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Smart Learning Environments

REVIEW

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Revealing the true potential and prospects of augmented reality in education

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Abstract

Augmented Reality (AR) technology is one of the latest developments and is receiving ever-increasing attention. Many researches are conducted on an international scale in order to study the effectiveness of its use in education. The purpose of this work was to record the characteristics of AR applications, in order to determine the extent to which they can be used effectively for educational purposes and reveal valuable insights. A Systematic Bibliographic Review was carried out on 73 articles. The structure of the paper followed the PRISMA review protocol. Eight questions were formulated and examined in order to gather information about the characteristics of the applications. From 2016 to 2020 the publications studying AR applications were doubled. The majority of them targeted university students, while a very limited number included special education. Physics class and foreign language learning were the ones most often chosen as the field to develop an app. Most of the applications (68.49%) were designed using marker detection technology for the Android operating system (45.21%) and were created with Unity (47.95%) and Vuforia (42.47%) tools. The majority of researches evaluated the effectiveness of the application in a subjective way, using custom-made not valid and reliable tools making the results not comparable. The limited number of participants and the short duration of pilot testing inhibit the generalization of their results. Technical problems and limitations of the equipment used are mentioned as the most frequent obstacles. Not all key-actors were involved in the design and development process of the applications. This suggests that further research is needed to fully understand the potential of AR applications in education and to develop effective evaluation methods. Key aspects for future research studies are proposed.

Keywords: Augmented reality, AR, Education, ICT, Training, Mixed reality

Introduction

The current epoch is marked by swift advances in Information Technology (IT) and its pervasive applications across all industries. The most prominent technological terms are Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), which have gained popularity for professional training and specialization. AR has been defined variously by researchers in the fields of computer science and educational technology. Generally, AR is defined as the viewing of the real physical environment, either directly or indirectly, which has been enriched through the addition of computer-generated virtual

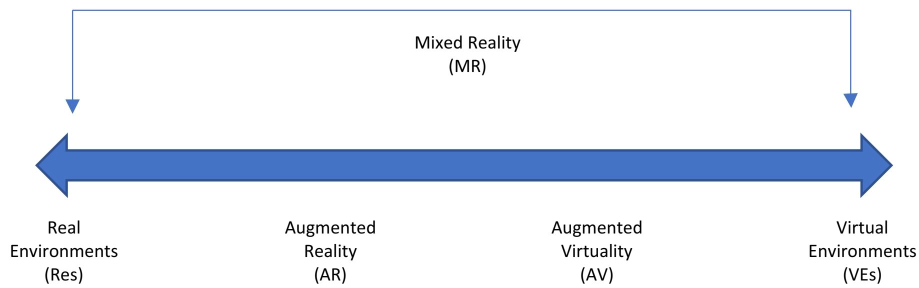

Fig. 1 Reality—Virtuality Continuum [Adapted from Milgram and Kishino's (1994)]

information (Carmigniani & Furht, 2011). Azuma (1997) described AR as a technology that combines the real with the virtual world, specifically by adding virtual-digital elements to the existing real data. This interactive and three-dimensional information supplements and shapes the user's environment. Azuma (1997) proposed that AR systems should exhibit three characteristics: (i) the ability to merge virtual and real objects in a real environment, (ii) support real-time interaction, and (iii) incorporate 3D virtual objects. Milgram and Kishino (1994), to avoid confusion among the terms AR, VR, and MR, presented the reality-virtuality continuum (see Fig. 1).

Figure 1 illustrates that Mixed Reality (MR) lies between the real and virtual environments and includes Augmented Reality (AR) as well as Augmented Virtuality (AV). AR refers to any situation where the real environment is supplemented with computer-generated graphics and digital objects. In contrast, AV, which is closer to the virtual world, augments the virtual environment with real elements (Milgram & Kishino, 1994). Unlike VR, AR aims to mitigate the risk of social isolation and lack of social skills among users (Kiryakova et al., 2018).

AR is recognized as a novel form of interactive interface that replaces the conventional screens of devices such as laptops, smartphones, and tablets with a more natural interface, enabling interaction with a virtual reality that feels completely natural (Azuma, 1997). AR can be classified into four main categories based on its means and objectives:

- *Marker-based AR*: Marker tracking technology uses optical markers (flat structures with long edges and sharp corners, also known as triggers or tags), captures the video input from the camera, and adds 3D effects to the scene. This type of augmented reality is mainly used to collect more information about the object and is widely used in department stores and industries (Schall et al., 2009).
- *Markerless or location-based AR*: This technology gets its name because of the readily available features on smartphones that provide location detection, positioning, speed, acceleration and orientation. In this type of AR the device's camera and sensors use GPS, accelerometer, compass, or other location-based information to recognize the user's location and augment the environment with virtual information (Kuikkaniemi et al., 2014).
- *Projection-based AR*: This type of AR typically uses advanced projectors or smart glasses to project digital images onto real-world surfaces, creating a mixed reality experience. Changing the movement on the surface of the object activates the display

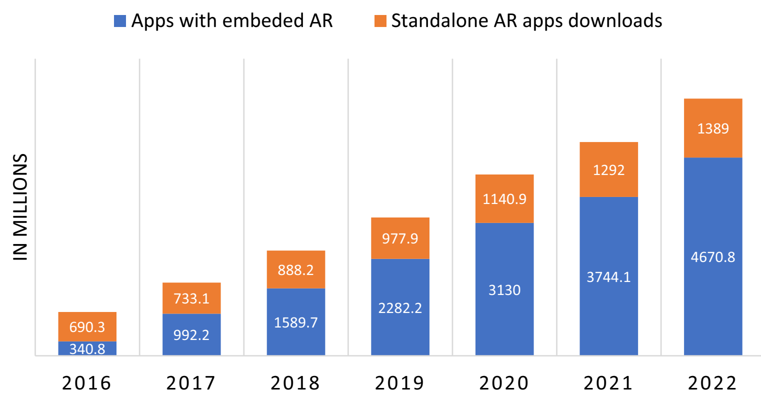

Fig. 2 Consumer mobile device augmented reality applications (embedded/standalone) worldwide from 2016 to 2022 (in millions) [Source: Statista, 2023a, 2023b]

of images. Projection-based AR is used to project digital keyboards onto a desk surface. In some cases, the image produced by projection may not be interactive (Billinghurst & Kato, 2002).

- *Superimposition-based AR*: In this type of AR overlay technology replaces an object with a virtual one using visual object recognition. This process usually occurs by partially or completely replacing the view of an object with an augmented view. First Person Shooter (FPS) games are the best example of augmented reality based on superimposition (Billinghurst & Kato, 2002).

It's important to note that these categories are not mutually exclusive, and some AR applications may use a combination of these types.

Mobile augmented reality has gained popularity in recent years, thanks to advancements in smartphones and more powerful mobile processors. It has opened up new possibilities for augmented reality experiences on mobile devices (Tang et al., 2015). Mobile AR is a technology that allows digital information to be overlaid on the real-world environment through a mobile device, such as a smartphone or tablet. This technology uses the camera and sensors of the mobile device to track the user's surroundings and overlay digital content in real-time. Mobile augmented reality applications can range from simple experiences, such as adding filters to a camera app, to more complex ones, such as interactive games or educational tools that allow users to explore and learn about their environment in a new way. Mobile AR app downloads have been increasing worldwide since 2016 (Fig. 2). The global AR market size is projected to reach USD 88.4 billion by 2026 (Markets & Markets, 2023).

Technological developments have brought about rapid changes in the educational world, providing opportunities for new learning experiences and quality teaching (Voogt & Knezek, 2018). It is no surprise that the field of education is increasingly gaining popularity for the suitability of Augmented Reality applications (Dunleavy et al., 2009; Radu, 2014). In recent years, many researches have been published that highlight the use and effect of AR in various aspects of the educational process, enhancing the pedagogical value of this technology (Dede, 2009).

It is worth mentioning the interest observed in recent years by Internet users in the Google search engine, regarding the term "augmented reality in education". According to the Google tool (Google Trends), the chart below shows the number of searches on the Google search engine for Augmented Reality in education from 2015 to the present.

Compared to the past, the use of AR has become considerably more accessible, enabling its application across all levels of education, from preschool to university (Bacca et al., 2014; Ferrer-Torregrosa et al., 2015). AR has greatly improved the user's perception of space and time, and allows for the simultaneous visualization of the relationship between the real and virtual world (Dunleavy & Dede, 2014; Sin & Zaman, 2010). Cheng and Tsai (2014) also noted that AR applications facilitate a deeper understanding of abstract concepts and their interrelationships. Klopfer and Squire (2008) highlighted the novel digital opportunities offered to students to explore phenomena that may be difficult to access in real-life situations. Consequently, AR applications have become a powerful tool in the hands of educators (Martin et al., 2011).

Augmented reality applications provide numerous opportunities for individuals of all ages to interact with both the real and augmented environment in real-time, thereby creating an engaging and interesting learning environment for students (Akçayır & Akçayır, 2017). AR apps are received positively by students, as they introduce educational content in playful ways, enabling them to relate what they have learned to reality and encouraging them to take initiatives for their own applications (Jerry & Aaron, 2010). The international educational literature highlights several uses of AR, which have been designed and implemented in the teaching of various subjects, including Mathematics, Natural Sciences, Biology, Astronomy, Environmental Education, language skills (Billingurst et al., 2001; Klopfer & Squire, 2008; Wang & Wang, 2021), and even the development of a virtual perspective of poetry or "visual poetry" (Bower et al., 2014).

The increasing interest in augmented reality and creating effective learning experiences has led to the exploration of various learning theories that can serve as a guide and advisor for educators considering implementing AR technologies in their classrooms (Klopfer & Squire, 2019; Li et al., 2020). The pedagogical approaches recorded through the use of appropriate AR educational applications include game-based learning, situated learning, constructivism, and investigative learning, as reported in the literature (Lee, 2012; Yuen & Yaoyuneyong, 2020).

By examining relevant literature and synthesizing research findings, a systematic review can provide valuable insights into the current state of AR applications in education, their characteristics, and the challenges associated with their implementation in several axes:

- *Identifying trends and characteristics*: It can explore the different types of AR technologies used, their educational purposes, and the target subjects or disciplines. This can provide an overview of the current landscape and inform educators, researchers, and developers about the range of possibilities and potential benefits of AR in education (Liu et al., 2019).
- *Assessing effectiveness*: A systematic review can evaluate the effectiveness of AR applications in enhancing learning outcomes. By analyzing empirical studies, it can identify the impact of AR on student engagement, motivation, knowledge acquisi-

tion, and retention. This evidence-based assessment can guide educators in making informed decisions about incorporating AR technologies into their teaching practices (Chen et al., 2020; Radu, 2014).

- *Examining implementation challenges*: AR implementation in educational settings may pose various challenges. These challenges can include technical issues, teacher training, cost considerations, and pedagogical integration. A systematic review can highlight these challenges, providing insights into the barriers and facilitating factors for successful implementation (Bacca et al., 2014; Cao et al., 2019).
- *Informing design and development*: Understanding the characteristics and challenges of AR applications in education can inform the design and development of new AR tools and instructional strategies. It can help developers and instructional designers address the identified challenges and create more effective and user-friendly AR applications tailored to the specific needs of educational contexts (Kaufmann & Schmalstieg, 2018; Klopfer et al., 2008).

This paper concludes by offering researchers guidance in the examined domain, presenting the latest trends, future perspectives, and potential gaps or challenges associated with the utilization of augmented reality (AR) in education. Supported by a series of research questions, the paper delves into diverse facets of AR applications, encompassing target audience, educational focus, assessment methods, outcomes, limitations, technological approaches, publication channels, and the evolving landscape of research studies over time. By addressing these questions, the study endeavors to provide a comprehensive understanding of the unique characteristics and trends surrounding AR applications in the educational context.

The paper is structured for easy readability, with the following organization: The "Material and Methods" section outlines the systematic review's methodology, inclusion/exclusion criteria, research questions guiding the analysis, and a list of quality criteria for chosen articles. In the subsequent "Results" section, the selection process results are detailed, aligning with the prior research questions. This section specifically delves into the technological approach, assessment methodology, quality outcomes, and key findings (including scope, outcomes, limitations, and future plans) of each study. Following this, the "Discussion" section offers a thorough analysis of the findings, unveiling opportunities, gaps, obstacles, and trends in AR in education. Lastly, the "Conclusion" section summarizes the systematic review's major findings and offers guidance to researchers pursuing further work in the field.

Materials and methods

In this scientific paper, a systematic literature review was conducted for the period 2016–2020 to determine the characteristics of augmented reality educational applications and whether they can be effectively utilized in various aspects of the educational process. The study followed a Systematic Literature Review (SLR) protocol, which involves identifying, evaluating, and interpreting all available research related to a specific research question, topic, or phenomenon of interest (Kitchenham, 2004). The paper is structured according to the PRISMA Checklist review protocol (Moher et al., 2009), which outlines the stages of the systematic literature review. The stages of the systematic literature review are framed by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses), which has a wide application in research that aims to study a topic in depth by examining the research that has already been done and published (Grant & Booth, 2009).

The electronic databases Science Direct, Scopus, Google Scholar, Web of Science, MDPI, PubMED, IEEExplore, and ACM Digital Library were searched for scientific articles using keywords (employing Boolean phrases) such as augmented reality, AR, application, education, training, learning, mobile, app, etc., according to PICO (Stone, 2002). The keywords used in the queries were as follows: (AR OR "augmented reality") AND (application OR education OR educational OR teaching OR app OR training OR learning OR mobile OR ICT OR "Information and Communication Technologies" OR tablet OR desktop OR curriculum). The selection of the aforementioned databases was based on considerations of comprehensiveness, interdisciplinarity, quality, international coverage, and accessibility. These databases collectively offer access to peer-reviewed journals and conference proceedings from diverse academic disciplines, ensuring a broad and reliable coverage of AR in education research. Additionally, the inclusion of Google Scholar allows for the identification of open access literature. Their reputation, interdisciplinary nature, and search capabilities further support a comprehensive and credible examination of the topic. The selected databases are known for their frequent updates, enabling the review to capture the latest research and stay up-to-date with the rapidly evolving field of AR in education. Data collection began in January 2021, and inclusion and exclusion criteria for the study are presented below.

Inclusion criteria

- Articles involving the use of Augmented Reality applications for educational purpose
- Studies published in English
- Scientific research from peer-reviewed journals and conferences
- Articles published between 2016 and 2020

Exclusion criteria

Research studies that were excluded from this review include theses, theoretical papers, reviews, and summaries that do not provide the entire articles. Additionally, studies that are "locked" and require a subscription or on-site payment for access were also excluded.

At the beginning of the data extraction process, a set of eight research questions was identified to guide the analysis:

RQ1. What is the target audience of the AR application?

RQ2. What educational areas or subjects are being targeted by the application?

RQ3. What type of assessment methods were utilized for the final solution?

RQ4. What were the outcomes achieved through the application of the proposed solution?

RQ5. What limitations or obstacles were noted in relation to the use of the application?

RQ6. What technological approaches were employed in the application's development?

Table 1 Quality criteria

#	Assessment question	Weight
C1	Is the paper published in a recognized source?	Conferences/Workshops: CORE A* or A (+1.5), CORE B (+1), CORE C (+0.5), not included in CORE ranking (+0) Journals: ranked Q1 (+2), ranked Q2 (+1.5), ranked Q3 or Q4 (+1), no JCR ranking (+0)
C2	Is the technological solution presented in details?	Yes (+1), Partially (+0.5), No (+0)
C3	Is there any evaluation/assessment method?	Yes (+1) / No (+0)
C4	What is the number of subjects in the assessment phase?	≥101 (+6), 81–100 (+5), 61–80 (+4), 41–60 (+3), 21–40 (+2), 1–20 (+1), 0 or not specified (+0)

RQ7. What are the primary channels for publishing research articles on AR educational interventions?

RQ8. How has the frequency of research studies on this topic changed over time?

The quality of the finally processed articles was assessed according to a series of criteria (Table 1). The CORE Conference Ranking (CORE Rankings Portal—Computing Research and Education, n.d.) and the Journal Citation Reports (JCR) (Ipscience-help.-thomsonreuters.com, 2022) were used for ranking conferences and journals accordingly. The maximum score for an article could be 10 points.

Results

Initially, a total of 3,416 articles were retrieved from the searches. A "clearing" stage was then conducted, consisting of several steps. First, duplicates and non-English articles were removed, resulting in 2731 articles. Second, titles and abstracts were screened, yielding 1363 potentially relevant studies. Third, articles that were not available, as well as reviews and theoretical papers not related to the topic, were eliminated. Finally, the studies that met the inclusion criteria were isolated, resulting in a total of 73 articles. The entire process is illustrated in Fig. 3. Figure 4 illustrates the quantity of Google searches conducted for the phrase "Augmented reality in education."

Table 2 illustrates the outcomes of the review process of the selected papers in terms of the technological methodology utilized and the characteristics of the assessment phase for the final solution. The analysis of the quality assurance results of the selected papers are presented in Table 4 (see Annex). According to the quality assurance criteria, 52.05% of the selected papers received a score above half of the total score, with a significant number of them (23.29%) scoring above 7.5. One paper achieved the maximum score, three papers scored 9.5, and one paper scored 9. Notably, 6.85% of the examined articles scored within the maximum 10% (total score = 9 to 10) of the rating scale.

Most studies employed a combination of diverse methodologies to evaluate the final solution, with 83.56% of the studies employing a questionnaire, 16.44% employing observation techniques, 16.44% interviewing the participants, and only 4.11% utilizing focus groups for subjective assessment. Objective assessments were developed in only 6.85% of the studies (Andriyandi et al., 2020; Bauer et al., 2017; Karambakhsh et al., 2019; Mendes

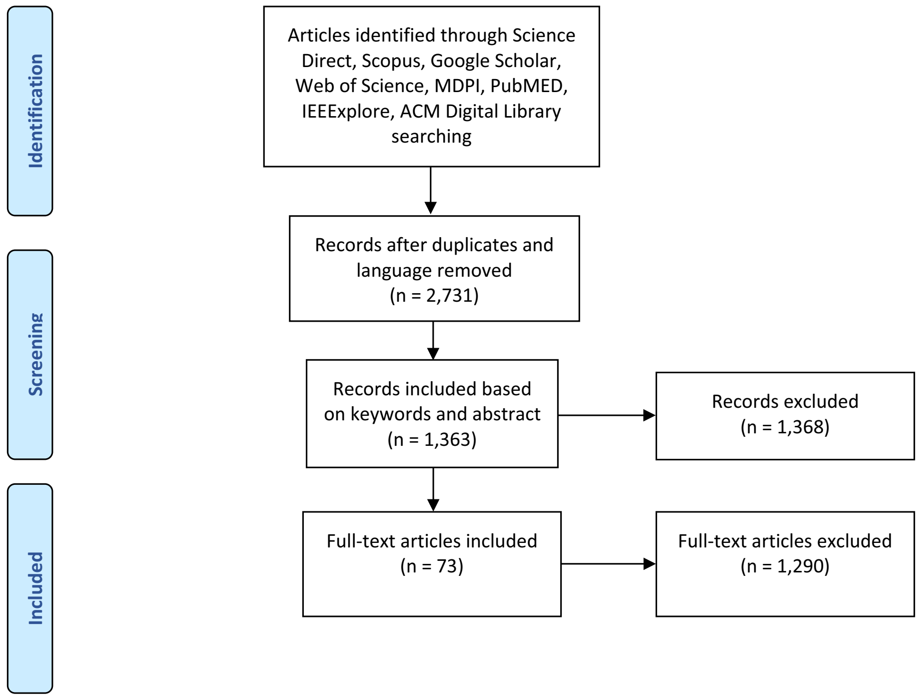

Fig. 3 PRISMA flowchart

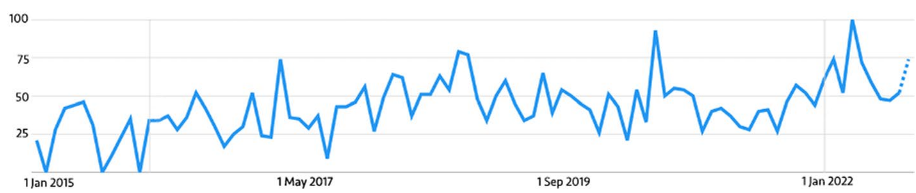

Fig. 4 Number of Google searches for the term "Augmented reality in education"

et al., 2020), with two studies utilizing automatic detection of correct results (Andriyandi et al., 2020; Karambakhsh et al., 2019), and one study using task completion time (Mendes et al., 2020). Approximately one third (31.51%) used achievement tests pre- and post-study to evaluate users' performance after the applied intervention. One study used an achievement test solely in the initial phase (Aladin et al., 2020), and another (Scaravetti & Doroszewski, 2019) only at the end. Concerning subjective assessment, each study employed various instruments depending on the application's characteristics, with custom-made questionnaires being used in almost two-thirds (61.90%) of the articles. The SUS was the most widely used well-known instrument (n = 7, 11.11%), followed by the IMMS (n = 4, 6.35%) and the QUIS (n = 3, 4.76%). The UES, TAM, SoASSES, QLIS, PEURA-E, NASA-TLX, MSAR, IMI, HARUS, and CLS were used in one study each.

Scientific journals were the primary source of publication (98.6%, n = 72), with only one paper (1.4%) presented at a conference. A significant proportion (38.82%) of the articles was published in computer-related sources. The publishing focus was almost equally divided between the education and learning field (18.82%) and engineering (16.47%). The health domain was slightly addressed, with only eight journals (9.41%),

Table 2 Review results

ID	Ref	Developer tools	Operating system	Device used	AR type	Assessment characteristics		
						Type and number of end users	Objective	Subjective (Type, Questionnaire = Valid/Reliable)
1	Akçayır et al., (2016)	Metaio Creator Program	iOS, Android	Smartphone	M, image-based	S(76)	–	I,Q, QLIS = V/R
2	Ayer et al. (2016)	–	–	smartphone, tablet	M	S,CG(88), S(108)	–	FG,Q, CM = –/–
3	Bal et al. (2016)	QRcode cards	–	mobile devices	M, QR codes	S,CG(25), S(25)	–	Q, CM = –/–
4	Carlson et al. (2016)	ARIS platform	iOS	tablet	M, QR codes	E(32)	–	Q, CM = –/–
5	Chen et al. (2016)	Vuforia, Unity	iOS, Android	tablet	L	C,ASD(6)	–	I,Q, CM = V/R
6	Lin et al. (2016)	Aurasma app (HP Reveal now)	–	smartphone, tablet	M	ES,C(21)	–	Q, CM = –/–
7	Montoya et al. (2016)	Vuforia, Unity	Android	smartphone, tablet	M	S(41)	–	Q, CM = –/–
8	Safar et al. (2016)	–	iOS	tablet	–	C,CG(21), C(21)	–	O,Q, CM = V/R
9	Santos et al. (2016)	ARToolKit, PointCloud SDK	iOS	smartphone, tablet	M	S,CG(13), S(18)	–	Q, SUS = V/R, HARUS = –/–
10	Sungkur et al. (2016)	Android Studio IDE, Eclipse IDE, Metaio SDK, Blender	Android	smartphone	M, QR codes	S(25)	–	–
11	Yilmaz (2016)	Metaio Creator Program	–	desktop PC, tablet	M, QR codes	T(30), C(33)	–	I,O,Q, TAM = V/R
12	Bauer et al. (2017)	Kinect SDK, Bresenham algorithm	Windows	laptop	S, image-based	n.d.(20)	Kinect, MRI	Q, n.d. = –/–
13	Bazarov et al. (2017)	Unity 3D, Vuforia, Qualcomm	iOS, Android	smartphone, tablet, AR headset	S, QR codes	S(24)	–	Q, CM = –/–
14	Crăciun et al. (2017)	Aurasma app (HP Reveal now)	–	smartphone	M	T(22)	–	O,Q, CM = –/–
15	Joo-Nagata et al. (2017)	Junaio	iOS	desktop PC, tablet	L	ES,CG,S(71), ES,S(72)	–	Q, CM = V/R
16	Moro et al. (2017)	Vuforia, Unity	Android	tablet	–	S(59)	AT (pre- and post-)	Q, CM = –/–
17	Pombo et al. (2017)	Vuforia, Unity	Android	smartphone, tablet	M, image-based	ES,S(74)	–	FG,O,Q,SUS = V/R
18	Turkan et al. (2017)	ARToolKit, OpenGL ES 2.0	iOS	tablet	M	S,CG(19),S(22)	AT (pre- and post-)	Q, CM = V/R
19	Vega Garzon et al. (2017)	Vuforia, Unity	iOS, Android	–	–	S(88)	AT (pre- and post-)	–
20	Wang, (2017)	Aurasma app (HP Reveal now)	iOS, Android	tablet	M	S,CG(15),S(15)	AT (pre- and post-)	O,I,Q, CM = V/R
21	Abd Majid et al. (2018)	Vuforia, Unity	Android	smartphone	M	S(25)	AT (pre- and post-)	O,I,Q, CM = –/–

Table 2 (continued)

ID	Ref	Developer tools	Operating system	Device used	AR type	Assessment characteristics		
						Type and number of end users	Objective	Subjective (Type, Questionnaire = Valid/Reliable)
22	Aebersold et al. (2018)	Video 3D graphics, hybrid approach	iOS	Tablet	—	S,CG(34),S(35)	AT (pre- and post-)	Q, CM = —/—
23	Alhumaidan et al. (2018)	Vuforia	–	Tablet	M	ES,S(9)	–	–
24	Chang et al. (2018)	Unity	–	tablet	M, image-based	ES,CG(55),ES(56)	–	Q, CM = —/—
25	Cheng et al. (2018)	Vuforia, Unity	Android	smart-phone	S	S,CG(35),S(35)	–	Q, CM = —/—
26	Cieza et al. (2018)	Extreme Programming (XP) methodology, Vuforia, Unity, MonoDevelop	Android	tablet	M	C(10)	–	–
27	Deb et al. (2018)	Vuforia, Unity	Android	smart-phone	M	C(10),T(2)	–	O, –
28	Iftene et al. (2018)	Metaio, Vuforia, ARToolKit, Maya, Unity	Android	smart-phone, tablet	M	P(6), S(12)	–	I,O,Q, QUIS = V/R
29	Kurniawan et al. (2018)	Vuforia, Unity, Floating Euphoria Framework	Android	smart-phone	M	S(60)	–	Q, CM = —/—
30	Layona et al. (2018)	Google Sketchup, 3Ds Max 2011, ActionScript 3.0, C#	Windows	laptop, tablet	M	S(157)	–	Q, SUS = V/R
31	Lorusso et al. (2018)	Vuforia, Unity, Adobe Illustrator	Android	smart TV, tablet	M	ES,S(25), PS(2)	–	O,Q, CM = —/—
32	Mahmood et al. (2018)	Unity, Vimedix	Windows	AR headset Hololens, Vimedix Ultrasound simulator	S	n.d	–	–
33	Mota et al. (2018)	MIT App Inventor, Vuforia, OpenGL	Android	smart-phone	M	E(47)	–	Q, n.d. = —/—
34	Mourtzis et al. (2018)	Microsoft HoloLens software, Unity 3D, Computer Aided Design (CAD) software	–	AR headset Hololens	–	n.d	–	–
35	Nguyen et al. (2018)	–	–	smart-phone	–	S,CG(6),S(6)	–	O,Q, CM = —/—

Table 2 (continued)

ID	Ref	Developer tools	Operating system	Device used	AR type	Assessment characteristics		
						Type and number of end users	Objective	Subjective (Type, Questionnaire = Valid/Reliable)
36	Bursali et al. (2019)	Pawtoon software (animations), Aurasma software (now HP Reveal), AirDroid app	Android	smartphone, interactive board	–	S,CG(46),S(43)	–	O,I,Q, CM = V/R
37	Cabero et al. (2019)	Metaio Creator, Eclipse, Unity, Adobe photoshop	iOS, Android	tablet	M	S(372)	AT (pre- and post-)	Q, IMMS = V/R
38	Collado et al. (2019)	Vuforia, Unity	–	tablet	M	T(29)	–	Q, CM = –/–
39	Fidan et al. (2019)	Vuforia, Unity	Android	tablet	M	S,CG(30),S(61)	AT (pre- and post-)	I,Q, CM = V/R
40	Karambakhsh et al, (2019)	Unity3D, Tensorflow library, Convolutional Neural Networks, 3D key points detectors, 3D array, cloud computing, AI, ML	Windows, Android	AR headset Hololens	–	n.d	AD	O, –
41	Khan et al. (2019)	ARToolKit, Layered marker generation tool (LMGT)	–	interactive board	M	T(20),S(55)	–	Q, CM = –/–
42	López-García et al. (2019)	Layar Creator (Blippar now)	–	smartphone, tablet	L	ES,S(106)	–	Q, PEURA-E = V/R
43	Mylonas et al. (2019)	Unity, GAIA AR Tool, Sketchup, Zxing	iOS	smartphone, tablet	M, QR codes	none	none	none
44	Sáez-López et al. (2019)	–	iOS, Android	smartphone	L	S,CG(22),S(69)	AT (pre- and post-)	Q, CM = –/–
45	Sahin et al. (2019)	Aurasma app (HP Reveal now)	–	smartphone	M, QR codes	S,CG(25),S(25)	AT (pre- and post-)	Q, IMMS = V/R
46	Sargsyan et al. (2019)	Metavision, Unity, Google Cloud Speech-to-Text API	–	Metavision's Meta 2 headset	S	n.d.(9)	–	–
47	Savitha et al. (2019)	–	–	smartphone	M	C,CG(4), C(4)	–	Q, CM = –/–
48	Scaravetti et al. (2019)	Diota software, 3DVia Composer	Windows	tablet, AR headset Hololens	S	S(59)	AT(post-)	Q, CM = –/–
49	Sonntag et al. (2019)	RaspberryPi, CAD, COMSOL MultiPhysics software, Hololens	–	AR headset Hololens	S	S(8)	–	I,Q, CM = –/–

Table 2 (continued)

ID	Ref	Developer tools	Operating system	Device used	AR type	Assessment characteristics		
						Type and number of end users	Objective	Subjective (Type, Questionnaire = Valid/Reliable)
50	Yip et al. (2019)	–	iOS, Android	smart-phone	M	S,CG(21), S(21)	AT (pre- and post-)	Q, CM = –/–
51	Aladin et al. (2020)	Vuforia, Unity	–	smart-phone	M	C(13)	AT(pre-)	Q, CM = –/–
52	Aljojo et al. (2020)	Visual Studio 2017, Unity, Vuforia	Android	smart-phone, laptop, desktop PC	–	S(40)	AT (pre- and post-)	Q, CM = –/–
53	Altmeyer et al. (2020)	Vuforia, Unity	iOS	tablet	M	S,CG(25), S(25)	AT (pre- and post-), TCT	Q, SUS = V/R
54	Andriyandi et al. (2020)	Vuforia, Unity, Adobe Photoshop	Android	smart-phone	M	I(10)	AD	Q, CM = –/–
55	Badilla-Quintana et al. (2020)	–	Android	AR headset	–	S(60)	AT (pre- and post-)	Q, MSAR = V/R, SoASSES = V/R
56	Bibi et al. (2020)	Unity	Android	smart-phone, tablet	M	C(5)	–	I,Q, CM = –/–
57	Conley et al. (2020)	Vuforia	iOS	smart-phone, tablet	M, QR codes	S(252)	AT (pre- and post-)	Q, CM = –/R
58	Dalim et al. (2020)	ARToolkit, Unity, Micro-soft Kinect's	Windows	Kinect, desktop PC, web camera	M	ES,CG,S(30), ES(90)	AT (pre- and post-)	Q, CM = –/–
59	Elivera et al. (2020)	Blippar, Blip-pbuilder	Android	smart-phone	M	S(30), I(3)	–	Q, SUS = V/R
60	Gargrish et al. (2020)	Vuforia, Unity	iOS, Android	smart-phone	M	none	none	none
61	Harun et al. (2020)	Vuforia, Unity	–	–	M	n.d	–	Q, QUIS = V/R
62	Henssen et al. (2020)	ITK-SNAP software, Unity	iOS, Android	tablet	M	S,CG(16), S(15)	AT (pre- and post-)	FG,I,Q, IMMS = V/R
63	Ibáñez et al. (2020)	Vuforia	Android	tablet	M, image-based	S(90)	AT (pre- and post-)	Q, IMMS = V/R
64	Macariu et al. (2020)	Vuforia, Unity, Adobe Illustrator	–	smart-phone, tablet	M	P(70), S(200)	–	Q, QUIS = V/R
65	Mendes et al. (2020)	Vuforia, Unity, Aryzon SDK	Android	Aryzon headset, smart-phone	M, QR codes	n.d.(18)	TCT	Q, SUS = V/R
66	Moreno-Guerrero et al. (2020)	–	–	smart-phone	–	S,CG(60), S(60)	–	Q, CM = –/–
67	Rossano et al. (2020)	Vuforia, Unity, Geogebra	–	tablet	M	S(33)	AT (pre- and post-)	Q, UES = V/R, NASA-TLX = V/R
68	Saundarajan et al. (2020)	–	iOS, Android	smart-phone	M	S(33)	AT (pre- and post-)	Q, CM = –/R
69	Sudarmilah et al. (2020)	–	–	smart-phone	M	n.d	AT (pre- and post-)	Q, CM = –/–
70	Thees et al. (2020)	Hololens, Unity, Vuforia	Windows	AR headset Hololens	M	S,CG(40), S(34)	AT (pre- and post-)	Q, SUS = V/R, CLS = V/R

Table 2 (continued)

ID	Ref	Developer tools	Operating system	Device used	AR type	Assessment characteristics		
						Type and number of end users	Objective	Subjective (Type, Questionnaire = Valid/Reliable)
71	Tsai, (2020)	–	iOS	tablet	–	S(83)	–	Q, IMI = V/R
72	Uiphanit et al. (2020)	Vuforia	–	smart-phone	M	S(40)	AT (pre- and post-)	Q, CM = –/–
73	Zhou et al. (2020)	Autodesk 3ds Max, Unity, Vuforia	–	smart-phone	M, image-based	n.d	–	I

[1] AR Types: M = marker-based, L = location-based, S = superimposition-based, P = projection-based

[2] Type of end users: E = educators; R = researchers; CG = control group; S = students; C = children; ASD = autism spectrum disorder; ES = elementary school; T = teachers; V = visitors; PS = psychologists; n.d. = not defined

[3] Type of objective assessment: AT = achievement test; AD = automatic detection of objects; TCT = task completion time

[4] Subjective assessment: CM = Custom Made, V = valid, R = reliable, FG = focus group, O = observation, Q = questionnaire, I = interview, n.d. = not defined; QLIS = questionnaire for laboratory inquiry skills; HARUS = questionnaire for AR with some evidence of validity and reliability; QUIS = Questionnaire for User Interaction Satisfaction; IMMS = Instructional Material Motivational Survey; PEURA-E = Sixth-grade primary education students' perception of the usefulness of augmented reality; MSAR = motivation scale of augmented reality; SoASSES = scale of acceptance of the use of augmented reality for secondary students; QUIS = Questionnaire for User Interaction Satisfaction; UES = User Engagement Scale; NASA-TLX = NASA task load index (subjective mental workload); CLS = cognitive load scale; IMI = Instructional Materials Motivation Survey; TAM = Technology Acceptance Model survey

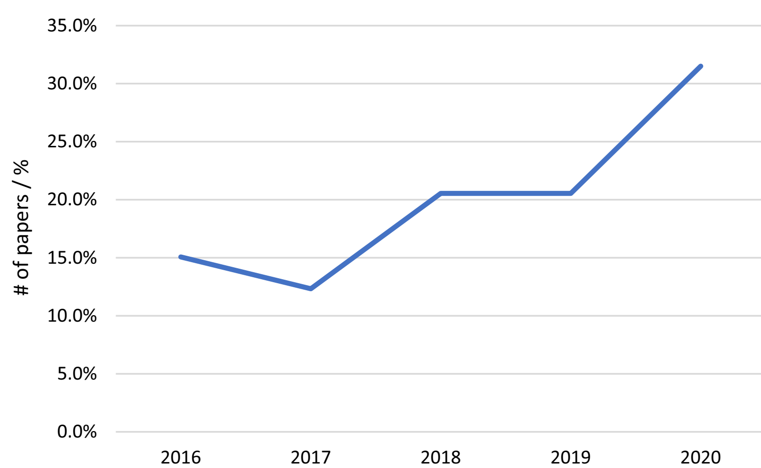

Fig. 5 Frequency of papers per year

followed by sources representing the environment (2.35%). Procedia Computer Science dominated the publishing sector, with 16 articles (21.92%), followed by Computers in Human Behavior (6.85%), the International Journal of Emerging Technologies in Learning (5.48%), and the IOP Conference Series: Materials Science and Engineering (4.11%). The remaining articles (n = 45) were distributed across 39 journals. Notably, over one-third (n = 28, 38.36%) of the studies lacked a JCR ranking. More than half (52.1%) of the reviewed papers were published after 2019 (see Fig. 5).

Table 3 provides a taxonomy for the classification and analysis of the studies included, which aids in the synthesis of findings and the detection of research patterns and gaps. This taxonomy can also function as a structured framework, assisting educators and researchers in categorizing, arranging, and comprehending the diverse

Table 3 Taxonomy of AR in education

Top Hierarchy	Objective of the Study	Educational Purpose	Research Focus	Research Methodology	Physical Requirements		Evaluation and Assessment		Educational Level	Subject Area	Type of Gamification	Challenges and Barriers	Publication Year	Quality Assessment
					Delivery Technology	Back-End Technology	Subjective assessment	Objective assessment						
	Enhancing learning	**Training**	**Pedagogical Integration**	**Experimental Studies**	**Screen**	**Stationary**	**Questionnaires**	**Automatic detection**	**K-12 Education**	**STEM Education**	**Reward Based gamification**	**Technical Challenges**		
Facets	Studies that primarily focus on how AR technology enhances the learning experience in educational settings.	Equipping learners with specific skills through immersive experiences, enabling them to effectively apply those skills in practical contexts.	Articles focusing on the integration of AR technology into educational practices and its impact on teaching and learning.	Research employing controlled experiments or interventions to assess the impact of AR on educational outcomes.	An electronic display surface, such as a computer monitor or smartphone, used to present augmented digital information within the physical environment, enriching the learning experience.	AR experiences that are accessed and interacted with using fixed, non-portable devices or equipment, such as desktop computers or interactive whiteboards, typically within a controlled learning environment.	Articles employing questionnaires to gather data on user experiences.	The system/application automatically detects correct results.	Research specific to primary and secondary education.	Articles related to science, technology, engineering, and mathematics education.	Involves using rewards, such as points, badges, or virtual items, to motivate and engage learners, with the aim of enhancing their educational experiences and outcomes.	Articles addressing technical challenges and limitations associated with AR adoption in educational settings.	Categorize articles based on their publication year to examine trends and developments over time.	Evaluate articles based on their methodological rigor and relevance to the research questions.
	Pedagogical approaches	**Teaching**	**Technical Development**	**Case Studies**	**Head Mounted Display**	**Mobile**	**Interviews, Observations, Focus Groups**	**Task completion time**	**Higher Education**	**Language and Literacy**	**Serious Games**	**Pedagogical Challenges**		
	Research that investigates the pedagogical approaches and instructional strategies associated with AR in education.	Guiding students through AR content to facilitate their understanding and application of knowledge and skills.	Research related to the technical development of AR applications, tools, and platforms designed for educational use.	In-depth examinations of specific educational institutions, courses, or programs that incorporate AR.	A wearable device, resembling glasses or a headset, that immerses the user in augmented reality by overlaying digital elements onto the real world, enabling interactive engagement with virtual objects and information.	Experiences that are accessible on portable devices, like smartphones and tablets, allowing learners to engage with AR content while on the move or in various learning settings.	Articles relying on interviews or observations for data collection.	Task completion time is measured by the system/application.	Studies related to colleges and universities.	Research centered around the application of AR for language learning and literacy development.	Incorporate educational content into gameplay, harnessing game elements to enhance students' intrinsic motivation.	Research exploring pedagogical challenges and considerations when integrating AR into the curriculum.		
	Technical Aspects	**Observing**	**Learning Outcomes**	**Surveys and Questionnaires**		**Cloud**		**Pre- and/or Post- study**	**Adult and Lifelong Learning**	**Arts and Humanities**	**No Gamification**	**Ethical and Privacy Concerns**		
	Articles that delve into the technical aspects of AR, such as the development of AR applications, platforms, and tools for educational purposes.	Monitoring and recording learner interactions and behaviors within AR environments to inform instructional improvements and assess learner progress.	Studies that assess the effects of AR on student learning outcomes, including academic achievement, knowledge acquisition, and skills development.	Studies utilizing surveys or questionnaires to gather data on AR implementation and its effects.		The utilization of cloud computing resources and services to support the storage, processing, and distribution of AR content and applications, enhancing accessibility and scalability for educational purposes.		Pre- and post-studies evaluate users' performance before and after the applied AR-based intervention.	Articles examining the use of AR in adult education and lifelong learning contexts.	Investigations of AR's role in arts, humanities, and creative subjects.	Elements are not integrated to enhance student motivation.	Studies discussing ethical and privacy issues related to AR use in education.		
			Motivation and Engagement	**Qualitative Research**			**Longitudinal Studies**			**Social Sciences**		**Cost and Resource Constraints**		
			Articles exploring how AR enhances student motivation, engagement, and interest in educational content.	Qualitative inquiries, such as interviews or content analysis, to understand the qualitative aspects of AR in education.			Articles tracking AR implementation over an extended period.			Investigations into the use of AR in social science education.		Research examining the cost-effectiveness and resource requirements of AR implementation.		
			Accessibility and Inclusivity							**Interdisciplinary**				
			Research addressing how AR can be made more accessible and inclusive for diverse learners, including those with disabilities.							Studies that span multiple subject areas and disciplines.				
			Teacher Training and Professional Development											
			Studies focused on preparing educators to effectively use AR in their teaching practices.											

aspects of applying AR technology in educational contexts. Tables 5, 6, and 7 subsequently (see Annex) presents the outcomes of the present study, built upon this taxonomy. The "Article id" in Tables 5, 6, and 7 is associated to the one presented in Table 2.

Table 2 presents the technological approach followed by each project. Almost two thirds (68.49%) of the published studies exploited marker-based AR, superimposition-based was found in 9.59% of the articles, while 5.48% followed the location-based approach. As far as the devices are concerned, the majority uses a smartphone (n = 37, 50.68%) or a tablet (n = 35, 47.95%), while 13.70% (n = 10) exploits a head mounted display. Two studies (2.35%) used an interactive board, one a smart TV, and two a Kinect camera. Almost half of the papers (45.21%) worked on an Android operating system, while 28.77% used the iOS and only 9.59% the Windows one. A great percentage (32.88%) did not report the used operating platform. It has to be noticed, that a study may have use more than one of the mentioned devices or operating systems during the experiments. Regarding the used platform and tools for developing the final solution, Unity was the most common one (n = 35, 47.95%), followed by Vuforia (n = 31, 42.47%), Aurasma (n = 5, 6.85%), ARKit or formerly Metaio (n = 5, 6.85%), and Blippar (n = 2, 2.74%). A great percentage (n = 11, 15.07%) did not provide any details on the used platform and tools. As seen in Table 8 (see Annex), the topics covered by the reviewed articles were widely dispersed.

The majority of the reviewed studies (n = 31, 42.47%) focused on the university level, followed by 26.03% (n = 19) that targeted secondary education, 21.92% (n = 16) primary education, 6.85% (n = 5) early childhood education, 1.37% (n = 1) nursery school, and 1.37% (n = 1) health professionals. Special education was addressed in only six papers (8.22%), while 6.85% (n = 5) did not specify the target population.

For a comprehensive overview, Table 9 (see Annex) outlines the primary outcomes, limitations, and future steps of the reviewed studies concerning the utilized applications.

Discussion

The present study involved the analysis of both qualitative and quantitative data obtained from a collection of articles. The qualitative data obtained allowed for the identification of the decisions and actions taken by authors in designing and developing educational AR applications, as well as the extent to which these applications have been utilized. Notably, the study's analysis of educational AR applications was not restricted to any specific age group, subject area, or educational context. Rather, the study aimed to examine the full spectrum of educational AR applications, both within formal and informal education settings. Unlike prior investigations, the current study provides a comprehensive overview of research conducted between 2016 and 2020, exploring a diverse range of study designs and methodologies.

Based on the findings, it was discovered that almost all research studies pertaining to the topic at hand were published in scientific journals. Nonetheless, upon closer examination and analysis of the publications, it was noted that 25 of the studies that were published in journals were, in fact, conference proceedings that were later categorized as journals (e.g., Procedia Computer Science, Procedia CIRP, etc.) with no ranking, making up 38.89% of the total. Roughly 43.03% of the journals that were included in the review were of top-quality and ranked Q1. Collectively, 61.11% of the journals had a ranking score (Q1–Q4), and were thus considered as reputable sources. The wide variety of publishing sources (43 in total for the 73 papers examined) suggests that there is no specialized journal or conference dedicated to the area of interest. Additionally, it signifies that there are various ways in which AR can be employed in educational settings, ranging from simple applications such as labeling objects in a classroom to more intricate applications such as simulations. The following examples illustrate the diverse range of AR applications in education:

- *Visualizing Concepts*: AR can be used to visualize abstract concepts such as the solar system, anatomy, and physics. By using AR, learners can see these concepts in 3D, making it easier to understand and remember.
- *Gamification*: AR can be used to create interactive games that teach learners various skills such as problem-solving, critical thinking, and collaboration. These games can be used to make learning more fun and engaging.
- *Virtual Field Trips*: AR can be used to take learners on virtual field trips, allowing them to explore various places and learn about different cultures, history, and geography.
- *Simulations*: AR can be used to create simulations that allow learners to practice real-world scenarios and develop skills such as decision-making and problem-solving. For example, medical students can use AR to simulate surgeries and practice various procedures or to operate a microscope. Engineers also use AR to simulate experiments in mechanical engineering, electronics, electrical engineering and constructions.

The advent of emerging technologies and the development of low-cost devices and mobile phones with high computing power have created opportunities for innovative AR solutions in education. Researchers tend to prefer publishing their studies in journals, which are considered the most prestigious and impactful sources, even though it may take years to publish compared to only a few months in a conference.

The distribution of published articles per year (Fig. 5) can be attributed to the appearance of the first commercially available AR glasses in 2014 (Google Glasses), followed by the release of Microsoft's Hololens AR headset in 2016. As a result, a greater number of AR applications in retail emerged after 2017, and the AR industry has continued to develop as the cost of required devices has become more affordable. Based on the results, research related to the use of AR and mobile technology for educational purposes is expected to increase significantly in the coming years. According to a recent report by ResearchAndMarkets.com, the global market for Augmented Reality in education and training is projected to grow from 10.37 billion USD in 2022 to 68.71 billion USD in 2026 at a CAGR of 60.4% (Research & Markets, 2023).

In terms of the technological background of the provided solutions, the Android operating system dominated the market in the second quarter of 2018, accounting for 88% of all smartphone sales (Statista, 2023a, 2023b). This finding is consistent with the research results, which indicated that almost half of the studies developed the application for the Android system. This can be attributed in part to the fact that Android is widely adopted, particularly among children and teachers in most countries, who tend to own cheaper Android smartphones rather than iPhones. However, it is now becoming a trend for any commercial application to target both iOS and Android phones, which explains the 28.77% of apps developed for the iOS operating system. Only a small percentage of the studies (9.58%, n = 7) worked with Windows, indicating a strong trend towards mobile AR technologies. One third of the studies (32.88%) did not specify any operating system.

The augmented reality industry is experiencing significant growth, which can be attributed to the increasing number of mobile users who are adopting this technology. Snap Inc. predicts that by 2025, around 75% of the world's population will be active users of AR technology. In addition, Deloitte Digital x Snap Inc. has reported that 200 million users actively engage with augmented reality on Snapchat on a daily basis, primarily through mobile applications. This trend is supported by the modern citizen profile, which is characterized by continuous mobility, limited free time, and greater reliance on mobile phones than PCs or laptops. According to a Statcounter study ("Desktop vs mobile", 2023), 50.48% of web traffic comes from mobile devices. Furthermore, mobile learning is increasingly popular, as evidenced by various studies (Ferriman, 2023).

With respect to development platforms and tools, the market is dominated by Unity (47.95%) and Vuforia (42.47%). This can be attributed to the fact that Unity's AR Foundation is a cross-platform framework that allows developers to create AR experiences and then build cross-platform applications for both Android and iOS devices without additional effort. Additionally, Unity is a leading platform for creating real-time 3D content. Vuforia is a software development kit (SDK) that facilitates the creation of AR applications by enabling the addition of computer vision functionalities, which allow the application to recognize objects, images, and spaces.

Marker-based AR was utilized in 68.49% of the studies, as it is simple and effective in providing a seamless user experience. This technology involves using a camera to detect a specific visual marker, such as a QR code, and overlaying digital content onto the marker in real-time. This allows users to interact with the digital content in a more intuitive way, as they can physically move the marker and see the digital content move along with it. Furthermore, marker-based AR has been in use for longer than other forms of AR and has a more established user base. Its popularity has been further enhanced by many companies and brands integrating it into their marketing campaigns and products. Additionally, its accessibility is a contributing factor, as it requires less processing power and hardware compared to other forms of AR, making it easier for users to access and experience on their mobile devices. Markerless AR, which uses GPS and other location data to place virtual content in the real world based on the user's location, is gaining popularity, but only 2.74% of the examined studies used it. There are also markerless AR systems that use machine learning and computer vision to track and overlay digital content onto real-world objects without the need for markers. While marker-based AR is currently the most common type of AR, other forms of AR are rapidly evolving and gaining traction. Nonetheless, the review indicates that markerless AR applications are still in the early stages of development. As AI, machine learning, and computer vision techniques continue to advance, researchers will need to adopt them to improve AR applications in several ways:

- *Object recognition and tracking*: AI algorithms can be used to improve the accuracy of object recognition and tracking in AR applications. Machine learning can be used to train algorithms to recognize specific objects and track their movements in real-time. This can improve the stability of AR overlays and create a more immersive user experience.
- *Content generation and personalization*: Machine learning can be used to generate and personalize AR content for individual users. Algorithms can analyze user behavior and preferences to generate relevant and engaging content in real-time.
- *Real-time language translation*: AI-powered language translation can be integrated into AR applications to enable real-time translation of text and speech.
- *Spatial mapping*: Machine learning algorithms can be used to create detailed 3D maps of the user's environment. This can be used to improve the accuracy and stability of AR overlays and enable more sophisticated AR applications, such as indoor navigation.
- *Predictive analytics*: Machine learning algorithms can be used to provide users with contextual information based on their location, time of day, and other factors, while AI can predict user behavior. This can be used to create a more personalized and relevant AR experience.

The aforementioned aspects can potentially lead to new opportunities for innovation in the field of AR educational applications. These opportunities can be expanded by developing and utilizing virtual assistants and digital avatars within the educational context. Digital avatars and characters created by artificial intelligence can be designed to respond more naturally to users' behavior and emotions, thereby enhancing engagement and interactions and improving the user experience. AI-powered avatars can also facilitate realistic interactions, leading to more immersive and enjoyable learning experiences. Additionally, AI-powered platforms can be used to create interactive training sessions that provide stimulating and engaging learning experiences. For example, a virtual environment can simulate real-life job situations to aid in employee training. Likewise, AI-powered tools can create interactive experiences in which students can explore virtual objects and concepts in real-time.

Based on the research findings, the process of technology assessment is an arduous, challenging, and time-consuming task, but it is necessary in any research endeavor. However, there is no established gold standard for the subjective evaluation of Augmented Reality applications, which creates a vague landscape that forces most researchers (61.90%) to use custom-made scales. Consequently, this renders research results non-comparable. Moreover, many studies do not utilize reliable and valid instruments, making their findings questionable and not generalizable. Out of the examined pool, 35 cases used non-valid scales, 33 cases used non-reliable scales, and 33 cases used neither reliable nor valid scales. The System Usability Scale (SUS) was used seven times, the Intrinsic Motivation Measurement Scale (IMMS) four times, the Questionnaire for User Interaction Satisfaction (QUIS) three times, and all other scales (Unified Theory of Acceptance and Use of Technology – UTAUT, Extension Scale—UES, Technology Acceptance Model—TAM, Socially Adaptive Systems Evaluation Scale—SoASSES, Quality of Life

Impact Scale—QLIS, Perceived Usability, and User Experience of Augmented Reality Environments—PEURA-E, National Aeronautics and Space Administration Task Load Index—NASA-TLX, Mixed Reality Simulator Sickness Assessment Questionnaire—MSAR, Intrinsic Motivation Inventory—IMI, Holistic Acceptance Readiness for Use Scale—HARUS, and Collaborative Learning Scale—CLS) were used only once each. In two studies (Conley et al., 2020; Saundarajan et al., 2020), even though the researchers tested the reliability of the questionnaires used, they did not assess their validity or use any established methodology to evaluate those questionnaires. Based on the presented results, the subjective satisfaction and assessment of AR solutions appear to be a daunting and challenging task. Therefore, there is a pressing need for the development of instruments that can capture the different aspects of a user's satisfaction (Koumpouros, 2016). In addition, it is essential to report users' experiences with the technologies used to enhance the completeness of research papers. Privacy protection and confidentiality, ethics approval and informed consent, and transparency of data collection and management are also essential. Legal and policy attention is required to ensure proper protection of user data and to prevent unwanted sharing of sensitive information with third parties (Bielecki, 2012). Conducting research involving children or other special categories (such as pupils with disabilities) requires great attention to the aforementioned issues and should follow all recent legislations and regulations, such as the General Data Protection Regulation (European Commission, 2012), Directive 95/46/EC (European Parliament, 1995), Directive 2002/58/EC (European Parliament, 2002), and Charter of Fundamental Right (European Parliament, 2000). The study also found that the number of end users participating in the assessment of the final solution is critical in obtaining valid results (Riihiaho, 2000). However, this remains a challenge, as only 19.18% of studies used 1 to 20 end users to evaluate the application, 20.55% used 21 to 40, 16.44% used 41 to 60, 9.59% used 61 to 80, and 21.92% used more than 80 end users. Only in four studies did both teachers and students evaluate the provided solution, although it is crucial for both parties to assess the solution used, particularly in the educational context, as they observe and assess the same thing from different perspectives.

In the examined projects, insufficient attention was given to primary and secondary education subjects, with only 21.92% and 26.03% of the efforts analyzed targeting these levels, respectively. Additionally, researchers should focus on subjects that are typically known for being information-intensive and requiring rote memory. The examined projects encountered several issues and limitations, including:

- small sample sizes,
- short evaluation phases,
- lack of generalizable results,
- need for end-user training,
- absence of control groups and random sampling,
- difficulty in determining if the solution has ultimately helped,
- considerations of technology-related factors (e.g., cost, size, weight, battery life, compatibility issues, limited field of view from the headset, difficulty in wearing the head-mounted displays, accuracy, internet connection, etc.),
- limited number of choices and scenarios offered to end users,

- subjective assessment difficulty,
- heterogeneity in the evaluation (e.g., different knowledge levels of the end users),
- poor quality of graphics,
- environmental factors affecting the quality of the application (e.g., light and sound),
- quick movements affecting the quality and accuracy of the provided solution,
- image and marker detection issues, and
- lack of examination of long-term retention of the studied subjects.

In terms of future steps, it is essential to obtain statistically accepted results, which requires a significant number of end users in any research effort. Additionally, it is crucial to carefully examine user subjective and objective satisfaction using existing valid and reliable scales that can capture users' satisfaction in an early research stage (Koumpouros, 2016). Researchers should aim to simulate an environment that closely resembles the real one to enable students to generalize and apply their acquired skills and knowledge easily. Other key findings from the examined studies include the need for:

- experiments with wider cohorts of participants and subjects,
- examination of different age groups and levels,
- use of smart glasses,
- integration of speech recognition techniques,
- examination of reproducibility of results,
- use of markerless techniques,
- enrichment of AR applications with more multimedia content,
- consideration of more factors during evaluation (e.g., collaboration and personal features),
- implementation of human avatars in AR experiences,
- integration of gesture recognition and brain activity detection,
- implementation of eye tracking techniques,
- use of smart glasses instead of tablets or smartphones, and
- further investigation of the relationship between learning gains, embodiment, and collaboration.

In addition, achieving an advanced Technology Readiness Level (TRL) (European Commission, 2014) is always desirable. An interdisciplinary team is considered to be extremely important in effectively meeting the needs of various end users, which can be supported by an iterative strategy of design, evaluation, and redesign (Nielsen, 1993). Usability testing and subjective evaluation are challenging but critical tasks in any research project (Koumpouros, 2016; Koumpouros et al., 2016). The user-friendliness of the provided solution is also a significant concern. Additionally, the involvement of behavioral sciences could greatly assist in the development of a successful project in the field with better adoption rates by end users (Spruijt-Metz et al., 2015).

Table 9 (see Annex) shows that AR technologies have been utilized in a variety of disciplines, educational levels, and target groups, including for supporting and enhancing social and communication skills in special education settings. Preliminary results suggest that AR may be beneficial for these target groups, although the limited number of participants, short intervention duration, and non-random selection of participants make generalization of the results challenging. Furthermore, the long-term retention of learning gains remains unclear. Nevertheless, students appear to enjoy using AR for learning and engaging with course material, and AR supports experiential learning, which emphasizes learning through experience, activity, and reflection. This approach to teaching can lead to increased engagement and motivation, improved retention and understanding, development of practical skills, and enhanced critical thinking and problem-solving abilities. In summary, AR has the potential to be a valuable tool for developing a range of skills and knowledge in learners.

An area of interest that warrants further investigation is the amount of time learners spend on each topic when utilizing augmented reality tools as opposed to conventional learning methods. This inquiry may yield valuable insights regarding the efficacy of AR-based

(1) The ease with which students learn the material delivered through AR.
(2) The amount of time required to learn the material when compared to conventional education.
(3) Whether the use of AR enhances students' interest in the topic.
(4) Whether students enjoy studying with AR more than they do with traditional methods.
(5) Whether AR amplifies students' motivation to learn.

interventions. Researchers ought to explore the following five key issues when providing AR-based educational solutions:

It is evident that the aforementioned parameters require at least a control group in order to compare the outcomes of the intervention with those of conventional learning. Additionally, it is essential to consider the duration of the initial intervention and the retesting interval to assess the retention of learning gains. Finally, it is crucial to expand research into the realm of special education and other domains. For example, innovative IT interventions could greatly benefit individuals with autism spectrum disorders and students with intellectual disabilities (Koumpouros & Kafazis, 2019). Augmented reality could be proved valuable in minimizing attention deficit during training and improve learning for the specific target groups (Goharinejad et al., 2022; Nor Azlina & Kamarulzaman, 2020; Tosto et al., 2021).

As far as the educational advantages and benefits of AR in education are concerned, AR holds immense potential for enhancing educational outcomes across various educational levels and subject areas:

- Enhanced Engagement: AR creates highly interactive and engaging learning experiences. Learners are actively involved in the educational content, which can lead to increased motivation and interest in the subject matter.
- Visualization of Complex Concepts: AR enables the visualization of abstract and complex concepts, making them more tangible and understandable. Learners can explore 3D models of objects, organisms, and phenomena, facilitating deeper comprehension.
- Experiential Learning: AR supports experiential learning by allowing students to engage with virtual objects, conduct experiments, and simulate real-world scenarios. This hands-on approach enhances practical skills and problem-solving abilities.
- Gamification and Game-Based Learning: AR can be used to gamify educational content, turning lessons into interactive games. This approach fosters critical thinking, decision-making, and collaborative skills while making learning enjoyable.
- Virtual Field Trips: AR-based virtual field trips transport students to different places and historical eras, providing immersive cultural, historical, and geographical learning experiences.
- Simulation-Based Training: Medical and engineering students can benefit from AR simulations that allow them to practice surgeries, experiments, and procedures in a risk-free environment, leading to better skill development.
- Personalization of Learning: AR applications can personalize learning experiences based on individual student needs, adapting content and pacing to optimize comprehension and retention.
- Enhanced Accessibility: AR can assist learners with disabilities by providing tailored support, such as audio descriptions, text-to-speech functionality, and interactive adaptations to suit various learning styles.

To provide a more comprehensive understanding of AR in education, it is essential to connect it with related research areas:

- Gamification and Game-Based Learning: Drawing parallels between AR and gamification/game-based learning can shed light on how game elements, such as challenges and rewards, can be integrated into AR applications to enhance learning experiences.
- Virtual Reality (VR) in Education: Contrasting AR with VR can elucidate the strengths and weaknesses of both technologies in educational contexts, helping educators make informed decisions about their integration.
- Cross-Disciplinary Approaches: Collaborative research involving experts in AR, gamification, game-based learning, VR, and educational psychology can yield innovative approaches to educational technology, benefiting both learners and educators.
- Learning Outcomes and Age-Level Effects: Future studies should delve into the specific learning outcomes facilitated by AR applications in different age groups and

educational settings. Understanding the nuanced impact of AR on various learner demographics is crucial.

- Subject-Specific Applications: Exploring subject-specific AR applications and their effectiveness can reveal how AR can be tailored to the unique requirements of diverse academic disciplines.

In conclusion, AR in education offers a myriad of educational advantages, including enhanced engagement, visualization of complex concepts, experiential learning, gamification, virtual field trips, and personalized learning. By linking AR research with related fields and investigating its impact on learning outcomes, age-level effects, and subject-specific applications, we can harness the full potential of AR technology to revolutionize education.

Summarizing, AR has positive indications and could significantly help the educational process of different levels and target groups. The innovation of various AR applications lies in the property of 3D visualization of objects—models. In this way, in the field of education, 3D visualization can be used for the in-depth understanding of phenomena by students, in whom the knowledge will be better impressed (Lamanauskas et al., 2007). Game-based learning, the Kinect camera or other similar tools and markerless AR should be further exploited in the future. Finally, it should be noted that in order to effectively achieve the design of an educational AR application, it is necessary to take into account the learning environment, the particularities of each student, the axioms of the psychology of the learner and of course all the theories that have been formulated for learning (Cuendet et al., 2013). In simpler terms, the use of AR applications in education makes learning experiential for learners and mainly aims to bridge the gap between the classroom and the external environment as well as to increase the ability to perceive reality on the part of students.

Research limitations

Our systematic literature review on AR in education, while comprehensive within its defined scope, has certain limitations that must be acknowledged. Firstly, the review was confined to articles published between 2016 and 2020, which may have excluded some recent developments in the field. Additionally, our focus on English-language publications introduces a potential bias, as valuable research in other languages may have been omitted. These limitations, though recognized, were necessary to streamline the study's scope and maintain a manageable dataset. We acknowledge the significance of incorporating more recent data, and already working to expand our research in future endeavors to encompass the latest developments, ensuring the timeliness and relevance of our findings. However, we believe that the period we examined is crucial, particularly due to the emergence of COVID-19, which significantly accelerated the proliferation of educational apps across various contexts. Hence, we consider this timeframe as a distinct era that warrants separate investigation.

Conclusion

The use of AR interventions shows promise for improving educational outcomes. However, to maximize its practical application, several aspects require further scrutiny. Drawing from an analysis of qualitative and quantitative data on educational AR applications, several recommendations for future research and implementation can be proposed. Firstly, there is a need to explore the impact of AR in special education, considering specific age groups, subject areas, and educational contexts. Additionally, studying the effectiveness of different methodologies and study designs in AR education is crucial. It is important to identify areas where AR can have the greatest impact and design targeted applications accordingly. Investigating the long-term effects of AR in education is essential, including how it influences learning outcomes, knowledge retention, and student engagement over an extended period. Understanding how AR can support students with diverse learning needs and disabilities and developing tailored AR applications for special education settings is also vital. Researchers should adopt appropriate methodologies for studying the impact of AR in education. This includes conducting comparative studies to evaluate the effectiveness of AR applications compared to traditional teaching methods or other educational technologies. Longitudinal studies should be conducted to examine the sustained impact of AR on learning outcomes and engagement by following students over an extended period. Mixed-methods research combining qualitative and quantitative approaches should be employed to gain a deeper understanding of the experiences and perceptions of students and educators using AR in educational settings, using interviews, observations, surveys, and performance assessments to gather comprehensive data. Integration strategies for incorporating AR into existing educational frameworks should be investigated to ensure seamless implementation. This involves exploring strategies for integrating AR into existing curriculum frameworks and enhancing traditional teaching methods and learning activities across various subjects. Providing teacher training and professional development programs to support educators in effectively integrating AR into their teaching practices is important. Additionally, exploring pedagogical approaches that leverage the unique affordances of AR can facilitate active learning, problem-solving, collaboration, and critical thinking skills development. The lack of specialized journals or conferences dedicated to educational AR suggests the need for a platform specifically focused on this area. The diverse range of AR applications in education, such as visualizing concepts, gamification, virtual field trips, and simulations, should be further explored and expanded. With the projected growth of the AR market in education, more research is expected in the coming years. Technological advancements should be leveraged, considering the dominance of the Android operating system, to develop applications that cater to both Android and iOS platforms. Furthermore, leveraging advancements in AI, machine learning, and computer vision can enhance object recognition and tracking, content generation and personalization, real-time language translation, spatial mapping, and predictive analytics in AR applications. Integrating virtual assistants, digital avatars, and AI-powered platforms can provide innovative and engaging learning experiences. Improving AR technology and applications can be achieved by investigating compatibility with different mobile devices and operating systems, exploring emerging AR technologies, and developing reliable evaluation instruments and methodologies to assess user experience and satisfaction. These recommendations aim to address research gaps, enhance the effectiveness of AR in education, and guide future developments and implementations in the field. By focusing on specific areas of investigation and considering the integration of AR within educational frameworks, researchers and practitioners can advance the understanding and application of AR in educational settings.

In conclusion, the utilization of AR interventions in education holds significant practical implications for enhancing teaching and learning processes. The adoption of AR has the potential to transform traditional educational approaches by offering interactive and personalized learning experiences. By incorporating AR technology, educators can engage students in immersive and dynamic learning environments, promoting their active participation and motivation. AR can facilitate the visualization of complex concepts, making abstract ideas more tangible and accessible. Moreover, AR applications can provide real-world simulations, virtual field trips, and gamified experiences, enabling students to explore and interact with subject matter in a way that traditional methods cannot replicate. These practical benefits of AR in education indicate its potential to revolutionize the learning landscape. However, it is important to acknowledge and address the limitations and challenges associated with AR interventions in education. Technical constraints, such as the need for compatible devices and stable connectivity, may hinder the widespread implementation of AR. Moreover, ethical considerations surrounding data privacy and security must be carefully addressed to ensure the responsible use of AR technology in educational settings. Additionally, potential barriers, such as the cost of AR devices and the need for appropriate training for educators, may pose challenges to the seamless integration of AR in classrooms. Understanding and mitigating these limitations and challenges are essential for effectively harnessing the benefits of AR interventions in education. While AR interventions offer tremendous potential to enhance education by promoting engagement, personalization, and interactive learning experiences, it is crucial to navigate the associated limitations and challenges in order to fully realize their practical benefits. By addressing these concerns and continuing to explore innovative ways to integrate AR into educational contexts, we can pave the way for a more immersive, effective, and inclusive educational landscape. Our systematic review highlights the substantial potential of AR in reshaping educational practices and outcomes. By harnessing the educational advantages of AR and forging connections with related research areas such as gamification, game-based learning, and virtual reality in education, educators and researchers can collaboratively pave the way for more engaging, interactive, and personalized learning experiences. As the educational landscape continues to evolve, embracing AR technology represents a promising avenue for enhancing the quality and effectiveness of education across diverse domains.

Annex

See Table 4, 5, 6, 7, 8, and 9.

Table 4 Quality assurance results

#	Paper	Year	Source Name	Source Type	C1 score	C2 score	C3 score	C4 score	Total score
1	Akçayır et al., (2016)	2016	Computers in Human Behavior	Journal	2	1	1	4	8
2	Ayer et al., (2016)	2016	Journal of Architectural Engineering	Journal	2	0.5	1	6	9.5
3	Bal et al., (2016)	2016	Procedia Computer Science	Journal	0	1	1	3	5
4	Carlson et al., (2016)	2016	Clinical Simulation in Nursing	Journal	2	1	1	0	4
5	Chen et al., (2016)	2016	Computers in Human Behavior	Journal	2	1	1	1	5
6	Lin et al., (2016)	2016	Displays	Journal	1.5	1	1	2	5.5
7	Montoya et al., (2016)	2016	Eurasia Journal of Mathematics, Science and Technology Education	Journal	1.5	1	1	3	6.5
8	Safar et al., (2016)	2016	Eurasia Journal of Mathematics, Science and Technology Education	Journal	1.5	0	1	3	5.5
9	Santos et al., (2016)	2016	Research and Practice in Technology Enhanced Learning	Journal	2	1	1	2	6
10	Sungkur et al., (2016)	2016	Interactive Technology and Smart Education	Journal	1.5	1	0	2	4.5
11	Yilmaz, (2016)	2016	Computers in Human Behavior	Journal	2	1	1	4	8
12	Bauer et al., (2017)	2017	Computers & Graphics	Journal	2	1	1	1	5
13	Bazarov et al., (2017)	2017	IOP Conference Series: Earth and Environmental Science	Journal	0	1	1	2	4
14	Crăciun et al., (2017)	2017	AIP Conference Proceedings	Journal	0	1	1	1	3
15	Joo-Nagata et al., (2017)	2017	Procedia Computer Science	Journal	0	1	1	6	8

Table 4 (continued)

#	Paper	Year	Source Name	Source Type	C1 score	C2 score	C3 score	C4 score	Total score
16	Moro et al., (2017)	2017	Anatomical Sciences Education	Journal	2	0.5	1	3	6.5
17	Pombo et al., (2017)	2017	2017 International Symposium on Computers in Education	Conference	0	1	1	4	6.5
18	Turkan et al., (2017)	2017	Advanced Engineering Informatics	Journal	2	1	1	3	7
19	Vega Garzon et al., (2017)	2017	Biochemistry and Molecular Biology Education	Journal	1	0.5	1	5	7.5
20	Wang, (2017)	2017	Procedia Computer Science	Journal	0	1	1	2	4
21	Abd Majid et al. (2018)	2018	International Journal on Advanced Science, Engineering and Information Technology	Journal	1	1	1	2	5
22	Aebersold et al., (2018)	2018	Clinical Simulation in Nursing	Journal	2	0.5	1	4	7.5
23	Alhumaidan et al., (2018	2018	International Journal of Child-Computer Interaction	Journal	2	1	0	1	4
24	Chang et al., (2018)	2018	Procedia Computer Science	Journal	0	1	1	6	8
25	Cheng et al., (2018)	2018	International Journal of Emerging Technologies in Learning	Journal	2	1	1	4	8
26	Cieza et al., (2018)	2018	Procedia Computer Science	Journal	0	1	0	1	2
27	Deb et al., (2018)	2018	Procedia Computer Science	Journal	0	1	1	1	3
28	Iftene et al., (2018)	2018	Procedia Computer Science	Journal	0	1	1	1	3
29	Kurniawan et al., (2018)	2018	Procedia Computer Science	Journal	0	1	1	3	5
30	Layona et al., (2018)	2018	Procedia Computer Science	Journal	0	1	1	6	8
31	Lorusso et al., (2018)	2018	Sensors	Journal	2	1	1	2	6

Table 4 (continued)

#	Paper	Year	Source Name	Source Type	C1 score	C2 score	C3 score	C4 score	Total score
32	Mahmood et al., (2018)	2018	Journal of Cardiothoracic and Vascular Anesthesia	Journal	1.5	1	0	0	2.5
33	Mota et al., (2018)	2018	Computers and Electrical Engineering	Journal	2	1	1	3	7
34	Mourtzis et al., (2018)	2018	Procedia Manufacturing	Journal	0	1	0	0	1
35	Nguyen et al., (2018)	2018	International Journal of Educational Technology in Higher Education	Journal	2	0	1	1	4
36	Bursali et al., (2019)	2019	Computers in Human Behavior	Journal	2	0.5	1	5	8.5
37	Cabero et al., (2019)	2019	Applied Sciences	Journal	1.5	1	1	6	9.5
38	Collado et al., (2019)	2019	Journal of Physics: Conference Series	Journal	0	1	1	2	4
39	Fidan et al., (2019)	2019	Procedia Computer Science	Journal	0	1	1	5	7
40	Karambakhsh et al, (2019)	2019	International Journal of Information Management	Journal	2	0.5	1	0	3.5
41	Khan et al., (2019)	2019	Sustainability	Journal	2	1	1	4	8
42	López-García et al., (2019)	2019	Applied Sciences	Journal	1.5	1	1	6	9.5
43	Mylonas et al., (2019)	2019	Electronic Notes in Theoretical Computer Science	Journal	1.5	1	0	0	2.5
44	Sáez-López et al., (2019)	2019	Comunicar	Journal	2	0.5	1	5	8.5
45	Sahin et al., (2019)	2019	Contemporary Educational Technology	Journal	2	1	1	3	7
46	Sargsyan et al., (2019)	2019	EPiC Series in Computing	Journal	0	1	0	1	2
47	Savitha et al., (2019)	2019	International Journal of Recent Technology and Engineering	Journal	0	0.5	1	1	2.5
48	Scaravetti et al., (2019)	2019	Procedia CIRP	Journal	0	1	1	3	5

Table 4 (continued)

#	Paper	Year	Source Name	Source Type	C1 score	C2 score	C3 score	C4 score	Total score
49	Sonntag et al., (2019)	2019	Procedia Manufacturing	Journal	0	1	1	1	3
50	Yip et al., (2019)	2019	Procedia Computer Science	Journal	0	0.5	1	3	4.5
51	Aladin et al., (2020)	2020	IOP Conference Series: Materials Science and Engineering	Journal	0	1	1	1	3
52	Aljojo et al., (2020)	2020	International Journal of Interactive Mobile Technologies	Journal	1	0.5	1	2	4.5
53	Altmeyer et al., (2020)	2020	British Journal of Educational Technology	Journal	2	1	1	3	7
54	Andriyandi et al., (2020)	2020	Telkomnika (Telecommunication Computing Electronics and Control)	Journal	1	1	1	1	4
55	Badilla-Quintana et al., (2020)	2020	Sustainability	Journal	2	0	1	3	6
56	Bibi et al., (2020)	2020	International Journal of Emerging Technologies in Learning	Journal	2	1	1	1	5
57	Conley et al., (2020)	2020	Procedia Computer Science	Journal	0	1	1	6	8
58	Dalim et al., (2020)	2020	International Journal of Human–Computer Studies	Journal	2	1	1	6	10
59	Elivera et al., (2020)	2020	IOP Conference Series: Materials Science and Engineering	Journal	0	1	1	2	4
60	Gargrish et al., (2020)	2020	Procedia Computer Science	Journal	0	1	1	0	2
61	Harun et al., (2020)	2020	Procedia Computer Science	Journal	0	0.5	1	0	1.5
62	Henssen et al., (2020)	2020	Anatomical Sciences Education	Journal	2	1	1	2	6
63	Ibáñez et al., (2020)	2020	Procedia Computer Science	Journal	0	1	1	5	7

Table 4 (continued)

#	Paper	Year	Source Name	Source Type	C1 score	C2 score	C3 score	C4 score	Total score
64	Macariu et al., (2020)	2020	Procedia Computer Science	Journal	0	1	1	6	8
65	Mendes et al., (2020)	2020	Computerized Medical Imaging and Graphics	Journal	2	1	1	1	5
66	Moreno-Guerrero et al., (2020)	2020	International Journal of Environmental Research and Public Health	Journal	2	0	1	6	9
67	Rossano et al., (2020)	2020	IEEE Access	Journal	2	1	1	2	6
68	Saundarajan et al., (2020)	2020	International Journal of Emerging Technologies in Learning	Journal	2	0.5	1	2	5.5
69	Sudarmilah et al., (2020)	2020	IOP Conference Series: Materials Science and Engineering	Journal	0	0.5	1	0	1.5
70	Thees et al., (2020)	2020	Computers in Human Behavior	Journal	2	1	1	4	8
71	Tsai, (2020)	2020	International Journal of Instruction	Journal	1.5	0	1	5	7.5
72	Uiphanit et al., (2020)	2020	International Journal of Emerging Technologies in Learning	Journal	2	1	1	2	6
73	Zhou et al., (2020)	2020	Virtual Reality & Intelligent Hardware	Journal	0	1	1	0	2

Table 5 Taxonomy-based review results (I)

Article id	Objective of the Study			Educational Purpose			Research Focus					
	Enhancing learning	Pedagogical approaches	Technical Aspects	Training	Teaching	Observing	Pedagogical Integration	Technical Development	Learning Outcomes	Motivation and Engagement	Accessibility and Inclusivity	Teacher Training and Professional Development
1	x			x					x			
2		x		x			x					
3	x				x		x					
4		x				x	x					
5	x				x		x				x	
6		x		x						x	x	x
7		x			x				x			
8		x			x				x			
9	x				x		x					
10	x				x		x	x				
11	x				x		x	x				
12	x		x		x		x	x				
13		x			x		x	x				
14		x			x		x		x			
15		x		x					x			
16	x				x				x	x		
17		x			x		x					
18	x				x		x					
19	x	x	x		x		x		x	x		x
20	x	x	x		x		x		x	x		
21	x		x		x		x		x	x		
22	x		x		x		x		x	x		
23		x			x		x					
24		x			x		x					
25		x	x		x		x		x			

Table 5 (continued)

Article id	Objective of the Study			Educational Purpose			Research Focus					
	Enhancing learning	Pedagogical approaches	Technical Aspects	Training	Teaching	Observing	Pedagogical Integration	Technical Development	Learning Outcomes	Motivation and Engagement	Accessibility and Inclusivity	Teacher Training and Professional Development
26	x			x					x			
27	x			x					x	x	x	
28	x	x			x		x		x			
29	x				x				x	x		
30	x				x			x	x	x		
31	x				x	x		x	x	x	x	
32		x			x	x	x	x	x			
33			x	x	x	x	x					
34			x	x			x					
35		x		x			x					
36	x				x				x	x		
37	x				x				x			
38			x		x			x				
39		x			x		x		x	x		
40	x				x		x	x				
41	x				x		x	x				
42	x	x	x		x		x		x	x		
43	x		x		x			x				
44	x		x		x		x					
45	x	x	x		x		x					
46	x		x		x			x	x			
47	x				x		x		x		x	
48	x				x		x		x			
49	x	x	x		x	x	x	x	x			
50	x	x	x		x		x			x		

Table 5 (continued)

Article id	Objective of the Study			Educational Purpose			Research Focus					
	Enhancing learning	Pedagogical approaches	Technical Aspects	Training	Teaching	Observing	Pedagogical Integration	Technical Development	Learning Outcomes	Motivation and Engagement	Accessibility and Inclusivity	Teacher Training and Professional Development
51	x				x		x	x	x	x		
52		x			x		x	x	x	x		
53	x				x		x	x	x	x		
54	x				x		x	x				
55	x				x		x	x	x	x	x	x
56	x				x		x		x	x		
57	x				x		x					
58		x			x		x					
59	x				x		x					
60		x			x		x					
61	x				x				x			
62	x				x				x			
63	x				x				x	x		
64	x				x		x					
65		x		x				x				
66		x			x		x					
67	x				x				x			
68	x				x				x			
69	x				x				x			
70	x				x				x			
71	x				x		x					
72	x				x			x	x			
73	x				x			x	x	x		

Table 6 Taxonomy-based review results (II)

Article id	Research Methodology				Physical Requirements					Evaluation and Assessment					
					Delivery Technology		Back-End Technology			Subjective assessment		Objective assessment			Longitudinal Studies
	Experimental Studies	Case Studies	Surveys and Questionnaires	Qualitative Research	Screen	Head Mounted Display	Stationary	Mobile	Cloud	Questionnairies	Interviews, Observations, Focus Groups	Automatic detection	Task completion time	Pre- and/or Post-study	
1	x				x			x		x	x				
2	x				x			x		x	x				
3	x				x			x		x					
4		x			x			x		x					
5	x				x			x		x	x				
6	x	x			x			x		x					
7	x				x			x		x					
8	x				x			x		x	x				
9		x			x			x	x	x					
10				x	x			x							
11	x				x		x	x		x	x				
12	x				x		x			x		x			
13			x		x	x		x		x					
14				x	x			x		x	x				
15	x				x		x	x		x					
16	x				x			x		x				x	
17				x	x			x		x	x				
18	x				x			x		x				x	
19		x			x			x						x	
20	x				x			x		x	x			x	
21	x				x			x		x	x			x	
22	x				x			x		x				x	
23	x				x			x							

Table 6 (continued)

Article id	Research Methodology				Physical Requirements					Evaluation and Assessment					
					Delivery Technology		Back-End Technology			Subjective assessment		Objective assessment			Longitudinal Studies
	Experimental Studies	Case Studies	Surveys and Questionnaires	Qualitative Research	Screen	Head Mounted Display	Stationary	Mobile	Cloud	Questionnairies	Interviews, Observations, Focus Groups	Automatic detection	Task completion time	Pre- and/or Post-study	
24	x				x			x		x					
25	x				x			x		x					
26	x				x			x							
27	x				x			x			x				
28				x	x			x		x	x				
29	x				x			x		x					
30				x	x		x	x		x					
31		x			x		x	x		x	x				
32	x	x				x	x								
33	x			x	x			x		x					
34	x	x				x									
35		x			x			x		x	x				
36	x				x	x		x		x	x				
37	x				x			x		x				x	
38	x				x			x		x					
39	x				x			x		x	x			x	
40	x			x		x			x		x	x			
41	x				x		x			x					
42			x		x			x		x					
43	x	x			x			x							
44	x				x			x		x				x	
45	x				x			x		x				x	

Table 6 (continued)

Article id	Research Methodology				Physical Requirements					Evaluation and Assessment					
					Delivery Technology		Back-End Technology			Subjective assessment		Objective assessment			Longitudinal Studies
	Experimental Studies	Case Studies	Surveys and Questionnaires	Qualitative Research	Screen	Head Mounted Display	Stationary	Mobile	Cloud	Questionnaires	Interviews, Observations, Focus Groups	Automatic detection	Task completion time	Pre- and/or Post-study	
46		x				x			x						
47	x				x			x		x					
48	x				x	x		x		x				x	
49	x					x				x	x				
50	x				x			x		x				x	
51	x				x			x		x				x	
52	x				x		x	x		x				x	
53	x				x			x		x			x	x	
54	x				x			x		x		x			
55	x					x				x				x	
56	x				x			x		x	x				
57	x				x			x		x				x	
58	x				x		x			x				x	
59	x				x			x		x					
60	x				x			x							
61	x									x					
62	x				x			x		x	x			x	
63	x				x			x		x				x	
64	x				x			x		x					
65	x				x	x		x		x			x		
66	x				x			x		x					
67	x				x			x		x				x	

Table 6 (continued)

Article id	Research Methodology				Physical Requirements					Evaluation and Assessment					
					Delivery Technology		Back-End Technology			Subjective assessment		Objective assessment			Longitudinal Studies
	Experimental Studies	Case Studies	Surveys and Questionnaires	Qualitative Research	Screen	Head Mounted Display	Stationary	Mobile	Cloud	Questionnairies	Interviews, Observations, Focus Groups	Automatic detection	Task completion time	Pre- and/or Post-study	
68	x				x			x		x				x	
69	x				x			x		x				x	
70	x					x				x				x	
71	x				x			x		x					
72	x				x			x		x				x	
73	x	x	x		x			x			x				

Table 7 Taxonomy-based review results (III)

Article id	Educational Level			Subject area					Type of Gamification			Challenges and Barriers			
	K-12 Education	Higher Education	Adult and Lifelong Learning	STEM Education	Language and Literacy	Arts and Humanities	Social Sciences	Interdisciplinary	Reward-based gamification	Serious Games	No Gamification	Technical Challenges	Pedagogical Challenges	Ethical and Privacy Concerns	Cost and Resource Constraints
1		x		x							x	x			
2		x		x						x		x			
3		x		x							x	x			
4		x						x		x		n.d	n.d	n.d	n.d
5	n.d	n.d	n.d				x				x	x			
6	x			x							x	x			x
7		x		x							x	x			
8	x				x						x				x
9	n.d	n.d	n.d		x						x	n.d	n.d	n.d	n.d
10		x		x							x	x			x
11	x							x			x	n.d	n.d	n.d	n.d
12			x					x			x	n.d	n.d	n.d	n.d
13		x		x							x	n.d	n.d	n.d	n.d
14		x		x							x	x			x
15	x					x					x		x		
16		x					x				x		x		
17	x			x							x		x		
18		x		x							x	x	x		
19		x						x			x	x	x		
20	x				x						x	x			
21	x			x							x	n.d	n.d	n.d	n.d
22		x						x			x	n.d	n.d	n.d	n.d
23	x							x			x		x		
24	x							x			x		x		

Table 7 (continued)

Article id	Educational Level			Subject area					Type of Gamification			Challenges and Barriers			
	K-12 Education	Higher Education	Adult and Lifelong Learning	STEM Education	Language and Literacy	Arts and Humanities	Social Sciences	Interdisciplinary	Reward-based gamification	Serious Games	No Gamification	Technical Challenges	Pedagogical Challenges	Ethical and Privacy Concerns	Cost and Resource Constraints
25		x		x							x	x			
26	x			x							x	n.d	n.d	n.d	n.d
27	x				x						x	n.d	n.d	n.d	n.d
28	x				x				x			n.d	n.d	n.d	n.d
29	x	x		x							x	x			
30	x							x			x	x			x
31	x						x				x	x			
32		x						x			x	x			
33		x		x							x	x			
34		x		x							x	x			
35		x		x							x	x			
36	x				x						x	x			
37		x		x		x		x			x	x	x		
38	x			x							x	x	x		
39	x			x							x	x		x	
40		x						x			x	x			
41	x				x						x	x			
42	x			x	x		x	x			x		x		
43	n.d	n.d	n.d					x			x	x			
44	x			x		x	x		x			x			
45		x				x					x		x		
46		x						x			x	x			
47	x				x			x			x	x			
48		x		x							x	x			

Table 7 (continued)

Article id	Educational Level			Subject area					Type of Gamification			Challenges and Barriers			
	K-12 Education	Higher Education	Adult and Lifelong Learning	STEM Education	Language and Literacy	Arts and Humanities	Social Sciences	Interdisciplinary	Reward-based gamification	Serious Games	No Gamification	Technical Challenges	Pedagogical Challenges	Ethical and Privacy Concerns	Cost and Resource Constraints
49		x		x							x	x			
50		x						x			x		x		
51	x				x						x	x	x		
52	x					x					x	x	x		
53		x		x							x	x			
54	n.d	n.d	n.d			x					x	x			
55	x			x							x	x	x	x	x
56	x				x						x	x	x		
57		x		x							x		x		
58	x				x						x		x		
59	n.d	n.d	n.d			x					x		x		
60	x			x							x		x		
61	x			x							x	x			
62		x						x			x		x		
63	x			x							x	n.d	n.d	n.d	n.d
64	x			x							x	x			
65		x						x			x	x			
66	x							x			x		x		
67	x			x							x	n.d	n.d	n.d	n.d
68	x			x							x	n.d	n.d	n.d	n.d
69	x				x	x			x			n.d	n.d	n.d	n.d
70		x		x							x	n.d	n.d	n.d	n.d
71		x			x					x			x		
72	x				x						x		x		
73	x							x			x		x		

Table 8 Domains covered

Domain	#	References
Electronics	1	Montoya et al. (2016)
Structural analysis	1	Turkan et al. (2017)
Microscope operation	1	Zhou et al. (2020)
STEM	1	Abd Majid and Abd Majid, (2018)
Biology, Geography	1	Iftene and Trandabăţ, (2018)
AR	1	Mota et al. (2018)
Sewing	1	Yip et al. (2019)
Educational technology	1	Cabero-Almenara and Roig-Vila (2019)
Energy efficiency	1	Mylonas et al. (2019)
Computer science	2	Akçayır et al. (2016), Bal and Bicen (2016)
Communication, social interaction	2	Chen et al. (2016), Lorusso et al. (2018)
Design	2	Ayer et al. (2016), Mourtzis et al. (2018)
Art	2	Cabero-Almenara and Roig-Vila, (2019), Sáez-López et al. (2019)
Qur`an	2	Aljojo et al. (2020), Andriyandi et al. (2020)
Reading	2	Bursali and Yilmaz, (2019), Cieza and Lujan, (2018)
Mechanical engineering	3	Bazarov et al. (2017), Cheng et al. (2018), Scaravetti and Doroszewski, (2019)
Chemistry/Biochemistry	3	Badilla-Quintana et al. (2020), Macariu et al., (2020); Vega Garzon et al. (2017)
History	5	Joo-Nagata et al., (2017), Pombo and Marques, (2017), Cabero-Almenara and Roig-Vila, (2019), Sahin and Ozcan, (2019), Elivera and Palaoag, (2020), Sudarmilah et al. (2020)
Medical interventions	5	Carlson and Gagnon, (2016), Aebersold et al., (2018), Mahmood et al., (2018), Sargsyan et al., (2019), Mendes et al., (2020)
Mathematics	6	Conley et al., (2020), Lin et al., (2016), Gargrish et al., (2020), Ibáñez et al. (2020), Rossano et al., (2020), Saundarajan et al., (2020)
Anatomy	7	Bauer et al., (2017), Moro et al. (2017), Kurniawan and Witjaksono, (2018), Layona et al., (2018), Karambakhsh et al., (2019), Henssen et al., (2020)
Other	7	Yilmaz, (2016), Pombo and Marques, (2017), Alhumaidan et al., (2018), Nguyen et al., (2018), López-García et al., (2019), Savitha and Renumol, (2019), Moreno-Guerrero et al., (2020)
Physics	9	Akçayır et al. (2016), Crăciun and Bunoiu (2017), Chang and Hwang, (2018), Collado et al. (2019), Fidan and Tuncel, (2019), Sonntag et al. (2019), Altmeyer et al. (2020), Harun et al. (2020), Thees et al. (2020)
Languages	9	Safar et al. (2016), Wang, (2017), Deb and Bhattacharya, (2018), Khan et al. (2019), Aladin et al. (2020), Dalim et al. (2020), Tsai, (2020), Uiphanit et al. (2020)

Table 9 Outcomes, limitations, future plans

#	Scope	Outcomes	Limitations	Future plans
1	The effects of the use of AR in science laboratories on university students' laboratory skills and attitudes towards laboratories	AR technology improved the students' laboratory skills and helped them build positive attitudes towards physics laboratories. It reduced the work load of the instructor	–	–
2	How AR and simulation game technologies would influence students' design processes	Beneficial behaviors were observed: students were able to break the tendency toward design fixation, to assess their designs using the AR application and generate additional concepts with better overall performance compared with the students who used paper-based formats	Limited number of choices offered by the application. The two technologies used (AR and simulation game) were not assessed independently. The aesthetics part of the design could not be evaluated automatically	Explore the benefits of the application without the aid of AR for visualization or without the simulation game for assisting users in assessing design concepts. Incorporate an aesthetic component into the design experience. Extend the breadth of the sustainable topics covered. Further developments will target additional user groups to understand how this type of learning approach might be able to engage the general public with sustainability and design concepts to increase interest and awareness of these fields
3	The effect of AR and QR Code integration on achievements and views of undergraduate students taking computer course	Achievement level of experimental group was higher	–	–
4	Integrating simulation and AR for health care education	It is an inexpensive way to enhance simulation, provide authentic interactions, and potentially assist learning. Could be a prospective method for other disciplines	Low response rate. There was no homogeneity in how the prototypes were examined. The representatives did not have the same level of knowledge. The scenarios implemented were rough and lacked flow, media and design refinement	–
5	How AR can help children with ASD to perceive emotions through facial expressions	ARVMS intervention effectively attracted and maintained the attention of children with ASD to nonverbal social cues and helped them better understand the facial expressions and emotions of the storybook characters	Selection biases might have operated among the study participants. The results of the study cannot be generalized to children with ASD who also have an intellectual disability	Experiments with more participants of all ages with ASD should be included

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
6	Facilitate the teaching of geometry to children with special needs to increase their confidence	Improved ability to complete puzzle game tasks when compared to the use of traditional paper-based methods. AR technology could enhance learning motivation and frustration tolerance in children with special needs	–	–
7	How the type of content (static or dynamic) affects the student learning perception and performance in AR applications	Better results were obtained using dynamic content. Students believe that learning the concepts is more easily when they use dynamic contents than when they use static ones	–	Development and use of the application to the full course of fundamentals of electronics. Integration of the application with the curriculum and its evaluation during the whole course in order to define the impact of static and dynamic contents
8	Evaluation of the effectiveness of the use of an AR application as a teaching and learning tool for instructing kindergarten children in the English alphabet	AR technology should be adopted at pre-school and kindergarten	Human limitation, which is represented by the children being at the first level of kindergarten in the State of Kuwait. Spatial limitation, as the study is confined to a kindergarten located in the Mubarak Al-Kabeer Educational Area in the State of Kuwait. Time limitation, as the study was conducted during the second semester of the 2015–2016 academic year. Technical limitation, as the study used tablets. Literary limitation, as the results of a search for reliable sources during the preparation of this study clearly demonstrated the scarcity of educational studies on this topic in the State of Kuwait as well as in the Gulf Cooperation Council and the Middle East. Lack of studies on the use of AR technology in kindergarten which can be assumed to be one of the vital limitations of this research study	Extra in-depth research studies are required, with larger sample sizes, examining the effects of using other AR apps on academic achievement in other grades such as elementary, middle, and high school. Study the impact of the use of AR on academic achievement in other subject areas
9	AR as a multimedia for learning vocabulary and how it enhances word recall	AR may lead to better retention of words and improve student attention and satisfaction	Small sample size and not generalizable results	Experiments with bigger sample size to explore deeper into how students can learn better with AR. Longitudinal studies are necessary to explore the evolution of students' knowledge and skills over time

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
10	Design, developed and use of a mobile AR application as a teaching tool to assist students and lecturers during teaching	AR proved helpful in understanding complex concepts of computer science that average students have much difficulty in understanding. The application can track and detect both markerless and marker-based images	–	The use of advanced augmentations in the form of 3D models and animations, which are more appealing. Development of location-based AR applications that can be used where students would be encouraged to engage in critical thinking
11	Reveal teachers' and children's opinions on Educational Magic Toys (EMT) using AR, to determine children's behavioral patterns and their cognitive attainment, and the relationship between them while playing EMT	EMT can be effectively used in early childhood education. Teachers and children liked EMT activity. Teachers had a high level of positive attitude toward EMT and perceived them as useful. Children like EMT, mostly flashcards, because 3D objects appear on cards. Children interactively played with these toys but not had high cognitive attainment. They prefer mostly pointing, responding, inspecting and turning behaviors while playing with EMT	Limitations due to presenting descriptive findings of behavioral pattern	Use of smart glasses. Development for different sample groups and for different educational fields
12	Development of a user-specific internal anatomy model using mirror-like AR	An image-based corrective registration to correct the errors that build up during system steps: motion capture, anatomy transfer, image generation and animation	The combined pipeline is not real-time due to expensive file read and write operations. Cannot correct the errors in orientation of the anatomy regions relative to the bones	Read color maps from memory and build a combined real-time system. Use image-based hybrid solution that use a 3D morphable model to fit to some features in 2D images. Posture reconstruction proposed by the Kinect SDK could be re- placed by more sophisticated approaches. Improvement in the skin registration by reducing the 9DOFs controllers to 6DOFs (3 rotations and 3 scales)
13	Use of AR for teaching engineering students of electrical and technological specialties	The AR app allows saving the teacher's time. Students tend to show sympathy and affection for this technology. AR is an economically effective technology. It provides students with more attractive and demonstrative content than paper didactic material	–	–
14	Analyze various curricular and extracurricular activities specifically designed for and undertaken by pre-service physics teachers	Pre-service physics teachers are confident in using MAR in their teaching and learning activities, and consider that the activities performed helped them develop the skills necessary for science teachers	–	–
15	Development and evaluation of an AR-based training program for cultural heritage	The m-learning scenario using AR technologies proved more effective and attractive for the participants	The results cannot be generalized. More factors affecting the results should be determined	Use more teaching scenarios in other disciplines. Reproducibility of the results in tertiary education or informal educational context

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
16	Whether learning structural anatomy utilizing VR or AR is as effective as tablet-based applications, and whether these modes allowed enhanced student learning, engagement and performance	Both VR and AR are as valuable for teaching anatomy as tablet devices, but also promote intrinsic benefits such as increased learner immersion and engagement	Limited number of participants. Sample demographics may also have played a role in the study outcome	Greater number of participants from a wider cohort of students. More advanced anatomical concepts and features to be implemented. Identify the optimal timeframe of lessons within VR and AR
17	Develop an interactive AR mobile application to support geocaching activities in outdoor environments, thus creating situated learning opportunities	This is a work-in-progress report of the EduPARK project's options regarding the AR content and triggers, and points out some future directions	Technical issues related to the markers' recognition. Preliminary empirical data have been collected	Develop markerless tracking for the application in the selected urban park. Freely offer to the public the final app. Use additional animated AR contents. Further evaluation. Enrich the app with more student activities
18	A new pedagogy for teaching structural analysis that incorporates mobile AR and interactive 3D visualization technology	The utilized AR design concepts have potential to contribute to students' learning by providing interactive and 3D visualization features, which support constructive engagement and retention of information in students. Application design was not well suited for all students (too complex). No good design, since the visualization features may have overwhelmed the students. Incorporating all AR design concepts and their respective features into one AR application design might be misleading	Only one example problem was tested. No statistically meaningful significance was found	The interaction interface along with instant feedback features of the application will be redesigned by splitting all interactions in an AR navigation mode and an AR interaction mode. Develop instructions on how to use the AR application. More examples will be integrated covering structural analysis. Integrate a feedback system in the app
19	Teach and learn biochemistry. Students to visualize the 3D molecular structure of substrates and products in order to learn metabolic pathways	Students developed skills that empower them to understand biochemical concepts. The tool provides a more objective way of evaluating the students	–	–
20	Examine the use of AR-based learning materials to high school students in the process of Chinese writing	AR techniques helped the intermediate-level students the most in their writing performance of content control, article structure and wording. The AR system supported the low-achievers to start writing the first paragraph more quickly, and enriched their ideas	Small number of students participated in each group and the period of time spent conducting the experiment was limited. No generalizable results	Investigate the AR-supported writing system for various writing topics. Explore how the AR system can support intermediate-level learners in their writing. Integrate an optional button on the AR screen to help learners decide the presentation mode of the AR information during the writing activity. A bigger sample of participants to be included in the study

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
21	Develop a learning application that supports STEM education based on guided discovery learning to assist the students through questions based on exposure to various evidence via AR	The students improved their marks in tests conducted at the end of the application usage. AR helps to encourage positive learning and enhance the student's motivation towards gaining knowledge	–	–
22	To teach nursing students how to correctly place the nasogastric tube	The AR module was better received compared with the control group with regard to realism, identifying landmarks, visualization of internal organs, ease of use, usefulness, and promoting learning and understanding	Small study conducted in one school with students who had some prior exposure to this skill	More studies are required to determine the effectiveness of this application in users who have not received any training or in other settings
23	A co-design approach involving primary school children in the design and evaluation of an AR textbook for collaborative learning experience	Key design features that can be implemented in school textbooks for a collaborative AR experience. Children are natural partners for co-design. Difficult to manage the time and efforts in each session. It is a more costly process that the traditional methods since it requires toolkits and prototypes. The qualitative data is messy	Research is specific to similar communities that share the same geographical location and ideological background	–
24	Development of an AR-based flipped learning mode for physics course	The students' learning achievements, learning motivation, critical thinking tendency, and group self-efficacy were significantly improved	There was no content for practice in the system. The time for the experiment was too short. Recognition failure inside the classroom because image-based AR was affected by lights and angles. Collaboration which is a factor that might affect students' learning outcomes in project-based learning, was not taken into account in the present study	Apply the approach to other course content by taking more factors (e.g., collaboration and personal features) into account
25	Development of an interactive teaching system that uses mobile AR to improve the learning efficiency of a mechanical drawing course	The AR class was significantly superior with regard to the degree of students' proficiency in the course's key, difficult content areas, their spatial imagination capability, and their interest in learning and study after class	Great developmental difficulties and high costs. Evaluating the teaching effect of this approach was limited by time, manpower, material resources and money. Short evaluation phase and small sample size, which led to the lack of a comprehensive detailed data analysis	Build a relatively stable AR teaching system development group, exploring industrialized models, demonstrations and applications, and improve the teaching effect evaluation mechanism

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
26	Improve the level of understanding of the usage of vowels and numbers for children in a nursery school using mobile AR techniques	Increased level of academic performance of vowel usage and the use of numbers	–	–
27	Create an AR application to facilitate learning of the letters of Hindi Varnamala and its corresponding hand gesture movements for sign language	Substantial improvement in sign language learning of the deaf-mute students	Usability hindrances	Use a full body human avatar and zoom in slowly on the hand to give the children a better perspective of the hand gestures
28	Develop an AR-based application to improve communication and collaboration skills and to ease the learning of biology and geography	Four applications were developed for eLearning (two focused on collaborative work of students and two on biology and geography). They were found attractive for the students. They could retain new information more easily, and tests designed as games contributed to reduce their stress	–	Introduction in all four applications of a component based on Alexa from Amazon to evaluate students that uses the AR applications. This component will use voice recognition to take answers from students and will automatically evaluate them
29	Development of a human anatomy learning system based on mobile AR	It helps students learn human anatomy more easily. It creates the desire of students to use this application higher as a complementary tool for learning and understanding human anatomy	–	Better guidance for beginner users, add visualization materials with more choices featured in multimedia platforms by using sound or video, easy-to-understand material annotation improvements with easier-to-understand language usage and user interface
30	Develop an AR application for learning human anatomy	AR helped students to understand easier the concepts of human anatomy and the whole experience was found more interesting. AR technology can be used as an alternative method for human body anatomy learning. The anatomical explanation and anatomical position of the human body added insight	–	Interaction and menu selection to be done without markers. Develop for more human anatomical systems and use animations. More detailed 3D texture graphics that can be retrieved from the scanned object. Apply the technology and proposed solution to other subjects
31	Development of an integrated system which combines the use of smart devices, a physical cube, AR, a smart TV, and a software application designed to stimulate cognitive and social functions in pre-school children	A positive impact of the activity at both the cognitive and the social level was observed. It was found easy to understand, elicits high levels of participation and social interaction, favors strategic behaviors, and can be used by the children with limited need of instruction and support by the adult	–	Testing the impact of the app on children with neurodevelopmental disorders, especially those involving deficits of executive functions, problem-solving skills and social abilities and communication skills or pragmatic competence such as children with ASD, preterm born children, or other vulnerable populations, including children from immigrant families, ethnic minorities, or low SES contexts

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
32	Use AR equipment for transthoracic and transesophageal echocardiography training	Allowed learners to practice image acquisition with AR with an understanding of the rationale for probe motions and manipulations. The mixed reality used helped trainees appreciate the specific views from the instructor's perspective	Limitations of the technology. The VR Hololens is expensive and compatible with the Vimedix simulator only. The headset is heavy, and prolonged use is associated with neck muscle fatigue. The headset has a limited battery life. The technology of VR/AR is not widely available on all simulators and is expensive to acquire and maintain. The remote applications (teaching and monitoring) are available within the limited range of the Wi-Fi network. There is a limited field of view from the headset	Immersive reality haptic techniques can be used to improve manual dexterity. Can be used to remotely teach multiple locations with a single instructor or remotely monitor multiple trainees' performance during a procedure
33	Present the VEDILS Framework, a development method and tool which enables teachers to design and deploy learning activities using AR	The framework and authoring tool was found suitable for supporting users without programming skills in developing their own apps. Block-based programming languages can help teachers to overcome their lack of programming skills. A high level of acceptance from lecturers and students	-	Support new technologies in the authoring tool. Integrate gesture recognition and brain activity detection with devices such as Leap Motion and EMOTIV Epoc+
34	Use AR in product design for engineering students	It has improved the designers' insight on the final product thus increasing error detection in the early stages of design and the confidence of the participants in their design	–	Creation of one platform in which multiple users may connect at the same time, each one equipped with a different headset or even by using other devices that support AR. Evaluation of the product design at the same time using a collaborative design platform. Integration of VR and holographic displays will be investigated
35	The concept development process for an interactive AR application that compensates for attending Orientation Week at a higher education institution	First time and experienced users were able to use the application. The existing functions found useful	–	Use Unity to redesign the application, improve functions for better performance and user experience enhancement. Refine the features, the user interface design and the architecture design and implementation

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
36	Comprehension and learning permanency and examine 5th grade students' attitudes towards AR applications	A high level of reading comprehension and learning permanency was reported. The students reported low anxiety levels. AR applications can be used effectively as educational aids for reading-related courses	The use of interactive boards only for reading experiences supported by AR technology with 5th grade students. Some technical problems were experienced (sound, light, internet connection speed and hardware properties of the interactive boards). The socio-economic characteristics of the students can also be regarded as a limitation of the research. The demographic characteristics of the students were not analyzed in this study	The effect of the use of AR materials on different school grade levels. Should be extended to cover writing, listening, speaking skills and grammar topics. Use smartphones, AR glasses and tablets
37	Design three applications for the subjects of Educational Technology, Anatomy and Art to assess it in terms of the motivation and academic performance improvement	AR constitutes a useful means to facilitate learning and knowledge acquisition. The Keller's IMMS diagnostic instrument appears to be a good predictor to explain the motivation, attention, confidence, relevance and satisfaction raised by the interaction with AR objects	Not generalizable results. Short duration of experiments	Bigger sample. Replicate the study with other groups of students and with students from other universities. Longitudinal study is required in order to verify the extent to which the findings remain constant
38	Evaluation of an AR-based motion graphing application for physics classes	The application was found useful in teaching physics, specifically motion graphs	–	Perform evaluation with experts. Changes to be performed in user interface (e.g. pausing the camera after gathering data) and data smoothening (changing the sampling frequency), maximizing the screen area for a graph to enhance closer inspection and juxtaposing all graphs in one view
39	The effects of Problem Based Learning assisted with AR on learning achievement and attitude towards physics subjects	Integrating AR into PBL activities both increased students' learning achievement and promoted their positive attitudes towards physics subjects. Students' long-term retention of the concepts was found. AR has a positive impact on cognitive and emotional improvement in science education. Researchers have to think of the health consequences of using AR in early-age students	The learning content was designed for only the seventh graders and learning contents of "force and energy" unit as physics subjects. No generalizable results. The study focused only on students' achievement and attitude in physics and not their cognitive and emotional features. AR applications designed as marker based, can be affected technically by light or dark to recognize the marker. It can be difficult to use FenAR with students with impairments or tactile disorders	Project-based, inquiry-based or other learning approaches can be integrated with AR technology and a comparative experimental study should be carried out to determine which approach is more effective on learning when combined with AR. Design a comprehensive theoretical model on the integration of PBL with AR

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
40	Use of AR for learning anatomy combined with a novel convolutional neural network for gesture recognition, which recognizes the human's gestures as a certain instruction	Neural networks can be combined with AR for medical learning and education systems. More accurate approach with more potential for adding new gestures	Shaking the hand and rapid movement was a weak point of this method	Improve the method and remove any interfere in preprocessing methods
41	Use of an ARToolKit-based Interactive Writing Board for designing confusion-free marker libraries. The board was used for teaching single characters of Arabic/Urdu to primary level students	The system improves students' motivation and learning skills. IWB improved student interest and was relatively easy to use	The board uses a single camera, therefore it is applicable to small groups only ($\leq$ 6 students). We grouped the distinct characters in one class which contradicts the actual teaching methodologies where similar characters are placed together. The current system is only used for teaching single characters in their isolated forms	Use the concept of layered markers for concatenation of the characters for Urdu, Arabic, and Pashtu characters. Use layered markers for interaction with different 3D objects on the board
42	Investigate how useful AR is in the school environment	AR can increase students' motivation and enthusiasm while enhancing teaching and learning	Not generalizable results. The study does not collect information from all the variables involved within the theoretical models considered. Lack of a comparison group or a focus group	A more rigorous controlled assessment of the learning. Supplement this investigation by studying the interaction of the presage, process, and product variables within the 3P model to see how they affect perceived acceptability and academic performance
43	Integrate AR into educational in-class activities aiming to enhance existing tools that target behavioral changes towards energy efficiency in schools		Good lighting is required for the system to function properly	Handle issues of misinterpretation of the surfaces due to lighting or other problems. Evaluate the system inside the classroom during actual educational activities
44	Analyze the impact that the integration of ubiquitous game approaches with AR has on learning in primary education	The proposed solution improved academic achievement and competence in information search and analysis, contributed to an increase in the level of fun and the potential for collaboration between students, and improved academic performance	-	-
45	Using AR in teaching old Turkish language mementoes	It appeared to motivate students and improve their academic performance	The subjectivity of the results due to the used questionnaires and data collection tools. Another limitation exists due to the used target groups (culture, language, etc.)	-

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
46	Software development process for an AR program that teaches the medical procedure known as the Lumbar Puncture	The software required excessive hand actions to achieve the desired goal. The app added physical and cognitive load to the users and distracted them from performing the Lumbar Puncture procedure. Metavision's headset was found suitable for medical education purposes	The original Cassette Player paradigm was inefficient and not suitable for further development of the system	Bigger sample and extended testing with medical students
47	AR application to support mild and moderate Intellectually disabled children in early childhood special education	Such applications can improve their children's attention and interest to the class session. The application helped the teachers to transfer the knowledge more easily. Early findings that such applications can improve the academic and behavioral characteristics of the children	-	-
48	Use of AR in mechanical design pedagogy in higher education	There was strong interest in the use of AR by the students. A visual overload can lead to a cognitive overload. The playful aspect of the application could harm learning since students play with the system without grasping the necessary information for the exercise. AR helped students to extract relevant information about the complexity of a system in a much easier way	To achieve a display on reality without having the feeling of superimposition assumes that the reality part is well hidden. The visual field is limited with the Hololens. The head moves more than the eyes. With the tablet the exploration of the mechanism is less absorbing than with the superimposition of information in front of the eyes. It has not been assessed the absence of uncomfortable situations nor the satisfaction of the users	Assess the usability of the AR system in an engineering educational context, in order to conclude if this modality allow to reach the educational goals with efficiency. Development of new scenarios on an automobile gearbox, and on a turbofan plane engine
49	Data-driven AR experiments for electricity and magnetism lab courses	Improved technical understanding,	-	A follow-up study to examine whether the AR application has influence on knowledge networking and the resulting knowledge structure of the learners
50	Evaluate the learning performance and the learning effectiveness and efficiency of AR videos as a teaching tool for threading tasks in a sewing workshop	Teaching with the use of AR videos help students gain a conceptual understanding, while facilitating a better understanding of complex issues, such as 3D processes. AR videos resulted in satisfaction with the learning experience and higher learning efficiency, especially for process learning-related activities. AR videos encouraged high levels of interactivity between students and the learning materials	The research findings relied heavily on the design of the used handouts and AR videos. Small sample size. Other limitations can be considered the absence of subtitles, and that there was no possibility to reduce the speed of the video	Future studies could consider a longer time span or extend their focus across subjects. Add subtitles and integrate a feature to be able the user to reduce the speed of the video

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
51	Develop an AR application with speech input to improve the pronunciation of preschool children in English	The application helped the non-native English-speaking children to improve their pronunciation in English and was found attractive	Unstable internet connection affects the quality of the service. The application needs a quiet workspace. Lighting affected the proper operation	The speech recognition should be built-in with the application to avoid interruption due to the network coverage. The marker should be replaced with the more features extraction. Invoke a conversational storytelling agent
52	Develop a mobile application with AR to help teaching stories of the Qu'ran in fourth grade students of elementary schools	Early finding. It seems able to assist the teachers as an educational tool in teaching at elementary schools in Saudi Arabia	The appropriateness of this application as an education application is not yet discovered	Develop it for more subjects in elementary schools to motivate the students in their learning process
53	A tablet-based AR application to support university students learning from hands-on experiments in physics education	Slightly higher learning gains in conceptual knowledge were detectable for the AR-supported lab work	More research is required to replicate these findings in different learning settings and other instructional domains	Use smart glasses instead of tablet. Test the application in real school settings to establish whether the system is easy to apply and manage by teachers and whether it can be successfully adapted to the demands of classroom learning, such as collaborative learning contexts. Implement eye tracking to investigate how AR affects attentional processes during learning
54	An interactive educational AR application to help study the tajweed of Qur'an which employees the FAST corner detection algorithm	FAST corner detection algorithm is fast enough in detecting the tajweed Qur'an. AR technology can help in learning Tajweed of Qu'ran. Lack in detecting tajweed objects simultaneously on one page of the Qur'an	Image detection problems due to Qu'ran image data and image resolution. Cannot recognize adjacent Tajweed or requires a longer detection process	-
55	Use of AR technology for children with and without special educational needs, to improve their academic achievement in chemistry lessons	Significant immediate academic achievement and content retention was observed. AR positively affects the academic achievement of students both with and without special educational needs. AR improved secondary school students' level of motivation in chemistry	Small number of participants. Time was limited to implement the intervention	Incorporation of embodied content for students with special educational needs. Incorporate AR at other educational levels. Replicate the study with other contents and subjects. Assess the long-term effects of using AR to reinforce academic achievement in students with special educational needs
56	Development of a mobile application, Smart Learning Companion (SLAC), for physical books that provide a virtual content for a book in order to improve the learning experience	SLAC was more effective and users enjoyed the learning experience. The use of native language reduced the learning time and users were more comfortable using the SLAC	-	Extend SLAC platform such that teachers and parents can also interact and provide feedback

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
57	Explore whether AR learning experiences (ManatarayAR) can support learning in statistics education	It was particularly advantageous for students without prior knowledge of statistical reasoning. There was no discernible difference in learning gains due to collaboration using AR	The learning objectives for the level of students in this study missed the mark. The participants were not prescreened prior to participating in the study and it is difficult to determine if they were over- or underprepared for the content. Cannot conclude if the learning activity was sufficient to produce long- term learning gains	Further investigation is necessary to adequately address the relationship between learning gains, embodiment, and collaboration
58	Teaching young children who are non-native English speakers about English terms for basic colors, 3D shapes, and spatial relationships	It enhances the engagement in learning and increases knowledge gain. The combination of AR and speech recognition technology can improve cognitive function. It has a significant effect mainly on the knowledge gain of 3-dimensional shapes and spatial relationships. Without the augmented visual feedback, the engagement decreases. Enjoyment was higher when using AR. More research is needed to discover the potential of AR for young children's activities, especially in the ways that it can be used for language learning	The results cannot be generalized due to small sample size. The noise level in the classroom might affect the speech recognition effectiveness	A setup without using a Kinect sensor. Markerless AR tracking, such as using the Vuforia library could be considered for future work. Implement the TeachAR system in head-mounted display-based AR, as the one of Microsoft HoloLense
59	Develop an AR mobile app to enhance the pedagogical approach in teaching history	A form of instructional media material was developed for teaching history. AR found usable and acceptable	-	-
60	Develop a mobile AR-based geometry learning application for teaching 3-D geometry in high school students	A mobile based geometry application was designed	No evaluation was conducted	-
61	The use of AR as a means of understanding in the teaching of electromagnetism	AR applications help in increasing students' educational accomplishment in the learning procedure compared with the use of traditional learning methods	-	-

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
62	Neuroanatomy learning using AR applications	AR applications can play a role in future anatomy education as an add-on educational tool, especially in learning three-dimensional relations of anatomical structures	Limited number of participants. The internal validity and reliability of the two used tests was found to be questionable. Another limitation was the limited time of the experiment. Another limitation of this study concerns the qualitative assessment (long time between the experiment and the focus group interview). The subgroup that took part in the qualitative assessment was a non-representative section of the total group of students who participated in the experiment is another limitation. Another limitation is the inclusion of cross-sectional imaging in the control group and testing on cross-sectional anatomy	Include a larger sample size
63	An AR application to practice the basic principles of geometry in students	AR-based learning environments can be more effective compared with web-based learning environments for students coming from public schools. Participants who used the AR-based application were more motivated towards the learning activity	Limited sample size. Only short-term retention of basic principles of Geometry was tested. The novelty effect could be to some degree responsible for the results shown. Data collected were self-reported. Instructors may have used different methods for teaching the basics of geometry at the beginning	A larger, multi-centric study must be designed and carried out in order to draw more robust conclusions
64	Development of an AR tool for chemistry education	AR applications attract more students in the class, supporting traditional teaching methods. The visual level is very important in learning, since students are retaining more easily new information. Tests based on AR can reduce students' stress. This application improves the interaction between students and professors	-	Add voice recognition to take answers from the students

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
65	An interactive tool to explore the benefits of Optical See-Through Augmented Reality (OST-AR) interfaces for training needle insertion for central venous catheterization (CVC) and explore if it complements conventional training practices	PINATA can complement the conventional training system, especially due to the visibility of the vessels inside the simulator. It reduces the dependence of the instructor without affecting the quality of training	Predictive validity was not assessed in this work since it requires a randomized controlled trial comparing performance performing the procedure in real patients. The tracking system is affected by external factors including light conditions. HMD causes some discomfort and has a limited FOV	Other applications for this type of tool to be explored, like a collaborative setup for training using handheld devices. A future extension consists of an ablation study to verify the influence of the proposed geometric information (e.g., conical placeholder) and how these graphical components influence the user's experience, performance and satisfaction
66	The use of AR in physical education for the development and acquisition of spatial orientation, as opposed to more traditional training based on the exhibition method	AR is effective in teaching high school students in the subject of physical education, especially for the acquisition of spatially oriented content. AR promoted an improvement in motivation, academic performance or receptivity towards the area of knowledge among the students	Limited sample which caused a low level of effect obtained by the comparative results between the control and experimental groups	Need for experts to continue contributing empirical experiences in which the effectiveness of different emerging resources, such as AR in the area of physical education as well as in the rest of the areas of knowledge, can be verified
67	Application of AR technology (Geo+) as support tool in primary school to learn solid geometry	Geo+ is effective in terms of student learning gain. AR improved concentration on the task	A ceiling effect was observed in investigating the learning effect which means that a different instrument to assess the pupils' learning before and after the use of the AR application should be used	More multimedia contents to be added to show more didactic concept concerning the solid figures, and some questions in order to self-assess the knowledge. A between-subject design study comparing a traditional lesson and the innovative Geo+, in order to verify if and how much Geo+ can substitute the work of teachers and to generalize the discovered findings
68	A mobile AR-based application (Photomath) on the achievement and attitude of learning algebraic equations for lower secondary school students in Malaysia	Photomath significantly enhances the learning of algebraic equations among students. However, the participants' belief and readiness towards Photomath are still at a moderate level	-	-
69	AR Gamification application as a learning media (AR EduGame) for Indonesian culture	The application improved students' learning outcomes	-	-

Table 9 (continued)

#	Scope	Outcomes	Limitations	Future plans
70	Effects of AR on learning & cognitive load in a university physics laboratory setting	AR did not show a learning gain, but the participants reported a significant lower extraneous cognitive load than the traditional condition. Novelty effects may have affected the results. Long-term learning effects may have been excluded	A complete randomization could not be achieved, and the sample was unbalanced regarding the pretest scores	More topics and study cases from university STEM education should be investigated. Complement the conceptual knowledge test with a traditional retention and transfer test to achieve a higher sensitivity for small differences in learning gains. Mobile eye tracking could be added to investigate learners' interaction in more detail
71	Comparison of traditional & AR game-based method on English vocabulary learning for foreign learners	Participants enjoyed the use of learning materials enriched by AR. AR learning environment was found highly motivating and enjoyable. AR-based learning material was found useful and beneficial for language skills	-	-
72	Development of an AR mobile application to enhance Chinese language vocabulary learning to Chinese students	Students' achievement was higher when using the AR application. The application helped students to pay more attention in the learning process and understand clearly	–	-
73	Immersive VR and image-based mobile AR were used to simulate the operation of microscopes in a biology lab course for K-12 students	The system was useful for helping K-12 students to recognize a microscope's structure and grasp the required operational skills. For the senior students, the effects of AR-assisted learning were not significant	-	Enrich the function of experiments based on VR and AR. Improve the user interface to make it easier. Measurement of the long-term learning effects

Abbreviations

AI	Artificial Intelligence
AR	Augmented Reality
ARVMS	Augmented reality-based video modeling storybook
AV	Augmented Virtuality
ASD	Autism Spectrum Disorder
CLS	Collaborative Learning Scale
CORE	Computing Research and Education
CM	Custom Made
DOF	Degrees of Freedom
EMT	Educational Magic Toys
FOV	Field of view
FPS	First Person Shooter
FG	Focus group
HMD	Head-mounted display
HARUS	Holistic Acceptance Readiness for Use Scale
ICT	Information and Communication Technologies
IT	Information Technology
IMI	Intrinsic Motivation Inventory
IMMS	Intrinsic Motivation Measurement Scale
JCR	Journal Citation Reports
MR	Mixed Reality
MSAR	Mixed Reality Simulator Sickness Assessment Questionnaire
NASA-TLX	National Aeronautics and Space Administration Task Load Index
PEURA-E	Perceived Usability User Experience of Augmented Reality Environments
PBL	Problem-based Learning
QLIS	Quality of Life Impact Scale
QUIS	Questionnaire for User Interaction Satisfaction
SLAC	Smart Learning Companion
SoASSES	Socially Adaptive Systems Evaluation Scale
SES	Socioeconomic status
SDK	Software development kit
SUS	System Usability Scale
SLR	Systematic Literature Review
TAM	Technology Acceptance Model
TAM	Technology Acceptance Model survey
TRL	Technology Readiness Level
UTAUT	Unified Theory of Acceptance and Use of Technology
UES	User Engagement Scale
VR	Virtual Reality

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References

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review, 20*, 1–11.

Akçayır, M., Akçayır, G., Pektaş, H. M., & Ocak, M. A. (2016). Augmented reality in science laboratories: The effects of augmented reality on university students' laboratory skills and attitudes toward science laboratories. *Computers in Human Behavior, 57*, 334–342.

Abd Majid, N. A., & Abd Majid, N. (2018). Augmented reality to promote guided discovery learning for STEM learning. *International Journal on Advanced Science, Engineering and Information Technology, 8*(4–2), 1494–1500.
Aebersold, M., Voepel-Lewis, T., Cherara, L., Weber, M., Khouri, C., Levine, R., & Tait, A. R. (2018). Interactive anatomy-augmented virtual simulation training. *Clinical Simulation in Nursing, 15*, 34–41.
Aladin, M. Y. F., Ismail, A. W., Salam, M. S. H., Kumoi, R., & Ali, A. F. (2020). AR-TO-KID: A speech-enabled augmented reality to engage preschool children in pronunciation learning. In *IOP conference series: Materials science and engineering* (Vol. 979, No. 1, p. 012011). IOP Publishing.
Alhumaidan, H., Lo, K. P. Y., & Selby, A. (2018). Co-designing with children a collaborative augmented reality book based on a primary school textbook. *International Journal of Child-Computer Interaction, 15*, 24–36.
Aljojo, N., Munshi, A., Zainol, A., Al-Amri, R., Al-Aqeel, A., Al-khaldi, M., & Qadah, J. (2020). Lens application: Mobile application using augmented reality.
Altmeyer, K., Kapp, S., Thees, M., Malone, S., Kuhn, J., & Brünken, R. (2020). The use of augmented reality to foster conceptual knowledge acquisition in STEM laboratory courses: Theoretical background and empirical results. *British Journal of Educational Technology, 51*(3), 611–628.
Andriyandi, A. P., Darmalaksana, W., Adillah Maylawati, D. S., Irwansyah, F. S., Mantoro, T., & Ramdhani, M. A. (2020). Augmented reality using features accelerated segment test for learning tajweed. *TELKOMNIKA (telecommunication Computing Electronics and Control), 18*(1), 208–216. https://doi.org/10.12928/TELKOMNIKA.V18I1.14750
Ayer, S. K., Messner, J. I., & Anumba, C. J. (2016). Augmented reality gaming in sustainable design education. *Journal of Architectural Engineering, 22*(1), 04015012.
Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments, 6*(4), 355–385.
Bacca, J., Baldiris, S., Fabregat, R., Graf, S., & Kinshuk. (2014). Augmented reality trends in education: A systematic review of research and applications. *Educational Technology & Society, 17*(4), 133–149.
Badilla-Quintana, M. G., Sepulveda-Valenzuela, E., & Salazar Arias, M. (2020). Augmented reality as a sustainable technology to improve academic achievement in students with and without special educational needs. *Sustainability, 12*(19), 8116.
Bal, E., & Bicen, H. (2016). Computer hardware course application through augmented reality and QR code integration: Achievement levels and views of students. *Procedia Computer Science, 102*, 267–272.
Bauer, A., Neog, D. R., Dicko, A. H., Pai, D. K., Faure, F., Palombi, O., & Troccaz, J. (2017). Anatomical augmented reality with 3D commodity tracking and image-space alignment. *Computers & Graphics, 69*, 140–153.
Bazarov, S. E., Kholodilin, I. Y., Nesterov, A. S., & Sokhina, A. V. (2017). Applying augmented reality in practical classes for engineering students. In *IOP conference series: Earth and environmental science* (Vol. 87, No. 3, p. 032004). IOP Publishing.
Bibi, S., Munaf, R., Bawany, N., Shamim, A., & Saleem, Z. (2020). Smart learning companion (SLAC). *International Journal of Emerging Technologies in Learning (iJET), 15*(16), 200–211.
Bielecki, M. (2012). *Leveraging mobile health technology for patient recruitment: An emerging opportunity*. Northbrook, IL: Blue Chip Patient Recruitment.
Billinghurst, M., & Kato, H. (2002). Collaborative augmented reality. *Communications of the ACM, 45*(7), 64–70.
Billinghurst, M., Kato, H., & Poupyrev, I. (2001). The MagicBook: A transitional AR interface. *Computers & Graphics, 25*(5), 745–753.
Bower, M., Howe, C., McCredie, N., Robinson, A., & Grover, D. (2014). Augmented reality in education–cases, places and potentials. *Educational Media International, 51*(1), 1–15.
Bursali, H., & Yilmaz, R. M. (2019). Effect of augmented reality applications on secondary school students' reading comprehension and learning permanency. *Computers in Human Behavior, 95*, 126–135.
Cabero-Almenara, J., & Roig-Vila, R. (2019). The motivation of technological scenarios in augmented reality (AR): Results of different experiments. *Applied Sciences, 9*(14), 2907.
Cao, Y., Zhang, S., Zhang, Y., & Li, X. (2019). Challenges and opportunities of augmented reality in education: A systematic review. *Interactive Learning Environments, 27*(8), 1059–1074.
Carlson, K. J., & Gagnon, D. J. (2016). Augmented reality integrated simulation education in health care. *Clinical Simulation in Nursing, 12*(4), 123–127.
Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E., & Ivkovic, M. (2011). Augmented reality technologies, systems and applications. *Multimedia Tools and Applications, 51*(1), 341–377.
Chang, S. C., & Hwang, G. J. (2018). Impacts of an augmented reality-based flipped learning guiding approach on students' scientific project performance and perceptions. *Computers & Education, 125*, 226–239.
Chen, C. H., Lee, I. J., & Lin, L. Y. (2016). Augmented reality-based video-modeling storybook of nonverbal facial cues for children with autism spectrum disorder to improve their perceptions and judgments of facial expressions and emotions. *Computers in Human Behavior, 55*, 477–485.
Chen, C. M., Cheng, B., & Chang, C. H. (2020). A systematic review of research on augmented reality in education: Advantages and applications. *Educational Research Review, 30*, 100326.
Cheng, J., Wang, Y., Tjondronegoro, D., & Song, W. (2018). Construction of interactive teaching system for course of mechanical drawing based on mobile augmented reality technology. *International Journal of Emerging Technologies in Learning (IJET), 13*(2), 126–139.
Cheng, K.-H., & Tsai, C.-C. (2014). Children and parents' reading of an augmented reality picture book: Analyses of behavioral patterns and cognitive attainment. *Computers & Education, 72*, 302–312. https://doi.org/10.1016/j.compedu.2013.12.003
Cieza, E., & Lujan, D. (2018). Educational mobile application of augmented reality based on markers to improve the learning of vowel usage and numbers for children of a kindergarten in Trujillo. *Procedia Computer Science, 130*, 352–358.
Collado, R. C., Caluya, N. R., & Santos, M. E. C. (2019). Teachers' evaluation of MotionAR: An augmented reality-based motion graphing application. *Journal of Physics: Conference Series* (Vol. 1286, No. 1, p. 012051). IOP Publishing.
Conley, Q., Atkinson, R. K., Nguyen, F., & Nelson, B. C. (2020). MantarayAR: Leveraging augmented reality to teach probability and sampling. *Computers & Education, 153*, 103895.

CORE Rankings Portal - Computing Research & Education. (n.d.) Retrieved from http://www.core.edu.au/conference-portal.
Crăciun, D., & Bunoiu, M. (2017). Boosting physics education through mobile augmented reality. In *AIP Conference Proceedings* (Vol. 1916, No. 1, p. 050003). AIP Publishing LLC.
Cuendet, S., Bonnard, Q., Do-Lenh, S., & Dillenbourg, P. (2013). Designing augmented reality for the classroom. *Computers & Education, 68*, 557–569.
Dalim, C. S. C., Sunar, M. S., Dey, A., & Billinghurst, M. (2020). Using augmented reality with speech input for non-native children's language learning. *International Journal of Human-Computer Studies, 134*, 44–64.
Deb, S., & Bhattacharya, P. (2018). Augmented Sign Language Modeling (ASLM) with interaction design on smartphone-an assistive learning and communication tool for inclusive classroom. *Procedia Computer Science, 125*, 492–500.
Dede, C. (2009). Immersive interfaces for engagement and learning. *Science, 323*(5910), 66–69.
Dunleavy, M., & Dede, C. (2014). Augmented reality teaching and learning. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop (Eds.), *Handbook of research on educational communications and technology* (4th ed., pp. 735–745). Springer.
Dunleavy, M., Dede, C., & Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. *Journal of Science Education and Technology, 18*(1), 7–22.
Elivera, A., & Palaoag, T. (2020). Development of an augmented reality mobile application to enhance the pedagogical approach in teaching history. In *IOP conference series: materials science and engineering* (vol. 803, no. 1, p. 012014). IOP Publishing.
European Commission. (2012). General data protection regulation: Proposal for a regulation of the European parliament and of the council. From EC justice. Data protection. Retrieved from ec.europa.eu/justice/data-protection/document/review2012/com_2012_11_en.pdf.
European Commission (2014). HORIZON 2020—WORK PROGRAMME 2014-2015, general annexes, extract from part 19—commission decision C(2014)4995. Retrieved from https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.
European Parliament (2000). Charter of fundamental rights of the european union (2000/C 364/01). Official Journal of the European Communities. Retrieved from www.europarl.europa.eu/charter/pdf/text_en.pdf.
European Parliament and the Council of 12 July 2002 (2002). Directive 2002/58/EC: Processing of personal data and the protection of privacy in the electronic communications sector. Retrieved from eur-lex.europa.eu/eli/dir/2002/58/oj.
European Parliament and the Council of 24 October 1995 (1995). Directive 95/46/EC: Protection of individuals with regard to the processing of personal data and the free movement of such data. Retrieved from data.europa.eu/eli/dir/1995/46/oj.
Ferrer-Torregrosa, J., Torralba, J., Jimenez, M. A., García, S., & Barcia, J. M. (2015). AR-BOOK: Development and assessment of a tool based on augmented reality for anatomy. *Journal of Science Education and Technology, 24*(1), 119–124.
Ferriman, J. (2023). 7 random mobile learning stats. LearnDash. https://www.learndash.com/7-random-mobile-learning-stats/.
Fidan, M., & Tuncel, M. (2019). Integrating augmented reality into problem based learning: The effects on learning achievement and attitude in physics education. *Computers & Education, 142*, 103635.
Gargrish, S., Mantri, A., & Kaur, D. P. (2020). Augmented reality-based learning environment to enhance teaching-learning experience in geometry education. *Procedia Computer Science, 172*, 1039–1046.
Goharinejad, S., Goharinejad, S., Hajesmaeel-Gohari, S., et al. (2022). The usefulness of virtual, augmented, and mixed reality technologies in the diagnosis and treatment of attention deficit hyperactivity disorder in children: an overview of relevant studies. *BMC Psychiatry 22*(4). https://doi.org/10.1186/s12888-021-03632-1.
Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal, 26*(2), 91–108.
Harun, F., Tuli, N., & Mantri, A. (2020). Experience fleming's rule in electromagnetism using augmented reality: analyzing impact on students learning. *Procedia Computer Science, 172*, 660–668.
Henssen, D. J., van den Heuvel, L., De Jong, G., Vorstenbosch, M. A., van Cappellen van Walsum, A. M., Van den Hurk, M. M., et al. (2020). Neuroanatomy learning: Augmented reality vs. cross-sections. *Anatomical sciences education, 13*(3), 353–365.
Ibáñez, M. B., Portillo, A. U., Cabada, R. Z., & Barrón, M. L. (2020). Impact of augmented reality technology on academic achievement and motivation of students from public and private Mexican schools. A case study in a middle-school geometry course. *Computers & Education, 145*, 103734.
Iftene, A., & Trandabăţ, D. (2018). Enhancing the attractiveness of learning through Augmented Reality. *Procedia Computer Science, 126*, 166–175.
Ipscience-help.thomsonreuters.com (2019). 2018 JCR data release. Retrieved from http://ipscience-help.thomsonreuters.com/incitesLiveJCR/8275-TRS.html.
Jerry, T. F. L., & Aaron, C. C. E. (2010). The impact of augmented reality software with inquiry-based learning on students' learning of kinematics graph. In *2010 2nd international conference on education technology and computer* (vol. 2, pp. V2–1). IEEE.
Joo-Nagata, J., Abad, F. M., Giner, J. G. B., & García-Peñalvo, F. J. (2017). Augmented reality and pedestrian navigation through its implementation in m-learning and e-learning: Evaluation of an educational program in Chile. *Computers & Education, 111*, 1–17.
Karambakhsh, A., Kamel, A., Sheng, B., Li, P., Yang, P., & Feng, D. D. (2019). Deep gesture interaction for augmented anatomy learning. *International Journal of Information Management, 45*, 328–336.
Kaufmann, H., & Schmalstieg, D. (2018). Physics-based user interfaces for augmented reality. *ACM Transactions on Computer-Human Interaction, 25*(5), 32.
Khan, D., Ullah, S., Ahmad, W., Cheng, Z., Jabeen, G., & Kato, H. (2019). A low-cost interactive writing board for primary education using distinct augmented reality markers. *Sustainability, 11*(20), 5720.

Kiryakova, G., Angelova, N., & Yordanova, L. (2018). The potential of augmented reality to transform education into smart education. *TEM Journal, 7*(3), 556.

Kitchenham, B. (2004). Procedures for performing systematic reviews. *Keele, UK, Keele University, 33*(2004), 1–26.

Klopfer, E., & Squire, K. (2008). Environmental Detectives: The development of an augmented reality platform for environmental simulations. *Educational Technology Research and Development, 56*(2), 203–228.

Klopfer, E., & Squire, K. (2019). Augmented reality and learning: A critical review. In J. Voogt & G. Knezek (Eds.), *International handbook of information technology in primary and secondary education* (pp. 325–338). Springer.

Klopfer, E., Squire, K., & Jenkins, H. (2008). Environmental detectives: PDAs as a window into a virtual simulated world. In *Handbook of research on effective electronic gaming in education* (pp. 143–166). Information Science Reference.

Koumpouros, Y. (2016). A systematic review on existing measures for the subjective assessment of rehabilitation and assistive robot devices. *Journal of Healthcare Engineering, 2016*, 1–10. https://doi.org/10.1155/2016/1048964

Koumpouros, Y., & Kafazis, T. (2019). Wearables and mobile technologies in autism spectrum disorder interventions: A systematic literature review. *Research in Autism Spectrum Disorders, 66*, https://doi.org/10.1016/j.rasd.2019.05.005.

Koumpouros, Y., Papageorgiou, E., Karavasili, A., & Koureta, F. (2016). PYTHEIA: A scale for assessing rehabilitation and assistive robotics. *World Academy of Science, Engineering and Technology, International Journal of Medical, Health, Biomedical, Bioengineering and Pharmaceutical Engineering, 10*(11), 522–526.

Kuikkaniemi, K., Turunen, M., Hakulinen, J., & Salo, K. (2014). Exploring user experience and user engagement in free mobile applications. *International Journal of Mobile Human-Computer Interaction (IJMHCI), 6*(2), 35–50.

Kurniawan, M. H., & Witjaksono, G. (2018). Human anatomy learning systems using augmented reality on mobile application. *Procedia Computer Science, 135*, 80–88.

Lamanauskas V., Vilkonis R. & Klangauskas A. (2007). Using information and communication technology for learning purposes: Students position on the issue. Europe Needs More Scientists—the Role of Eastern and Central European Symposium, 8–11 November 2006, Tartu, Estonia, 151–164.

Layona, R., Yulianto, B., & Tunardi, Y. (2018). Web based augmented reality for human body anatomy learning. *Procedia Computer Science, 135*, 457–464.

Lee, K. M. (2012). Augmented reality in education and training. *TechTrends, 56*(2), 13–21.

Li, Z., Huang, R., Li, G., & Song, Y. (2020). Augmented reality in education: A systematic review and synthesis of literature. *Educational Research Review, 30*, 100326.

Lin, C. Y., Chai, H. C., Wang, J. Y., Chen, C. J., Liu, Y. H., Chen, C. W., & Huang, Y. M. (2016). Augmented reality in educational activities for children with disabilities. *Displays, 42*, 51–54.

Liu, D. Y., Navarrete, C. C., & Chang, Y. C. (2019). Trends in augmented reality research: A systematic review of journal publications from 2008 to 2017. *IEEE Access, 7*, 1019–1035.

López-García, A., Miralles-Martínez, P., & Maquilón, J. (2019). Design, application and effectiveness of an innovative augmented reality teaching proposal through 3P model. *Applied Sciences, 9*(24), 5426.

Lorusso, M. L., Giorgetti, M., Travellini, S., Greci, L., Zangiacomi, A., Mondellini, M., & Reni, G. (2018). Giok the alien: An ar-based integrated system for the empowerment of problem-solving, pragmatic, and social skills in pre-school children. *Sensors, 18*(7), 2368.

Macariu, C., Iftene, A., & Gîfu, D. (2020). Learn chemistry with augmented reality. *Procedia Computer Science, 176*, 2133–2142.

Mahmood, F., Mahmood, E., Dorfman, R. G., Mitchell, J., Mahmood, F. U., Jones, S. B., & Matyal, R. (2018). Augmented reality and ultrasound education: Initial experience. *Journal of Cardiothoracic and Vascular Anesthesia, 32*(3), 1363–1367.

Markets and Markets (2023). Augmented reality market industry report, size, segment, key players, scope, 2030. Retrieved April 11, 2023, from https://www.marketsandmarkets.com/Market-Reports/augmented-reality-market-82758548.html.

Martin, S., Diaz, G., Sancristobal, E., Gil, R., Castro, M., & Peire, J. (2011). New technology trends in education: Seven years of forecasts and convergence. *Computers & Education, 57*(3), 1893–1906.

Mendes, H. C. M., Costa, C. I. A. B., da Silva, N. A., Leite, F. P., Esteves, A., & Lopes, D. S. (2020). PIÑATA: Pinpoint insertion of intravenous needles via augmented reality training assistance. *Computerized Medical Imaging and Graphics, 82*, 101731.

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems, 77*(12), 1321–1329.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Prisma Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Medicine, 6*(7), e1000097.

Montoya, M. H., Díaz, C. A., & Moreno, G. A. (2016). Evaluating the effect on user perception and performance of static and dynamic contents deployed in augmented reality based learning application. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(2), 301–317.

Moreno-Guerrero, A. J., Alonso García, S., Ramos Navas-Parejo, M., Campos-Soto, M. N., & Gómez García, G. (2020). Augmented reality as a resource for improving learning in the physical education classroom. *International Journal of Environmental Research and Public Health, 17*(10), 3637.

Moro, C., Štromberga, Z., Raikos, A., & Stirling, A. (2017). The effectiveness of virtual and augmented reality in health sciences and medical anatomy. *Anatomical Sciences Education, 10*(6), 549–559.

Mota, J. M., Ruiz-Rube, I., Dodero, J. M., & Arnedillo-Sánchez, I. (2018). Augmented reality mobile app development for all. *Computers & Electrical Engineering, 65*, 250–260.

Mourtzis, D., Zogopoulos, V., & Vlachou, E. (2018). Augmented reality supported product design towards industry 4.0: A teaching factory paradigm. *Procedia Manufacturing, 23*, 207–212.

Mylonas, G., Triantafyllis, C., & Amaxilatis, D. (2019). An augmented reality prototype for supporting IoT-based educational activities for energy-efficient school buildings. *Electronic Notes in Theoretical Computer Science, 343*, 89–101.

Nguyen, N., Muilu, T., Dirin, A., & Alamäki, A. (2018). An interactive and augmented learning concept for orientation week in higher education. *International Journal of Educational Technology in Higher Education, 15*(1), 1–15.

Nielsen, J. (1993). *Usability engineering*. Morgan Kaufmann Publishers Inc https://doi.org/10.1145/1508044.1508050.

Nor Azlina Ab Aziz & Kamarulzaman Ab Aziz (2020). Application of augmented reality in education of attention deficit hyperactive disorder (ADHD) children. Neurological Disorders and Imaging Physics, Volume 4, Chapter 10, https://iopscience.iop.org/book/edit/978-0-7503-1822-8/chapter/bk978-0-7503-1822-8ch10.pdf.

Pombo, L., & Marques, M. M. (2017). Marker-based augmented reality application for mobile learning in an urban park: Steps to make it real under the EduPARK project. In *2017 International symposium on computers in education (SIIE)* (pp. 1–5). IEEE.

Radu, I. (2014). Augmented reality in education: A meta-review and cross-media analysis. *Personal and Ubiquitous Computing, 18*(6), 1533–1543.

Research and Markets (2023). Augmented reality in training and education global market report 2023. Research and Markets - Market Research Reports - Welcome. Retrieved April 11, 2023, from https://www.researchandmarkets.com/reports/5735149/augmented-reality-in-training-education-global.

Riihiaho, S. (2000). Experiences with usability evaluation methods. Helsinki University of Technology Laboratory of Information Processing Science.

Rossano, V., Lanzilotti, R., Cazzolla, A., & Roselli, T. (2020). Augmented reality to support geometry learning. *IEEE Access, 8*, 107772–107780.

Sáez-López, J. M. S. L., Sevillano-García, M. L. S. G., Pascual-Sevillano, M. Á. P. S., Sáez-López, J. M., Sevillano-García-García, M. L., & de los Ángeles Pascual-Sevillano, M. (2019). Application of the ubiquitous game with augmented reality in Primary Education. *Comunication Media Education Research Journal*, *27*(2).

Safar, A. H., Al-Jafar, A. A., & Al-Yousefi, Z. H. (2016). The effectiveness of using augmented reality apps in teaching the English alphabet to kindergarten children: A case study in the State of Kuwait. *EURASIA Journal of Mathematics, Science and Technology Education, 13*(2), 417–440.

Sahin, N., & Ozcan, M. F. (2019). Effects of augmented reality in teaching old Turkish Language mementoes on student achievement and motivation. *Contemporary Educational Technology, 10*(2), 198–213.

Santos, M. E. C., Taketomi, T., Yamamoto, G., Rodrigo, M. M. T., Sandor, C., & Kato, H. (2016). Augmented reality as multimedia: The case for situated vocabulary learning. *Research and Practice in Technology Enhanced Learning, 11*(1), 1–23.

Sargsyan, N., Bassy, R., Wei, X., Akula, S., Liu, J., Seals, C., & White, J. (2019). Augmented reality application to enhance training of lumbar puncture procedure: Preliminary results. In *Proceedings of 32nd international conference on* (Vol. 63, pp. 189–196).

Saundarajan, K., Osman, S., Kumar, J., Daud, M., Abu, M., & Pairan, M. (2020). Learning algebra using augmented reality: A preliminary investigation on the application of photomath for lower secondary education. *International Journal of Emerging Technologies in Learning (iJET), 15*(16), 123–133.

Savitha, K.K, & Renumol, V.G. (2019). Effects of integrating augmented reality in early childhood special education. *International Journal of Recent Technology and Engineering, 8*(3), 2277–3878.

Scaravetti, D., & Doroszewski, D. (2019). Augmented Reality experiment in higher education, for complex system appropriation in mechanical design. *Procedia CIRP, 84*, 197–202.

Schall, G., Jetter, H.-C., & Reitmayr, G. (2009). Towards mobile augmented reality for spatially aware computing. *Virtual Reality, 13*(4), 223–234.

Sin, A. K., & Zaman, H. B. (2010). Live solar system (LSS): Evaluation of an Augmented Reality book-based educational tool. In *2010 International symposium on information technology* (vol. 1, pp. 1–6). IEEE.

Sonntag, D., Albuquerque, G., Magnor, M., & Bodensiek, O. (2019). Hybrid learning environments by data-driven augmented reality. *Procedia Manufacturing, 31*, 32–37.

Spruijt-Metz, D., Hekler, E., Saranummi, N., Intille, S., Korhonen, I., Nilsen, W., et al. (2015). Building new computational models to support health behavior change and maintenance: New opportunities in behavioral research. *Translational Behavioral Medicine, 5*, 335–346. https://doi.org/10.1007/s13142-015-0324-1

StatCounter (2023). Desktop vs mobile vs tablet market share worldwide. StatCounter Global Stats. https://gs.statcounter.com/platform-market-share/desktop-mobile-tablet.

Statista (2023a). mHealth (mobile health) industry market size projection from 2012 to 2020 (in billion U.S. dollars). Retrieved fromhttps://www.statista.com/statistics/295771/mhealth-global-market-size/.

Statista (2023b). Smartwatch OS share worldwide 2022 | Statistic. Retrieved fromhttps://www.statista.com/statistics/750328/worldwide-smartwatch-market-share-by-platform/.

Stone, P. W. (2002). Popping the (PICO) question in research and evidence-based practice. *Applied Nursing Research*. https://doi.org/10.1053/apnr.2002.34181

Sudarmilah, E., Irsyadi, F. Y. A., Purworini, D., Fatmawati, A., Haryanti, Y., Santoso, B., & Ustia, N. (2020). Improving knowledge about Indonesian culture with augmented reality gamification. In *IOP conference series: Materials science and engineering* (Vol. 830, No. 3, p. 032024). IOP Publishing.

Sungkur, R. K., Panchoo, A., & Bhoyroo, N. K. (2016). Augmented reality, the future of contextual mobile learning. *Interactive Technology and Smart Education*.

Tang, A., Owen, C. B., Biocca, F., & Mou, W. (2015). Examining the role of presence in mobile augmented reality through a virtual reality comparison. *Computers in Human Behavior, 45*, 307–320.

Thees, M., Kapp, S., Strzys, M. P., Beil, F., Lukowicz, P., & Kuhn, J. (2020). Effects of augmented reality on learning and cognitive load in university physics laboratory courses. *Computers in Human Behavior, 108*, 106316.

Tosto, C., Hasegawa, T., Mangina, E., et al. (2021). Exploring the effect of an augmented reality literacy programme for reading and spelling difficulties for children diagnosed with ADHD. *Virtual Reality, 25*, 879–894. https://doi.org/10.1007/s10055-020-00485-z

Tsai, C. C. (2020). The effects of augmented reality to motivation and performance in EFL vocabulary learning. *International Journal of Instruction, 13*(4).

Turkan, Y., Radkowski, R., Karabulut-Ilgu, A., Behzadan, A. H., & Chen, A. (2017). Mobile augmented reality for teaching structural analysis. *Advanced Engineering Informatics, 34*, 90–100.

Uiphanit, T., Unekontee, J., Wattanaprapa, N., Jankaweekool, P., & Rakbumrung, W. (2020). Using augmented reality (AR) for enhancing Chinese vocabulary learning. *International Journal of Emerging Technologies in Learning (IJET), 15*(17), 268–276.

Vega Garzón, J. C., Magrini, M. L., & Galembeck, E. (2017). Using augmented reality to teach and learn biochemistry. *Biochemistry and Molecular Biology Education, 45*(5), 417–420.
Voogt, J., & Knezek, G. (Eds.). (2018). *International handbook of information technology in primary and secondary education*. Springer.
Wang, Y. H. (2017). Exploring the effectiveness of integrating augmented reality-based materials to support writing activities. *Computers & Education, 113*, 162–176.
Wang, C., & Wang, A. (2021). Exploring the effects of augmented reality on language learning: A meta-analysis. *Educational Technology & Society, 24*(2), 105–119.
Yilmaz, R. M. (2016). Educational magic toys developed with augmented reality technology for early childhood education. *Computers in Human Behavior, 54*, 240–248.
Yip, J., Wong, S. H., Yick, K. L., Chan, K., & Wong, K. H. (2019). Improving quality of teaching and learning in classes by using augmented reality video. *Computers & Education, 128*, 88–101.
Yuen, S. C. Y., & Yaoyuneyong, G. (2020). The use of augmented reality apps in K-12 education: A systematic review. *Journal of Educational Technology & Society, 23*(4), 133–150.
Zhou, X., Tang, L., Lin, D., & Han, W. (2020). Virtual & augmented reality for biological microscope in experiment education. *Virtual Reality & Intelligent Hardware, 2*(4), 316–329.

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