4G mobile connection. For the tests, two tablets (a Samsung Tab A7 SM-T500 with 3Gb of RAM and a 4th generation iPad Air with 4Gb of RAM) and two smartphones (a Samsung Galaxy A22 5G and a Samsung Galaxy A90 5G, both with 6Gb of RAM and running on Android 11) were used. The average latency (measured as the time spent since the request is sent from a user to the instant when it is received by all users) was 205 milliseconds. There was no appreciable difference in latency between WiFi and cellular network, but for messages sent from a mobile phone the latency was significantly lower than the one measured for messages sent from a tablet (mean value of 96 ms vs. 245 ms). For this PoC, the latency value was not affected by the number of clients connected or the amount of messages exchanged by the end users. For more complex applications, the resources allocated in the backend should be properly tuned in order to guarantee the desired latency.

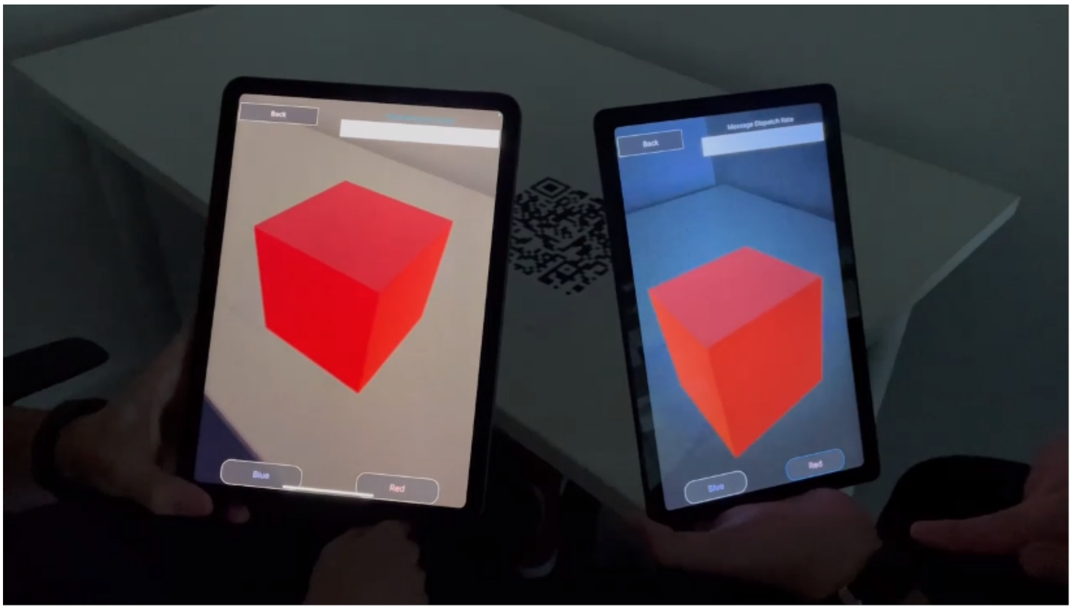

Figure 3.4: *The AR Cube PoC accessed by two users sharing the same AR marker.*[6]

One of the parameters of the application is what is called the *dispatch time*, which is the time interval between two consecutive messages from the same user. For interactions generating many events (such as the rotations of the cube when swiping the screen), the user could generate up to 30 events per second. To prevent the application from slowing down (or even to saturate the network, for more data intensive applications), events are stored in a queue and then sent together once the dispatch time has elapsed. This way, it is possible to find a balance between the smoothness of the rotation and the amount of events sent. When a reasonable dispatch time value was selected (from 0.01 to 0.04 seconds), every user was able to experience a very smooth cube rotation. The dispatch time could also be set automatically by the application: if the user does not select a value, the app estimates the latency (by measuring the time elapsed between sending a message and receiving it back) and modifies the dispatch time accordingly until the desired latency value is achieved.

[6] A video demo is available at `https://anon.to/pwRr4W`

Finally, the PoC shows how easy it is to develop for *cleAR*. The object model properties, the application logic and the integration with the library for multi-device access required less than 400 lines of code. To enable multi-user interactions in the application, the developers only needs to register the events that affect all the users (the rotations and the color changes, in this PoC), to add a call to the function that generates a notification for these events, and to create a subscriber object which receives the notifications and modifies the app context which will then propagate the information to every user.

3.5.2 xAPI Data Analysis

The second PoC features a LRS that collects data from users accessing a web page (Figure 3.5 shows the UI of the app). The application keep tracks of both active interactions (mouse clicks, text entered, etc.) as well as passive ones such as time spent on the page or date of access. The data is collected in the form of statements which use a vocabulary specifically created for the demo application. The server side uses Learning Locker, and all statements are stored in a MongoDB[7]. This PoC simulates the process of data collection that could be performed in a generic AR application, and was built to test the integration of *cleAR* with Learning Locker[8] and scikit-learn, as well as the ability of the architecture to handle huge volumes of data without appreciable delay. Learning Locker is the standard data repository for storing learning activity statements generated by xAPI. xAPI is a web service that enables the secure sending and storing of learning experiences to an LRS. xAPI statements use JSON format and at their core they are formed by the triplet *Actor–Verb–Object*. The *Actor* represents the person performing a specific action (the *Verb*), while the *Object* could be another person or an xAPI activity on which the actor acts upon. xAPI statements can optionally include additional information such as *Timestamps*, *Context* or *Results*, to provide more detailed information. Apart from the client interface for the user, another web page allows the statements to be downloaded, possibly applying different kind of filters, in a JSON format for further processing. Furthermore, a script performs weekly incremental backups of the database, copying the statements from the AWS instance where the LRS is running to a local storage.

Learning Locker provides an interface for filtering the data and for the creation of dashboards for data visualisation. This way, a user can explore and visualise informa-

[7] `https://www.mongodb.com/`
[8] `https://learninglocker.atlassian.net/wiki/spaces/DOCS/overview`

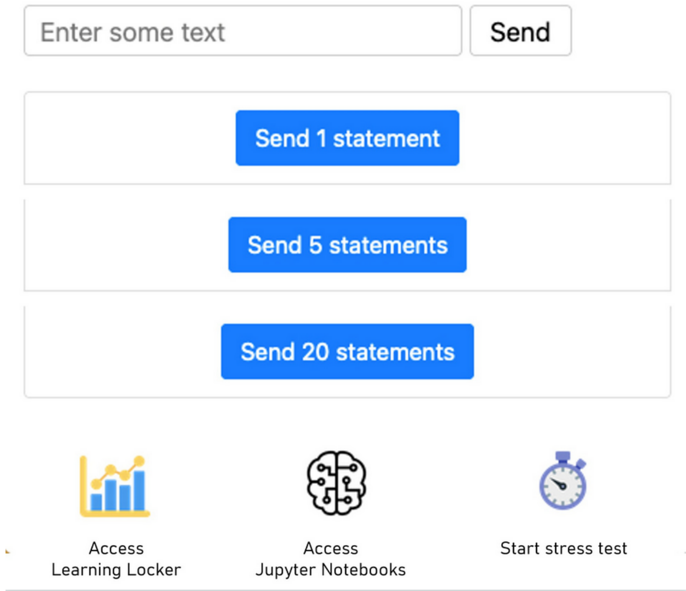

Figure 3.5: *The user interface of the xAPI Data Analysis PoC. Statements are generated manually or automatically, by starting a stress test or by tracking user activity. Additional UI elements allow accessing the Learning Locker where the statements are stored as well as the notebooks used to create the AI models.*

tion without having to write a single line of code. Besides the tools offered by Learning Locker, a set of functions for data cleaning, data exploration, data modelling and data visualisation were developed. These functions allow more experienced users to get more insights than the ones provided by Learning Locker and to run classification, predictive and clustering algorithms. Even though the code has to be modified and adapted for each application, using xAPI as a data format allows the creation of a standard set of library calls that favours data reuse.

To measure the ability of the deployed solution to handle the processing and storage of xAPI statements, a stress test was performed where 10 clients were generating multiple statements per seconds. A short summary of the testing conditions is available in Table 3.2. During the test, the clients sent close to 80000 statements to the LRS. The average delay between the sending of a statement and its availability on the LRS was 145 ms, with a maximum delay of 314 ms.

The statements generated during the stress test were also used as training data to create a simple ML classification model. The data storage and AI analytics modules of the architecture were used to fetch the data and perform the preprocessing step, which parses the data stored as JSON to extract the relevant input features. The independent variables used to train the model are extracted from the triplet <actor, verb, object> associated with each xAPI statement, as well as additional information such as the time delay between consecutive statements. The only statements used to train the model were the ones using *sample* as their verb, and a typical statement would be for example <*client-01, sample, 1.04*>. The object value for these statements is a number sampled from a gaussian distribution whose mean and variance depend on the client that generated it. The statements were preprocessed to obtain a two-column input matrix – *ID* and *sample* – which could be fed to a linear classifier. Later, at test time, the model was able to successfully predict which client generated a specific statement, based on the value passed in the object of the statement triplet.

Table 3.2: *xAPI statements sent during the stress test of the second Proof of Concept app.*

Test	Statements/batch	Wait time	Statements
1	15	10s	**1653**
2	30	5s	**6614**
3	30	2s	**16534**
4	50	1s	**55116**
Total			**79917**

3.5.3 AR Geography Quiz

The last PoC implemented is a more complex AR application that simulates an interactive geography quiz which, for example, could be used in a classroom to evaluate the knowledge of the students regarding subjects they recently studied (see Figure 3.6 for an example of what the teacher interface looks like).

In this example, AR Foundation was used to create an AR scene in Unity where the user sees a 3D model of the Earth and she can change what she sees by swiping the finger on the display or by physically moving around the 3D element. In the application, one teacher and one or more students connect to the same virtual room to participate in the quiz (the video linked in footnote 9 only shows interactions between the teacher and one student, for the sake of simplicity, but the PoC also supports one-to-many

[9] A video demo is available at `https://anon.to/4Ulhto`

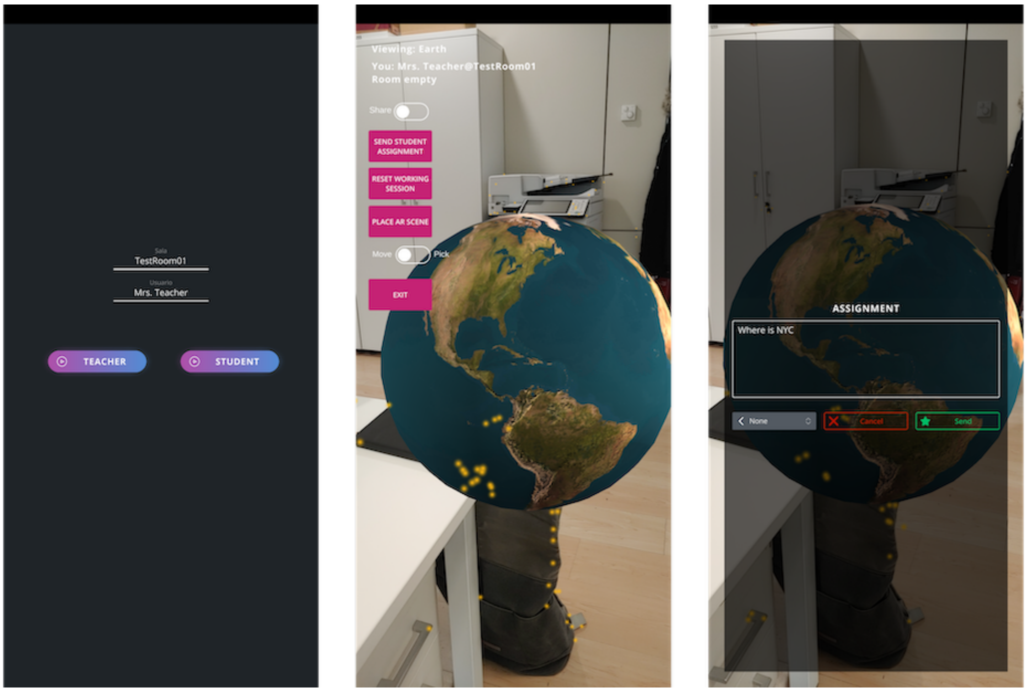

Figure 3.6: *The AR Geography Quiz application. From left to right: the login screen, the augmented content, the "send question" view.*[9]

interactions). The application works in two modalities. In the first one, each user can freely explore the augmented content, either by rotating the globe or by actually moving around it, and there is no shared experience between users. In the second modality, one user can force every other user to watch the globe from their perspective, and it is in this modality that the users are sharing their interactions. For example, the teacher has the ability to force every user to see the 3D Earth from his Point of View (PoV), forcing the AR camera position to be the same for all users, and to send questions such as *Where is Canada?* to a specific user. When that happens, the student who received the question will then share their camera PoV (effectively controlling what other users are seeing on their device) and he can answer the question by placing a marker on the globe. Once that is done the teacher will re-gain control of the application and mark whether the student answered correctly. A multi-user AR application for education can make the learning experience more engaging and promote collaboration between users by enabling interactions with the environment and also with other students.

This PoC , like the first one, uses *Orkestra* for multi-user interactions management, and it has been compiled for both desktop and mobile (Android and iOS) platforms. A server is used to store and forward all the events and messages passed between the clients, and an online database is used to store the questions, answers and the progress of each student.

3.6 Final remarks

In this Chapter *cleAR*, an architecture enabling the creation of interactive and collaborative AR applications for education, was presented. To define the design objectives of *cleAR*, a survey of the existing literature on the subject was performed. Then, the architecture requirements were gathered from a survey completed by primary and secondary school teachers. *cleAR* is composed of four different modules, responsible for enabling multi-user interactions, data storage, data analytics and visualisation. Three demo applications were created to demonstrate that the architecture complies with the design objectives. *cleAR* will help developers in the creation of AR applications that could be easily included in existing school curricula. This in turn will provide the teachers with a suite of tools that enables them to keep records of student activity, add smart analytics and automatically create reports about student progress and retention.

Table 3.3: *Summary of design objectives fulfilled by each proof of concept application.*

	Design Objective				
Proof of Concept	Interoperability DO1	Multi-user DO2	Data Storage DO3	AI support DO4	Easy to develop DO6
AR Cube	✓	✓		✓	✓
xAPI Data Analysis		✓	✓	✓	✓
AR Geography Quiz	✓	✓	✓		

The PoCs developed demonstrate how *cleAR* fulfils the design objectives identified in both the literature and the conducted survey. Table 3.3 summarises which design objectives are satisfied by each PoC. AR Cube is clearly interoperable, as it has been tested on several operating systems. It also shows that multi-user capabilities can be easily integrated into any application. This PoC also implements an AI-based algorithm that automatically sets the value of the *dispatch time* based on the current network conditions. The xAPI Data Analysis PoC is a web-based application which allows multiple users to interact and stores the interaction statements in a learning record repository. Enabling storage of xAPI statements is straightforward, and AI support is guaranteed by the implementation of classification models which use the data gathered from the recorded statements as input features. The last PoC, AR Geography Quiz, is more complex than the first two PoCs. It has been developed for both web and mobile platforms and is inherently multi-user. It also demonstrates that *cleAR* enables data storage in the developed applications as all the interactions, as well as the questions and answers, are stored.

The architecture presented can work with most of the software suites currently in use to produce AR applications. Since it is modular, developers can choose which parts of the architecture should be integrated into existing applications. As the majority of existing AR apps are client only, the most critical aspect for integration with existing software is the provision of a server which provides all the desired functionalities. It is recommended at first to integrate the data storage and visualisation modules, and only later add multi-user and AI functionalities.

CHAPTER

4

Validation of the Proposed Architecture

This Chapter presents an application called *ARoundTheWorld*, a multiplatform AR application for education. It is based on the *cleAR* architecture presented in Chapter 3, and designed with the help of secondary school teachers. The app provides interoperability, multi-user support, integration with LMSs and data analytics capabilities, thus simplifying the development of collaborative AR learning experiences. *ARoundTheWorld* was developed with the purpose of validating, in an educational environment, the *cleAR* architecture. The application has been tested by 44 students and 3 teachers from 3 different educational institutions to evaluate the usability as well as the impact of collaboration functionalities in the engagement of the students.

4.1 Overview

In the last few years, significant improvements in both hardware and software have led to a proliferation of AR applications for mobile devices and AR headsets, and extensive research has been conducted on the integration of AR in education (Akçayır and Akçayır 2017, Chen et al. 2017a, Dinis et al. 2017, Ibáñez and Delgado-Kloos 2018, Masneri et al. 2022b, Pellas et al. 2019). However, despite these advancements and research efforts, the use of AR in primary and secondary schools is still not common (Commission et al. 2023). The main reasons behind this were identified in Chapters 2 and 3, namely the limited collaboration capabilities of existing apps, the inability to create new content and the difficulty of adapting to existing school curricula. In Chapter 3, *cleAR* was presented as an interoperable architecture. It enables the creation of multi-user AR applications and simplifies the development process. *cleAR* also allows the stakeholders to add new content to existing applications, track user progress and integrate application data into the LMS used by the teachers.

The analysis of the answers provided by the teachers allowed the identification of 6 DOs, as described in Section 3.4. A conceptual evaluation of the *cleAR* architecture was performed through the creation of 3 PoCs (presented in Section 3.5). The aim of this initial evaluation was to demonstrate that *cleAR* fulfils the aforementioned DOs.

This new Chapter builds upon such previous work and introduces *ARoundTheWorld*, a multiplatform collaborative AR geography game. The primary goal of the application is to demonstrate the potential of the *cleAR* architecture for creating interoperable applications that can be integrated into school curricula[1]. Additionally, the game aims to enhance student engagement through the collaborative functionalities provided by *cleAR*. The application has been developed incorporating feedback from the teachers of a Basque primary and secondary school association[2] and it has been evaluated after being tested with 44 students in three different educational institutions. Once the test was complete, teachers were interviewed while students were asked to fill in a short questionnaire about the *ARoundTheWorld* UI and the UX it offered. The questionnaire also asked about the app effectiveness as a tool for raising the engagement of the students and enabling collaboration between them. To perform a quantitative evaluation about *ARoundTheWorld* collaboration capabilities, the app collected data – in the form of xAPI statements (Clarke et al. 2020) – about its usage, the number of interactions between students and their performance.

The choice of Geography as the application domain is motivated by the fact that geographical exploration is an integral part of child development (Catling 1993), and the use of maps helps students improve spatial thinking skills (Collins 2018). The application is structured as a quiz where students take turns to answer Geography questions.

[1]The application is open source and the code can be accessed at `https://github.com/tv-vicomtech/ARoundtheworld`

[2]`https://ikastola.eus/`

If a student is struggling to answer a question, other students can interact in the augmented space and provide hints to the active user. *ARoundTheWorld* works both as a mobile and a web application, is easily extensible and provides several logging and tracking mechanisms, which can be easily integrated into the LMS of the school to enable automatic tracking of the progress of the students.

The main contributions of this Chapter can be summarised as:

- A complete description of the application and the feasibility of implementing the different components of the *cleAR* architecture to fulfil all the design objectives.
- A qualitative evaluation of the technology integrated in the application, based on the questionnaires filled in by the 44 students and the interviews with their teachers.
- An analysis of the data collected by the application during the user study, with a focus on the effects of collaboration capabilities on the quiz results and the engagement of the students.

The number of users who participated in the study is not representative of the whole student population. The aim, in this case, is not to demonstrate the positive effects of AR in schools, but rather to validate the architecture presented in a real educational setting, and not only through the development of PoCs.

The rest of the Chapter is structured as follows: Section 4.2 covers the relevant state of the art. Section 4.3 describes the implementation details of *ARoundTheWorld*, while Section 4.4 outlines our methodological framework and the evaluation process. In Section 4.5, the results obtained from the student questionnaires and teacher interviews are described, together with the quantitative analysis of the data collected through the application. Finally, Section 4.6 presents some final remarks.

4.2 **Related Work**

A recent review of AR applications used in education (Iqbal et al. 2022) mentions that collaborative learning in AR represents a critical research direction, but so far very few studies provide collaborative functionalities in an AR environment (Choi et al. 2017, Pan et al. 2021). The work from Cai et al. (2017) presents an application that makes use of a Kinect camera to extract 3D information from the scene and display virtual magnetic induction lines. In (Takahashi et al. 2018), the authors designed a large scale AR and projection system, modifying the gymnasium of the school, to create a learning game for children with ASD, which was designed to keep their attention focused on the content provided. Laviole et al. (2018) presented a markerless application for learning how an artificial neural network works, where the students can manually tweak the values of the network parameters and see how it affects the ability of the network to classify images.

As it heavily relies on visual representation of data, several technologies have been exploited to make the teaching of Geography more effective and engaging. In the context of AR, Palaigeorgiou et al. (2018) used a projector to create tangible 3D maps with which up to three students could interact at the same time. Xefteris and Palaigeorgiou (2019) extended the concept of tangible maps by including the usage of programmable robots to guide the students through a virtual journey. A collaborative AR app for teaching geography and geology is the one presented in (Wellmann et al. 2022). The app relies on a AR sandbox[3] to display the content and it allows teacher to modify its behaviour by writing code in the form of Jupyter notebooks.

As far as evaluating the effectiveness of AR applications for education, the vast majority of the studies highlight a positive (albeit limited) effect derived from using the technology. Chang et al. (2022a) performed a meta-analysis of 134 studies which suggests that AR benefits all the learning outcomes evaluated, with the largest effect being on students performance. A systematic review of 45 studies (da Silva et al. 2019) reaches the same conclusions, but highlights the many differences in the evaluation protocols, which complicate the statistical analysis of AR effectiveness across different applications.

AR applications are often implemented as serious games, in which using gamification concepts the students can more easily learn and retain concepts that would otherwise not interest them. Oh et al. (2017) described a game-based simulation where the users can study the properties of light such as reflection and refraction. López-Faican and Jaen (2020) created a multiplayer game in which children can improve their communication skills by practicing in an AR environment, while Çelik and Yangın Ersanlı (2022) described a gamified AR app used in a Content and Language Integrated class.

[3] `https://ar-sandbox.eu/`

Several publications focus on the importance of effective UIs and UXs in enhancing student engagement. A systematic review of the literature analysed 49 studies (Law and Heintz 2021a) and identified a lack of information about usability and user experience frameworks, suggesting that there is a disconnect between Human-Computer Interaction (HCI) and TEL communities, as well as a lack of AR-specific UX evaluation metrics. The work of Thamrongrat and Law (2019) evaluated the learning effect for teaching 3D geometry using an AR application compared to traditional learning, as well as the user engagement of the students using the app compared to the ones in the control group. Another study (Alrashidi et al. 2017) compared the effectiveness of learning software debugging concepts using an AR application versus a non-AR approach.

Applications used in schools usually generate data that are stored on the school LMS. A standard that is recently gaining traction for collecting data about the activities of the learners is eXperience API, an open-source software specification that makes it possible to collect data about a wide range of learning experiences. This is achieved by sending each activity that needs to be recorded to a LRS in a consistent and secure format (Clarke et al. 2020). The activities are collected as statements stored as JSON objects. Statements can be tuned to a specific use case by defining a vocabulary of valid statements. Secretan et al. (2019) described a system where xAPI is used to perform learning analytics in an AR environment, while Wu et al. (2020) used xAPI to collect data for a 3D design course.

4.3 Collaborative AR application

This Section describes how the application is implemented and how the developed application fulfils the DOs presented in Section 3.3.3. The application, called *ARoundTheWorld*, is a collaborative geography quiz in which students answer a set of questions prepared by the teacher. Once started, the application sends a question to the first student (for example, *Where is Kyoto?*). The student answers by placing a pin on the 3D globe of the Earth shown in the augmented space. Other students can collaborate with the active user in two ways. They can suggest to her in which continent the answer is located and – once the user has placed the pin but has not confirmed her choice yet – by sending a *thumbs up* or *thumbs down* feedback[4]. Once a student answers, the application sends a new question to the next user, and repeats the process until all the

[4]A video description of the application is available at this link: `https://anon.to/a7NPy8`

questions have been answered. Figure 4.1 shows the application workflow, highlighting the interactions of teacher and students.

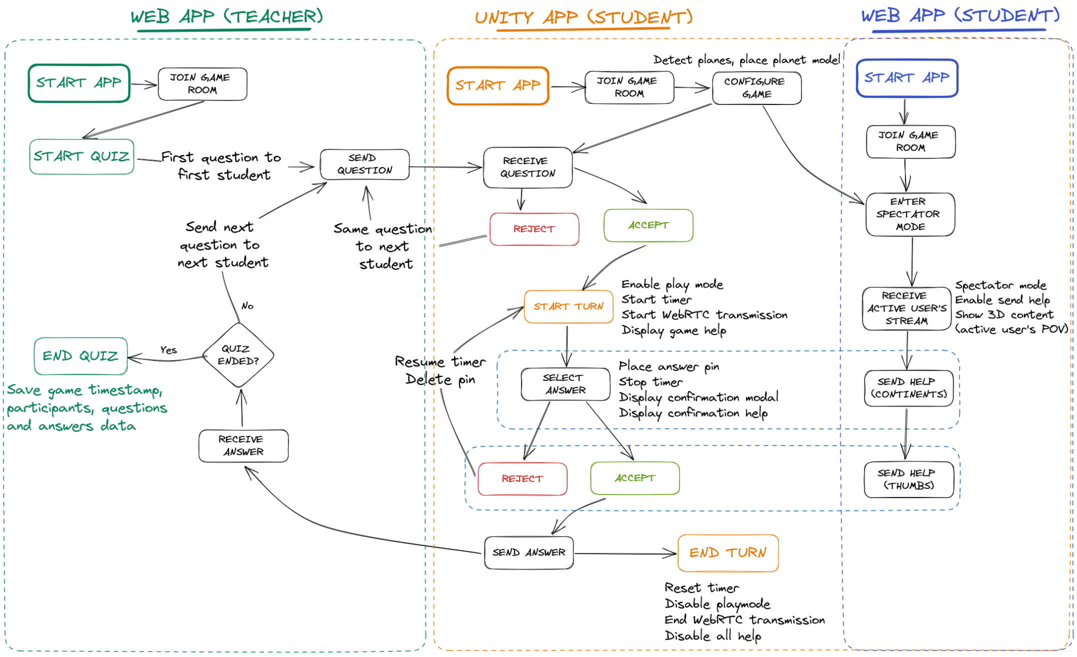

Figure 4.1: *Workflow of the ARoundTheWorld application.*

The application considers three types of users (*teacher*, *players* and *watchers*), depending on their role and their means of interacting with other users. The first role is that of the students participating in the quiz, – the *player* – described above. Another role is that of the *teacher*, who controls the overall status of the app through a web-based interface. The final role – the *watcher* – is that of the students who are not actively participating in the quiz (i.e., they are not answering any questions). They can watch what other students are doing and give them clues to find the correct answer. This role was designed to let students without an AR capable device engage with the players by checking what they are doing and collaborate with them by suggesting the correct answer.

The application is designed to require minimal supervision from the teacher to let him or her interact as much as possible with the students. As shown in Figure 4.2, the teacher interface consists of four parts:

- A 3D representation of the augmented content as viewed by the active user (that is, the student who is answering the current question).

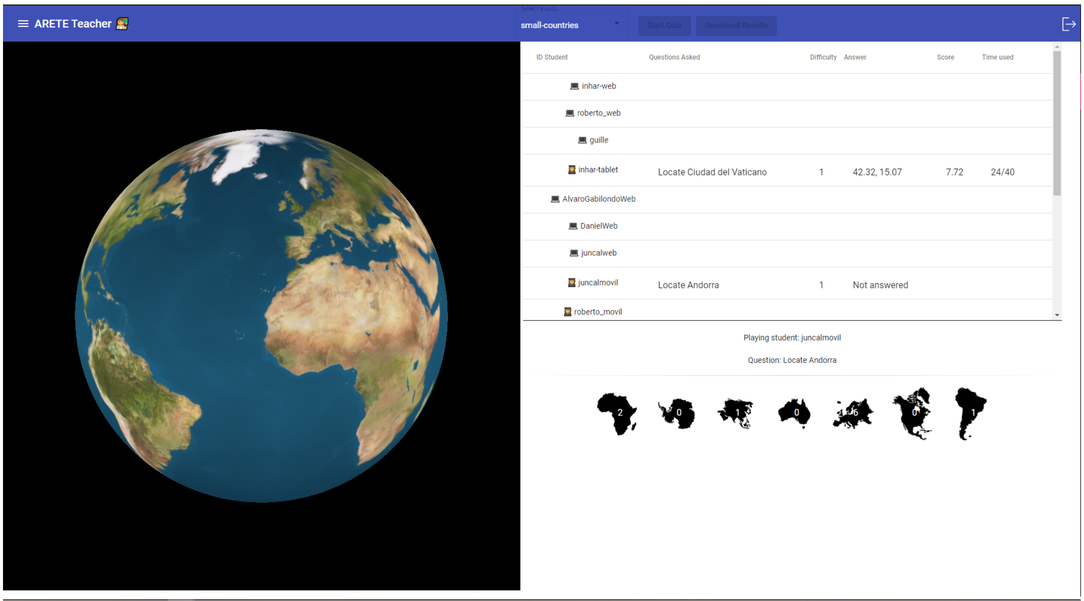

Figure 4.2: *The web-based teacher interface of the ARoundTheWorld application.*

- The list of users connected to the app, together with the current score of the players and the last question they answered.
- The suggestions sent to the student currently answering the question.
- A dashboard (accessible in a separate tab) with charts of the scores achieved by each student across different sets of questions.

The teachers who filled in the questionnaire described in Chapter 3 mentioned that one of the factors limiting the usage of AR apps in schools is the lack of customisation capabilities. In this respect, *ARoundTheWorld* provides an additional web interface from which the teacher can create new sets of questions. To minimize the amount of work required by the teacher, the coordinates of each location are computed automatically using the Wikimedia API[5] and the questions are stored as JSON files, which are directly added to the application. The interface of the *watchers* is web-based, too, and has a look and feel similar to the teacher interface.

For the application to successfully achieve interoperability (**DO1**), several types of hardware as well as software libraries need to be supported. In the aforementioned survey, the teachers reported a wide spectrum of devices available in their schools.

[5] `https://www.mediawiki.org/wiki/Wikimedia_REST_API`

Chromebooks and Android tablets were the most commonly used but other options included laptops, PCs, smartphones (both Android and iOS based) and iPads. Furthermore, while none of the teachers reported using AR headsets such as HoloLens, it is believed that such devices provide the best AR learning experience for users. For this reason, the application supports Microsoft Mixed Reality Toolkit and is fully compatible with HoloLens devices. The application for mobile and tablet devices has been developed using Unity 2020.3 and the AR functionalities are provided by the AR Foundation framework. The web application has been built using Typescript and Three.js (to enable 3D content to be displayed in the browser). All the logging data and the statements collected during app usage are stored in a Mongo database in the Learning Locker instance deployed on AWS. Porting to HoloLens and iOS devices is achieved through, respectively, Unity integration with Microsoft MR Toolkit and by exporting the Unity project file to an XCode environment.

The application supports multi-user capabilities (**DO2**) by relying on the functionalities provided by the *cleAR* architecture, which provides the *Orkestra* library for sharing 1-to-1 or broadcast message passing (Masneri et al. 2022a) with minimal changes to the existing code base. When a student is asked to answer a question, she becomes the active user. She shares the camera position (which determines her view of the 3D globe) as well as the position of the pin, once placed, with the other users. The other students will then see, on their devices, the 3D globe in the same way the active user does. For users on a mobile device this happens directly in the augmented space, while users using a PC will see the globe in a virtual 3D environment on a `<canvas>` element. At the same time, suggestions from users are shared in a broadcast fashion, so that every student knows about the suggestions sent by others. Finally, the teacher interface shares information about the current question, the score obtained by the active user after receiving her answer and the cumulative score of each user. The information is shared 30 times per second and it allows a smooth UX for every participant. The bandwidth usage is low since only basic data types such as strings and numbers are shared between users and the delay is below 15 milliseconds on both WiFi and mobile networks. A previous approach tried to combine message passing and the transmission of the screen of the active user, using WebRTC, to the students using a PC to better simulate the AR experience (Matsumoto et al. 2023). Unfortunately, such a solution has proven not to be scalable. Due to the poor support Unity has for WebRTC servers such as Janus, the application suffered delays which severely impacted the performance. With more than

5 users the UX was severely affected, and the app became unusable when more than 10 users were connected to the same session.

To comply with the data analytics design objectives (**DO3**, **DO4** and **DO5**) the application enables data collection through the storage of xAPI statements on a Learning Locker instance. Storing statements across each session enables the application to keep track of user activity and to store additional logging messages that simplify application debugging. Learning Locker provides basic analytics and plotting capabilities through a web interface, as well as filtering and exporting the data in CSV format. These functionalities have been extended through the development of a Python package[6] that includes methods to perform advanced data exploration and plotting, as well as running common machine learning models on xAPI statements data. One of the aims of the package is to simplify data analysis as much as possible, enabling teachers without development skills to extract valuable information from the collected data. For this reason, the package directly integrates GPT-4 (OpenAI 2023, Osmulski 2023), so that users with a valid OpenAI Key can use natural language to debug or generate code when needed. The package has been used to analyze the data collected during the evaluation of the app and the results will be presented in Section 4.5.

Finally, to demonstrate how the aforementioned architecture enables developers to easily create multi-user applications (**DO6**), the developer of *ARoundTheWorld* was asked if and how the architecture helped him in the development process. The developer mentioned that the architecture API enabled him to add multi-user functionalities in a transparent way. He neither had to deal with low-level networking issues nor implement platform specific methods. While it was not possible to estimate the amount of lines of code or hours saved by using *cleAR*, the developer said that he was satisfied with the capabilities of the architecture and would use it again for future projects. Nevertheless, in order to enable teachers to create an ecosystem of collaborative AR applications for education, the developer mentioned that the availability of authoring tools to easily create applications on top of the *cleAR* architectural design would be desirable.

4.4 **Evaluation**

Our study aims to investigate how collaborative AR solutions may benefit the learning experience, and which are the usability issues of multi-user, multiplatform applications.

[6] `https://stocastico.github.io/xapi_analysis/`

In the literature, unfortunately, there is no agreement on how to conduct evaluation of AR-based educational apps. The survey from Santos et al. (2013) analyses 87 AR applications and the evaluation protocols included interviews, observing and coding overt behaviour and expert reviews. Of those who used questionnaires, the majority crafted their own. Among the works that used established questionnaires, some relied on the ISONORM Usability questionnaire (Prümper 1999), Technology Acceptance Model (Davis and Venkatesh 1996), Constructivist Multimedia Learning Environment Survey (Maor 1999), Instructional Material Survey (Keller 1987), Intrinsic Motivation Inventory (Ryan and Deci 2000). The number of participants in the evaluation of AR applications for education varies a lot depending on the study. The systematic review of the literature published by Masneri et al. (2020), of which Chapter 2 represents an extension, shows that the number of participants varies between 2 and 290 participants. Another survey by Santos et al. (2013) analysed studies where the number of participants ranged from 4 to 419.

In this work, a questionnaire which adapts and extends the Positive System Usability Scale (P-SUS) (Brooke et al. 1996, Sauro and Lewis 2011) was used. The questionnaire included a few additional questions to specifically evaluate the collaborative capabilities of the application. The questions, presented in Appendix B, were grouped into 4 classes depending on what they were evaluating: the interest of the application as an educational tool, the usability of the app, its collaboration capabilities and its functionality. Additionally, the participants could provide free-form feedback about the overall experience and whether they would recommend it to other students. Finally, an interview with the teachers was conducted to collect their feedback about the learning experience, how collaboration may impact the involvement of the students, how AR apps could be used to evaluate the students knowledge of a subject and how they would take advantage of the data collected through the application.

At the beginning of the evaluation, the participants were briefed about the experiment and its purpose and were asked to sign a consent form. The questionnaires were anonymous but had an ID associated, so that during data analysis it was possible to associate the answers to the questionnaires with the data collected from each device through the xAPI statements. The evaluation involved 44 students from 3 educational institutions in San Sebastian (*Colegio Salesianos Donostia*[7], *IES Xabier Zubiri Manteo*[8]

[7]`https://www.salesianosdonostia.com/es`
[8]`https://zubirimanteo.hezkuntza.net/es/inicio`

and *Universidad de Deusto*[9]) between March and May 2023. Each experiment involved students of different ages (14, 17 and 19 years old) and their corresponding teachers. None of the participants had previous experience with AR applications, but they were familiar with the hardware devices (smartphones, tablets and PCs) used during the evaluation. In each school, the students were split into two groups: the first one represented the *players*, tasked with answering the quiz questions using the application on mobile or tablet devices, while the second group represented the *watchers*, who used a laptop or PC to see how the students answered the quiz and provided suggestions along the way. Table 4.1 shows the number of participants in each experiment, as well as details about the type of devices used when interacting with the application.

Table 4.1: *Details of the demographics and number of devices used across each test.*

Participants	Gender		Players		Watchers	**Total**
	Males	Females	Tablets	Smartphones		
14 year-old	9	8	4	5	8	**17**
17 year-old	16	1	3	6	8	**17**
19 year-old	6	4	3	6	1	**10**
Total	**31**	**13**	**10**	**17**	**17**	**44**

Once each participant had a device assigned, they were asked to connect to the application by selecting the session ID representing the experiment and the user ID. The latter would be used as the *Actor* value for the xAPI statements generated while using the application. After a short Q&A session to clarify doubts about the app usage the teacher started the quiz and the students would then take turns to answer two sets of questions. Once the quiz was over, the teacher stopped the data collection and was able to check the score of each student and to export the data. After logging out of the session, the students filled in the questionnaires while the post-study interview with the teacher was conducted.

4.5 Results and Discussion

In this Section, the results of the survey as well as the data collected from the app are presented and discussed. An extended version which also includes a subgroup analysis

[9] `https://www.deusto.es/es/inicio`

of the data split for different age group, is available in the code and data repository[10]. The quantitative results from the responses to the post-intervention survey (shown in Appendix B) are summarised in Figure 4.3. They are shown as stacked bar charts (Friedman and Amoo 1999), where the chart on the left refers to the answers to each question and the chart on the right to the groups of questions mentioned in Section 4.4. From the figure it can be appreciated that the application was very well received by the students and that every question except the first one was answered positively (*Agree* or *Strongly agree*) more than 60% of the time. The average rating for each question ranges from 3.45 to 4.43, with limited variability across answers, with the standard deviation being below 1 for most of the questions. The plot on the right in Figure 4.3 shows similar results: the students assigned the highest score to questions related to Usability, especially question 2 (*I found the application to be simple*) and 3 (*I thought the application was easy to use*). The questions related to Functionality received a high score as well, while the ones relating to the Educational content of the app show the highest variability: those questions received the highest amount of negative answers while also receiving the highest score more than 40% of the time.

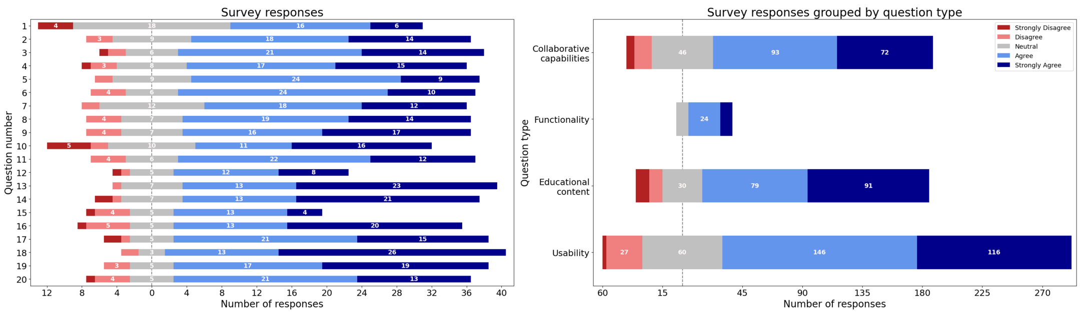

Figure 4.3: *Left: survey results on each question. Right: survey results grouped by question type.*

The bar plots of Figure 4.4 are used to identify differences in the answers of the students, based on their role when using the app and the device they used. Somewhat surprisingly the *watchers* gave a slightly higher mean score, albeit with a much higher variability in the answer. As for the device type, the users on an Apple device (iPhone or iPad) gave a higher score compared to students using an Android device or a PC, but the differences are not statistically relevant.

[10] `https://github.com/Stocastico/Evaluation_paper`

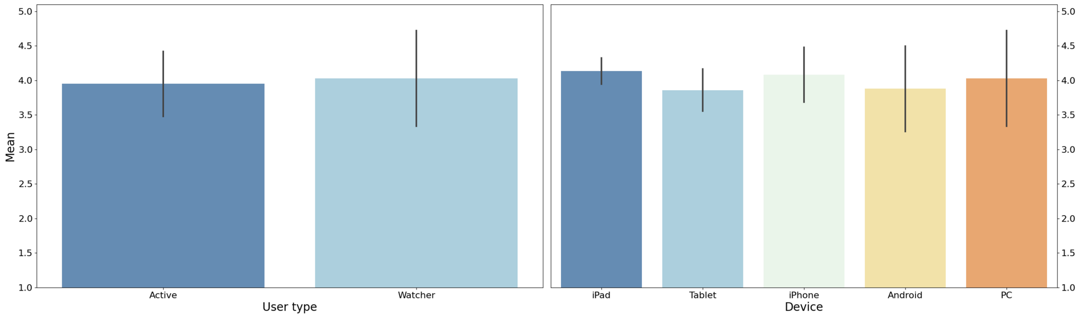

Figure 4.4: *Mean score of the questionnaire answers. The vertical bars represent the standard deviation.*

Figure 4.5 shows the mean score and the standard deviation for the questionnaire answers grouped by user. It shows the split of the students by age, their role when using the app and the device they used. From this visualization an outlier can be easily identified, represented by the only student in the 19 year-old group who used a PC and was the only non-active user in that session. The reason for the lower score, as identified by the comments provided by the student in the questionnaire, was that the experience for him did not feel particularly immersive nor collaborative, as his role was fairly different from that of his classmates.

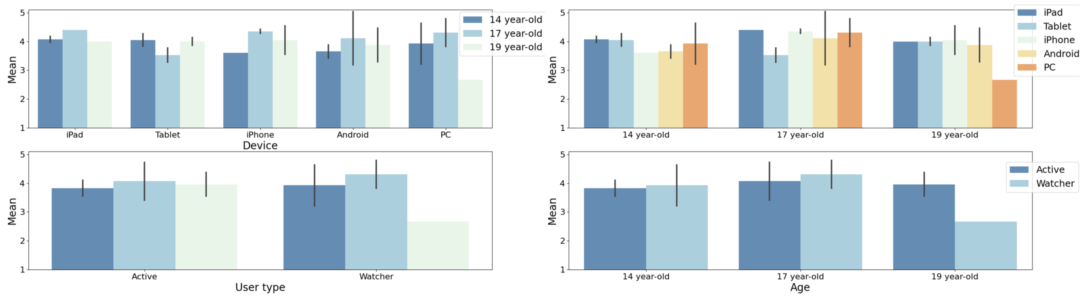

Figure 4.5: *Survey results split by user type. Left: Average question score by device used and student role. Right: Average question score by students age.*

Since *ARoundTheWorld* collected data in the form of xAPI statements, an analysis of the data received was conducted. This showed that there is a correlation between the score in the questionnaire and the number of statements collected by the application for each user. The actions registered by the app include both interactions between students, such as the suggestions sent, and the interactions of a user with the app. As shown in Figure 4.6, there is a high variability in how much the students interacted. It is clear, though, that the *players* (the students using a mobile device and interacting with the augmented content) were much more involved in using *ARoundTheWorld*. This is probably because their role was much more interactive and immersive.

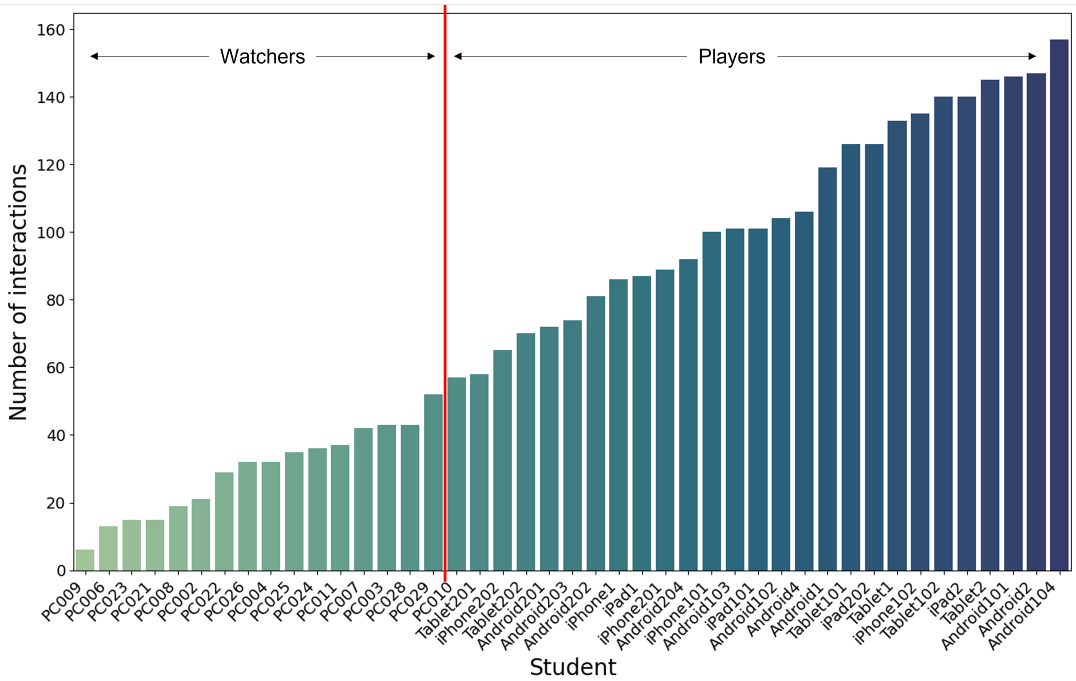

Figure 4.6: *Interactions with the application for each student (identified by the device used).*

An interesting aspect to analyse is whether there is any correlation between the number of interactions of each student and the answers they have given to the survey questions. Two statistical approaches were followed. First, a correlation analysis was performed to check whether there was a relation between the number of interactions and the average scores given to the questions by the students, by calculating the Pearson correlation coefficient. The second approach is that of hypothesis testing. This checks whether the answers given by students with a high number of interactions are significantly different from the answers given by students who had a low number of interactions. A two-sample T-test assuming equal variances has been used for testing (Welch 1947). In both cases, a significance level of $p < 0.05$ was established. Since the interactions between the *watchers* (students on a PC) and *players* (students on a mobile device) are significantly different, it was also performed an analysis for these specific subsets of the data as well.

Unfortunately, the analysis performed is not conclusive. None of the tests returned a p-value below the significance level, and the correlations identified (most notably between the interactions of students on a PC and their answers to the survey) are not statistically significant.

A similar analysis was conducted to inspect whether there were correlations between the score obtained in the quiz and the answers in the survey. In this case as well, no statistically significant correlation was found. This was expected since the app was designed to ask questions of varying difficulties, but the difficulty level of the questions received by a student did not change during the test. As expected, students who received easier questions achieved a higher score and there is indeed a significant correlation between these two variables.

Another interesting correlation to analyse was the one between the mean score obtained in the survey and the number of suggestions sent by the user. The statements about suggestions are an interesting variable because for each question, every user (besides the *active player*, the one answering the current question) was able to send two suggestions. For this reason, many such statements were collected during the trial. To encourage students to provide suggestions, the application assigned points for each correct suggestion. In this case the analysis showed a significant positive correlation ($r = .37$, $p = .044$), meaning that the most engaged students were the ones that gave a higher score in the survey.

Finally, a clustering analysis of the data was performed, to check if it is possible to identify distinct groups of users. In this case, the focus was only on the students who used a mobile device, since they provided a greater number of features to work with. The average time left per question, the number of suggestion accepted, the total number of interactions and the mean value of the answers in the survey were the four variables considered. A dimensionality reduction using PCA (Jolliffe 2002), shown on the left in Figure 4.7, revealed that the first two principal components explained more than 70% of the variance in the data. Additionally, a biplot analysis indicated that the most relevant variable for the first principal component was the number of user interactions, while for the second one it was the results of the survey.

As the number of data points is small, a hierarchical clustering algorithm (Caliński and Harabasz 1974) was used. A Silhouette score (Rousseeuw 1987) computed for cuts between 2 and 6 suggested that the optimal number of clusters in this case was either 2 or 4. The clustering results (shown in Figure 4.7, right) identified one big group of students characterised by having a particularly high number of interactions and another one having a higher score in the survey answer. The other two clusters were harder to characterise. In one case it was not possible to clearly identify a common feature in the data, while in the other the cluster only contained two members, and the intra-cluster variable suggests that those data points are probably outliers.

After running the trials in the educational institutions, a post-intervention interview with the teachers was conducted. The 3 teachers seemed very intrigued by the possibility of easily being able to use AR in school without having to resort to any specific hardware. They especially valued the fact that the collaborative features of *ARoundTheWorld* encouraged the students to work together to provide the answer, either through the features of the application or simply by talking to each other. Another relevant point for the teachers was the possibility of adding new content on their own, as well as the fact that they could export the results to the school LMS. The teachers were more sceptical about the AI features provided by the backend. They mentioned that the vast majority of their colleagues do not have sufficient knowledge to perform the analysis on their own. They would rather prefer using a PowerBI or Tableau interface to visualise data and extract basic reports. The teachers also mentioned that the role of the *watchers* was too passive and that in longer experiments these students might lose interest. They suggested enabling the role of active user when using a PC, even if that means not using AR components but a browser-based 3D graphics library.

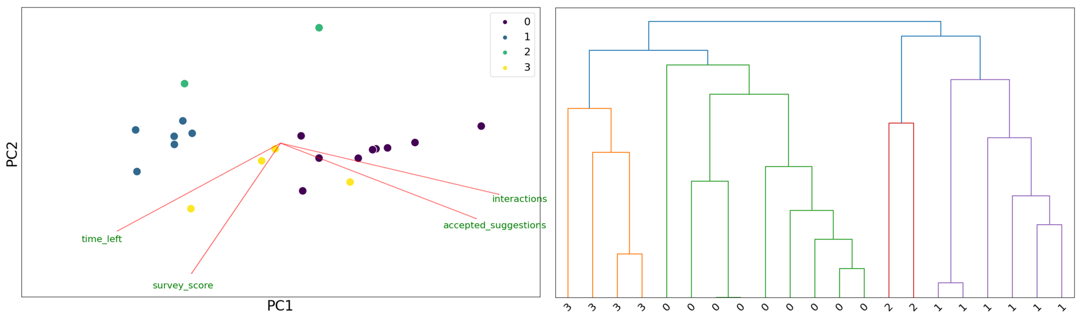

Figure 4.7: *Left: Clustering of the active users data on the PCA space. Right: the dendrogram representing the hierarchical clustering.*

4.6 Final remarks

In this Chapter, *ARoundTheWorld* was presented, a multiplatform AR application which implements collaborative capabilities and gamification concepts. The application is based on a Geography quiz and it fulfils the design objectives identified in Chapter 3. The evaluation, conducted with 44 students and 3 teachers, and the analysis of the xAPI statements showed that students evaluated very positively the application. Additionally, it was measured a small but statistically significant correlation between the ratings in the questionnaire and the engagement of the students. Furthermore, post-study interviews with the teachers identified the collaborative capabilities and the possibility of personalising the app content as being key factors for a sustained usage of AR apps. In fact, one of the teachers suggested the possibility of adding more collaborative features, such as a chat system or speech-based interactions to make the application more immersive and more appealing when used in a distributed setting.

Part IV

Conclusions

CHAPTER

5

Conclusions and future work

In this final Chapter, the main findings of this research are presented. Besides summarising the Ph.D. work, the scientific contributions are presented and potential directions for future research are explored. Different ways to extend the work outside the field of education or applying it to other technologies beyond AR are suggested.

5.1 Summary

This dissertation has demonstrated that it is possible to develop collaborative, multi-platform AR solutions for education thanks to a modular architecture that provides useful functionalities for both software developers and educators. This work has been possible thanks to an extensive collaboration between researchers, educators and software developers, as well as through the participation in the ARETE project.

At first, an extensive study of the state-of-the-art was performed to analyse recent research work where AR applications for education were described. The aim of the study was threefold:

- Identify the works describing interactive, multi-user or collaborative AR experiences and compare their main features.
- Understand the motivation behind the usage of AR as an educational tool.

- Measure the impact of using AR in the classroom, by analysing pre-/post- test results or comparing grades versus a control group.

The systematic study of the literature clearly identified a lack of works where multi-user collaborative apps are presented, as well as the lack of a common framework providing multiplatform support for such applications. This led to the decision of developing *Orkestra*, an open-source library that enables real-time communication between different devices and that, thanks to C# and Python bindings, can be used on many different platforms such as web apps, iOS or Android devices and HMDs like the Microsoft HoloLens.

Then a collaboration with teachers from secondary schools was established to pinpoint what are the limiting factors in the adoption of AR applications in education and what these apps should provide in order to be used effectively. Based on the teachers answers, eleven requirements (summarised in Table 3.1) were identified, and an architecture was defined based on six design objectives: interoperability (DO1), multi-user support (DO2), data collection (DO3), data visualisation (DO4), AI-based analytics (DO5) and ease of development (DO6).

An architecture named *cleAR*, that fulfils all the aforementioned design objectives, was developed and tested through the development of three PoCs (*ARCube*, *xAPI Data Analysis* and *AR Geography Quiz*). The architecture is composed of 4 different modules (Real-time multi-user interactions, Data storage, AI-based analytics and Visualisation tools). A modular architecture offers several advantages, since it is easier to extend and maintain. It also allows developers to choose which modules to include in their existing applications.

Finally, the architecture was validated by implementing a multi-user Geography quiz. The application, called *ARoundTheWorld*, has been tested by 44 students with ages ranging from 13 to 19 under the supervision of 3 teachers. A set of post-study interviews with the teachers, the analysis of the surveys filled in by the students after using the apps and the analysis of the data collected during the app usage demonstrate that the application fulfils the requirements identified by the teachers. All the code developed during this research has been released as open-source to enable researchers to build upon this work and further enable the usage of AR solutions in the education sector.

In summary, this research provides progress beyond the state of the art for the usage of collaborative AR solutions for education, by presenting an architecture that takes into account the teachers requirements for using AR solutions at school. Applications based on *cleAR* can be adapted to the specific needs of the teachers, integrate with the LMS of the school and provide valuable data to analyse the progress of the students.

5.2 Contributions

The main contribution of this research has been the definition of an architecture for the creation of multi-user AR experiences across different platforms, general enough to be easily adapted to many different use cases and scenarios and ready for any technological update such as the release of new hardware devices or software libraries.

As a result of the objectives mentioned in Section 1.3, the main contribution can be translated into four specific outcomes:

C1: An in-depth analysis of the state-of-the-art that allows to identify the state of current research on AR in terms of what kind of solutions are currently used in schools, what is the motivation for using AR in education and what effect does AR applications have on students motivation and retention of the topics studied. This is described in Chapter 2 and reflected in publications P1 and P2.

C2: The development of a multiplatform software library, called *Orkestra*, which allows multi-user interactions in real-time applications. This is described in detail in Section 3.4.1 and reflected in publication P3.

C3: The definition of *cleAR*, a modular architecture for the creation of AR solutions that satisfies all the requirements identified by teachers and that enables in a seamless fashion multi-user capabilities. This is described in Chapter 3 and reflected in publications P4 and P5.

C4: The implementation and validation of *ARoundTheWorld*, an AR application based on the architecture, that has been tested in three different educational institutions and that validates all the required design objectives. This is described in Chapter 4 and reflected in publications P6 and P7.

The contributions delivered the following publications:

P1: Masneri, S., Domínguez, A., Wild, F., Pronk, J., Heintz, M., Tiede, J., Nistor, A., Chiazzese, G., & Mangina, E. (2020). **Work-in-progress-ARETE-An Interactive Educational System using Augmented Reality.** In D. Economou, A.

Klippel, H. Dodds, A. Pena-Rios, M. J. W. Lee, D. Beck, J. Pirker, A. Dengel, T. M. Peres, & J. Richter (Eds.), 2020 6th International Conference of the Immersive Learning Research Network (iLRN): Conference Proceedings (pp. 283-286). `https://doi.org/10.23919/iLRN47897.2020.9155186`

P2: Masneri, S., Domínguez, A., Zorrilla, M., Larrañaga, M., & Arruarte, A. (2022). **Interactive, collaborative and multi-user augmented reality applications in primary and secondary education. A systematic review.** JUCS-Journal of Universal Computer Science, 28(6), 564-590. `https://doi.org/10.3897/jucs.76535`

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P6: Masneri, S., Domínguez, A., Pacho, G., Zorrilla, M., Larrañaga, M., & Arruarte, A. *(Submitted in 2023, July).* **A Collaborative AR Application for Education: from Architecture Design to User Evaluation.**

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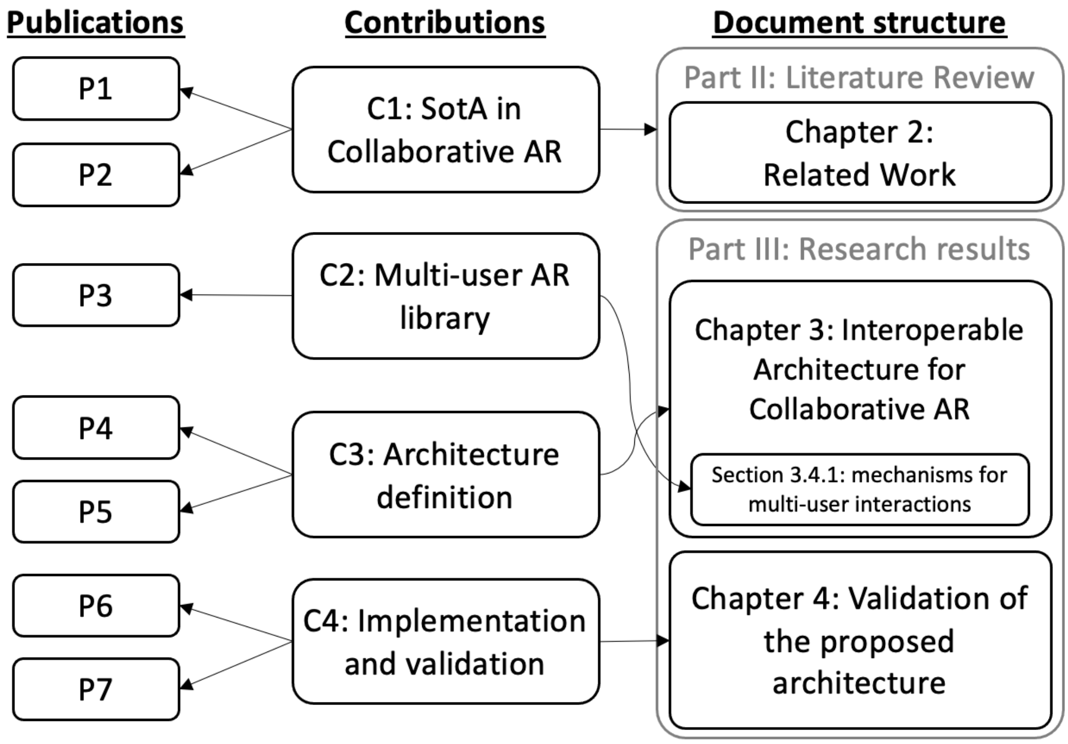

Figure 5.1: *The relations between the work described in this document, its main contributions and the publications produced.*

Figure 5.1 summarises the contributions of this work and its related publications. Furthermore, all the code developed is available as open source in several GitHub repositories:

- The data analysis conducted while performing the systematic literature review described in Chapter 2 is available at `https://github.com/Stocastico/AR_SLR_Paper`.
- *Orkestra* has separated repositories for the client (`https://github.com/tv-vicomtech/orkestraClient`) and server (`https://github.com/tv-vicomtech/orkestraServer`) implementations, as well as a separate one for the Unity version (`https://github.com/tv-vicomtech/orkestralibUnity`).

- The 3 PoCs created for the conceptual evaluation of *cleAR*, together with the (anonymised) data collected from the teachers surveys, are available at `https://github.com/Stocastico/ARchitecture_paper`, and the library used to simplify the analysis of xAPI statements is available at `https://github.com/Stocastico/xapi_analysis`.

- The code of *ARoundTheWorld* is hosted at `https://github.com/tv-vicomtech/ARoundtheworld`, while the data collected from the students questionnaires and their analysis is available at `https://github.com/Stocastico/Evaluation_paper`.

5.3 Future work

Throughout the development of the research work, the analysis of the literature, the definition and evaluation of the architecture and the interviews with the teachers, several opportunities to complement and extend the research were identified.

Developing an authoring tool which simplifies and speeds up the creation of collaborative AR experiences would enable creators to greatly increase the availability of AR educational software. While this is not a new idea (Rajaram and Nebeling 2022, Thanyadit et al. 2022), so far no such software has been used to create commercial applications, and there are no authoring tools which allow incorporating collaborative capabilities in AR applications.

Related to the development of an authoring tool is the addition of AI-based tools that enable the creation of 3D models, either from static 2D images (Mildenhall et al. 2021) or from text description (Deitke et al. 2023, Poole et al. 2022), since the creation of the 3D assets is one of the most time-consuming tasks when developing AR content. Including such functionality in an easy-to-use way, ideally through a front-end which directly interact with the authoring tool, would enable the creation of AR apps without the need of professional software developers or 3D designers.

AI models could also be further integrated in the architecture. While a basic support is already available, both for the optimisation of parameters in the application and for supporting the analysis of the data, more advanced models such as chatGPT Code Interpreter (OpenAI 2023) could fully automate the data analysis tasks, which the teachers consider hard to complete on their own. Furthermore, other generative models could be used to speed-up the development or the creation of new content.

Another future research direction revolves around enabling the *cleAR* architecture to support newer hardware platforms, for example the recently released Apple AR Vision Pro. So far, the architecture supports several platforms (Microsoft HoloLens, web, Android and iOS devices), but it lacks software that enables to easily add support to other ones. Restructuring the code in such a way would make the architecture able to support a wider variety of platforms as well as making it easier to maintain in the future.

Finally, it would be interesting to extend the scope of this research to other domains. On one side, it should be straightforward to extend the architecture to VR applications since every functionality should work out of the box, provided that support for different hardware (like Oculus Quest, for example) is added. On the other side, it would be interesting to investigate how *cleAR* should be modified to support use cases in other domains such as medicine or manufacturing. Collaborative AR has several applications in these domains, but the requirements of an architecture analog to the one presented in this work are probably different from the ones described in Chapter 3, and this will in turn lead to different design objectives.

Part V

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Part VI

Appendix

APPENDIX

A

Teacher survey

This is the survey that was presented to the teachers and whose results helped defining the requirements of the architecture presented in Chapter 3. The survey was created as a web-based form and, depending on how a teacher answered, not all the questions were presented. The survey included also some background information as well as images. Furthermore, some of the questions only admitted answers from a predefined set. We omitted these redundant information for brevity, but the interested reader can find the full version of the survey online[1].

	Question
Q1	What is the main subject you teach?
Q2	How many years of experience do you have?
Q3	What is the average number of students per class in your school?
Q4	What is the educational level of your classes?
Q5	Are you a dynamizer in your school?
Q6	How many smartphones are available in your schools?
Q7	How many tablets are available in your schools?
Q8	How many desktop PCs are available in your schools?
Q9	How many laptops are available in your schools?

[1] `https://anon.to/oBIuF6`

	Question
Q10	If other devices are available, please specify the type of device and the number.
Q11	Have you ever used technological tools to facilitate student learning, beyond office tools or video calls? These tools can be mobile applications, web applications, 3D visualizations, simulations...
Q12	What tools have you used?
Q13	What aspects would you highlight of the tools you have used?
Q14	Which of the following aspects are present in the tools you have used?
Q15	Have you used augmented reality during your teaching years?
Q16	Do you think that augmented reality applications could facilitate the learning of your students?
Q17	Would you like to use augmented reality more often during your classes?
Q18	What do you need to use (or increase the use of) augmented reality in your teaching?
Q19	What kind of devices have you used to teach with augmented reality?
Q20	How would you evaluate your level of satisfaction using augmented reality in your teaching?
Q21	How should AR apps change to improve your satisfaction when using them?
Q22	How comfortable do you feel using augmented reality in your teaching?
Q23	Do you believe that using AR apps in class has favored students learning?
Q24	What kind of applications (not necessarily augmented reality) would you like to use in class?
Q25	How would your students use this app?
Q26	Do you think that augmented reality can be an added value in teaching?
Q27	What do you think are the advantages of augmented reality when using it at school?
Q28	And what are its drawbacks?
Q29	Do you think that technology (not necessarily augmented reality) can help teachers measure student learning and the ability to retain the subjects studied?
Q30	What features are you most interested in in an augmented reality application?
Q31	If you had an application to create augmented reality educational content, would you use it to create your own app?
Q32	What kind of educational content would you create with that application?

	Question
Q33	In the European project ARETE, we are developing software that allows us to easily create collaborative augmented reality applications. How do you think you could use this technology in your work?
Q34	We are also developing artificial intelligence applications to facilitate the work of teachers. How do you think you could use artificial intelligence in your work?

APPENDIX

B

Student questionnaire

The following is the questionnaire that students were asked to fill after using *ARoundTheWorld*, the application described in Chapter 4. Students were asked to fill a 20-item subjective questionnaire, using a Likert scale from 1 to 5 to assess their agreement with each sentence. The items in the questionnaire belong to four different clusters, depending on the aspect to evaluate (collaborative aspects, app usability, functionality, interest as an educational tool). Questions Q12 and Q15 were filled only by students who used the mobile applications, as the ones using the web interface could not receive suggestions but only provide them. Q18 and Q20 were framed slightly differently for users on a mobile device or using a PC: for the former group, the question referred to the usage of AR, while for the latter it was about the inclusion of 3D elements in the application.

	Question
Q1	I think that I would like to use the application frequently.
Q2	I found the application to be simple.
Q3	I thought the application was easy to use.
Q4	I think that I could use the application without the support of a technical person.
Q5	I found the various functions in the application were well integrated.
Q6	I would imagine that most people would learn to use the application very quickly.
Q7	I found the application very intuitive.
Q8	I felt very confident using the application.
Q9	I could use the application without having to learn anything new.
Q10	I would like to use the application during a test.
Q11	Being able to provide suggestions made me feel more involved.
Q12	Receiving suggestions made me more confident when answering a question.
Q13	At all times I have been able to understand what the person who had to respond to the exercise was doing.
Q14	I find it more interesting to solve the exercises through the application than through a web page or in writing.
Q15	Suggestions from my classmates have helped me when answering the exercise.
Q16	The device used has allowed me to use the application easily.
Q17	I would like to use the application to learn new concepts.
Q18	Being able to use augmented reality/ 3D elements makes the application more entertaining.
Q19	There are several ways to collaborate with my classmates through the application.
Q20	Thanks to augmented reality / 3D elements I have felt immersed in the learning activity.

APPENDIX

C

Resume

Stefano Masneri received the B.Sc. degree in information technology and the M.Sc. degree in telecommunications from the Università degli Studi di Brescia, Italy, in 2005 and 2008, respectively. He has worked at several research institutions (Vicomtech, Max Planck Institute for brain research, Fraunhofer HHI for telecommunications, CNIT) in Spain, Germany and Italy. There he worked on many national and European research projects in areas such as computer vision, signal processing, data analysis and augmented reality. He is now working at NTT DATA as a technical manager, overseeing several projects related to the implementation of generative artificial intelligence in the banking and energy sector.