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S.I. : VR IN EDUCATION

Systematic review and meta-analysis of augmented reality in educational settings

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Abstract

Augmented reality (AR) is an important technology to enhance learning experiences. Many studies have been conducted to establish the tendencies, affordances and challenges of this technology in educational settings. However, these studies have little analyzed important issues such as the special needs of specific users or the impact of AR on education through the quantitative analysis of the data. This paper presents a literature review that covers 61 studies published between 2012 and 2018 in scientific journals and conference proceedings. As a result, it identifies the status and tendencies in the usage of AR in education, the impact of this technology on learning processes, open questions as well as opportunities and challenges for developers and practitioners. The results indicate that AR has a medium effect on learning effectiveness ($d = .64$, $p < .001$). The most reported advantages of AR systems in education are "learning gains" and "motivation." Otherwise, it is also important to mention that only one of the AR systems of the studies includes *accessibility features*, which represents a setback in terms of social inclusion. Therefore, given the apparent multiple benefits of using AR systems in educational settings, stakeholders have great opportunities to develop new and better systems that benefit all learners. This technology covers a wide range of topics, target groups, academic levels and more. This could be an indicator that AR is achieving maturity and has successfully taken root in educational settings.

Keywords Augmented reality · Education · Inclusive learning · Information technologies · Literature review · Meta-analysis

1 Introduction

Augmented reality (AR) is an important technology that combines reality with virtuality (Akçayir and Akçayir 2017; Azuma 1997). Teachers, engineers, researchers and practitioners are developing different tools and methodologies that include this technology, to benefit students and teachers by enriching the learning and teaching experiences. However, as reported by Wu et al. (2013), studies related to AR remain immature compared to studies of other technologies in education.

Since Tom Caudell coined the term augmented reality in the early 1990s (Lee 2012), this technology has experienced a rapid growth. This growth has accelerated from 2010 due probably to improvements in mobile computing power and functionality, which has led to AR systems being integrated into mobile devices making this technology available to a greater number of users (Bower et al. 2014). Augmented reality has a wide variety of fields of applications such as medicine, tourism, entertainment and education (Akçayir and Akçayir 2017). Sometimes it is confused with virtual reality (VR), but while VR immerses the user in a totally virtual environment, AR is rather a blending between virtuality and reality (Carmigniani et al. 2011).

In education, AR has been used to design pedagogical tools to enrich learning and teaching experiences (Garzón et al. 2017). Many studies indicate that AR technologies allow students to acquire knowledge in a more significant

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way, helping them to develop special skills that are much more difficult to obtain with other pedagogical resources (Akçayir and Akçayir 2017; Cheng and Tsai 2013; Safar 2017). For example, AR provides the learner easy access to unobservable phenomena such as the movement of the sun in simulated classroom contexts (Tarng et al. 2018), or the behavior of magnetic fields (Cai et al. 2017), among others, which have been identified by teachers and previous research as troublesome for students.

Nevertheless, as a developing technology, AR has barriers to overcome such as usability (Akçayir et al. 2016), resistance from teachers (Lee 2012) and overload of information (Akçayir and Akçayir 2017; Turan et al. 2018). There are also technical issues such as difficulties in detecting user's location (Palmarini et al. 2018) specially indoors, and limitations in pattern recognition that affect the ergonomics applications (Fraga-Lamas et al. 2018).

This systematic review seeks to increase the literature on the implications of the use of AR in education by answering the following research questions:

- RQ1 What are the trends of augmented reality?
- RQ2 What is the most common field of education for augmented reality applications?
- RQ3 Have these applications considered special needs of particular users?
- RQ4 What are the advantages of using augmented reality in educational environments?
- RQ5 What are the disadvantages and challenges of using augmented reality in educational environments?
- RQ6 What is the impact of augmented reality on learning effectiveness of students?

To present AR trends in education (RQ1), we consider two aspects. First, we present the evolution over time regarding the number of publications in journals and conference proceedings. Then, we identify the levels of education in which AR is most applied. Concerning the fields of education (RQ2), we use the broad fields of education proposed by the International Standard Classification of Education ISCED (UNESCO 2011) to identify the domain of the applications of AR involved in the selected studies. This study interprets special needs of users (RQ3), as physical disabilities (deafness, blindness, etc.) and mental disabilities (learning difficulties, attention deficit disorder, etc.). Advantages of using AR in educational settings (RQ4) refer to positive outcomes and attitudes of students when using AR systems (academic level improvement, motivation, creativity, autonomy, etc.). In contrast, disadvantages of using AR in educational settings (RQ5) have to do with negative impact of AR systems on students (complexity, technical aspects, multitasking, etc.). Finally, we conducted a meta-analysis to investigate the impact of AR on learning effectiveness of students (RQ6). Learning gain was used as the dependent variable to measure learning effectiveness. This gain is defined as the improvement in student scores between the beginning and the end of the intervention through AR applications. This improvement was assessed based on Cohen's *d* effect size for quantitative studies. The effect size is defined as a quantitative reflection of the magnitude of some phenomenon that is used to address a question of interest (Hedges and Olkin 2014; Kelley and Preacher 2012). The effect size is commonly used to quantify the effectiveness of an intervention, in the present case, the effectiveness of AR systems in educational environments regarding students' learning gains.

The remainder of this paper is structured as follows: Sect. 2 discusses related previous studies. Section 3 presents the process carried out to develop the search, which includes an explanation of the work performed in each of the three stages (planning the review, conducting the review and reporting the review). Section 4 presents the most relevant findings of the systematic review to answer the research questions. Section 5 discusses the meaning of the findings, and finally, Sect. 6 concludes the paper and proposes possible routes for future research.

2 Related work

Many studies aim to define the state of the art of AR in relation to education. These studies allow researchers to know the trends, the benefits and the limitations of this technology in education and give a starting point to new developments. Table 1 summarizes some systematic review studies, on issues related to the application of AR in educational settings.

In addition to these, other studies have defined, after a systematic literature review, the status, trends, advantages and challenges of AR in educational scenarios (Antonioli et al. 2014 ; Chen et al. 2017; Mekni and Lemieux 2014; Radu 2014; Wu et al. 2013). However, these studies do not offer answers to issues like special needs of users or disadvantages of using AR systems in educational settings. Hence, with this systematic review, we want to enhance the literature and provide some directions for future research.

3 Methods

This study follows the guidelines proposed by Kitchenham and Charters (2007), who suggests that systematic reviews involve three main stages: planning, conducting and reporting the review.

Table 1 Summary of some systematic reviews related to the usage of AR in educational environments

Study	Review purpose	Studies reviewed	Main findings
Bacca et al. (2014a, b)	This review analyzed studies published between 2003 and 2013 from six indexed journals. It is focused on uses, advantages, limitations, effectiveness, challenges and features of AR in educational environments	32	There is an increase in the number of published studies in the last four years. Most applications of AR are related to Natural Sciences and Humanities and Arts. The most reported advantages of using AR in education are learning gains, motivation, interaction and collaboration
Diegmann et al. (2015)	This reviewed focused on empirical studies to analyze the benefits of using AR in comparison with other conventional learning tools	25	The most reported advantage of using AR in education is the improved learning curve. That is, students learn faster and easier with AR applications compared to non-AR applications. The reduction in the cost of AR technologies has helped to spread its use in educational environments
Tekedere and Göker (2016)	This study conducted a meta-analysis focused on AR applications for education in order to establish a new point of view for future research. The analysis covers the period between 2005 and 2015.	15	The use of AR applications for education has increased in the last five years. The meta-analysis indicated an average effect size of $d = .67$ that corresponds to "medium" effect. This may indicate that application of AR technologies in education has positive effects on students.
Akçayir and Akçayir (2017)	This review analyzed studies published between 2011 and 2016. It is focused on year, learner type, advantages and challenges of AR in educational environments	68	There is an increase in the number of published studies in the last four years. The most reported advantage in the studies is that it promotes enhanced learning achievements

3.1 Planning the review

This stage involved the definition of the strategy to identify the most relevant literature to answer the research questions. We accomplished an iterative double check focused on scientific journals indexed in the Social Sciences Citation Index (SSCI) database, and conference proceedings indexed in the Conference Proceedings Citation Index-Science (CPCI-S) database. We used the Web of Science (WoS) site to perform the search.

We used the search terms "Augmented Reality AND Education," "Augmenting Reality AND Education" and "Mixed Reality AND Education." The search parameters were set as follows: Document type: "Article." Language: English. The first search allowed us to find 635 articles. Then, we established categories: "Education & Educational Research," "Education, Scientific Disciplines" and "Computer Science Interdisciplinary Applications." After these new filters, we found 345 articles.

These articles were carefully read by two of the researchers to identify the suitability of each article for the study. Articles that did not accomplish the inclusion and exclusion criteria (see Sect. 3.1.1) were discarded. Finally, 61 studies were identified as relevant to the purpose of this review.

3.1.1 Inclusion and exclusion criteria

Papers selected for the systematic review satisfied the following criteria:

- Studies related to the research questions
- Studies that include case studies
- Studies that followed a qualified peer-review process
- Studies must consist of pretest and posttest design (for the meta-analysis)
- Studies must consist of experimental and control groups (for the meta-analysis)

Since the systematic review focused on educational settings, we excluded papers which, despite meeting all the prior criteria, were not focused on education. The flowchart of the systematic review is shown in Fig. 1.

3.2 Conducting the review

This stage took place once the phase of *planning the review* was completed. We designed a data extraction form (spreadsheet document) with the following elements: study name, year of publication, journal of publication, sample size, target group, field of education, reported advantages, reported disadvantages, time dimension and main findings. Two of the researchers proceeded to read each paper individually and to extract the relevant data. Cohen's kappa statistic was

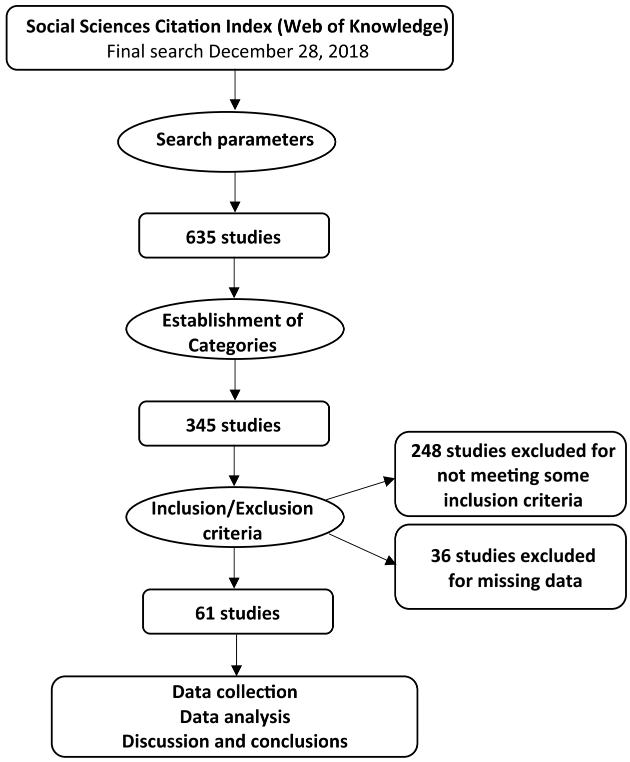

Fig. 1 Flowchart of the systematic review

used to measure intercoder reliability. This value was found to be 0.94, which corresponds to almost perfect agreement as stated by Cohen (1968). Occasional disagreements were discussed and resolved by consensus.

3.3 Reporting the review

In this stage, we analyzed, synthesized and presented the most relevant information that answered the research questions previously established in the planning stage. The results of the study are summarized in the *Findings* section.

3.4 Meta-analysis

We conducted a meta-analysis to measure the learning gains of students when they use AR systems. Glass (1976, p. 3) defined meta-analysis as "the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating findings." Our meta-analysis included 27 pretest–posttest control (PPC) design studies. In this research design, students are assigned to experimental and control groups, and each student is evaluated before and after the treatment (Morris and DeShon 2002). The PPC design provides a more effective framework to estimate the treatment effects compared to studies with only posttest measures or with no control group. Therefore, we did not take into account other research design studies for the meta-analysis.

In addition, *level of education* and *field of education* were defined as the independent variables. The effect size per level of education indicates how each target group benefits from AR systems. Similarly, the effect size per field of education indicates how each domain subject benefits from AR systems.

Learning gains were assessed based on Cohen's d effect size. To calculate the d value, we used the effect size estimate recommended by Morris (2008). This estimate was calculated using Eq. (1) and allowed us to obtain an unbiased estimate of the population effect size.

$$d = \frac{\left(M_{\text{POST-E}} - M_{\text{PRE-E}}\right) - \left(M_{\text{POST-C}} - M_{\text{PRE-C}}\right)}{\text{SD}_{\text{PRE}}} * C_{\text{P}} \quad (1)$$

$M_{\text{POST-E}}$ and $M_{\text{PRE-E}}$ are the mean scores of the experimental groups for the posttest and pretest. $M_{\text{POST-C}}$ and $M_{\text{PRE-C}}$ are the mean scores of the control groups for the posttest and pretest. SD_{PRE} is the pooled standard deviation and was calculated using Eq. (2). Finally, C_{p} is the bias correction and was calculated using Eq. (3).

$$\text{SD}_{\text{PRE}} = \sqrt{\frac{\left(N_{\text{E}} - 1\right)\text{SD}^2_{\text{PRE-E}} + \left(N_{\text{C}} - 1\right)\text{SD}^2_{\text{PRE-C}}}{\left(N_{\text{E}} + N_{\text{C}} - 2\right)}} \quad (2)$$

N_{E} and N_{C} are the sample sizes of the experimental and control groups. $\text{SD}_{\text{PRE-E}}$ and $\text{SD}_{\text{PRE-C}}$ are the standard deviations of experimental and control groups for the pretest.

$$C_{\text{P}} = 1 - \frac{3}{4\left(N_{\text{E}} + N_{\text{C}} - 2\right) - 1} \quad (3)$$

To interpret the effect size values, we used the following classification: $d = .2$ (small effect), $d = .5$ (medium effect), $d = .8$ (large effect) (Cohen 1992), $d = 1.20$ (very large effect) and $d = 2.0$ (huge effect) (Sawilowsky 2009).

4 Findings

4.1 Trends of augmented reality

This subsection presents the trends of AR taking into account two aspects. First, we present the evolution over time regarding the number of publications in journals and conference proceedings. Then, we identify the levels of education in which AR is most applied.

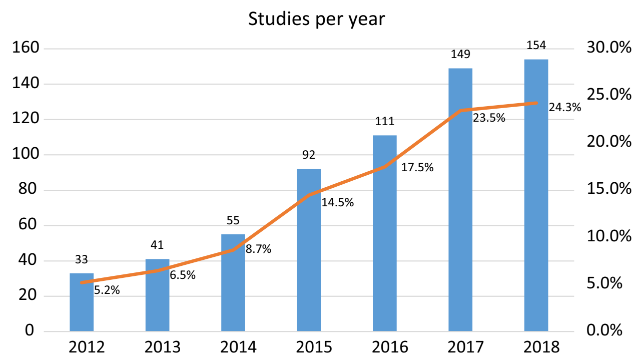

Fig. 2 Studies related to the application of AR in education per year (WoS)

4.1.1 Evolution over time

Of the 61 studies selected for the literature review, 4 studies were published in 2012 (6.67%), 9 in 2013 (15%), 12 in 2014 (20%), 13 in 2015 (21.67%), 12 in 2016 (20%), 8 in 2017 (11.67%) and 3 in 2018 (5%). However, these percentages do not represent the total amount of studies published every year. In order to identify the actual evolution over time concerning the application of AR systems in educational settings, we used the initial results of the search. Figure 2 shows the distribution per year of the 635 articles from 2012 to 2018.

The search indicates that, as previous studies have stated (Akçayir and Akçayir 2017; Bacca et al. 2014a, b), the number of published studies is increasing year after.

4.1.2 Education level

Educational level refers to the educational stage of the target groups that participated in each study. To identify this, we used the International Standard Classification of Education (UNESCO 2011) of the United Nations. The distribution is rather consistent for children (*Early childhood education* and *Primary education*), teenagers (*Lower secondary education* and *Upper secondary education*) and *Bachelor's or equivalent level*. *Post-secondary non-tertiary education* was not considered as a target group in any of the selected studies. This level of education corresponds to vocational education and training (VET) and is composed of students that have completed secondary education (or most of it) and want to be prepared for a specific labor without enrolling to a university. There is evidence that students in these groups lack motivation, concentration, attention, among others (Bacca et al. 2015), which are some of the main advantages that AR systems can offer as stated in Sect. 4.4. Two studies correspond to the category *Not elsewhere classified*. It refers to studies that did not contemplate any specific target group but use a mixture of participants (different ages) to validate the AR application. None of the selected studies had post-graduate students (Master or PhD degrees) as a target group. Table 2 shows the percentages of application of AR systems by target group.

4.2 Education field

Concerning education fields, we used the broad fields proposed by the International Standard Classification of Education ISCED (UNESCO 2011) in order to identify the domain of the applications of AR involved in the selected studies. As was expected, data collected show that most uses of AR in education are related to the broad field of *Natural sciences, mathematics and statistics*. It supports the findings reported in prior researches by Bacca et al. (2014a, b) and Blake and Butcher-Green (2009), and has to do probably with the advantages that AR provides when teaching *Abstract concepts* as demonstrated by Ibáñez et al. (2014).

Augmented reality applications related to *Arts and humanities* are almost exclusively oriented to the narrow field of *Arts*. This is one of the most common educational fields reported in the selected studies. Augmented reality may represent a new way to utter the talents of the artists since it helps to explore audiovisual techniques in a deeper way (Wei et al. 2015). Nevertheless, most uses of AR in *Arts and humanities* are the various museums applications that can be found worldwide. This technology brings art collections to life and allows rich media content such as images, video, and 3D environments and animations to be layered over real environments or objects (Chang et al. 2015).

Applications related to *Social sciences, journalism and information* are focused on psychology, and none is related to journalism or information. All the applications related to the field of *Engineering, manufacturing and construction* are focused on engineering. Even though the study reports one study related to the application of AR in subjects related to *Education,* there is still a lot to develop in this field.

Table 2 Percentage of studies analyzed per target group

Target group	Number of studies	Percentage (%)
Early childhood education	1	1.6
Primary education	19	31.1
Lower secondary education	11	18.0
Upper secondary education	9	14.8
Post-secondary non-tertiary education	0	0.0
Short-cycle tertiary education	1	1.6
Bachelor's or equivalent level	18	29.5
Master's or equivalent level	0	0.0
Doctoral or equivalent level	0	0.0
Not elsewhere classified	2	3.3

Table 3 Percentage of studies analyzed per education field

Broad field	Number of studies	Percentage (%)
Natural sciences, mathematics and statistics	30	49.2
Arts and humanities	10	16.4
Social sciences, journalism and information	7	11.5
Information and communication technologies	5	8.2
Engineering, manufacturing and construction	4	6.6
Health and welfare	4	6.6
Education	1	1.6
Business, administration and law	0	0.0
Agriculture, forestry, fisheries and veterinary	0	0.0
Services	0	0.0

We could not find any evidence of using AR in the broad fields of *Business, administration and law; Agriculture, forestry, fisheries and veterinary;* and *Services*. Therefore, innovative researchers have opportunities to develop applications that support the learning of these topics. Table 3 presents the percentages of usage of AR by broad field of education.

4.3 Consideration of special needs of the users

Schmitz et al. (2015) presented "HeartRun." This is a cardiopulmonary resuscitation (CPR) training approach for school kids that includes aids for blind and visually impaired people, as well as for children with learning disabilities. This is the only study that considers special needs of users among those selected for this study. Thus, just 2.5% of the studies included applications that contain features that address special needs of users.

This finding seems to validate the results of Bacca et al. (2014a, b) and Wu et al. (2013) who pointed out that only a few systems have been designed for users with special needs and disabilities. We emphasize the need for further research to recognize diversity in educational settings and address diversity using AR applications. Hence, it is important that stakeholders begin to take into account the criteria provided by the Web Accessibility Initiative (WAI) in the mobile accessibility guideline (WAI 2016), as well as the Global Public Inclusive Infrastructure (GPII) proposed by Vanderheiden and Treviranus (2011).

4.4 Advantages of using augmented reality in educational environments

A hundred percent of the selected studies reported some kind of advantage when using AR systems in education. Table 4 summarizes the advantages reported in the 61 selected studies. It is important to clarify that these are only some of the advantages more commonly reported in the studies. Likewise, most studies reported more than one advantage.

Learning gain is the most common reported advantage. Studies stated that, when using AR systems, students improve their academic performance. This improvement was reported not only by data, but also for different teachers and the students themselves. Among others, Chang et al. (2013) mentioned an academic activity held in South Korea, which focused on the integration of AR to assist students learning of socio-scientific issues. They demonstrated that students guided through AR obtained better scores than those who were guided through traditional approaches.

Motivation is the second most common reported advantage. Studies informed that the students felt more motivated by using AR applications, compared to other pedagogical tools. A comparative review of the impact of using AR in educational settings carried out by Radu (2012) shows that the use of AR increases the motivation in the students, who expressed they had fun while learning and were willing to repeat the AR experience. Likewise, a study conducted at a middle school in Madrid by Di Serio et al. (2013) demonstrated through qualitative and quantitative data that the inclusion of AR was a motivation factor when it was integrated into the learning environments. This motivation may be a direct consequence of another very important advantage reported in the selected studies: *Sensory engagement*. Roberto et al. (2011) expressed that *Sensory engagement* "is related to how children learn in their natural mode, using several of their senses in a constructive process." Namely, activating multiple senses in the learners' brain improves knowledge retention (Cheng and Tsai 2013) which is a great advantage in the learning process.

Table 4 Percentage of studies analyzed per reported advantages

Advantages	Number of studies	Percentage (%)
Learning gains	51	83.6
Motivation	46	75.4
Abstract concepts	16	26.2
Autonomy	16	26.2
Sensory engagement	14	23.0
Memory retention	9	14.8
Collaboration	8	13.1
Creativity	4	6.6
Accessibility	3	4.9

Another common advantage reported in the selected studies when using AR has to do with the possibility of facilitating the comprehension of *Abstract Concepts* (Akçayir et al. 2016; Chang et al. 2013; Lin et al. 2013). Studies mentioned that AR is ideal to explain things that cannot be observed. Ibáñez et al. (2014) presented the results of a study in which they compared an AR-based application with its equivalent web-based application to learn the basic concepts of electromagnetism. They obtained consistent evidence that suggests that AR-based applications contribute to increase academic achievement in a more efficient way compared to traditional web applications.

Memory retention has been also reported as an advantage of using AR in educational settings. This technology not only helps retain knowledge, but also gives the student the possibility of retaining it for longer periods of time compared to other pedagogical methodologies (Chiang et al. 2014; Sommerauer and Müller 2014; Zhang et al. 2014). Santos et al. (2014) analyzed 87 research articles on AR learning experiences. They concluded that AR provides three important elements: real-world annotation, contextual visualizations, and vision-haptic visualizations, which favor the long-term memory in the human brain.

Autonomy is other important advantage described in the selected studies. The combination of real and virtual worlds increases the autonomy of students taking into account their natural abilities and motivation for using technological devices (Ferrer-Torregrosa et al. 2015; Ibáñez et al. 2014).

Collaboration was also signaled as a major advantage. Augmented reality creates possibilities for collaborative learning around virtual content (Bujak et al. 2013) which can facilitate learning, since it allows learners to interact with their partners, as well as with the educational content. *Accessibility* and *Creativity* are other advantages described in the selected studies. The aforementioned advantages can be an indicator of the numerous benefits that can be obtained when using AR in educational settings.

4.5 Disadvantages of using augmented reality in educational environments

Fifteen percent of the selected studies reported some disadvantages or problems when using AR in educational settings. Table 5 summarizes the main disadvantages reported in the selected studies.

The most reported disadvantage refers to the *Complexity* of using AR especially when applied to children. Being a novel technology, which involves multiple senses, becomes sometimes a very complex tool especially for those who do not have technological abilities (Herpich et al. 2014).

Teachers participating in some studies manifested having *Technical difficulties* when using AR in their classrooms. This may be caused by the scarce technical training from part of some teachers to manage the AR systems, which could limit their use in educational environments. Another reported issue related to AR systems is *Multitasking*. As Radu (2012) indicated, students expressed that AR applications demand too much attention, which can be a distraction factor. This can cause students to ignore instructions or important stages of the experience.

Table 5 Percentage of studies analyzed per reported disadvantages

Disadvantages	Number of studies	Percentage (%)
Complexity	6	9.5
Technical difficulties	5	7.9
Multitasking	4	6.3
Resistance from teachers	2	3.2

Finally, *Resistance from teachers* has been reported as a possible difficult of the implementation of AR in educational environments. Some teachers may prefer having total control over content, despite recognizing the benefits of using AR applications (Wu et al. 2013).

4.6 Impact of augmented reality on learning effectiveness of student

To identify the impact of AR on students learning effectiveness, we calculated the Cohen's d effect size of each quantitative study using the means and standard deviations for experimental and control groups. When a study reported several mean scores and standard deviations, they were averaged, and the averages were used to calculate the effect size (Bernard et al. 2004). Table 6 shows the studies that were considered for the meta-analysis.

The mean effect size calculated from the studies was $d = .64$ with a 95% confidence interval of .55–.74. This value corresponds to a medium effect as indicated by Cohen, which supposes that AR has a positive impact on learning gains. We assessed heterogeneity tests Q and I^2, to validate the use of a random-effects model. The Q statistic was proposed by Cochran (1954) and represents the amount of heterogeneity among the studies. Under the hypothesis of homogeneity, the Q statistic follows a Chi-square distribution with $k - 1$ degrees of freedom (k, number of studies). The Q value in this study was greater than the critical value (χ^2) according to the Chi-square distribution (Lancaster and Seneta 2005), which indicates heterogeneity among the studies (see Table 7). However, Q statistic does not report the extent of heterogeneity, only its statistical significance. To overcome this limitation of the Q test, Higgins and Thompson (2002) proposed the I^2 index. This index measures the extent of heterogeneity dividing the difference between the Q value and its degrees of freedom by the Q value itself,

Table 6 Studies analyzed in the meta-analysis

References	N	Experimental				Control			
		M_{PRE}	S_{PRE}	M_{POST}	S_{POST}	M_{PRE}	S_{PRE}	M_{POST}	S_{POST}
Chen and Tsai (2012)[a]	116	–	–	–	–	–	–	–	–
Hsiao et al. (2012)[a]	482	–	–	–	–	–	–	–	–
Cai et al. (2013)	50	67.42	19.19	80.42	15.46	67.65	15.84	78.69	13.94
Hsiao (2013)[a]	66	–	–	–	–	–	–	–	–
Chang et al. (2014)	135	57.68	14.14	71.01	12.75	59.04	15.91	58.09	12.23
Zhang et al. (2014)	74	5.93	3.21	8.04	3.05	5.98	3.21	6.70	3.70
Sommerauer and Müller (2014)	101	1.75	1.11	3.64	1.31	1.81	1.16	2.59	1.28
Ibáñez et al. (2014)	64	3.25	1.17	6.11	1.40	3.38	1.10	5.00	1.87
Jee et al. (2014)[a]	142	–	–	–	–	–	–	–	–
Chang et al. (2015)	55	39.41	9.66	65.84	11.82	43.33	11.68	55.31	11.64
Barma et al. (2015)	150	4.90	1.20	6.20	1.11	5.08	1.37	5.95	1.25
Tarng et al. (2015)	60	52.8	13.50	77.50	11.00	53.2	17.1	69.3	12.3
Ibanez et al. (2016)	82	5.21	2.19	6.31	1.63	4.55	2.01	4.92	2.12
Chen et al. (2016)	71	86.33	7.78	71.89	14.56	83.83	11.73	62.69	15.23
Akçayir et al. (2016)	76	1.99	0.68	3.22	0.51	2.24	0.59	2.93	0.52
Juan et al. (2016)	38	7.54	2.00	9.00	1.56	8.23	1.43	9.6	0.72
Tarng et al. (2016)	56	40.89	13.83	48.44	14.09	38.62	16.81	39.17	17.9
Cai et al. (2017)	42	25.95	6.36	42.50	7.63	25.95	6.99	40.38	8.50
Mumtaz et al. (2017)	45	108.74	17.26	136.27	18.45	98	13.56	114.32	19.03
Joo-Nagata et al. (2017)	143	5.04	2.38	13.57	3.88	5.23	2.19	11.08	4.22
(Wang 2017)	103	3.87	0.85	4.23	0.85	3.62	0.85	3.65	0.79
Tosik Gün and Atasoy (2017)	88	12	4.88	15.43	5.11	12.46	3.98	14.5	4.83
Calle-Bustos et al. (2017)	70	1.95	0.48	7.45	1.34	2.50	0.67	6.86	1.44
Liou et al. (2017)	27	22.15	8.78	73.55	10.781	21.15	8.08	64.76	16.76
Karagozlu (2018)	147	19.10	7.51	79.11	11.721	19.35	9.25	53.99	16.58
Tarng et al. (2018)	56	38.39	7.77	85.36	10.54	40.18	7.73	78.75	7.89
Medina et al. (2018)	18	53.33	19.44	95.56	6.85	48.89	25.58	84.00	15.54

M_{PRE} and M_{POST} are the mean scores of the pretests and posttests for experimental and control groups. S_{PRE} and S_{POST} are the standard deviations of the pretests and posttests for experimental and control groups

[a]Indicates papers that did not provide mean scores and standard deviations, but, instead, provided effect size values

Table 7 Summary of meta-analysis results

Variable	Value
Number of samples (K)	27
Total sample size (N)	2557
Effect size (d)	0.64
p (d)	< .001
Heterogeneity test (Q)	55.00
Critical value (χ^2)	40.113
I^2	52.72
Z	13.16
95% Lower limit	0.55
95% Higher limit	0.74

all multiplied by 100. The I^2 index can be interpreted as the percentage of the variability between the studies due to heterogeneity. The I^2 value found in this meta-analysis ($I^2 = 52.72$) indicates a medium heterogeneity as suggested by Huedo-Medina et al. (2006). Additionally, a probability value (p) lower than 0.01 leads us to reject the null hypothesis of homogeneity and accept the alternate hypothesis of heterogeneity. These values shown in Table 7 support the assumption of the random-effects model (Borenstein et al. 2010).

4.6.1 Effect size per level of education

To identify the effectiveness of AR per level of education, we calculated the average effect size for each educational stage. Having into account that the number of quantitative studies in the meta-analysis is relatively small, the number of studies per target groups is also small. For this analysis, only the target groups that participated in the quantitative studies were taken into account. Data analysis indicates that there are no significant differences according to the level of education. The effect size values found indicate that AR has a medium impact on each of the four levels of education that were considered for this meta-analysis. Table 8 summarizes the meta-analysis per level of education.

4.6.2 Effect size per broad field of education

To identify the effectiveness of AR per subject, we calculated the average effect size for each broad field of education. Taking into account that the number of studies is relatively small, the number of studies per broad field is also small. For this analysis, only the broad fields of education reported in the quantitative studies were taken into account. Analysis indicates that AR has a large effect on learning *Arts and humanities* and Health and welfare. Likewise, results show a medium effect on learning *Social sciences, journalism and information* and *Natural sciences mathematics and statistics*. Finally, results indicate a small to medium effect on learning *Health and welfare* and a small effect on learning *Education*. Table 9 summarizes the meta-analysis per broad field of education.

Table 8 Summary of meta-analysis per level of education

Variable	Primary education	Lower secondary education	Upper secondary education	Bachelor or equivalent level
K	9	5	5	8
N	596	562	723	676
d	.65	.60	.70	.62
p (*d*)	< .01	< .01	< .01	< .01
Z	6.98	4.12	6.90	6.62

5 Discussion

The results of the systematic review seem to indicate that AR is an important technology that may be reaching maturity. We can notice that AR applications are present not only in education but also in medicine, tourism, industry, entertainment, among others (Eishita and Stanley 2018; Fraga-Lamas et al. 2018; Rojas-Muñoz et al. 2018; Yim et al. 2017)

The integration of AR systems in mobile devices has led that along with the spread of those devices (Statista 2015), the development and use of AR technologies are increasing worldwide. This may be one of the causes of the steady increase in the number of publications since 2010 identified by this and other studies (Akçayir et al. 2016; Bacca et al. 2014a, b; Chen et al. 2017; Diegmann et al. 2015). Therefore, it could be concluded that as the use of mobile devices expands, especially in developing countries, the use of AR technologies will also increase.

The most common target group in the selected studies is *Primary education*. Augmented reality systems give students the possibility to learn while playing. This can be very motivating for children, especially to learn unobservable concepts that are difficult to understand (Parhizkar et al. 2012). However, these systems require technological abilities and tend to demand too much attention, which can be a distracting factor that confuses children. Similarly, the second most common target group is *Bachelor or equivalent level.* These groups are usually composed of people between 17 and 24 years old. Namely, they are mature enough to handle the technology, but they frequently need pedagogical aids to acquire knowledge.

The analysis of the data does not show significant differences in effect sizes per level of education. Therefore, the results seem to indicate that the level of education does not moderate the impact of AR on education. However, it is necessary to take into account that the number of studies in some levels of education is too low or inexistent.

Most studies were applied in the broad field of *Natural sciences, mathematics and statistics* which coincides with the results by Bacca et al. (2014a, b) and Chen et al. (2017). These subjects include many *Abstract concepts*

Table 9 Summary of meta-analysis per broad field of education

Variable	Natural sciences mathematics and statistics	Arts and humanities	Social sciences, journalism, and information	Information and communication technologies	Health and welfare	Education
K	15	3	2	3	3	1
N	1544	323	197	203	174	116
d	.69	.96	.71	.36	.81	.27
p (*d*)	< .01	< .01	.02	< .01	< .01	< .01
Z	10.54	6.12	2.13	2.83	3.95	4.12

that are more easily comprehended by the help of AR applications (Cai et al. 2013; Chiu et al. 2015). Oppositely, we could not find evidence of the application of AR in the fields of *Business, administration and law*; *Agriculture, forestry, fisheries and veterinary*; and *Services*. These fields of education could benefit from the apparent multiple benefits of AR systems, which lead us to encourage researchers to explore the possibilities in these areas.

The analysis of the data allowed us to identify that just one single AR application (in the selected studies) includes aids for users with some type of disability. The process of development of AR applications should include engineers (to develop programming), educators (as thematic experts) and other specialists in order to generate qualified educational resources (Cuendet et al. 2013). Similarly, a diverse team should ensure that AR applications include features that enable people with any type of disability to interact with them, considering the special needs and preferences of students and teachers.

Advantages of using AR in educational settings go from psychological to learning aspects. There is convincing evidence of the multiple benefits that this technology can provide to educational scenarios (Akçayir and Akçayir 2017). With respect to previous studies, we found no new reported advantages. *Learning gains* continue to be the most reported advantage of AR systems in education followed by *motivation*. It is important to mention that each new study continues to report multiples benefits that help improve, not only the academic level of students, but also many other personality traits as autonomy, creativity and collaboration. In addition, the fact that AR systems increase students' motivation and academic achievement could eventually reduce the costs associated with grade repetition and early school/college dropout, and the social problems that these events may cause.

Despite the apparent multiple benefits that AR brings to education, this technology has still some difficulties to overcome, such as complexity, technical issues and some resistance from teachers. Fifteen studies reported some kind of disadvantage when using AR systems in educational settings. However, these disadvantages have to do with the fact that this is a developing technology. Hence, it may be concluded that, as this technology advances, most of its problems will be fixed (Bower et al. 2014). Besides, having into account that the benefits of its use seem to be clear, it is worthwhile to continue working and developing strategies to overcome them.

The meta-analysis indicates that AR has a medium effect size on learning effectiveness of students. It is very important, considering that the effect size of educational technology found by two separate studies was found to be $d = 0.35$ by Tamim et al. (2011) and $d = 0.546$ by Chauhan (2016).

The effect of AR on learning gains was found to be medium on each level of education considered in the analysis. Due to the lack of data, it was not possible to calculate the effect size on *Early childhood education*, *Post-secondary education*, *Short-cycle education*, *Master's level* and *Doctoral level*.

Concerning broad field of education, AR has a large effect size on *Arts and humanities* and *Health and welfare*. Data show a medium effect size on *Social sciences, journalism and information* and *Natural sciences, mathematics and statistics*. The effect was found to be small to medium on *Information and communication technologies* and small *Education*. Due to the lack of data, it was not possible to calculate the effect size on *Engineering, manufacturing and construction, Business, administration and law*; *Agriculture, forestry, fisheries and veterinary*; and *Services*.

6 Limitations of the study

This literature review has some limitations that must be kept in mind for further research. There are some important research questions that might give important information respect to the trends, affordances and challenges of AR systems in education, which were not addressed in this study. For example, this study does not state what are the research groups or institutions that develop AR systems for education. The study does not reveal what are important funding sources for developers and practitioners. The study does not establish what are the technological tools (software development kits) that are used to develop the AR applications. In addition, further research should include the analysis of other moderating variables in order to provide a more complete understanding of the impact of AR on education.

Besides, after the analysis of the data, we do not specify what features should include AR systems to better their accessibility for people with disabilities. We do not propose any possibility of solution for none of the found challenges. Further research needs to be done to give an answer to the aforementioned issues in order to provide other directions and continue to enlarge the knowledge about AR systems for educational environments. Besides, with the intention of ensuring the accuracy of the quantitative information, it is imperative that further research includes bigger samples.

7 Conclusion and future work

This work presents a systematic literature review and meta-analysis of 61 studies focused on AR applications for education. Results seem to indicate that AR is an important technology that may be reaching maturity. We can notice that AR applications are present not only in education but also in medicine, tourism, industry, entertainment, among others. The number of published studies related to applications of AR in education has been steadily increasing since 2010. This must do probably with the integration of AR systems in mobile devices such as smartphones and tablets, which has led that along with the spread of those devices, the development and use of AR technologies are increasing, worldwide. Therefore, it could be concluded that as mobile devices usage spreads, especially in developing countries, the usage of AR technologies will also increase.

With this literature review, it is pretended not only to show the status of AR in education, but also to establish a route for the stakeholders to guarantee the right inclusion of AR systems in educational scenarios. This route includes three main lines of work. First, it is important that governmental institutions, industry and educational institutions increase their inversions in projects focused on the development of AR systems, with the intention of expanding the benefits of this technology. Second, software developers should engage in the solution of technical difficulties of AR pedagogical tools to facilitate their usage, especially for people with low technological skills and people with disabilities. Finally, researchers should continue to conduct more studies to demonstrate the effectiveness of the inclusion of AR systems in teaching–learning processes.

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