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Review

Augmented Reality: Current and New Trends in Education

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Abstract: The educational landscape is an environment prone to change due to the volatile and ever-changing nature of the digital society in which we all live. Although the world moves at different speeds and any generalization is bound to have some exceptions, there is evidence from research conducted in different places and contexts that educational methods are becoming increasingly digitized and driven by technological innovation. Among the technological trends fueled in many cases by the COVID-19 pandemic and the need to stay at home but online, augmented reality solutions received an additional boost as a valid and versatile educational technology worth exploring and eventually integrating into several teaching methods already in use. Although the technology still faces problems related to affordability, accessibility, and the technical skills required of users, some ongoing projects have already provided evidence that using augmented reality solutions as teaching and learning tools can improve teacher and student learning outcomes by increasing engagement and interactivity. The same issues arose when personal computers, tablets, and smartphones were first discussed as valuable tools for education and have now found their way into most classrooms. This paper reviews some of the key concepts related to augmented reality, as well as some current trends, benefits, and concerns related to its integration into educational contexts in areas such as life sciences, engineering, and health. The work conducted and presented in this paper provides an interesting insight into a technology that has given rise to global phenomena such as Pokémon Go, and continues to improve in terms of portability, usability, and overall user experience. Throughout the paper and in the conclusion section, we discuss the relevance of using the best features of augmented reality and how they can contribute to positive educational outcomes.

Keywords: augmented reality; education; EdTech; survey

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1. Introduction

One of the fundamental challenges education is facing in the upcoming decade is the evolution of educational methods. Traditional teaching approaches and strategies seem more and more insufficient in regards to adapting to the digital society. The model of a school in which a professor opens a coursebook and starts reading a lecture, which students have to learn by heart, pass the exam and forget, is starting to become inadequate [1–5]. This approach is inefficient, ineffective, and unfitted to 21st-century challenges, especially when the knowledge is widely and easily available. In today's world, one of the most important skills is not remembering, but the ability to quickly find the relevant information, analyze it correctly, and apply it in practice.

Nowadays, in the current educational framework, in most developed countries, active and pedagogical educational methods are used, following new active teaching and learning strategies. These strategies are based on new methods and new methodologies essentially developed in the 21st century, such as problem solving, innovative and creative teaching methods, online modes, and others [6]. These strategies improve the skills to face the new challenges of the 21st century, facilitate the transfer of knowledge in an engaging way, stimulate the interest of students and pupils and provide new experiences, including interpersonal ones. What cannot be neglected is the emotional involvement of students, as young people absorb knowledge more easily when they are interested in the subject and understand its applicability [7,8]. Therefore, a strong emphasis should be placed on activating methods used in the classroom. One way to realize this concept is by introducing numerous educational technology (EdTech) tools into the curriculum [7,9].

The use of information and communication technologies improves students' attitude towards learning [10], as it motivates learners and develops multiple skills of an individual student or a group of students [11]. Therefore, EdTech is a rapidly growing and constantly evolving field of research, as the needs and expectations of students, labor markets, and increasing global competition force changes in the education system. Universities and schools are facing many challenges in the way they teach. According to the Digital Education Survey [12], 75% of U.S. teachers believe that digital learning content will completely replace printed textbooks within the next decade, and 42% of U.S. classrooms use a digital device every day. Laptops, desktops, and tablets are the most common devices used in the classroom, with more than half of teachers reporting that each is used at least weekly.

More and more schools and universities are incorporating technology-enhanced content delivery into their programs. Typically, it is used in the form of blended learning, i.e., videos, apps, websites, games, and massive open online courses (MOOCs, e.g., Coursera) [13]. The most popular tools are computer-based simulations, online quizzes and exams, recorded video lectures, video conferences, and webinars. However, mobile applications are still rarely used in education and mostly replicate the functionalities of other platforms [14].

Augmented Reality (AR) is one of the most promising and fastest growing technologies. In 2022, this market was valued at USD 38.56 billion, and it is estimated that it will reach a value of USD 597.54 billion by 2030 [15]. In addition, analysts at Business Insider Intelligence estimate that the number of users of this technology will grow to over 1.7 billion by 2024. Moreover, EdTech was valued at USD 254.80 billion in 2021 and is expected to reach USD 605.40 billion by 2027 [16].

AR is an interactive experience that enriches the real world with digitally generated images and sounds. The uses for this functionality are numerous, including providing a novel and engaging way to acquire knowledge and information during a teaching or learning process. Surveys and reports indicate that most students remember AR-based lessons better and conclude that AR is a more memorable environment than lab-based demonstrations [17,18].

The most common use of AR is in mobile applications. Unlike virtual reality (VR), AR does not require expensive hardware. According to the Pow Research Center, 73% of teens have access to a smartphone. Thus, AR is available to the majority of the target audience [19]. Therefore, this technology has great potential to be used with printed materials, such as AR-enabled illustrations in a textbook that come to life on the user's phone, allowing for interaction and in-depth analysis. Education becomes more accessible and engaging with the ability to move from 2D non-interactive educational illustrations to 3D interactive ones.

Among the most significant trends in EdTech, AR has the leading position [20]. The use of AR can provide students with additional information and facilitate the understanding of complex concepts. AR applications are usually used to capture students' attention [21] and explain abstract and difficult concepts [22].

Despite the growing interest in this topic, we are aware of only a few relevant review papers. One of the most comprehensive works is [23], where the authors reviewed AR applications intended to complement traditional curriculum materials for K-12. However, their literature review was conducted in 2012. To our knowledge, no such comprehensive review has been published since then. In addition, other factors motivated us to conduct this research. The first is the advent of fifth-generation mobile technology, the implementation of which heralds massive changes in the field of virtual and augmented technologies [24]. The second is the COVID-19 pandemic situation, which forced the development and implementation of such solutions in education. For the purpose of this research, two different and complementary sources were used. The review is based on the literature from 2018 to 2022. However, for Section 8, a Cordis database of projects [25] funded by the European Union (EU) Framework Programs for Research and Innovation (FP1 to Horizon) was analyzed. It includes the most recent projects that have been launched recently and have not yet been subject to proper scientific review. The second source was chosen to present the current trends and potential directions of the development of AR in education, with the most recent data available.

According to the scope purposes, the main research questions addressed by this paper are:

- RQ1: What types of applications (in the context of the technology) are the most popular/used? What is the core AR technology? What external devices are being used? Which senses are stimulated?
- RQ2: In which areas of education is AR technology most in demand/most popular? Why? Which are the most advanced/already in use?
- RQ3: What types of validation methods are used to test AR educational applications?
- RQ4: Has the current world situation (COVID-19) influenced AR in education in any way?

What follows is an overview of the major trends, opportunities, and concerns associated with AR technology in education. In Section 2, we briefly introduce key aspects of AR technology. In Section 3, we present the review methodology with general qualitative data analysis in Section 4. Section 5 answers RQ1 by discussing the technologies used in AR educational applications. We then summarize the most interesting educational AR solutions in Section 6, answering RQ2. RQ3 is discussed in Section 7, where we provide a comprehensive review of methods for evaluating the effectiveness of such applications. Furthermore, we explore the educational benefits of AR applications in Section 8 and conclude the paper with a discussion and suggest possible future research (considering RQ4) in Section 9.

2. Background

2.1. Augmented Reality

AR is based on the superposition of virtual elements in the user's perceptual space, creating the illusion that these synthesized elements are also real. Unlike VR, AR does not replace reality with an immersive and synthetic environment, but rather combines it with the real elements that surround the user, enhancing or conditioning the user's perception of the real scene. In VR, the user does not directly observe the real scene that surrounds them—they are immersed in a fully synthesized environment—although it is intended that this virtual environment (usually 3D and photorealistic) is perceived as real [17,26].

2.2. AR Definitions and Concepts

The term AR was coined by Caudell and Mizzell in 1992 [27], where they proposed a head-mounted display that would assist Boeing 747 assembly line workers in construction and assembly tasks (see Figure 1).

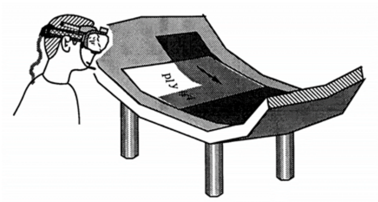


Figure 1. Head-mounted display proposed by Caudell and Mizzel in 1992.

However, the systematization of the concept of AR, as it is currently known and accepted by the academic community, was presented by [17], based on the contribution of [28], when the author argued that an AR visualization system must be present or have three properties:

1. Combines real and virtual.
2. Interactive in real time.
3. Registered in 3D.

Various definitions have been proposed [17,26,29–31], all of which remain very close to the original reference by Milgram and Kishino [28], who developed a conceptual framework for the topic of Virtual Environments (VE) and which resulted in a taxonomy that still deserves acceptance.

Figure 2 represents the classification of real–virtual worlds, ordering them by their degree of mixing of the real and the virtual. At the extreme left, we have the experience of the real as it is lived in a "natural" way, without the need for any visualization system. Thus, according to [28], the visualization device that comes closest to the real environment is the one that allows the user to look directly at the real world without any mediation process.

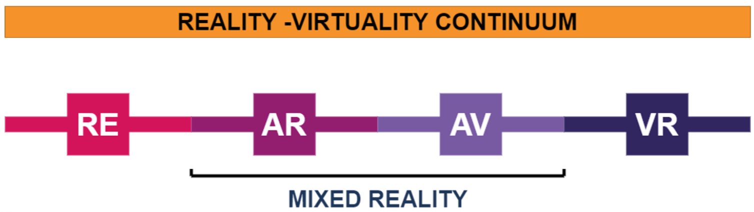
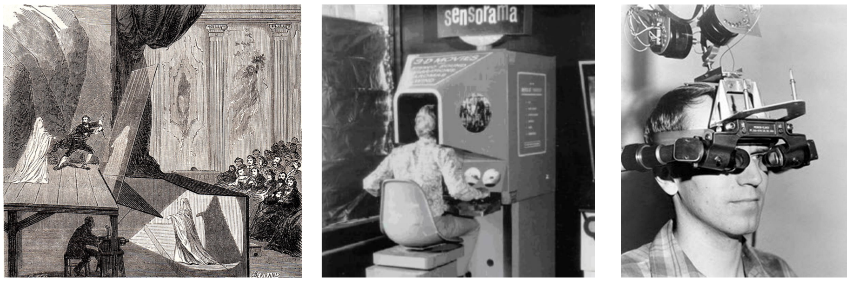


Figure 2. Real–virtual continuum.

At the other end of the spectrum, we have total immersion in a virtual environment. This typically corresponds to VR systems, where the entire environment is synthesized and virtual. In between, we have a whole set of applications called Mixed Realities, which treat the real and virtual scenarios in a hybrid way. AR overlays virtual information on the real scenario. Augmented Virtuality superimposes real elements on the virtual stage. There is no absolute criterion in the virtual continuum that allows us to define fixed boundaries between concepts, only qualities that can be relativized and compared.

2.3. The Precursors of AR

We can go back at least to the nineteenth century to find inventions that conceptually share the main characteristics of AR, even if they were not called by that name or systematized in the same way. One of the most notable is the ghos effect, used in the theater in the mid-19th century to superimpose in the spectator's field of vision images coming from two scenarios physically separated by a glass. This expressive technique aimed to enrich the narrative by producing a dramatic and visual effect, and was popularized under the name of Ghost Pepper's Effect [32] (see Figure 3a).



(a) (b) (c)

Figure 3. (**a**) Ghost Pepper's Effect, 1862. (**b**) Sensorama, 1962. (**c**) Head-Mounted Display by Ivan Sutherland, 1968.

During World War II, the British military's Mark VIII Airborne Interception Radar Gunsighting windscreen project developed a system very close to the concept of AR, superimposing in the pilot's field of view the information coming from the radar, showing whether the target is a friend or enemy plane [33]. Between the post-war period and the development of Ivan Sutherland's see-through head-mounted display, which provided the first true experience of AR, several devices saw the light of day in a timid and scattered way. Better known as one of the first virtual reality devices, the Sensorama (see Figure 3b), developed in 1962 by Morton Heilig, was a system that stood out for its attempt to create a totally immersive experience for the user, involving the various senses such as touch and smell in addition to sight and hearing [34].

The development of the SketchPad system during his PhD project in 1963 made Ivan Sutherland famous as one of the pioneers of computer graphics and graphical user interfaces (GUI). The input system, based on the light pen, favored the concept of direct manipulation, later systematized by [35] within Human–Computer Interaction. However, because of the work put into the design and creation of the See-Trough Head-Mounted Display (see Figure 3c), Sutherland is now undoubtedly considered a major contributor to the history of AR.

3. Methodology

This study was conducted as a scoping literature review (SLR). The methodology used was based on best practice and guidelines proposed by other researchers [36–38]. The aim of this SLR was to assess the current state of AR in a broad area of education. The literature search was conducted using the protocol shown in Figure 4 on 20 November 2022, in the Scopus database. The search string was ("augmented reality") AND ("education") OR ("learning") OR ("teaching"). The results were limited to open access articles written in English in the last five years, as they are viewed and cited more frequently than restricted access articles [39,40]. In addition, open access content leads to greater public engagement with faster impact and increased interdisciplinary conversation among researchers.

The initial search yielded 2546 papers, including 1482 journals and 713 conference proceedings, 269 reviews, 25 editorials, and 17 book chapters. Only open access papers (933 in total) were included in the further analysis.

We then analyzed the content of all articles that met the following inclusion criteria:

1. The content of the article should be relevant to preschool, primary, secondary, or higher education;
2. The paper must present at least the preliminary version of an AR tool (no sketches, drafts, or paradigms);
3. The tool described in the paper should be used for learning or at least tested with students and/or educators;
4. The paper should report on the impact of the tool provided;
5. The full paper should be freely accessible.

The above inclusion criteria limited the results to 598 research papers. The data collected from the included articles are as follows:

1. Simple publication details such as title, authors, year, etc.
2. What are the most frequently used keywords in AR articles?
3. What subfield of education do AR studies focus on?
4. What are the types of AR applications?
5. What technologies are used for AR applications?
6. What senses do AR applications engage?
7. How are AR applications validated?

All the above data will be further analyzed in this paper.

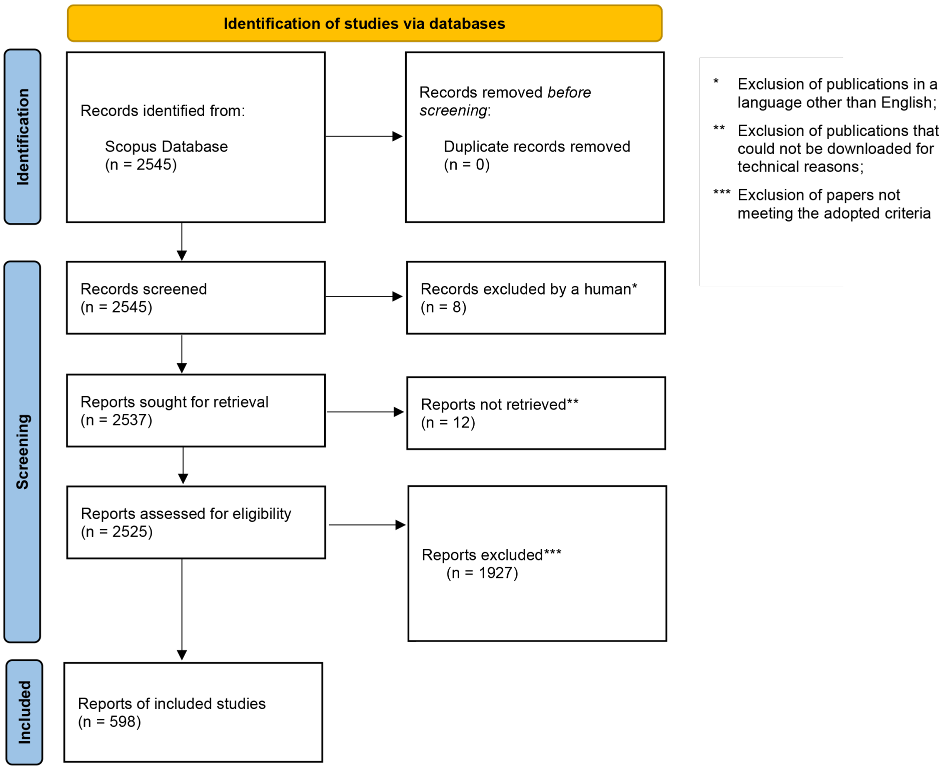
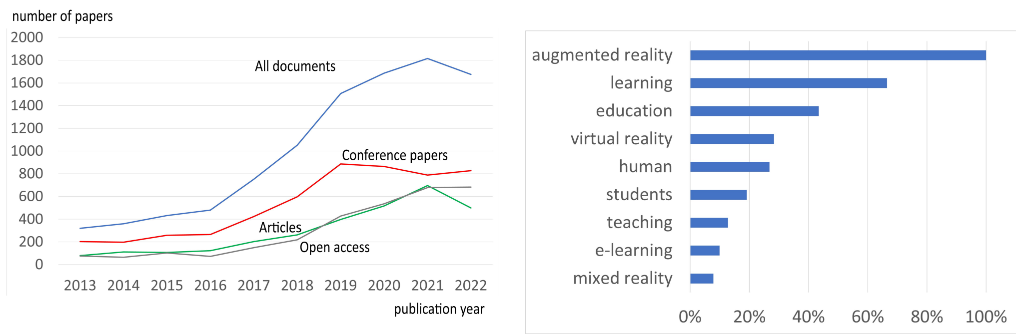


Figure 4. Scopus keywords search based on PRISMA flow diagram [41].

4. General Qualitative Data

Figure 5a presents the distribution of the publication year of papers based on the Scopus database according to our criteria. In general, the graph has an increasing tendency, which could be expected in the case of modern technological development. One can also observe the slowdown of the increase between 2019 and 2021. Since 2016, there has been a significant increase in the number of open access publications, due to the global trend of increasing accessibility and availability of scientific papers. In addition, there is a significant decrease in post-conference publications between 2019 and 2021. The changes observed in the graph are definitely determined by the international situation caused by the COVID-19 pandemic.

Figure 5b illustrates the distribution of keywords in the analyzed articles. AR is clearly the most used one, but it was not indicated as a keyword in some articles that actually discuss its application. This could be due to several reasons, the first being that some researchers decided to use broader or similar terms such as Mixed Reality or Virtual Reality. The second one is that in some papers AR is not treated as the main subject, but rather as a tool to reach the assumed goal, e.g., in education or e-learning. Finally, it is worth noting, as it is rather unexpected, that only a few articles discussing AR in education use keywords such as teaching, learning, education, or students.

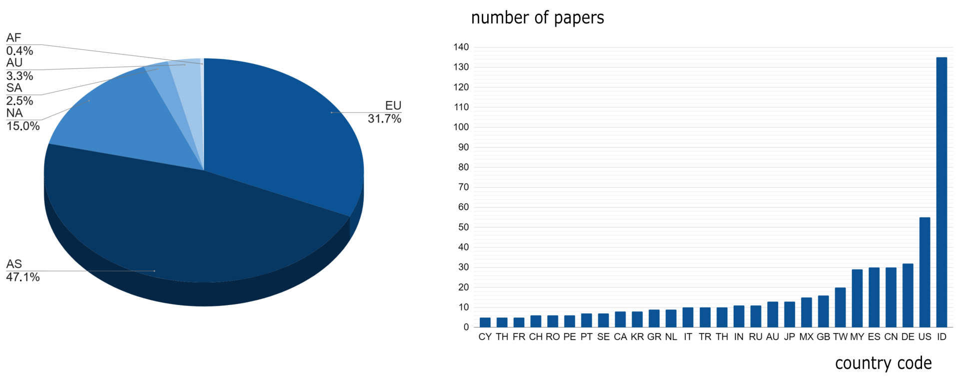


(**a**) (**b**)

Figure 5. AR in education (**a**) publications per year until 20 November 2022 (**b**) most commonly used keywords.

Figure 6a shows the distribution of papers by continent. It can be observed that works from Asia represent almost 50% of all papers, and this is due to the abundance of papers coming from Indonesia, an issue that will be discussed in the course of this analysis. The European contribution in the field of AR comprises about a quarter of all papers, followed by North America with about 15% of the papers. The aggregate contribution of the other continents amounts to 6.2% of all articles.

As can be seen in Figure 6b, which shows the distribution of papers by country of origin, Indonesia is an undisputed leader. However, most of the papers were published as post-conference proceedings (Journal of Physics: Conference Series), which are indexed in the Scopus database. The scope of these publications, the level of detail, and the scientific value do not match those published in scientific journals, as they have completely different requirements and objectives. Thus, Indonesia's leading position in AR publications should not be taken for granted, as its position is based on a single conference event. The second position is occupied by the USA, a de facto leader in AR studies. The next positions are fairly evenly distributed between Asian and European countries, with some contributions from Mexico and Australia.



(**a**) (**b**)

Figure 6. The distribution of papers according to (**a**) continents (**b**) the country of origin.

5. Technologies Used in AR Applications

Most AR-based technologies use a combination of hardware-based accelerometer and gyroscope information coupled with SLAM [42–44] and other feature-matching-based techniques. This is used to capture video in order to localize and accurately map a virtual overlay in the real world [45].

5.1. Software

There are many development tools available for AR development, and they all have different advantages and disadvantages. Some of the most popular are Apple ARKit [46] for IOS devices, ARCore [46] for Android devices, and Vuforia Engine [47] for both, but with a paid business model. There are AR development platforms and SDKs for more specialized use cases such as the Bosch Common AR Platform [48] for automotive, SmartReality [49] for construction, Inspace (River Fox) [50] for CAD visualization, and DAQRI Worksense [51] for more industrial use cases.

Some toolkits, such as holo|one sphere [52], are designed for easy setup and prototyping. Other kits are developed by larger companies specifically to work with their own platforms, such as Amazon Sumerian [53] for Amazon, ARCore for Google, and Spark AR Studio [54] for Facebook. Although most AR toolkits have their own dedicated development platforms, many of them either support or are supported in various contexts by more well-known game engines such as Unity [55,56] or Unreal Engine [57]. As new toolkits and development engines are frequently created and others become obsolete, there are many more that are not mentioned, such as Wikitude (ver: 9.13), ARToolKit (ver: 1.1.11), HPReveal (ver: 6.0.0), Blippbuilder (ver: 1.1.4), Augmentir (ver: 1.4.24), ZapWorks (ver: 6.5), EasyAR (ver: 4.6.1), PlugXR (ver. 5.0), MaxST (ver: 5.0.2), Kudan (ver: 1.6.0), DeepAR (ver: 5.2.0), and ARmedia (ver. 1.1.1).

Hardware

From a hardware aspect, AR applications can run on heads-up displays, holographic displays, smart glasses, handheld devices, or fully immersive goggles with a camera pass-through.

AR devices use a variety of different methods to project or display an image. Immersive goggles and handheld devices almost exclusively use a single screen or binocular VR screens to display an image. HUD (Head-Up Display), holographic displays, and smart glasses use more diverse methods. These can range from holographic images projected onto intermediate screens to light field technology that uses multiple LCD screens with a combined backlight or waveguides that project the light directly onto the retina. A sample of the differences can be seen in Figure 7.

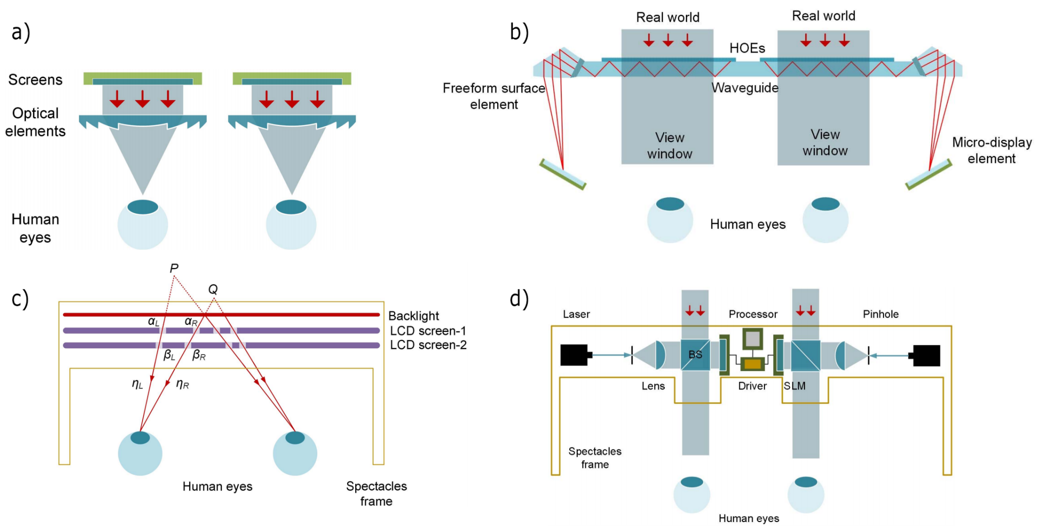


Figure 7. Examples of AR/VR technologies. (**a**) Full VR or camera pass-through AR, (**b**) waveguide-based binocular vision technology, (**c**) light-field display technology, and (**d**) computer-generated holographic display technology [58].

Devices designed primarily for AR include Microsoft HoloLens [59], Magic Leap One [60], Google Glass [51], and Meta 2 [61], to name a few. There are also some more specialized AR hardware options such as the Daqri Smart Helmet [62]. The display AR devices most commonly used in education are juxtaposed in Table 1. In addition, Figure 8 shows the variation in devices used in education over the past few years. As it can be seen, mobile devices are the most used (80%). As far as AR glasses are concerned, only HoloLens enters the picture (20%).

Only a few works mention the use of external devices to deepen the immersion of the user and to enhance their experience. It is often associated with an additional analysis of the user's movement, e.g., using a Kinect [63] sensor or an external device necessary to perform the exercise [64]. The most commonly used external devices in educational AR applications are presented in Table 2.

Table 1. Display AR devices most often used in education.

Device		**Characteristics (RES, FOV)**	**Usage Count**	**e.g., Ref.**
Tablet/Mobile Phone		like the device used	478	[65–67]
HoloLens		ver.1 1268 × 720 34° ver.2 2048 × 1080 52°	82	[68–70]
Magic Leap		1280 × 960 50°	13	[71–73]
Google Glass		640 × 360 83°	12	[74–76]

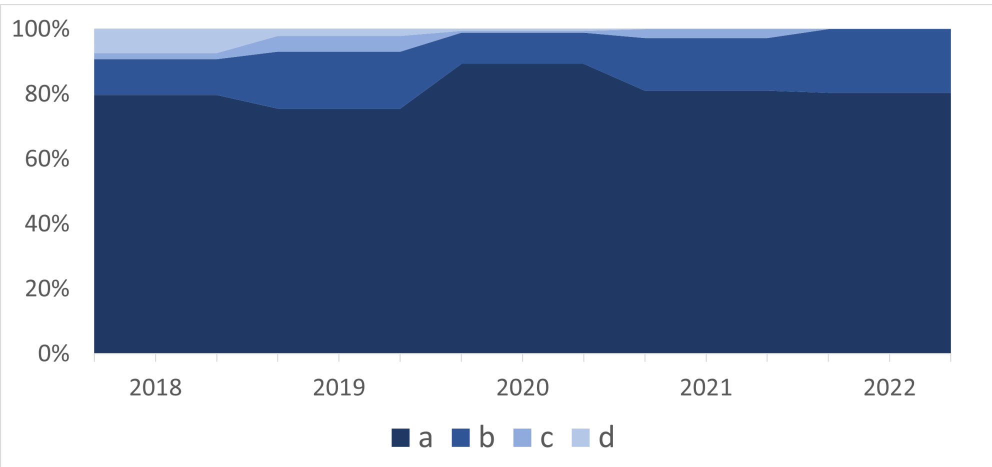


Figure 8. Percentage distribution of most commonly used AR technology in education over the years: a—tablet/mobile; b—HoloLens; c—Magic Leap; d—Google Glass.

Table 2. External devices supporting AR technology in education.

Devices	Context of Use	e.g., Ref.
Kinect	Hand movement detection to learn tooth brushing technique	[63]
Leap Motion	Hand and finger tracking device for visualizing hand anatomy	[75]
Projector	Process projection that simulates a real production process and displays additional data	[77]
Motion Capture	Tracking operator's hands for manual assembly task verification	[78]
Magic Mirror	A teaching device for anatomy courses	[79]
Microscope	Microscope-based AR environment successfully implemented for spinal surgery	[80]

5.2. Assets Used in AR Applications

AR applications follow a slightly different set of rules when it comes to the assets and what can be shown to the user than other types of high-end development. The objects that are placed in an AR space need to look and feel as if they are actually present in that space, rather than appearing as a simple overlay. This is typically achieved with high-resolution models and textures, reflection probes sampled from the camera [81,82], lighting color and direction estimation [83,84], surface and people detection [85], surface occlusion [86], virtual shadows [87], and subtle post-processing effects [88]. All of these bring an AR object closer to looking like a real object. However, all of these systems are very expensive in terms of computing power. This is especially important when you consider that AR devices tend to be at the lower end of the computing power spectrum.

However, there are some workarounds that can be applied. One method is to reduce the number of polygons in applications by replacing them with baked normal maps, using simpler tracking algorithms such as Aruco markers [89], or by deliberately avoiding hyper-realism.

5.3. AR Environments, Scenarios, and Limitations

AR scenarios tend to be heavily influenced by the hardware they run on and the toolkits used to create them. Heads-up displays and holographic displays generally use optical guides to project an image into the user's eye or onto a transparent screen. Because of this, colors in holographic displays are added on top of real-world colors, rather than replacing them. This severely limits color variation in AR and often results in a blooming effect on any model or environment displayed. True backgrounds and darker colors can only be achieved on fully immersive or camera pass-through-based systems, as these do not have such limitations [58].

AR has far fewer limitations than its fully immersive VR counterpart. AR systems do not require open spaces with no physical obstacles, as the user is still able to see the real world. Lighting constraints are less severe, as localization methods are more robust, but inherently less accurate. All of this means that AR is a tool that can be used in almost any given setting, placed in a controlled office environment, a classroom with multiple people, an industrial setting, or even outdoors [90,91].

Some limitations that may occur are related to low light and non-stationary environments. AR headsets require moderately good lighting because the device's camera cannot perform feature recognition on black or blurred images. In addition, fully moving environments, such as a moving car, will provide additional accelerometer values that current AR algorithms do not account for [92].

Another advantage of AR over traditional VR is that the real-world environment can be seen through the device, reducing the likelihood of nausea due to conflicting senses [2]. This means that AR can be used more easily in educational environments and by less experienced users.

6. Taxonomy of Scientific Papers

In order to present the trends and directions of development in a specific field, we have gone through the latest publications using the methodology presented in Figure 4. In the analyzed scientific papers, only a few types of scenarios can be found and easily distinguished. Most of them present simple visual solutions. Users can familiarize themselves with educational content by observing prepared augmented objects. There are also more advanced scenarios where learners are more involved in the exercises performed. Apart from watching, they have to interact with non-real objects, which can be called "learning by doing"—a teaching method that provides very good educational results [93]. In another type of scenario, AR is used to evaluate the user's performance in a given task. Such a user receives virtual feedback and can make their own reflections on their work. The type of AR scenario must be adapted to the age and ability of the learner. In addition, the field of study or the subject being taught will determine more appropriate tasks and the level of user involvement. A summary of the scenarios used in AR educational tools is presented in Table 3.

Table 3. Types of scenarios used in AR educational tools.

Scenario Type	Usage [%]	e.g., Ref.
Simple visual solutions	54%	[72,79,94]
Learning by doing	35%	[65,66,95]
Evaluation of user's performance	9%	[96]

Since AR allows additional information to be added next to real objects, it is usually used as a tool to visualize elements that cannot be observed easily or at all in a safe environment. This feature indicates the possible application in such domains as engineering (machine and robot simulation, architecture) [97], life sciences (physics, chemistry, biology, astronomy) [98], general education, medicine, arts/humanities, and special needs. The percentage distribution of these domains based on the above search criteria is shown in Figure 9. In this section, we present the most interesting and recent applications related to these educational domains, as well as their content analysis.

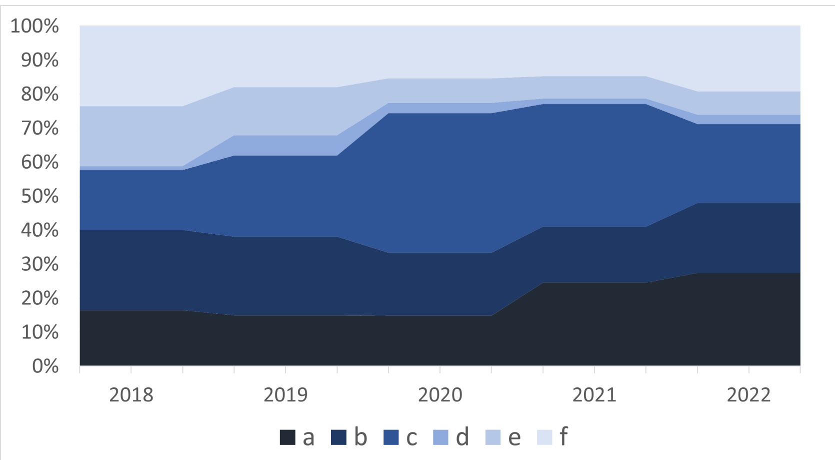


Figure 9. Percentage distribution of the most popular education domains based on Scopus keywords search over the years: a—medicine, b—engineering, c—life sciences, d—special needs, e—arts/humanities, f—general education.

6.1. AR in Engineering

It is believed that the pioneering AR technology was the application implemented in 1992 for the needs of aviation tycoon, Boeing Company [27]. The application was used to improve the assembly of electrical circuits by presenting assembly manuals using the HUD system. The nearly 30-year history of using AR for engineering has evolved considerably, and new technological solutions have provided better tools for successful implementation of AR. From simple mixing of live images captured by a camera and generated by a computer [99], to transparent displays mounted in goggles [100], to the latest solutions such as displays in contact lenses [101,102]. The most popular engineering domains using AR applications for educational purposes are shown in Figure 10.

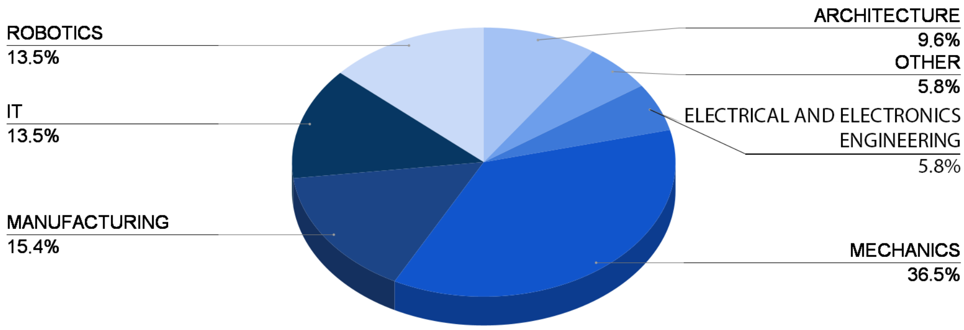


Figure 10. Percentage distribution of the most common engineering domains in which AR is being used for educational purposes.

A very interesting but underestimated form of AR presentation is video mapping [103], where real objects are enriched with visual information generated by laser projectors. The modified environment can be used to attract students' attention, for rapid prototyping [104], to signal danger, or to imitate certain properties such as hardness, humidity, etc. This type of approach eliminates the need for additional equipment such as goggles or a portable display. Engineering AR applications can be divided into three groups based on their purpose: enriching the real environment with additional information [105], explaining or instructing the user [106], and drawing the user's attention to important elements. A good example of such a solution is the driver assistance system, which can assist the driver by recognizing and interpreting road signs [107]. Another interesting AR solution is a help desk video communication application which, in addition to voice consultations, provides additional information displayed on real images [108].

The possibilities of AR technology are widely used to illustrate or explain the operation of complex spatial constructions, which is a very effective alternative to two-dimensional forms of communication such as illustrations and printed technical documentation. An example of such an approach is the educational application used to illustrate the principle of electromechanical mechanisms [109]. The students, equipped with HoloLens glasses or a tablet, can observe the internal elements of a particular mechanism tested on the laboratory stand (see Figure 11). It is possible to identify components and their locations, explore the mechanism, and thus more easily identify the kinematic chain or transmission power flow. The application has been tested on engineering students and bachelor of technology students divided into two groups: using AR and using only paper documentation and CAD. The evaluation indicated improvements for the AR users.

Figure 11. Tablet and HoloLens glasses scenario presenting the analysis of an electric actuator [109].

Modern technological solutions, the assumptions of Industry 4.0, ubiquitous process automation, and contemporary ways of managing production are leading to evolving expectations toward the future engineering workforce. This leads to a necessary change in technical education to meet the needs of the market. The curriculum of studies is enriched with subjects conducted with AR and VR support, which allows an organization to simulate teamwork on projects in a relatively simple way [110]. This type of solution closely imitates the specificity of future work under the supervision of industry experts (see Figure 12). The authors of the implementation achieve very good educational results, while the incurred costs for the revitalization of the educational process remain relatively low.

Similar systemic solutions are currently being implemented in German higher education [110] in projects such as ELLI—"Excellent Teaching and Learning in Engineering Science" or the MOOC program. The creation of virtual laboratories with various industrial machines and equipment will allow any technical school to have access to the same training opportunities. The second stage of this project involves the implementation of AR-based interfaces as a basic form of interaction with virtual laboratories.

In [111], two mobile AR solutions were analyzed. The applications were designed to teach students about Karnaugh maps. The first application is keypad based, while the second is marker based. The researchers asked about the usability (effectiveness, efficiency, and satisfaction) of each application using the System Usability Score and Handheld Augmented Reality Usability Score models. The keypad-based application was found to score higher on the usability scale.

Education is not confined to the desks of schools and universities, but continues well into the world of work, regardless of the career path chosen. AR can also be useful for optimizing manual activities at the workstation. Modern workplaces are equipped with systems of sensors, cameras, and AI, which are able to analyze the manual work of a laborer and, based on this, propose the optimal work flow in AR [112]. The advantage of this solution is a constant adaptation of the system to individual psychophysical abilities, taking into account their development and other factors that may escape analytical definition.

(**a**) (**b**)

Figure 12. Physical manufacturing cell (**a**) and its virtual equivalent (**b**) [110].

6.2. AR in Life Sciences

The second most popular domain using AR as an educational tool is life sciences. The percentage distribution of the most popular life sciences domains using AR for educational purposes is shown in Figure 13. More than 50% of them are applicable to education such as physics and chemistry. AR is a great solution for simulating phenomena that cannot be replicated in the real world, facilitating the understanding of complicated physical and chemical reactions.

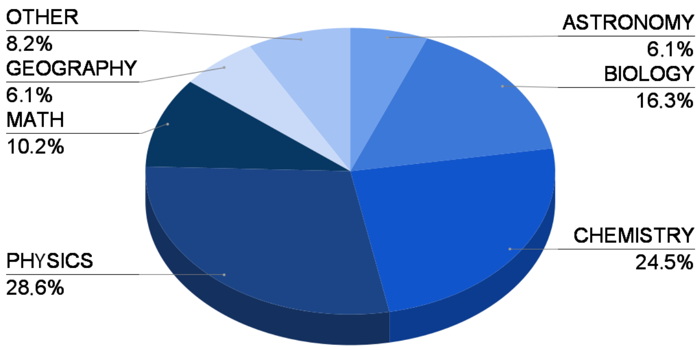


Figure 13. Percentage distribution of the most popular life sciences domains using AR for educational purposes.

In [113], where the authors evaluated the impact of learning enhanced by a marker-based augmented reality environment, an important case is presented. They created an application to explain light absorption, refraction, mirrors, and lenses. A total of 45 students (experimental and control groups) from the 7th grade of a public secondary school participated in the study. The author has demonstrated that the augmented reality application is successful in terms of students' academic achievement and the longevity of their learning based on pre-test and post-test results. Similarly, in the study [114], researchers used the HoloLens headset to support the education of faculty members in the area of biological molecular structures. The study showed high objective and subjective effectiveness of the tested AR application with a high level of engagement. Participants in the AR training indicated an ease of understanding of the animated structures presented, which clearly explained complex biological processes.

In [115], the authors created content-rich AR note cards using a free HP Reveal app and a smartphone. The information on the notecards was based on Organic Chemistry I reactions, and they presented only a reagent and a substrate. When students pointed their smartphone camera at the cards while using the HP Reveal app, an AR video was played that showed the product of the reaction, as well as a real-time explanation of the mechanism of how the product is formed. The HP Reveal app has also been used to create AR videos of lab equipment, featuring a virtual expert who guides the user through the setup and operation of the equipment.

A very interesting example of the use of AR in life science education is presented in [116]. The authors introduce the Real-World-Oriented Smartphone AR Learning System (R-WOSARLS), an AR smartphone tool for observing seasonal constellations. The data are based on information from the planetarium of the Nagoya City Science Museum. The creators of the tool conducted two experiments to evaluate the effectiveness, educational value, and learner satisfaction of the system in tertiary and secondary educational institutions. The results show that R-WOSARLS facilitates the acquisition of knowledge for constellation observation and learning, and increases learners' motivation to acquire additional knowledge about astronomy.

AR applications in biology are also ubiquitous. For example, in [117] the authors presented an AR pervasive game that aims to promote learning about plants in the local environment. Players collect plants in their area and grow them at home to create a garden, all in AR. The game combines physical elements such as plant pots with sensors and RFID tags with information about the plant with virtual elements such as AR representations of the plant. The goal of the research is to study the change in experience when the entire game is transferred back to the real world, and thus explore the educational benefits that can be achieved when the game remains in AR. A summary and discussion of the use of

AR/VR in the field of biology can be found in [118], where the authors focus on answering questions that are crucial for a productive implementation of AR/VR. First, they discuss the production and dissemination of AR/VR-ready materials that are user friendly and widely available. Second, they analyze positive and negative experiences reported by test subjects when performing identical tasks in AR and VR environments. Finally, they investigate subjects' perception of pre-recorded narratives during AR/VR immersion. In terms of biology, most of the papers focus on human anatomy and biological functions. They will be presented in the next section.

6.3. AR in Medicine

AR can also be used with great success in the medical field. Virtual simulations can provide a realistic, immersive environment for effective training of medical and dental professionals. AR and VR offer the ability to experience emergency situations and practice decision making without the real-world consequences to patients.

6.3.1. AR in Medical Education

The use of AR and VR in medical education has many advantages, such as higher learner engagement and motivation, development of spatial knowledge representation, strengthening of technical skills, improvement of contextualization of learning, possibility of level adjustment according to the learner's needs, and also development of individual or team skills [119,120]. There are several good examples in the literature showing the implementation of AR in medical education and training.

Anatomy is one of the most important courses in all kinds of medical studies, from physiotherapy and nursing to medicine. Even simple AR and VR applications can visualize all parts of the body, such as bones, joints, muscles, and organs. In addition to in-depth visualization, students can see how a selected part of the human body works, giving a sense of reality. Such applications increase students' anatomical knowledge and improve 3D understanding of anatomical structures [79]. Moreover, users are able to use them in the course, but also individually after class for revising. In [121], the authors test the mobile application dedicated to the teaching–learning process of the spinal cord. Using AR technology, it was possible to capture the abstract nature of this part of the body. The learning process was evaluated as very fruitful, and the students were able to explore interactive 3D rotating models on the macroscopic scale to familiarize themselves with theoretical content, animations, and simulations related to the physiology of the spinal cord. More complex systems are also explored. The combination of two medical fields can be even more interesting. For example the combination of anatomy and radiology, as in [79], where the AR Magic Mirror is being tested. The Magic Mirror is a system that allows users to explore anatomical structures in correlation with medical images using an image of their own body. In the Magic Mirror, users see a reflection of themselves with virtual information superimposed on a display that acts as a digital mirror. The system is shown in Figure 14. Such an AR Magic Mirror system can be successfully integrated into medical curricula and has great potential as a teaching tool for anatomy courses. It provides a unique learning experience and students' results are comparable to those achieved with traditional learning methods such as atlases and textbooks. However, students with poor spatial skills and three-dimensional imagination can take advantage of learning with the app. Traditional methods combined with augmented and virtual reality provide exceptional learning results, as proven in [79,122,123].

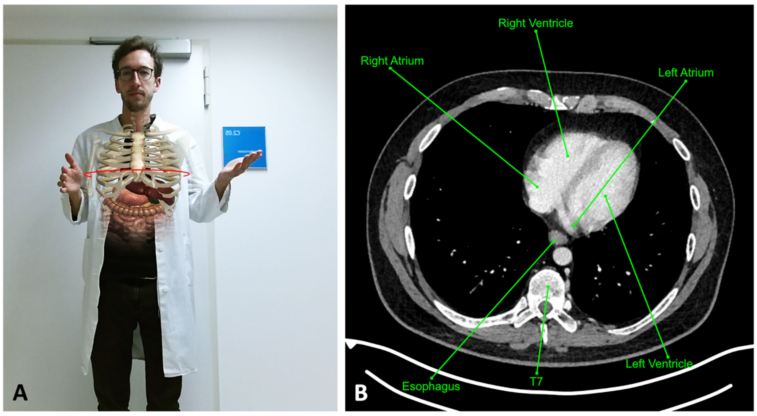


Figure 14. AR Magic Mirror system: (**A**) AR view with virtual anatomy models superimposed on the user; (**B**) CT section image corresponding to the slice at the height of the virtual red circle in the AR view [122].

Mixed reality involves a learning-by-doing approach and can help students practice some important skills, such as motor skills. In [122], researchers create an AR application to develop skills needed for an ultrasound examination. A significant advantage for learners is the immediate feedback they receive and the ability to follow different scenarios and virtually examine different patients. Another benefit for users is the freedom of time and place for training at a reasonable cost.

Both AR and VR medical learning tools are constantly evolving as the needs of medical professionals become more clearly defined. An example of this is the VR Anatomy project (VRAna), which aims to improve the level of detail in skeletal anatomy learning tools [124]. The medical training field also employs the use of digital twins for anatomy training and patient-based training [125]. AR has its uses both in training and outside of it as an assistive tool to improve success rates. One such tool is xVision from Augmentics, which overlays a patient's 3D virtual anatomy on top of the real patient [126]. AR is also being used to teach students central venous catheterization at their own pace [127].

There are many examples of VR medical training and surgical planning. One such VR procedure planning software is Surgical Theater, which allows neurosurgeons to rehearse and later demonstrate neurosurgical procedures to patients before the actual procedure [128]. Similar to the above are programs such as FundamentalVR, which allows surgeons to exercise, practice, and improve their surgical techniques in a haptic-controlled environment. This is made available to users through both VR systems and AR systems such as Microsoft's HoloLens [129]. A very similar tool that provides comparable training outcomes is OSSO VR, which is also a surgical training tool with haptic feedback, but also it additionally includes multiplayer support [130]. For more general training and more realistic scenarios, there is Health Scholars, an AI-based performance assessment tool designed specifically for first responders and clinicians. The tool addresses emergency care training for adult and pediatric scenarios in prehospital, general care, perioperative, and obstetrical settings [131].

Most of the applications mentioned in this section cover specific topics in medical education and are intended primarily as supplemental teaching aids. There are also some AR applications, such as HoloAnatomy, which are intended to cover an entire curriculum in a digitized form [132].

Both VR and AR are prominent in medical education and in assisting medical professionals during procedures. VR seems to be more prominent in the training phase, while AR is more common when real patients are involved. This is the case for training on real patients, for informing patients about upcoming procedures, and even for assisting medical professionals during actual procedures.

6.3.2. AR in Medical Treatment

According to [133], the scope of AR application in medicine includes not only training (education), but also treatment, which involves operating rooms, therapy, and rehabilitation. Surgery planning can be an area where AR has a lot of potential. Recently, a few AR solutions have become available on the market. In 2018, the FDA approved the first medical AR application—Novarad's OpenSight AR System [134]. The Open Sight AR System works with the Microsoft HoloLens headset and allows the surgical plan to be adapted to the actual case. Preoperative images in 2D, 3D, and 4D (from MRI, CT, or PET) are superimposed on the patient's body in real time [135]. Another FDA-cleared AR solution is GLOW800, i.e., AR GLOW800 surgical fluorescence for vascular neurosurgery, the solution offered by Leica Microsystems [136]. Thanks to GLOW800, surgeons have a complete view of anatomy and physiology, they can observe cerebral anatomy and real-time vascular flow in a single image, which helps them make key decisions and actions during vascular neurosurgery.

6.4. AR for Special Needs Education

Students with special educational needs tend not to benefit much from traditional classroom teaching methods [137]. They tend to struggle with the rapid introduction of new topics, lack of examples, insufficient explanations, practice, and review needed to cover multiple subjects [138]. Although this is an age-old problem, with the recent advancements in AR technology, there have been new additions that attempt to bring a solution to this issue.

Studies that have looked at AR for the disabled or developed such applications are becoming more common as the technology advances. As a relatively new field, there are some conflicting results. For example, it is currently unclear whether AR increases or decreases the cognitive load of students, as there are several studies that contradict each other. What is known is that it is a new, emerging technology and both students and teachers need time to get used to it [139].

Regardless of the cognitive load, most of the work on AR with students with disabilities has shown it to be an effective technology for independently teaching students all sorts of topics ranging from wayfinding, numeracy, shopping, emotion recognition, literacy, and even physical skills. More importantly, this seems to be true for students with a very wide range of disabilities, including intellectual disabilities, autism spectrum disorder and attention deficit hyperactivity disorder, students with Down syndrome, and even students who are visually or auditively impaired [140]. In [141], the authors proved that immersive technologies such as AR and VR are an effective alternative to teaching and learning classical orientation and mobility tasks to students with visual impairments. Moreover, both students and teachers were enthusiastic about this technology.

A core issue and a critical question about technology is whether it remains engaging after it has lost its novelty factor. For students with attention disorders, it seems to be one of the factors, if not the main one, that keeps their attention focused on the learning aspect [142].

Some of the AR applications developed for children with intellectual disabilities include an AR tabletop game that teaches children math and how to handle real-world currencies [143]. In the area of geometry, an application has been developed that motivates students through the use of AR geometric puzzles. It is particularly promising as it proves that disabled students can complete tasks on their own without the help or constant supervision of mentors [144].

There are AR apps for people who either have difficulty learning to speak or need to relearn due to trauma. The idea proposed by K. T. Martono and his team has not been evaluated on real patients, but has been deemed useful by therapists who work directly with their target audience [145]. In some cases, AR is even being used to teach mentally challenged children about their local fruits and vegetables. However, in the case of Fancy Fruits, the studies have only been short term, and the long-term results are uncertain [146].

Because there are so many solutions and they have been proven to work in most cases, some authors have decided to delve deeper into the theory behind why and how these systems work as an effective teaching tool. Colpani and Homem, for example, not only explained the importance of gamification to the field, but also created a framework for future researchers in the field [147].

It has been observed that students taught with AR tend to outperform their peers taught with traditional methods over the long term [148]. Once the major issues of cost and the steep learning curve for teachers with AR are resolved, its usefulness in our educational systems should become apparent [139,144].

7. Application Evaluation Methods

Although application design and development is a core part of any AR development process, evaluation is undoubtedly an essential activity. It allows the team to validate that what is being developed meets the needs and expectations of the users and provides valuable feedback on issues such as performance, usability, and accessibility of the technology. Evaluation, at its core, refers to the act of assessing something according to pre-selected metrics that are used to measure, calculate, judge, or estimate its value in a concrete context. An initial review of the existing literature revealed that the establishment of a standard or commonly used framework for the evaluation of AR solutions, although continuously worked on for more than a decade, has not reached as much consensus compared to the evaluation of mobile applications or the more common websites accessed on laptop or desktop computers.

For example, Bach and Scapin [149] discuss how evaluation methods used in other domains could be adapted to evaluate AR systems. When analyzing some of the work carried out and the merging and bridging of methods and tools from other scientific fields, there are some core aspects to consider, such as the focus on the technology or on the user experience, the type of data collected during the evaluation, and also potential collaborative activities when using the AR solution. These core aspects are mentioned in the work of Swan, Gabbard, and Dunser [150–152].

However, user experience is not really considered as a relevant issue in AR studies. A literature review by Anastassova et al. [153] points out that a considerable amount of evaluation activities in AR have focused on the development of ad hoc systems and their evaluation in artificial or informal settings. The analysis of specific user needs has been largely neglected. Where it has been considered, it has been carried out by a small group of experts through a series of quick field studies based on the activities of future users or simply by using questionnaires. Unfortunately, the situation in this field is stagnant, both in general and in educational AR applications.

One of the most important steps in evaluating an AR application as an educational tool is to test its performance. As shown in Table 4, about 63% of the papers use the UX questionnaire as the main evaluation tool. While it provides necessary feedback on the user experience and technical side of the application, it does not provide researchers with information about the actual effectiveness or performance of the application. For this goal, which is an essential step, some kind of performance verification is required, and this was described in only 204 articles. An ideal evaluation process that includes both methods was implemented in only 87 articles. Table 5 illustrates the most commonly used validation methods and provides their description, content, and procedures in detail.

Table 4. Methods evaluating AR application as an educational tool.

Method Type	Usage Count	e.g., Ref.
UX questionnaire	376	[154–157]
Performance Verification	204	[65,66,95,158]
Hybrid method (UX and PV)	87	[159–162]

Table 5. Studies evaluating students' performance.

Method	Content of Use	Experimental Protocol	Participants	Results	Ref.
Expert validation	AR application addressing the heart's anatomic structure for pre-service science teachers' laboratory learning.	• Introduction of the app and marker. • Use of the app in a laboratory environment. • Dissection. • Juxtaposing the app with dissection and general evaluation.	30 pre-service teachers taking the biology laboratory course.	• The app provides the user with information about the anatomy of the heart before they were engaged in the dissection. • The app provides students with rich content related to the subject. • By making small structures visible, it creates the opportunity to learn by doing.	[163]
Automatic validation	AR application to assist and guide operators involved in manual assembly processes in real time.	• Depth camera tracks human motions in the workstation environment. • The camera focus on the upper body of the operator and on their hands in particular. • Visual feedback indicates whether the worker performed an incorrect action.	12 inexperienced operators, both female and male with various anthropocentric parameters.	A real industrial case was adopted to evaluate the benefits of the developed technology compared to the traditional approach in terms of the learning rate, which increases by 22% with a reduction in manual process duration up to −51% during the first assembly cycles.	[78]

Table 5. *Cont.*

Method	Content of Use	Experimental Protocol	Participants	Results	Ref.
Pre and post-test	Magic Mirror as a system for combined anatomy and radiology teaching.	A non-announced examination with 20 multiple choice questions similar to the anatomy part of the first main German medical examination.	749 first-year medical students and 72 students from follow-up elective course.	• A pre and post-test revealed significant improvements in test scores between the two tests for the Magic Mirror. • Students with low mental rotation test scores benefited from the Magic Mirror and achieved significantly higher post-test scores compared to students with a low MRT score in the theory group.	[79]
Observation	Insights into how current mobile AR interfaces affect co-located group collaboration.	Participants performed collaborative tasks with virtual models that have three different levels of complexity. The session was a video recorded for further analysis.	20 participants (11 female, 9 male) in groups of 4 (snowball sampling).	• AR allows collaborators to dynamically switch focus between a work-space and a communication space. • AR apps induce high mental load and frustration and lead to a reduction in group interaction.	[164]

In conclusion, regarding the evaluation of AR solutions, there is no universal methodology or set of tools, but rather a balance between user experience and performance validation tasks [165]. The framework for evaluating each solution depends fundamentally on the attributes related to user experience, the technology developed, and the problem addressed [166].

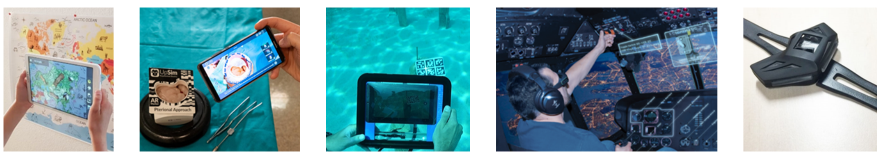
8. Educational Advantages of AR Applications

For a better insight into current AR trends in education, a Cordis database of projects [167] funded by the European Union (EU) Framework Programs for Research and Innovation (FP1 to Horizon 2020), running from 2019 to 2024, was filtered. From the obtained results, 133 projects were selected that deliver results based on AR technology. Published abstracts of these selected projects were additionally analyzed, and those whose results are applicable in the field of learning and training were selected and divided according to the application area. The result is shown separately in Table 6.

Table 6. Projects related to AR in education in training, 2019–2024, co-financed from EU Framework Programs for Research and Innovation.

Field of Application	Number of Projects
Medicine	10
General	7
Cultural heritage	7
Manufacturing	6
Sport and recreation	2
Transport	2
Total	34

Based on the previous selection methodology, it is possible to identify projects that provide general purpose educational platforms that can be used for different educational purposes. One example is the AR Interactive Educational (ARETE) project [168], which brings together businesses and academia to create a unique AR educational platform for educating children in science, technology, engineering and mathematics (STEM), literacy, and positive behavioral intervention. The project examined in this article is a continuation of a previous pilot study called AdHd Augmented (AHA) [169], which developed the WordsWorthLearning AR platform [170] to enhance learning in children diagnosed with Attention Deficit Hyperactivity Disorder (ADHD). The ARETE project is developing different educational scenarios, available on mobile applications, which show students additional content after pointing a tablet or smartphone at content from a book. An example of using the WordsWorthLearning platform is shown in Figure 15a.



(a) (b) (c) (d) (e)

Figure 15. Projects related to AR in education in training, for the period 2019–2024, co-financed from EU Framework Programs for Research and Innovation. (**a**) WordsWorthLearning AR platform in teaching geography, (**b**) UpSurgeOn AR platform for neurosurgeon training, (**c**) UWAR AR platform developed in iMARECULTURE project, (**d**) WrightBroS AR platform for pilot training, and (**e**) Atomic Bands wearables.

However, it can be noted that the largest number of projects related to AR training are used in the field of medicine, especially in the field of surgery, with the aim of better and cheaper training of doctors and reducing the number of bad practices that can have a lasting effect on the patient's health. An example of this is the UpSurgeOn Academy project [171], which develops AR applications in combination with the UpSim physical simulator. The screen of the mobile device shows the exact position of the patient and the course of the operation, while the neurosurgeon simultaneously refines his mental and manual skills on the UpSim physical simulator. The cost of purchasing the above system is EUR 800.00 for one neurosurgeon, which is a negligible amount compared to the average cost of training neurosurgeons, which is approximately EUR 1 million in EU countries. An example of the use of the UpSurgeOn system is shown in Figure 15b.

The importance of cultural heritage is emphasized in all basic documents of the EU, in particular in Article 3 of the *Treaty on European Union*, which states that the EU respects its rich cultural and linguistic diversity and ensures the preservation and promotion of Europe's cultural heritage. It is particularly important to ensure that information on cultural heritage is available to all European citizens, especially when the heritage is protected or intended to show the former appearance of cultural property (e.g., underwater archaeological sites). This is the main objective of the iMARECULTURE project [172], within which special UWAR software has been developed using the Unity 3D framework libraries for the purpose of 3D imaging and development of AR underwater archaeological sites. The models were created for the purpose of educating visitors by displaying protected archaeological sites in AR technology on large screens in a museum environment (so-called Dry Visit) or on the screen of a mobile device (so-called Underwater Visit). An example of use is shown in Figure 15c.

AR has also been used to communicate artifacts and knowledge in the context of museums. An example of its potential is the AR exhibit at the Banco de Portugal's Money Museum, where a collection of precious coins from the 16th century can be interactively explored in a mirror setup. The visitor uses the ticket to virtually manipulate replicas of the coins. AR, like other digital technologies, allows the user to relate to the content on display in a first-person state [173], playing an important role in the construction of the contemporary museographic experience.

In modern manufacturing, there is a strong link between humans and automation, which requires new methods and tools to design and operate optimized workstations in terms of ergonomics, safety, efficiency, complexity management, and job satisfaction. AR technology can provide appropriate human–machine interfaces in an intelligent manufacturing environment supported by an industrial cyber–physical system. Such a system is planned to be implemented within the HyperCOG project [174], where AR applications will be linked to the continuous learning of production workers.

Today, AR technology is commercially used in automotive applications to provide drivers with information about vehicle movements on a head-up display, significantly increasing their reaction time and improving traffic safety. However, in the context of traffic learning and training applications, various flight or driving simulators are being developed to reduce training costs. One such system is implemented in the WrightBroS project [175] as one of the first flight simulators based entirely on AR technology instead of current architectures based solely on Head-Up Display. An example of its use is shown in Figure 15d.

The use of AR technology in sports and recreation is also interesting because it helps professional athletes improve their technique while improving their performance. However, there are also projects such as Atomic Bands [176] that show recreational athletes the correct movements to use when exercising. The key components of the Atomic Bands AR system are wearable, as shown in Figure 15e, worn on the wrists or ankles, allowing athletes to learn proper movement without having to stand in front of a camera.

The cases mentioned above clearly show the possibility of using AR technology to simulate business environments where students are faced with real problems that need to be solved. However, technology alone cannot improve the educational process, and it is necessary to think about appropriate teaching methodologies that allow the acquisition of powerful knowledge from learning about real problems implemented on AR platforms.

In this sense, reference research indicates that it is necessary to apply modern educational methods in which the student is at the center of promoting critical thinking and the teacher is the leader who guides the student in the learning process.

Dewey promoted the philosophy of "learning by doing" and introduced the term Project-Based Learning (PBL) [177] as a teaching method in which problems of real situations in practice are used as a starting point and incentive for acquiring and implementing new knowledge [178]. The potential benefits of PBL are reflected in the development of skills such as teamwork and independent work, professional and interpersonal skills, practicing empathy, analyzing and critical thinking, explaining concepts and communicating, independent and collaborative learning, multidisciplinary problem solving, and applying learning content to the real world. A somewhat new approach is inquiry-based learning (EBL), which is intended to result in strong, purpose-built expertise [179] or higher-level knowledge. Research is a way of teaching and learning that consists of questioning, hypothesizing, and discovery. Furthermore, integrating AR into the research teaching environment can be a motivational factor due to sensory engagement, as activating multiple senses improves knowledge retention [180]. Numerous authors, based on research and projects conducted, point out the advantages of using AR in education as an increase in creativity, more fun learning and an increase in motivation to learn [181], an increase in autonomy and motivation of students to use technological devices [182], easier understanding and explanation of things that they cannot apply and observe [183], the possibility of retaining knowledge for a longer period compared to other pedagogical methods [184], as well as enabling contextual visualization that favors long-term memory [23]. Therefore, AR technology has excellent possibilities for the development of new systems and covers a wide range of topics and academic levels, which is why it has already partially taken root in education and other spheres of life.

9. Conclusions and Future Directions

When reviewing the research and scientific works on the broadly understood application of AR in education, one cannot help but notice that the level of interest in using this technology is growing rapidly. However, the growth dynamics of AR publications slowed down in 2020, probably due to the COVID-19 pandemic. On the one hand, this is due to a significant decrease in post-conference publications caused by mass cancellations of such events. On the other hand, it should be noted that any research work on AR often requires contact with a large number of users of the implemented systems, which was significantly hindered by the restrictive sanitary regulations. Despite a number of such negative factors, there has been an increase in the number of publications on the subject. Interestingly, a significant increase in the share of open access publications has been observed for about three years. This is a consequence of changes in the business models of publishers and scientific research institutions.

Worldwide publications on AR applications are geographically dominated by researchers in Asia, Europe, and North America, reflecting the technological leadership of these continents. While a large proportion of these are very worthwhile scientific publications, a very disturbing phenomenon was observed. Among the reviewed papers, there was an unnatural over-representation of publications from Indonesia, which unfortunately differed significantly in quality from the rest of the reviewed papers. Probably, the review system was at fault here.

Mobile devices are still the most common technology solution for AR systems. Compact size, built-in rear video camera, autonomous use, high system standardization, and relatively low purchase cost are the attributes that favor this solution. However, users of mobile AR systems note several drawbacks, the most important of which are low immersion and inconvenience of use. Mobile devices almost always require hand holding, and the use of static grips severely limits the application's functionality. The exceptions are projector-based AR systems designed for users such as car drivers, whose position and field of view tend to be fixed. AR systems designed as eyeglasses with built-in transparent displays do not have these disadvantages. Based on the review, there is a growing interest in products like HoloLens. The upward trend is due to a gradual decrease in the cost of such devices and a more competitive choice of products (e.g., Apple). What's more, they are definitely the most comfortable way to experience AR. Solutions based on static workstations equipped with a camera, computer, and monitor or projector already exist in trace quantities and are attracting the interest of researchers from developing countries as the cheapest alternative to commercial solutions. AR systems are also increasingly used as part of MR solutions. Visual markers, now past their prime, are being replaced by multi-camera object recognition systems. Real-world environments enriched with interactive 2D/3D visual forms provide numerous educational, cognitive and assistive opportunities. They allow the user to fully concentrate on the task at hand and the AR system acts as a teacher, assistant or consultant. The review shows that the main form of interaction with an AR system is the image. Through the use of multiple sensors, active gaze-based interaction has become possible. AR systems are beginning to use gaze as a complement to controllers and the displays they control, making interactions more comfortable and intuitive for the user. In addition, sound is still an important form of communication, and this includes both audio and voice/speech messages. AR systems with controller sets often use haptic communication, which works well in situations where the visual focus is on other elements of the scene. However, there is a noticeable trend to eliminate controllers altogether in favor of the user's hands. The user can wear gloves with tracing or haptic systems, or bare hands can be used and their detection is performed by optical tracking. In the reviewed works, other external devices for multisensory interaction with the system are occasionally found. However, these should be considered as niche and often highly specialized solutions. However, with the continuous development of technologies such as motion capture, speech, gaze, and brain activity recognition, the characteristic of AR systems will be based on multi-channel human–computer interaction. Special attention should be paid to haptic interfaces and muscle electrical stimulation solutions, which can significantly improve human–computer feedback.

AR technology is increasingly used in general education and life sciences, especially in physics and chemistry. This is because some concepts and phenomena are easier to understand when they are visualized. In addition, AR allows information to be presented in an attractive and engaging way. Education supported by AR and VR becomes much more tailored to the way students, who are digital natives, experience the world [185]. Gamification elements and audiovisual content can significantly increase student engagement, and it has been shown that learners improve their performance when using AR. What is more, AR has been used successfully in engineering, mainly for machine process simulation and architectural visualization, as future engineers need to develop both three-dimensional skills and spatial imagination. AR helps them acquire these essential engineering skills by illustrating and explaining complex spatial constructions, mechanical or electrical mechanisms, and highly abstract concepts such as electromagnetic fields, etc., by drawing the user's attention to critical elements. Students can practice critical decision-making and safely explore hazardous and emergency situations. Another area of education that benefits from AR is medicine. The main advantage of AR medical training is the ability to interact with simulated body parts and gain experience that is closer to reality than textbook knowledge or video footage. It is noteworthy that medical education seems to be more dominated by VR-based applications compared to applied medicine, which is more AR focused. Surprisingly, there is relatively little interest in solutions that aim to support people with disabilities in general, due to the low awareness of universal design in the research and scientific communities.

This review has shown that the establishment of a standard or common framework for the evaluation of AR solutions, although in development for over a decade, has not reached the same level of consensus as the evaluation of mobile applications or websites. Most authors use standard usability testing methods based on HCI guidelines, tailoring tools and techniques to the type of project. It is always a challenge to choose the tools that best fit the purpose of the evaluation. Available tools include questionnaires, interviews, observation grids, and monitoring technology support, and they are built according to the chosen research methodology, or the combination of more than one, and may be combined in different techniques such as focus groups, walkthroughs, real case scenario simulations, and think aloud testing. The type of data and the method of its collection must be congruent with the purpose of the evaluation and the factors chosen to be evaluated. A systematic literature review by Valeria Martins [166] compiled several commonly used characteristics to measure the usability of AR applications, such as ease of use and learning, user satisfaction, and application attractiveness. However, the evaluation may also include additional concerns that are less oriented towards the user experience and more related to the effectiveness in enhancing the learning process. Both UX and application goal-related issues must be given similar priority. It is recommended that an iterative approach be used during the development process to ensure a reduction in the number of issues that arise during the evaluation phase. However, based on the literature review, we found a disturbingly low level of validation. It seems that scientists often focus their attention on achieving an intended goal without verifying its effectiveness. However, unvalidated solutions should not be introduced quickly, especially in medical and engineering education, as they can stimulate the acquisition of bad habits or wrong actions. As a result of the combination of an iterative approach during the development phase [186] and a rigorous attitude towards the evaluation phase, it is possible to collect objective data (i.e., task completion times and accuracy/error rates, scores, position, movement, number of actions, etc.) and subjective data (i.e., subjective user ratings and opinions) related to user preferences, interaction problems, system bugs, and even missing functionalities. Unfortunately, we have noticed that validation methods that provide objective data (e.g., based on biomedical measurements) are relatively rarely used. Their substantive value is much more reliable than the subjective opinions or feelings of users. Therefore, objective validation methods should be considered to measure user engagement, creativity, concentration, and emotional state. This type of validation allows developers to know exactly where and under what circumstances the user encountered difficulties. It is a much better approach than a questionnaire/interview where the user gives a subjective overall rating. The ongoing development of external devices, such as wireless EEG headsets [187], optical sensors for eye/hand tracking and motion capture, or various biomarker monitoring devices [188], should encourage researchers to use objective validation methods to prevent the creation of a useless or potentially counterproductive application.

In summary, we should expect a continued strong growth of interest in the implementation of AR systems in education, especially in teaching and learning at higher education institutions, more so as many of them can be successfully used to develop skills of students who will perform their jobs and support remote communication, control, and management systems.

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