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# Interactive, Collaborative and Multi-user Augmented Reality Applications in Primary and Secondary Education
# A Systematic Review

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ABSTRACT

Augmented reality is a technology that enhances human perception with additional, artificially generated sensory inputs to create a new experience which enriches human vision by combining natural with digital elements. Augmented reality development dates back to the early nineties but it is only in the last decade, thanks to improvements to hardware and software, when it has begun to be rapidly incorporated in several fields, including education. This study presents a systematic review of the literature on the use of augmented reality applications in primary and secondary schools, with a specific focus on collaborative, multi-user and interactive applications. The aim of the study is to investigate the characteristics of such applications, the processes that led to their adoption, and their effectiveness in enhancing the learning experience. This study synthesises a set of 100 publications from 2015 to 2020 and performs a qualitative analysis of their content. The review describes the current state of the art in research in augmented reality for education and provides future research lines, as well as trends for the future of such applications in educational settings, analysing the relevance of the multi-user interaction challenge within the augmented reality ecosystem.



## 1. Introduction

Digital transformation is profoundly impacting and disrupting every facet of society, and education is no exception. In recent decades, Augmented Reality (AR) has broken into the educational area. Despite being first introduced in 1992 as a training tool for Air Force pilots [1], it took many years before AR was first applied in schools as a tool to facilitate learning. Nowadays, thanks to the widespread adoption of devices that support AR applications, as well as the availability of software libraries such as ARKit[1] or ARCore[2] 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 [2, 3, 4] or have provided insights on the status of the technology as well as

[1] developers.google.com/ar/
[2] developer.apple.com/documentation/arkit/

suggestions for future research [5, 6, 7, 8]. Other reviews have focused on specific subjects, such as Science, Technology, Engineering and Maths (STEM) [9, 10]; on specific topics such as AR-based serious games [11, 12, 13], the evaluation of the usage of AR in schools [14, 15] or the impact of AR applications in learning effectiveness [16]. Table 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 [17], 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. To the best of our knowledge, only the work of Phon et al. [18] evaluates the usage of collaborative AR applications for education, by reviewing publications on the subject from 2000 to 2013. Given the many advancements of AR technology in the last few years, we believe that a systematic review of more recent publication is required, in order to see how AR apps are used as tools to improve collaboration between students as well as between students and teachers, or how multi-user interfaces 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 [19], has long been used as an educational approach to improve students' learning and performance [20, 21]. 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 neither an interactive media nor inherently a multi-user tool: it is up to researchers and developers to provide such functionalities in an AR-based educational application. With this work, we aim to evaluate which publications described AR applications that provided the following features:

- *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 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 other users' devices;

- *collaboration*: besides being multi-user, a collaborative app engages its users to collaborate or compete to reach a goal or complete a task.

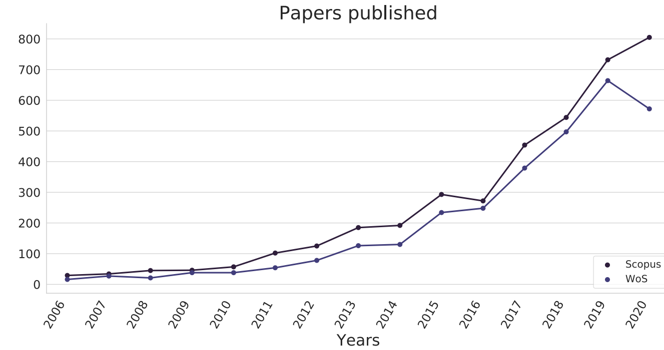


Fig. 1: Numbers of papers published per year with topic "augmented reality" and "education" from 2006 to 2020.

Furthermore, we are also interested in analysing how the usage of these applications affected the students' engagement and their academic performance.

The main contribution of this paper is to provide 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. We decided to consider only the articles published from 2015 to the end of 2020, since in 2015 the number of publications related to the application of AR in education has seen a huge increase (as shown in Fig. 1).

The Research Questions (RQ) that we addressed with this study are:

- 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 students' knowledge of a subject? How is this evaluated?

Table 1: Summary of SLRs about usage of AR in education.

| Study | Year | Purpose | Studies reviewed | Findings |
|---|---|---|---|---|
| Systematic review and meta analysis of augmented reality in educational settings [16] | 2019 | Identify the status and tendencies in the usage of AR in education | 61 | AR has a medium effect on learning effectiveness; lack of studies considering accessibility features in AR apps |
| Augmenting the learning experience in primary and secondary school education: a systematic review of recent trends in augmented reality game-based learning [8] | 2019 | Explore the combination of AR with game-based learning (ARGBL) | 21 | Motivation and enrichment are pillars of ARGBL; ARGBL compares favourably to traditional learning |
| Augmented reality for STEM learning: A systematic review [9] | 2018 | Perform qualitative analysis of the characteristics of AR apps for STEM learning | 28 | Most apps offer exploration or simulation activities, but usually without providing assistance in carrying out learning activities; similar design features across all studies |
| Advantages and challenges associated with augmented reality for education: A systematic review of the literature [2] | 2017 | Identify advantages of AR in education and identify current gaps in AR research | 68 | Conflicting results regarding cognitive overload of AR; low usability is the main challenge of AR apps for education |

Besides answering these research questions, we will also discuss the different technologies used by such applications, for example, the hardware required (Head Mounted Display (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.

The rest of the paper is structured as follows. Section 2 describes the methodological design of the study, including an explanation of the work done to plan, conduct and report the review. Section 3 presents the findings of the systematic review and the answers to the research questions. Section 4 discusses the results obtained and suggests possible research lines as well as trends for the future of AR in education. Finally, Section 5 summarises the conclusions of the paper.

## 2. Method

For this review, we followed the guidelines proposed by Kitchenham et al. [22] and framed the search using the PICOC criteria [23]:

- **Population**: Applications, Developers
- **Intervention**: Collaborative, multi-user and interactive AR applications
- **Comparison**: Students' results in classes using 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. We used the online tool Parsifal[3] to conduct the first two steps of the review while the third was performed using Google Forms[4] and collecting 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[5].

### 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. We

[3] parsif.al
[4] https://forms.gle/D7NHktgfaRmAeWTS8
[5] <removed for review>

have selected publications from IEEExplore, Scopus, Springer and ISI Web of Science, as these four digital libraries collect practically everything that is published in the area of technology enhanced learning. We used the search terms *Augmented Reality*, *Education* ∨ *Learning*, *Collaborative* ∨ *Interactive* ∨ *Multi-user*, *Application* ∨ *Evaluation*, as we wanted to include only papers that could help address RQ1 and RQ3. For this work, we only considered papers which appeared online from 2015 to the end of 2020. The search returned 1829 results, of which 238 were marked as duplicates. We read the abstract of the remaining 1591 articles and, applying the inclusion and exclusion criteria specified below, we were left with 260 articles. We finally proceeded to read the selected articles and excluded 160 further articles, thus selecting 100 articles for the literature review. Table 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, we required that the studies:

- Were published from 2015 to 2020 (both inclusive);
- Describe an AR application which has actually been implemented;
- Have a target audience of primary and/or secondary school students.

The decision of including only works with an audience comprised of primary or secondary students was taken because this study was conducted in the context of the ARETE project[6], a H2020 European project studying multi-user AR applications for primary and secondary schools.

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.

Fig. 2 shows a flowchart depicting the systematic review process. The 260 papers were reviewed, evenly split, by three 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 260 eligible papers). The interrater agreement, as defined in [24] was 0.88 for the abstracts and 0.73 for the papers.

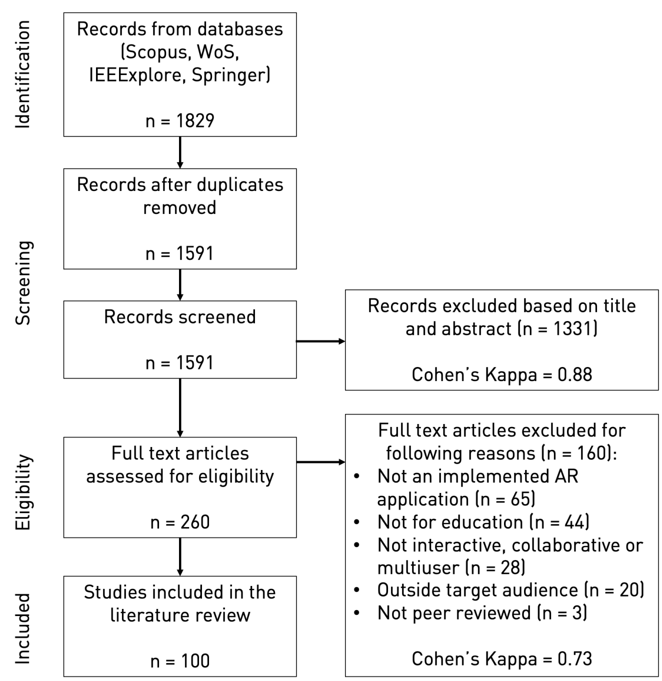


Fig. 2: Prisma flowchart of the search protocol.

## 3. Results

In this section we present the results of the three RQs introduced in Section 1, 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. We will also briefly analyse and summarise the main characteristics of the AR applications described in the studies selected.

[6] <removed for review>

Table 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 - 2020 | 136 | 48 | **37** |
| Scopus | TITLE-ABS-KEY ( “Augmented reality” AND ( “Education” OR “Learning” ) AND ( “Interactive” OR “multi-user” OR “multiuser” ) AND ( “Application” OR “Evaluation” ) ) AND ( PUBYEAR > 2014 ) | 521 | 65 | **98** |
| 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 - 2020 | 904 | 69 | **72** |
| Web of Science | “Augmented reality” AND (“Education” OR “Learning”) AND (“Collaborative” OR “Interactive” OR “multi-user” OR “multiuser”) AND (“Application” OR “Evaluation”) | 268 | 56 | **53** |

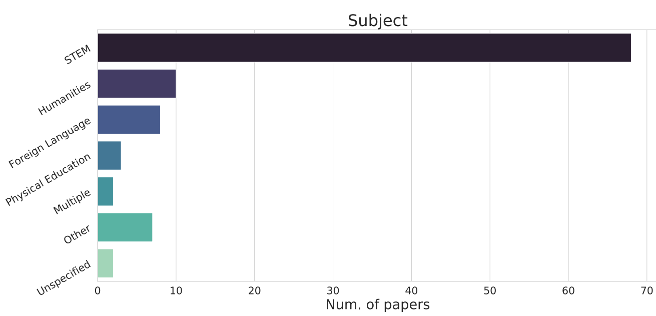


Fig. 3: Subjects covered in the studies analysed.

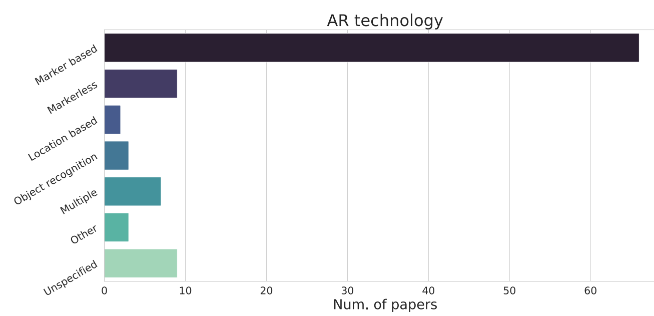


Fig. 4: Different types of AR used in the studies analysed.

### *3.1. Overview of reviewed studies*

Of 100 studies reviewed, most of them (73 articles) were published in 2018 or afterwards. The vast majority (68 studies) of the AR apps analysed cover STEM subjects, while 18 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. Fig. 3 summarises the subjects covered by the AR apps analysed in this SLR.

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 9 and 2 articles, respectively. Fig. 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 we notice a similar pattern. Most of the studies describe apps which have been developed for smartphones or tablets using the Unity[7] framework, often in conjunction with the Vuforia[8] Standard Development Kit (SDK). Some studies, usually the oldest ones, describe systems using projectors or PCs with depth sensor cameras such as Microsoft Kinect[9]. Only six articles describe apps which require HMDs or smart glasses [25, 26, 27, 28, 29, 30]. This

[7] unity.com/
[8] developer.vuforia.com/
[9] developer.microsoft.com/en-us/windows/kinect/

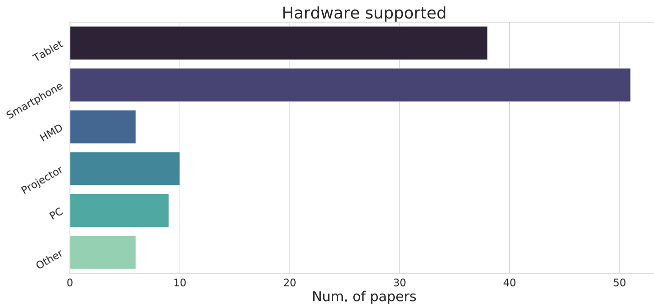


Fig. 5: Device types supported by the AR applications.

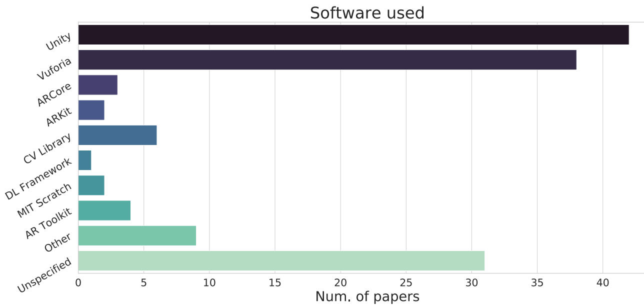


Fig. 6: Software used to develop AR applications.

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[10] and frameworks such as A-Frame[11], only the works of Abriata [31] and Protopsaltis et al. [32] 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. Usage of specialised Computer Vision (CV) libraries or Deep Learning (DL) framework 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 third of the studies did not provide information about it.

Fig. 5 and 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 100 since the same application could support more than one device and likewise it may have been developed using several software libraries.

Unfortunately, researchers very rarely publish their code alongside their peer reviewed publication. Of all the studies we analysed, only four [33, 34, 35, 31] publicly released the source code of their application. 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 it is very rare that 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).

[10] threejs.org
[11] a-frame.io

### 3.2. *Interactive and collaborative capabilities of AR applications*

This subsection addresses the first research question. We analysed interactive, multi-user and collaborative capabilities of the AR apps described in the selected studies. We categorised the studies 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 we defined are as follows:

- *Basic interactivity*: the student can interact with the app through User Interface (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 students' 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 interaction*: where the augmented content shown to the student depends on the relative positions of different markers or devices.

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

We are particularly interested in these applications because interactive learning environments have been shown to have a positive impact on the students' education [36]. At the same time, collaborative learning offers the students several benefits at the social, psychological, academic and assessment level [37]. In Table 3, we classify the 100 articles we reviewed 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.

As far as the interactive capabilities of an AR application are concerned, there are a few studies worth mentioning. In [29], the authors implemented a mixed reality system based on HoloLens[12] 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 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. Other studies use multiple markers to increase interactivity. The work of Wang et al. [118] 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. [122]. 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. In [120], 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. [81], 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.

Only a few studies experiment with other senses beyond sight. The work of Kenoui and Mehdi [108] uses the IBM Watson SDK[13] 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 [75] 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. [93] 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

[12] www.microsoft.com/en-us/hololens

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

Table 3: Classification of articles according to interactivity and collaboration capabilities.

| Interaction type | Articles |
|---|---|
| Basic interactivity | [38, 39, 40, 41, 42, 43, 44, 45, 32, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 33, 29, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84] |
| Object interaction | [42, 45, 85, 86, 28, 87, 88, 26, 89, 90, 91, 92, 93, 94, 35, 95, 96, 97, 98, 99, 100, 101, 102, 25, 103, 104, 105, 106, 107, 30, 108, 109, 110, 78, 111, 82, 84] |
| Quiz or gamification | [38, 45, 32, 47, 34, 112, 113, 58, 114, 63, 100, 102, 25, 104, 115, 27, 116, 79, 111, 81] |
| Behaviour tracking | [32, 53, 33, 58, 62, 98] |
| Augmented interaction | [44, 87, 117, 88, 118, 34, 119, 120, 121, 122, 69, 123, 124, 31, 116, 81, 84] |
| Multi-user | [28, 117, 26, 34, 93, 120, 125, 121, 126, 100, 102, 115, 106, 70, 27, 116, 109] |
| Collaborative | [117, 26, 89, 34, 93, 35, 120, 100, 102, 115, 106, 27, 109] |

et al. [102], the app is an 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. [26]: the authors created a smart-glasses-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.

### 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 marker-less 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 Thamrongat et al. [99]. A more recent work by the same authors [111] 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 [52] 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., tridimensional data changing over time) in comparison to books, blackboards or videos. The work of Cao and Liu [86] describes 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[14] while a set of markers are used to generate the augmented content. In [82], the authors use advanced features provided by ARKit (such as joint detection) together with object tracking technologies to provide interactions and visualizations through sketches drawn on the device.

In the context of collaborative and multi-user applications, AR similarly helps to provide 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 [127].

Some of the reviewed studies used AR applications as rad-

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

ically new tools that could improve skills and grades of children with mental or developmental disabilities: Luna et al. [46] describe an application that helps students with Attention-deficit/hyperactivity disorder (ADHD) improve their English literacy skills. Similarly, the work of Chen et al. [71] uses AR together with concepts maps to teach kids with Autistic Spectrum Disorder (ASD) different types of social cues designed to help them when meeting people. Takahashi et al. [106] 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.

In [128], the authors check the effects of using mixed reality applications and how it impact the students' motivation. They show that while such apps does not significantly impact the motivation to learn, it increases the students' motivation 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 [129], 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.

### 3.4. *Effectiveness of collaborative AR applications*

This subsection addresses the third research question. Of the 100 studies selected for this SLR, only 84 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 8 studies employed 100 or more students for the evaluation. Fig. 7 shows the histogram representing the distribution of users who tested the AR application across the studies selected for review.

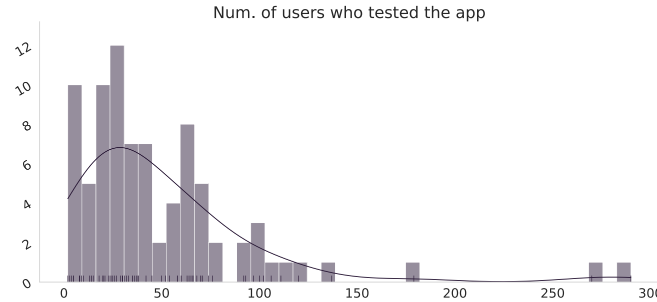


Fig. 7: Histogram of the participant in user tests across different studies (grey) and its smooth density estimate (black).

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,
- asking the teachers to fill out surveys after the experiment.

While the first two options try to objectively measure the impact of using AR, by analysing the students' grades, the third option relies on the personal judgement of the teachers and can, in principle, be subject to bias. In Table 4, we classify the 100 reviewed articles into the categories described above. Some of the studies can appear on multiple rows in the table, meaning that they evaluate students' results 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 [58], as here the researchers developed a system which, apart from the AR application, included a Database 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 [99] 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

Table 4: Classification of studies according to the method used to evaluate effectiveness of AR in the classroom.

| Evaluation type | Articles |
|---|---|
| Pre and post tests | [38, 44, 86, 48, 87, 49, 58, 112, 54, 90, 113, 94, 95, 119, 60, 61, 121, 63, 99, 102, 104, 67, 115, 70, 27, 71, 72, 110, 76, 78, 79, 111, 80, 81] |
| Control group | [42, 87, 49, 58, 117, 55, 56, 57, 99, 102, 68, 69, 105, 106, 110, 79, 111, 80] |
| Teacher survey | [45, 46, 47, 48, 87, 58, 50, 88, 51, 52, 53, 26, 89, 118, 33, 35, 59, 95, 60, 96, 120, 125, 121, 98, 126, 63, 102, 104, 68, 123, 27, 71, 81, 82, 83] |

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. From this, the authors conclude 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 [87] 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 grades and the distribution of mistakes in the different quizzes. They conclude 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 conclude 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 59 studies presenting a quantitative evaluation of the results, none of them conclude that using AR in the classroom has a negative impact on the students' results and their level of engagement in the classroom. Even though in many cases the improvement over traditional teaching methods is limited, only the work of Carlos-Chullo et al. [110] does 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 students' results) two other possible explanations are the novelty effect [130], 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 [131], which makes it harder for researchers to publish studies with negative results.

## 4. Discussion

This study shows that the research community is very active in investigating how AR applications can improve education and facilitate students' understanding of difficult concepts. Even though collaboration and participation by students is often seen as a key towards improving knowledge retention, we still see a lack of support for cooperation mechanisms in AR applications for education: of the 100 studies analysed, only 17 described multi-user application and only 13 employ some sort of collaboration between users. ARGBL is also quite uncommon, as only 11 articles describe applications which implement gamification concepts.

By reviewing the existing literature we have also identified several issues that are preventing the widespread adoption of collaborative AR in the classroom:

- Lack of authoring tools: with the exception of the works of Lytridis et al. [107] and Whitlock et al. [132] there is no authoring tool that simplifies the creation of AR experiences. This means that every AR application has to be developed from scratch, requiring longer development times and multiplying the amount of work required from the developers.

- Lack of standardisation for the description of AR experiences: of all the papers we analysed, none of them 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 [133] for AR-based learning experiences was only released in February 2020, while the ETSI Augmented Reality Framework[15] for the interoperability of AR components has not been published yet. We believe that 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 there are currently efforts being made to solve this issue [134], it does severely hinders the possibility of quickly creating new AR apps for primary and secondary schools: very often the apps never leave the prototype stage and they are not turned into a fully-fledged product or used further in the classroom.

- Code publication: another issue with most of the studies we reviewed is that only a small fraction of the authors published the code of the AR application. This means that other researchers cannot build upon the results of previous researchers: even for the more interesting and cited articles there will be no follow up work, with the exception of that from the original authors.

We noticed that studies claiming to have a stronger positive impact on educational achievements are the ones where the AR application is part of bigger learning environments. We believe that providing automatic logging functionalities, for example through xAPI [135], 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 learning analytics techniques for the analysis and improvement of students' 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 advancement 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[16] is currently limited because only the most recent devices have hardware capable of supporting them. Nonetheless, we believe these are key technologies that enable more immersive experiences and facilitate collaboration.

Most of the studies we reviewed, with the exception of the works described in [95, 108, 75], 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 and they could 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. [27] and López-Faican and Jaen [109] use PUN[17], a network library that enables communication across different devices, but 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 class-

[15] www.etsi.org/committee/1420-arf

[16] www.w3.org/TR/webxr/

[17] www.photonengine.com/pun

room, 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 education 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.

## 5. Conclusion

In this paper we presented a systematic review of the literature relative to applications of immersive, collaborative and multi-user AR in education. We analysed 100 studies and evaluated their technical characteristics and their advantages compared to traditional teaching tools as well as the impact they had on knowledge retention. We believe that the findings described in Sections 3 and 4 can be useful for researchers in driving the design of the next generation of AR applications.

With the first Research Question (RQ1) we wanted to identify which studies described interactive, multi-user and collaborative AR experiences, and we compared the main features of the AR applications described. Every paper presented AR-based interactions, but only a few applications provided multi-user and collaborative capabilities. Our analysis showed that Unity and Vuforia, the de-facto standard tools for creation of AR applications, do not provide researchers and developers the tools to easily include collaboration mechanisms in AR applications.

The second Research Question (RQ2) aimed to understand the motivation behind the usage of AR as an educational tool. In this case we analysed both the motivations presented by the researchers and the results of surveys conducted on students. 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 students' engagement.

Finally, the objective of the third Research Question (RQ3) 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. Only the work of Lin et al. [113] presents 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.

### 5.1. Limitations of this study

This review was limited in that it examined articles from four databases: IEEExplore, ISI Web of Science, Scopus, and Springer, from 2015 to 2020. The articles in these databases are considered to have a high impact on the field; however, the latest technical reports and business demonstrations of AR in education were excluded from this review, which may limit the representation of the state of the art. Nevertheless, despite the number of papers included in this review being limited, the selection process followed a systematic process in order to avoid bias.

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