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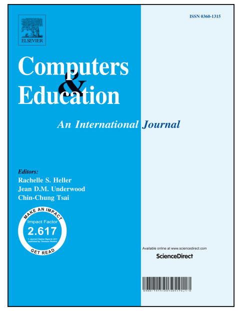

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Augmented reality for STEM learning: A systematic review

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Abstract

This study presents a systematic review of the literature on the use of augmented reality technology to support science, technology, engineering and mathematics (STEM) learning. It synthesizes a set of 28 publications from 2010 to 2017. A qualitative content analysis is used to investigate the general characteristics of augmented reality applications in STEM education, the instructional strategies and techniques deployed in the studies reviewed, and the evaluation approaches followed in the interventions. This review found that most augmented reality applications for STEM learning offered exploration or simulation activities. The applications reviewed offered a number of similar design features based on digital knowledge discovery mechanisms to consume information through the interaction with digital elements. However, few studies provided students with assistance in carrying out learning activities. Most of the studies reviewed evaluated the effects of augmented reality technology in fostering students' conceptual understanding, followed by those that investigated affective learning outcomes. A number of suggestions for future research arose from this review. Researchers need to design features that allow students to acquire basic competences related with STEM disciplines, and future applications need to include metacognitive scaffolding and experimental support for inquiry-based learning activities. Finally, it would be useful to explore how augmented reality learning activities can be part of blended instructional strategies such as the flipped classroom.

Keywords

Augmented reality; Applications in STEM education; Interactive learning environments; Systematic review.

Research highlights

1. A review of the literature on AR technology to support STEM education is shown.
2. Most AR applications use trigger mechanisms to aid the consumption of information.
3. Some AR applications allow the exploration of digital assets to build knowledge.
4. AR STEM education research should focus on science skill-based outcomes.
5. AR STEM applications should offer metacognitive and experimental support.

Title

Augmented reality for STEM learning: A systematic review

1. Introduction

Augmented reality (AR) is a 3D technology that enhances the user's sensory perception of the real world with a contextual layer of information (Azuma, 1997). AR has become a popular topic in educational research in the last decade (Akçayır & Akçayır, 2017; Bacca, Baldiris, Fabregat & Graf, 2014). The main determinants of AR acceptance in the educational arena include the availability of low-cost handheld devices with innovative features that allow the deployment of AR-based applications, and the recognition of AR by the New Media Consortium (www.NMC.org) and the Educause Learning Initiative (www.educause.edu) as one of the most promising technologies for both higher and K-12 education. AR's media characteristics, namely sensory immersion, navigation and manipulation, seem to work as promoters of positive emotions while learning, and create more efficient and better learning outcomes (Cheng & Tsai, 2013; Wu, Lee, Chang & Liang, 2013). Some researchers have pointed out that AR has potential educational affordances which are especially useful in the science, technology, engineering, and mathematics (STEM) fields, including spatial ability, practical skills, conceptual understanding, and scientific inquiry learning (Bujak, Radu, Catrambone, Macintyre, Zheng & Golubski, 2013; Cheng & Tsai, 2012; Dunleavy, Dede & Mitchell, 2009; Wu, Lee, Chang & Liang, 2013). This study focuses on scientific educational contexts.

Among the most popular educational contexts of application of AR-technology are the humanities and arts (Di Serio, Ibáñez & Delgado, 2013; Liu & Tsai, 2013), eHealth (Calle-Bustos, Juan, García-García & Abad, 2017), engineering, manufacturing and construction (Henderson & Feiner, 2011), and science (Kerawalla, Luckin, Seljeflot & Woolard, 2006; Martín-Gutiérrez, Saorín, Contero, Alcañiz, Pérez-López & Ortega, 2010; Squire & Jan, 2007). Each study provides valuable insight into the learning advantages that this technology might provide in its application field, and some reviews have synthesized the results of previous studies to identify broader research trends (Akçayır & Akçayır, 2017; Bacca, Baldiris, Fabregat, & Graf, 2014; Radu, 2014). However, there are few recent studies providing comprehensive explanations of the educational effects and implications of AR in the STEM fields (Cheng, & Tsai, 2013). To fill this gap, this study systematically reviews and synthesizes the relevant literature, and analyzes the main tendencies and uses of AR in educational STEM settings together with its advantages and limitations in terms of providing insights for helpful AR design features and promising instructional processes to be included in future AR STEM learning environments. Specifically, the present study poses the following three research questions:

1. What are the general characteristics and specific design features of AR-based learning applications for STEM-AR studies?
2. What are the instructional processes followed by STEM-AR studies?
3. What are the measured outcomes addressed in AR for STEM learning studies?

2. Related Work

Augmented reality is a 3D technology which merges the physical and digital worlds in real time. Applications based on this technology rest on three pillars: tools to track information about real-world objects of interest; hardware and software to process information; and devices to show the user the digital information integrated into the real environment (Azuma et al., 2001; Carmigniani et al., 2011). AR technology is often described with reference to its two predominant modes of tracking information from the physical world. The first is image- or maker-based AR, which requires recognition of a marker or specific object to bring up digital information; the second is location-based AR, which makes use of a device's GPS to identify locations at which computer-generated information should be superimposed.

Currently, AR is a popular technology that has become an important focus on research education in recent years. Systematic reviews of research and applications have found that AR has potential for pedagogical applications, have identified drawbacks of the technology and suggested future research topics. These reviews are usually focused on the use of AR technology within a broad range of educational contexts and provide relevant insights about how AR technology assists students' learning. Indeed, Radu (2014) presents a meta-review of 26 publications and identifies a list of the positive and negative impacts of educational AR technology on student learning. Radu concludes that AR is helpful in increasing students' motivation, fostering collaboration among students, developing spatial abilities, and improving performance in physical tasks. Regarding AR's negative impacts, Radu points out that AR imposes an extra cognitive load on students and causes usability problems. In a recent study, Akçayır and colleagues (2017) present a systematic review of 68 research articles that used AR in educational settings. They consider factors such as the publication year, learner type, and technologies in AR, and compile the advantages and challenges of using AR in educational settings. Their study reports a recent increase in the number of AR studies and concludes that AR technology might potentially support learning and teaching when pedagogical issues such as "need for more class time, unsuitability in crowded classrooms, instructors' inadequate experience with technology"(Akçayır & Akçayır, 2017, pp. 8) and usability problems have been overcomed. Finally, Bacca and colleagues (2014) present a systematic review that analyzes 32 studies published between 2003 and 2013 in six indexed journals; they analyze uses, advantages, limitations, effectiveness, challenges, and features of AR in educational settings. These authors found an increase in the number of published studies about AR in education from 2009 to 2013, and identify science and the humanities and arts as the fields where AR has been used the most. They claim that the main advantages of AR are learning gains, motivation, interaction, and collaboration, whereas the main limitations of the technology are due to usability problems. Unlike the previous articles, Cheng and Tsai (2012) find valuable trends and potential research directions for AR-related science learning. They review journals from the Web of Knowledge and Scopus databases from 2004 to 2011, and select 12 articles or studies using AR in science learning. They note the AR features, educational context, participants and affordances in science learning. Based on their findings, they propose that future research should use mixed methods of investigating learning process and focus more on exploring learner experiences rather than on usability.

The abovementioned studies offer a synthesis that is crucial to understanding the affordances, barriers and trends of AR technology in educational settings. However, most of these reviews are not specific to STEM fields, or they do not report advances made in recent years.

3. Method

3.1. The manuscript selection process

To find relevant literature sources, seven well-known online research databases were used which are related to education and technology (ACM Digital Library, ERIC, IEEExplore, ISI Web of Science, ScienceDirect, Scopus, and Springer), using the query string: "augmented reality" AND (education OR learning) AND (STEM OR science OR technology OR engineering OR mathematics). The last search was conducted on 22 August 2017. The search produced 1358 results from previously-used search terms, including 616 duplicates, which were deleted. Titles and abstracts were reviewed to determine whether they were suitable for the purposes of the study. During this examination, a set of inclusion and exclusion criteria were adopted (see Table 1). Authors developed this criteria list by adapting established criteria used in earlier reviews (e.g. Akcayir, & Akcayir, 2017; Cheng, &Tsai, 2012; Zydney, & Warner, 2016) and considering that previous studies (Akcayir & Akcayir, 2017; Zydney & Warner, 2016) already presented complete reviews before 2010. By reviewing titles and abstracts, the number of articles was narrowed down to 112. The selected articles then were examined by the first author to determine whether they were suitable for the purposes of the study. The second author independently reviewed approximately 20% of the articles to confirm the reliability of the coding method. The intercode agreement rate for coding was 96.6%. Disagreements between the two coders were resolved through discussion and further review of the disputed studies. The articles were downloaded and the methods sections reviewed in order to verify that the articles met the criteria for inclusion in the review. The second author independently reviewed approximately 20% of the downloaded articles. The intercode agreement was initially 97.3%, and this was brought to 100% after discussion. A total of 28 articles met the criteria for inclusion in the final review.

TABLE 1

Table 1: Inclusion and exclusion criteria

3.2. Analysis

The articles that met the inclusion criteria were analyzed using a qualitative content analysis method, which is a thematic analysis concentrating on the relationship between content and context (Elo & Kyngäs, 2008; Hsieh & Shannon, 2005). The authors defined a group of categories for analysis with their corresponding sub-categories, according to each research question. Categories were useful for grouping studies according to their shared characteristics. During the systematic review process, several sub-categories emerged and others were refined in order to reflect the emerging information. Two of the authors of this article manually coded the studies separately according to their characteristics and classified them according to the categories and sub-categories defined. In the case of discrepancy, the coders resolved this through discussion.

4. Results

In this section, we present the results of the three research questions, focusing on the themes of the augmented reality application design, the main approaches followed by instructors when using augmented reality to facilitate learning, and the evaluation of the interventions.

4.1. Overview of reviewed studies

Of the 28 studies reviewed from 2010 through 2017, the majority of these studies (24 articles) were published after 2013. National science standards [National Science Teachers' Association, 2014] were used to classify the topics covered in the studies into the following areas: physical sciences (10 articles), mathematics (seven articles), life sciences (seven articles), earth sciences (three articles), and multidisciplinary (one article). The preferred educational context was the in-class context (19 articles), followed by out-of-class activities with eight articles. Two of the in-class interventions took place in laboratories, whereas the out-of-class interventions took place in a science museum (three), botanical garden (two), in a nature center (one), one in school (one), and one at home learning activity. The participants in the studies were mostly middle school students (12 articles) and higher education students (seven articles). Other studies focused on elementary students (three articles), primary school students (two articles), high school students (one articles) technical students (one article), or cut across multiple school levels (two articles). The number of student participants in the studies ranged from 20 to 874. Most of the studies were carried out with less than 90 participants (21 studies). Other studies were carried out with a number of participants ranging from 92 to 146 (six studies); the study of Bursztyn (2017) was carried out with 874 participants. In terms of the duration of instruction, most of the studies were done in a unique session ranging from seven to 180 minutes (14 articles), four studies did not give details about the duration of intruction, and 10 articles reported studies that lasted up to 18 weeks. An overview of the research studies is provided in Table 2.

TABLE 2

Table 2: Background information on reviewed articles

4.2. General characteristics of AR applications

This section addresses the first research question. Twety-eight different augmented reality applications were tested by researchers. Table 3 shows an overview of these applications in terms of building tools, type of application, and augmented reality features included.

4.2.1. *Building tools*

Regarding the building tools used in the 28 studies reviewed, most of these were self-developed native applications which used self-programmed device sensors (11 studies). Eight studies used augmented reality development tools: Vuforia (five studies), Metaio (one study), Layar (one study) and Aurasma (one study). Finally, eight studies did not specify the building tool used for the implementation of their testbed.

4.2.3. *Application type*

The review of the literature highlights three categories of educative applications: (a) exploration applications (13 applications) which in turn were divided into augmented books (two applications), augmented marks (seven studies), and the use of a point of interest to trigger digital information (four studies); (b) simulation tools (12 applications); and (c) games (two applications).

4.2.2 *AR features*

In 71.4% of the interventions, image-base AR technology was used, whereas 25% were location-based. One of the studies did not specify the AR feature used. The applications used a great variety of digital information to augment the real world. More than half of the applications reviewed used at least two types of digital information, eight applications used three different digital elements, four applications used two elements, and three applications used four elements. The rest of the applications (35.7%) used only one type of digital element. Regarding the type of digital element used by the applications, 46.4% of the studies reviewed used text, nearly half of them (42.8%) used 2D images, a nearly a third of the applications (32.1%) used animations, and 3D objects and videos were used in 28.5% of the applications. There were also applications that provided audio information (10.7%), and applications that connected the real world with the World Wide Web (7.1%).

TABLE 3

Table 3: General characteristics of augmented reality applications

4.3. Instructional process

According to Akdeniz (2016), instruction can be defined as the whole process applied for learning to occur and for the development of the target behavior that learners are expected to show. The process should be carried out in a stimulating learning environment where students carry out activities that will facilitate learning and help develop behavior appropriate for the gains students are supposed to make (Clark & Starr, 1968; Moore, 2007). The approaches followed by teachers to achieve the fundamental aims of instruction are called instructional strategies (Akdeniz, 2016), and the rules, procedures, tools and skills used to deploy the instructional strategies are called instructional techniques (Günduz, 2016).

This section addresses the second research question. It presents the instructional strategies and techniques used in the studies reviewed. For each feature described below, one or two examples of applications are given to illustrate how the feature has been used in the AR-based applications. An overview of these design features is provided in Table 4.

4.3.1 *Instructional strategies*

Instructional strategies have been classified under a number of taxonomies according to how the process functions, how the information is produced, how the information is acquired by learners or how they are based on the instructional models that act as sources for strategies (Akdeniz, 2016). Following this latest approach, the 28 studies reviewed can be grouped into three categories: instruction through presentation; instruction through discovery; and cooperative learning.

Eight of the applications reviewed provide students with general ideas about a subject; then, these ideas are progressively differentiated in terms of details and specificity following a presentation instructional strategy as defined by Akdeniz (2016). Applications such as the one presented by Gopalan (2014) are augmented books. In these augmented books, students can select the appropriate viewpoint for the 3D virtual models appearing out of the book pages (Billinghurst, Kato & Poupyrev, 2001). Liou and colleagues (2016) present a more active approach which takes into account the interactive characteristics of the technology. Their application allows students to explore basic materials knowledge by providing three-dimensional interactive animations. When students touch the interactive models on the handheld device, more detail information about the model appears as well as interactive animations and videos.

Scientific discovery instructional strategy is a highly self-directed and constructivistic strategy for learning. This instructional strategy requires that learners construct knowledge for themselves by discovering, as opposed to being told about something (Bruner, 1961). The scientific discovery instructional strategy was used in 13 of the studies reviewed. These studies can be classified in three different families. Huang et al. (2016) is representative of the first family of studies. These authors use AR technology to enhance the on-site information in a botanical garden setting and to allow students to become immersed in environmental exploration in an authentic outdoor environment. Students who participated in this family of studies have an active role in building an understanding of the discovered information. Ibáñez et al. (2014) present an in-class interactive AR application which is representative of the second family of studies. This AR application follows Bruner's (1961) guidelines for providing effective instruction by allowing students to infer knowledge through their interaction with 3D digital objects representing circuit elements, presenting relevant content in a structured way, and giving immediate feedback (Ibáñez et al., 2014). Finally, a third family of applications uses discovery instructional strategy in a blended learning environment where (1) the AR application provides the information and/or data for measurement and (2) in-class activities promote hypothesis formation, data analysis, and reflection (Kamarainen, Metcalf, Grotzer, Browne, Mazzuca, Tutwiler & Dede, 2013).

Finally, seven studies were guided by a cooperative/collaborative instructional process. These studies used blended learning environments where the AR learning tool was used individually, and the collaboration was carried out in the real world. For example, in a study carried out by Cascales-Martínez et al. (2017) students did individual activities using an AR tool while collaborate in the real world to solve mathematical problems (Cascales-Martínez, Martínez-Segura, Pérez-López & Contero, 2017).

4.3.2 *Factors considered when selecting instructional techniques*

Although all the 28 studies reviewed consider the characteristics of the learners such as age, duration of the intervention and physical learning environment, only one third of the studies consider specific characteristics of learners to select teaching techniques or discriminant factors affecting learning outcomes.

When dealing with low- and high-achieving learners, AR technology has proved sometimes useful in improving learners' cognitive outcomes. For instance, Lin and colleagues (2015) found that students with average and low academic achievement exhibit small and medium levels of learning effectiveness, while students with high academic achievement do not benefit from the use of AR technology. The former knowledge of learners also seems to have a cause-and-effect relationship on students' behavior during the teaching-learning process, and it was used in (Ibáñez, Di Serio, Villarán & Delgado, 2016) to guide students towards more effective instruction. However, in AR-based learning environments, the relationship between learner characteristics such as gender or learning style and learning outcomes has not yet been established.

Finally, Cascales-Martínez et al. (2017) carried out a study with students with special educational needs in a real educational setting. The instructional content focused on understanding and managing money, coins, and banknotes. The results of the study showed a significant increase in the level of knowledge and motivation in students with learning disabilities, learning disorders not otherwise specified, and attention deficit hyperactivity disorder.

4.3.3 *Instructional techniques*

Following the classification of instructional techniques provided by Gündüz (2016), we identified five different instructional learning techniques in the studies reviewed: observation, inquiry, game, role-play, and concept maps. A study was considered to use observation as an instructional technique when learners triggered digital information such as image, text, video, or animation by interacting with the AR-based tool. When using observation as an instructional technique, the learner receives information in a passive way. A more active learner role was necessary for a study to be considered as using inquiry-based learning. This required the use of an AR-based tool providing at least one of the operations of science inquiry, namely generating hyphotheses, designing comparisons, collecting observations, analyzing data, and constructing interpretations (Quintana, Reiser, Davis, Krajcik, Fretz, Duncan, Kyza, Edelson & Soloway, 2004). Studies that used elements of game mechanics were classified in the category of games. There were also studies that used a dramatization technique known as role-play, where students are asked to behave in fictional situations as the character they represent. Finally, studies were considered to use a concept-map instructional technique when the AR-based tool allowed the tagging and connection of concepts related to the instruction.

The instructional learning technique most often deployed was observation (14 studies). Six of these 14 studies deployed structured observation, whereas eight of them allowed students free observation of the contents. Structured observation was used in studies supported by augmented books (Martín-Gutiérrez, Saorín, Contero, Alcañiz, Pérez-López & Ortega, 2010), by digital resources via mobile devices (Estapa & Nadolny, 2015), or by a set of augmented reality learning activities organized as a learning flow (Ibáñez, Di Serio, Villarán & Delgado, 2014). Free observations allowed students to choose both the content and the order in which to explore it, and were deployed through AR-based simulators (Tarng, Lin, Lin & Ou, 2016) or through AR learning tools based on marker images that simply served as triggers for AR content (Liou, Bhagat & Chang, 2016).

The second instructional technique most often used in the studies reviewed was inquiry (10 studies). One of these studies documents how the narrative structure of a board game, the physical floor materials, a student's first-person embodied experiences, the third-person live camera feed, and the augmented-reality symbols become integrated in a inquiry learning activity (Enyedy, Danish & DeLiema, 2015). Laboratories and museums were used in four studies as community spaces to gain expertise about STEM topics using augmented reality technology. Two of these studies reporting interventions carried out in laboratories were augmented reality tools supporting inquiry activities in real laboratory settings (Akçayır, Akçayır, Pektaş & Ocak, 2016; Frank & Kapila, 2017), and two further studies reported the use of AR-based simulators in science museums (Salmi, Thuneberg & Vainikainen, 2017; Yoon, Anderson, Lin & Elinich, 2017). Five studies used AR-based simulators to deploy the inquiry instructional technique. The use of computer simulations in inquiry-based learning has been found to be ineffective in improving learning processes and outcomes (Kirschner, Sweller & Clark, 2006; Settlage, 2007). Consequently, some researchers have studied the difficulties that learners might encounter in the discovery learning process (Rutten, Van Joolingen, & Van der Veen, 2012) and have proposed scaffolding to overcome these difficulties. Despite this, only one of the studies reviewed included scaffolding to support inquiry-based learning (Ibáñez, Di-Serio, Villarán & Delgado, 2016).

Game formats were used as instructional techniques in two studies. One of these studies deployed a virtual environment with outdoor activities that took advantage of the benefits of games providing immersion-in-context, rewards for correctness, and immediate feedback in response to student interaction (Bursztyn, Walker, Shelton & Pederson, 2017). The other study presented an alternative reality game where students were asked to solve mathematical problems using virtual money (Cascales-Martínez, Martínez-Segura, Pérez-López & Contero, 2017).

One study used role-play combined with inquiry as an instructional technique in the context of field trip learning. Role-play is a well-known and commonly used drama technique in education as an instructional technique (Gündüz, 2016). The study reports how augmented reality helped students to discover relevant information according to their specific role in an out-of-class activity (Kamarainen, Metcalf, Grotzer, Browne, Mazzuca, Tutwiler & Dede, 2013).

In one study (Chen, Chou & Huang, 2016), concept maps were integrated into AR learning to develop a learning system for an elementary school science course. The system was developed to help students explore and organize what they learned in the course. The AR-based learning tool allowed students to establish the structure of course knowledge by drawing digital links connecting real images representing the main concepts to be studied.

TABLE 4

Table 4: Instructional processes followed in the reviewed articles

4.4. Evaluation of interventions

This section addresses the third research question. It presents the research purposes, methods, and outcomes used in the studies reviewed (see Table 5).

4.4.1. Research purposes

Four research purposes emerged from the studies reviewed. Evaluating the effects of AR learning was the main focus of 25 studies; investigating the affective domain during AR learning was a goal in 15 studies; evaluating the influence of learner characteristics in the AR learning process was the purpose of four studies, and assessing the impact of designing an AR system for AR learning was within the scope of five studies (see Fig. 1 and Table 5).

More than two thirds of the studies (67.8%) had more than one research purpose, and one of them (Cascales-Martínez, Martínez-Segura, Pérez-López & Contero, 2017) had three different purposes. More than half of the studies (53.5%) investigated the effects of AR learning and the affective domain during AR learning. Evaluating the effects of AR learning was the sole research purpose of eight studies (see Fig. 1 and Table 5).

FIGURE 1

Figure 1. Research purpose frequency

4.4.2. Research approaches

Among the 28 analyzed proposals (see Table 4) there were quantitative studies (13), qualitative studies (five) and mixed-method studies (10).

Quantitative studies were most often employed (46.4%) and these were divided into eight quasi-experimental studies and five experimental design studies.

The qualitative studies included three content analysis studies which interpreted recorded material to understand knowledge construction by learners in collaborative AR-based inquiry learning environments (Chiang et al., 2014; Wang et al., 2014), and to gain insights about the benefits of personalizing of learning in AR learning environments to help focus students' attention (Ibáñez et al., 2016). The other two qualitative studies presented an interpretative study and an ethnography study, respectively. The interpretative study examined the potential of AR as a distributed learning interface for learning and warned about the risks of over-distribution with respect to usability (Cuendet et al., 2013) whereas Enyedy et al. (2015) documented a case study and traced how the narrative structure of a board game, the student's first-person embodied experiences, and the augmented-reality symbols became integrated into scientific inquiry activities.

More than a third of the studies reviewed (35.7%) combined quantitative and qualitative research methods for a better understanding of the learning process. Three different combinations of quantitative and qualitative studies were found. The first type of combination was used in five studies, a representative example of which is the work presented by Yoon and colleagues (2017) who combined a quasi-experimental method with interpretation. Although the quasi-experimental part of their study showed that students in the AR condition showed greater knowledge gains when compared with students in the non-AR condition, the qualitative part of their study showed that AR capabilities enabled the visualization of typically invisible causal mechanisms that underlie complex phenomena, and played an important role in the knowledge acquisition of the experimental group. The second type of mixed methods (four studies) combined experimental design with interpretation. For instance, Huang et al. (2016) presented quantitative results that suggested that an AR location-based intervention made at a botanical garden helped students to develop a positive emotional attatchment to the experimental activities, whereas interviews showed students' willingness to learn more about the environment. Finally, Zimmerman et al. (2016) used a quasi-experimental study to prove that an experimental group using an AR learning tool gained more knowledge about the life cycle of trees than a control group, and combined this quasi-experimental study with an ethnographic study to find three sociotechnical interactions that contributed to triggering situational interests during the summer camp learning experience deployed.

4.4.3. Learning outcomes

This section focuses on measures of student outcomes. Eighteen studies examined possible effects of using AR-based learning environments on learners' emotions while the remaining studies did not included any assessment of emotional states. Motivation was the emotional state that appeared in most studies (seven in total), followed by attitude, enjoyment and engagement, which appeared in five, four and four studies respectively. Other emotional states considered were satisfaction, immersion, flow, and interest (see Fig. 2).

FIGURE 2

Figure 2. Frequency of affective outcomes

The 28 studies reviewed were classified into two broad categories according to the type of cognitive outcomes measured: lower-level cognitive outcomes and higher-level cognitive outcomes. The first category included works dealing with simpler cognitive processes stated on the revised Bloom's taxonomy (Anderson, L.W., & Krathwohl, D.R., 2001): remember, and understand. The second category included works dealing with more complex cognitive processes of the aforementioned taxonomy implying create, apply, analyze, and evaluate.

The most common cognitive outcome measured was the ability to remember information (18 studies). These studies typically used a pre/posttest format, with multiple-choice or short-answer questions to assess retention of the presented material in much the same form in which it was presented. One of these studies also assessed long-term retention (Cai et al., 2017) by administering a delayed posttest one week after the instructional period concluded. For three of the 18 studies mentioned above, augmented reality learning affordance related to the acquisition of enhancing spatial skills was key to the understanding of scientific phenomena (Cuendet et al., 2013; Lin et al., 2015; Martín-Gutiérrez et al., 2010). Three studies measured learners' understanding of STEM topics, through the construction of concept maps (Chen et al., 2016); pre- and posttests aiming to assess learners' understanding of lunar concepts after observing lunar phases over a month (Tarng et al., 2016); and pre- and posttests to assess tasks related to the training of spatial skills (Cuendet et al., 2013).

Six studies measured high-level cognitive outcomes related to students' effectiveness in applying procedures to solve STEM problems, analyze their results and self-evaluate their progress. In (Cascales et al., 2016), students with special needs were able to solve mathematical problems by interacting with an AR-based learning tool and with their peers. Their learning gains were measured through pre- and posttests that assessed whether they could solve a set of mathematical problems by applying their knowledge. In (Chen et al., 2015) students carried out a self-evaluation of their learning achievements in terms of solving problems related to earth science phenomena involving day, night, and seasons. Ibáñez and colleagues (2014) used pre- and posttests to measure students' learning effectiveness in a problem-solving activity in physics, using a marker-based electromagnetic laboratory. Chiang and colleages (2014) analyzed how students created knowledge, in their work students' activities were recorded and then analyzed to study the knowledge construction phases during an inquiry-based learning activity related to an ecological learning situation. In (Enyedy et al., 2015), students worked in a blended learning environment, trying to conceptualize a physics phenomenon. The learning effectiveness of the activity was documented using recordings of students' answers to open-ended questions on the subject. Wang and colleagues (2014) analyzed students' behavior in an inquiry-based learning activity, using video recordings of the intervention. Their results showed high frequencies for high-level inquiry behaviors, such as interpreting experimental data or drawing conclusions in an AR simulation system and a traditional 2D simulation system. However, the AR simulation system engaged the students more thoroughly in the inquiry process.

4.4.4. Problems reported

Only seven studies reported problems with augmented reality technologies that might affect the effectiveness of learning activities (see Table 5). A problem reported in three of the studies reviewed was that students need to be trained in the use of augmented reality technology before using it in learning activities. Another study goes further, suggesting that the training be extended to instructors in order to expand the use of this technology in current courses. The most frequent complaints in studies including usability measurement were the system did not provide immediate feedback (two studies), the system was slow, or the interface was not intuitive. A more serious concern arose from instructors who reported student distraction, probably caused by the novelty effect (Frank et al., 2017; Ibáñez et al., 2016; Kamarainen et al., 2013).

TABLE 5

Table 5. Research purposes, methods, and outcomes

5. Discussion

5.1. Design of augmented reality applications

The results show that the reviewed AR-based learning applications for STEM are evenly distributed among physics, mathematics and life sciences topics. Most of the interventions related to life sciences topics took place in out-of-class settings using location-based AR-features, whereas physics and mathematics interventions usually were made in-class using marker-based or image-based location AR features. Moreover, life sciences topics were mostly deployed using AR-based exploration tools, with inquiry learning activities orchestrated by teachers, while physics and mathematics interventions were generally devoted to exploration or simulation, with an emphasis on the understanding of STEM phenomena. It would be interesting to see more studies on the use of in-class AR technology incorporating scientific inquiry orchestrated by teachers and supported more actively for the AR learning tools.

It worth noting that assets were used differently in life sciences topics than in physics or mathematics. In the first case, assets provided factual knowledge or helped students to become immersed in the educational context by superimposing digital elements related to the narrative of the lesson. In the second case, assets either allowed the student to see invisible phenomena or helped students to visualize 3D concrete or abstract objects. Therefore, assets were mainly used to increase students' visual perception, and some studies also included tangible objects (Cuendet et al., 2013; Ibáñez et al., 2014). This is reasonable since students are more likely to have stronger visual and read-write learning styles (Drago & Wagner, 2004). However, it would be interesting to use audio assets, for instance, to achieve a higher immersion in the learning context.

5.2. Instructional processes

A significant proportion of the studies reviewed promoted instructional strategies based on the students' consumption of information in support of in-class learning activities in cross-sectional studies. Even though these studies reported that learning instruction was effective, it would be interesting to carry out further research to evaluate whether learning effectiveness is retained over time or by students familiar with the use of AR technology. It seems advisable to shift to instructional strategies where students play a more active role in the teaching/learning process, taking advantage of the potential learning affordances of this emergent technology.

Augmented reality has also driven instructional constructivist strategies where students have the freedom to discover information through interaction, thus potentially promoting the self-construction of knowledge. However, more research is still needed in this area. In particular, it is necessary to determine how AR-based tools can be designed to help students to construct knowledge (Zydney & Warner, 2016) and to find instruments to measure whether students are indeed building knowledge. On the other hand, researchers have reported learning problems for some students when they have the freedom to discover information using AR technology in STEM fields (Dunleavy, Dede & Mitchell, 2009; Ibáñez, Di-Serio, Villarán-Molina & Delgado-Kloos, 2015). Therefore, it is necessary to find effective scaffolding mechanisms to help students in the discovery process as well as in inquiry activities for scientific methods (Rutten, Van Joolingen & Van der Veen, 2012).

Some studies used AR technology to support collaborative instructional processes by providing knowledge-sharing features and the use of differentiated roles (Kamarainen et al., 2013). Knowledge-sharing features included the sharing of pre-established text, images, 3D objects and animations (Chen et al., 2015), and the possibility of adding new text and images to the AR collaborative application (Chiang et al., 2014; Zimmerman et al., 2016). These can be considered as initial attempts to use AR technology to facilitate collaborative instructional processes. There is room for further improvement, as collaborative learning can be defined in terms of procedural elements including group interaction, interdependency amongst group members and individual accountability (Cuseo, 1992; Vassileva, 2008), which have not been considered in the studies reviewed.

The number of different instructional techniques used in the reviewed studies was limited to five. However, learning affordances of augmented reality on education seems to be suitable for instructional techniques such as massive open online courses or flipped classroom. Indeed, despite the high interest MOOCs generate, they have large number of dropouts (Gregori, Martínez, & Moyano-Fernández, 2018). Recent studies suggest the need to include active learning support to break limitations of MOOC model. These studies point out that learning materials should be able to ensure the continuous activity of the learners (Hew, 2018; Ollé, & Namestovski, 2017). In this regard, AR technology could be used to facilitate students with learning interactive tools that could be uses as support of MOOCs' courses. On the otrher hand, flipped classroom instructional approach introduces changes in the use of in-class and out-class activities. In particular, outside class time is designed for students to gain knowledge at the remembering and understanding levels through the presentation of learning content using taped lectures (Hwang, Lai, & Wang, 2015). However, some studies have point out that students found taped lectures less engaging and more distracting than the typical classroom lecture (Jensen, 2011). Recommendations to improve the flipped classroom approach include the use of out-of-class learning activities to elicit students' engagement and exploration (Lo, 2018). Since AR technology allows users the interactive exploration of augmented environments, it seems interesting to explore the use of AR-technology to support learning activities for out-of-class activities in inverted classrooms.

Finally, most of the studies reviewed emphasized a description of the AR applications and how students worked with them, rather than a justification for using them to support an instructional strategy. In fact, the studies rarely included factors such as learning goals or characteristics of students, which may affect the selection of the instructional strategies employed. This finding is consistent with the work of Cheung and Hew (2009) in mobile learning.

5.3. Measures of student outcomes

Evaluations made in quantitative studies suggest that augmented reality technology fosters positive affective states of students, such as motivation, engagement, and attitudes toward STEM subjects, that have proved to be effective in promoting learning benefits; these act through the mediation of usability on learning outcomes (Choi & Baek, 2011; Kye & Kim, 2008; Dunleavy et al., 2009). Some of the studies reviewed claim that AR helps to decrease cognitive load or enhances spatial ability, but these do not provide conclusive results. These two outcomes have been suggested as potential learning affordances for augmented reality (Cheng & Tsai, 2013); hence, it would be interesting to carry out further investigation to determine whether there is a real contribution from AR to the acquisition of the aforementioned outcomes.

The cognitive outcome evaluated in the majority of quantitative studies is knowledge acquisition. However, evaluations were made with ad-hoc questionnaires elaborated by authors, which assessed low-level cognitive outcomes over brief periods of time. Although these results are encouraging, it is expected that an interactive technology such as AR, with proven capabilities to engage students in learning activities, can also support critical thinking, problem-solving, collaboration, and self-directed learning (Jaramillo, 2017). On the other hand, previous reviews have already warned of the possibility that the novelty effect is totally or partially responsible for the successful results shown (Akçayır & Akçayır, 2017; Bacca et al., 2014; Cheng & Tsai, 2012). Therefore, it is advisable that future works determine the effectiveness of AR in fostering high-level cognitive outcomes over longer periods of time. Finally, the AR learning environments reviewed reveal that there is a maturity in the use of AR to support constructivist or collaborative instructional strategies; what is missing is the provision of evaluations of the impact of AR technology on the acquisition of scientific inquiry or collaborative specific competences.

Most of the qualitative research carried out in the studies reviewed involved descriptive accounts of how events, processes, and activities were perceived by participants. These basic interpretative studies helped in a better understanding of learning processes by focusing on the total picture rather than breaking it down into variables. However, only a few of these studies provided new insights about how knowledge sharing, inquiry, or discussion processes were promoted by the use of AR technology using different instructional designs. Affordances of augmented reality in STEM learning are encouraging; thus, it is important to continue an exploration of how the learning experience occurs in different instructional designs, and to use these new insights for the development of future AR-based STEM learning environments.

In terms of the types of learners selected for these research studies, only two articles focused on gifted or special needs students. Thus, there is a need for future research to explore how augmented reality learning environments can be used with more diverse populations of students. These results are aligned with previous findings in other review studies in education (Cheng & Tsay, 2012; Zydney & Warner, 2016). Furthermore, most of the studies reviewed did not consider learner characteristics such as gender, age difference, prior knowledge, or skills. It would be interesting to understand the impact of AR features such as enhancement of visualization and interactivity in affective or cognitive outcomes according to learner characteristics. An understanding of this, along with the interactivity capabilities of augmented reality, will be useful in deploying adaptive learning interventions (Liu, McKelroy, Corliss & Carrigan, 2017).

Finally, some studies report usability problems that are more closely related to the AR learning enviroment design than to the AR technology itself. Researchers should be committed to finding new design techniques in a way that allows educators to take advantage of the main affordances of this emergent interface and to avoid barriers to acceptance due to the design of learning environments.

6. Conclusions

This study presents a review of the state of the art in AR as a promising technology for supporting STEM learning; although it is not intended to be comprehensive, it provides important findings that can be useful for instructional design and researchers.

The first research question aimed to identify the general characteristics and specific design features of AR-based learning applications for STEM-AR studies. In this regard, three categories of AR-based learning applications for STEM emerged from the literature: exploration, simulation and, to a lesser extent, game-based applications. Exploration applications were mainly used for life sciences topics in out-of-class settings, using location-based AR, whereas simulation applications were used mainly for mathematics and physics instructional learning environments, carried out in in-class settings using either image-based or marker-based AR. Most of the studies reviewed reported applications which superimpose text, images and animations to enhance the learning experience; however, these rarely stimulate senses other than sight. It would be interesting to explore the use of assets such as audio and haptic elements to foster higher levels of immersion.

The second research question was formulated to examine the instructional processes followed by STEM-AR studies. In this regard, it was found that some studies deployed simple strategies based on the consumption of information, others were devoted to instructional constructivistic strategies based mostly on simulations, and a small number included collaboration between learners. Few studies provided students with assistance in carrying out learning activities. Some of the drawbacks associated with AR technology in education are that AR promotes distraction and increases cognitive load for students. Therefore, in addition to access to information, students require assistance in selecting and interpreting information in AR-based learning environments. This review recommends that future research embed a scaffolding mechanism to support better metacognitive processes, which might help with the aforementioned drawbacks of this technology. Additionally, experimental support might also be useful in those instructional processes that use inquiry-based learning. Finally, collaborative instructional strategies might be enhanced by including features that support group interaction, interdependence among group members, and individual accountability.

Finally, the third research question sought to determine the main learning outcomes measured by STEM-AR studies. It was found that the studies measured mainly affective and cognitive outcomes using cross-sectional experiments. Although the reviewed studies offer a synthesis crucial to understand affordances and the barriers of AR technology in educational settings, few of them provide new insights about how learning experiences take place in STEM learning environments using AR technology. There is therefore a need for researchers to diversify their measures and to include an assessment of deepened understanding that goes beyond remembering facts and content. It may be also useful to include measures of the acquired capacities to build hypotheses, to contrast them, and to build new knowledge from interactions with the augmented environment and in pairs. It is also advisable to complement quantitative measures with qualitative ones, in order to gain a better understanding of how AR technology can support STEM learning.

6.1. Limitations of the study

This review was limited in that it examined articles from seven databases: ACM Digital Library, ERIC, IEEExplore, ISI Web of Science, ScienceDirect, Scopus, and Springer, from 2010 to 2017. The articles in these databases are considered to have a high impact on the field; however, the latest technical reports and business demonstrations of AR in STEM learning were excluded from this review, which may limit the representation of the state of the art for these applications. Although the number of papers included in this review was limited, the selection process was completed using a systematic process in order to avoid bias.

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Inclusion criteria	Exclusion criteria
(a) Published between January 2010 and August 2017.	(a) Studies that mentioned the term "augmented reality" but were about "virtual reality" or "mixed reality".
(b) Peer-reviewed journal article.	(b) Used for professional learning (e.g., teacher education).
(c) Available in full-text.	(c) Emphasized application design and development as opposed to students' outcomes.
(d) Empirical research.	
(e) Related to science learning.	
(f) Described applications for augmented reality in science education as primary component.	

Table 1: Inclusion and exclusion criteria

Primary author (year of publication)	Science domain	Educational level	Educational context	No. of students	Duration of instruction
Akçayır, M. (2016)	Physics	Higher education	In-class (Laboratory)	76	15 h
Bursztyn, N. (2017)	Earth Sciences	High school	Out-of-class	874	20 min
Cai, S. (2017)	Physics	Middle	In-class	42	1 h
Cascales, A. (2017)	Mathematics	Primary	In-class	22	9 h
Chen, C.H. (2016)	Life Sciences	Primary	In-class	71	180 min
Chen, C.P. (2015)	Earth Sciences	Middle	In-class	144	55 min
Chiang, T.H. (2014)	Life Sciences	Elementary	In-class	57	120 min
Cuendet, S. (2013)	Mathematics (Geometry)	Technical	In-class	24	90 min
Dünser, A. (2012)	Physics	Middle	In-class	10	18 min
Enyedy, N. (2015)	Physics	Elementary	In-class	43	15 weeks
Estapa, A. (2015)	Mathematics	Higher education	In-class	61	-
Frank, J.A. (2017)	Physics	Higher education	In-class (Laboratory)	75	10 min
Gopalan, V. (2014)	Multidisciplinary	Middle	In-class	70	-
Gutiérrez, E. (2016)	Mathematics (Geometry)	Higher education	In-class	20	-
Huang, T.C. (2016)	Life Sciences	Middle	Out-of-class (botanical garden)	21	8 h
Ibáñez, M.B. (2014)	Physics	High school	In-class	64	40 min
Ibáñez, M.B. (2016)	Physics	Middle	In-class	82	100 min
Kamarainen, A. M. (2013)	Life Sciences	Middle	In-class	71	35 h
Lin, H.C.K. (2015)	Mathematics (Geometry)	Middle	In-class	76	-
Liou, W.K. (2016)	Life Sciences	Higher education	Out-of-class	92	18 weeks
Martín, J. (2010)	Mathematics (Geometry)	Higher education	In-class	24	9 hours
Salmi, H. (2017)	Physics	Middle	Out-of-class (science museum)	146	1 month
Sommerauer, P. (2014)	Mathematics	Primary, middle, high school	Out-of-class (science museum)	101	90 min
Tarng, W. (2015)	Life Sciences	Middle	Out-of-class (campus butterfly garden)	120	6 weeks
Tarng, W. (2016)	Earth Sciences	Elementary	In-class	56	1 month
Wang, H.Y. (2014)	Physics	Higher education	In-class	40	15 min
Yoon, S. (2017)	Physics	Middle	Out-of-class (science museum)	58	11 min
Zimmerman, H.T. (2016)	Life Sciences	Elementary, families	Out-of-class (nature center)	42	7 weeks

Table 2: Background information on reviewed articles

Primary author (year of publication)	Building tools	AR Features	Type	Assets
Akçayır, M. (2016)	Metaio	Image-based (markers)	Simulator	Text, video, animations
Bursztyn, N. (2017)	Native app. (Android, iOS)	Location-based	Game	Text, images, videos
Cai, S. (2017)	Native app. (3D modeling tool 3DS Max and graphics engine Java 3D)	Image-based (Kinect RGB camera)	Simulator	Animations
Cascales, A. (2017)	Native app. (TUIO protocol)	Image-based (video projector and two cameras)	Game	Text
Chen, C.H. (2016)	Not specified	Image based	Exploration	Text, image, 3D model
Chen, C.P. (2015)	Not specified	Image-based (turntable, PC, webcam)	Simulator	Image
Chiang, T.H. (2014a)	Native app. (iOS)	Location-based	Exploration	Image, text, websites
Cuendet, S. (2013)	Not specified	Image-based (markers)	Simulator	Image
Dünser, A. (2012)	Native app.	Image-based	Exploration	Text, video, animations
Enyedy, N. (2015)	Not specified	Image-based (markers)	Simulator	Video
Estapa, A. (2015)	Layar Creator	Location-based	Exploration	Video, websites, audio, image
Frank, J.A. (2017)	Native app. (iOS)	Image-based (markers)	Exploration	Video, text
Gopalan, V. (2014)	Not specified	Image-based	Exploration	Text, image, video
Gutiérrez, E. (2016)	Vuforia	Image-based	Exploration	3D model
Huang, T.C. (2016)	Not specified	Location-based	Exploration	Text, image
Ibáñez, M.B. (2014)	Unity 3D, Vuforia	Image-based	Simulator	Text, image, animation
Ibáñez, M.B. (2016)	Unity 3D, Vuforia	Image-based	Simulator	Text, image, animation
Kamarainen, A. M. (2013)	FreshAiR, Vuforia	Location-based	Exploration	Text, image, audio, video
Lin, H.C.K. (2015)	Not specified	Image-based (markers)	Exploration	3D object
Liou, W.K. (2016)	Unity 3D, Vuforia	Image-based (markers)	Exploration	3D object, animation, video, audio
Martín, J. (2010)	Native app.	Image-based	Exploration	3D object
Salmi, H. (2017)	Not specified	Not specified	Simulator	Not specified
Sommerauer, P. (2014)	Aurasma	Image-based	Exploration	Video
Tarng, W. (2015)	Native app. (Android)	Location-based	Simulator	3D model, animation
Tarng, W. (2016)	Native app. (Android)	Location-based	Simulator	3D model, animation
Wang, H.Y. (2014)	Native app.	Image-based (markers)	Simulator	Text, 3D model, animation
Yoon, S. (2017)	Native app.	Image-based	Simulator	Animation
Zimmerman, H.T. (2016)	Native app.	Image-based	Exploration	Text, images

Table 3: General characteristics of augmented reality applications

Primary author (year of publication)	Instructional strategies	Learner characteristics considered	Instructional techniques
Akçayır, M. (2016)	Discovery	ICT competences	Inquiry
Bursztyn, N. (2017)	Discovery	Student major Student initial interest in the topic Gender	Game
Cai, S. (2017)	Presentation	Student's physics achievements	Observation
Cascales, A. (2017)	Cooperative/Collaborative	Students with special needs	Game
Chen, C.H. (2016)	Discovery	-	Concept map
Chen, C.P. (2015)	Cooperative/Collaborative	Learning style ICT competences	Inquiry
Chiang, T.H. (2014)	Cooperative/Collaborative (field trip)	-	Observation
Cuendet, S. (2013)	Cooperative/Collaborative	-	Structured observation
Dünser, A. (2012)	Presentation	-	Observation
Enyedy, N. (2015)	Cooperative/Collaborative	-	Inquiry
Estapa, A. (2015)	Discovery	-	Structured observation
Frank, J.A. (2017)	Presentation	-	Inquiry
Gopalan, V. (2014)	Presentation	-	Structured observation
Gutiérrez, E. (2016)	Presentation	-	Structured observation
Huang, T.C. (2016)	Discovery	-	Field trip
Ibáñez, M.B. (2014)	Discovery	ICT competences	Structured observation
Ibáñez, M.B. (2016)	Discovery	Previous knowledge	Inquiry
Kamarainen, A. M. (2013)	Discovery (field trip)	-	Role-play
Lin, H.C.K. (2015)	Presentation	Low/medium/high-performing students	Observation
Liou, W.K. (2016)	Presentation	-	Observation
Martín, J. (2010)	Presentation	-	Structured observation
Salmi, H. (2017)	Discovery	Low/medium/high-performing students Gender	Inquiry
Sommerauer, P. (2014)	Discovery	-	Observation
Tarng, W. (2015)	Discovery	-	Inquiry
Tarng, W. (2016)	Discovery	-	Observation
Wang, H.Y. (2014)	Cooperative/Collaborative	-	Inquiry
Yoon, S. (2017)	Discovery	-	Inquiry
Zimmerman, H.T. (2016)	Cooperative/Collaborative	-	Observation

Table 4: Instructional processes followed in the reviewed articles

Primary author (year of publication)	Research purpose				Research approach	Affective outcomes	Cognitive outcomes	Problems reported
	A	C	D	L				
Akçayır, M. (2016)	X			X	Mixed method (quasi-experimental study; interpretative study)	Satisfaction Motivation Enjoyment Attitude	Remembering information	Students need to be trained in technology
Bursztyn, N. (2017)	X	X			Quasi-experimental study	Motivation	Remembering information	-
Cai, S. (2017)				X	Quasi-experimental study	Attitude	Remembering information	Students need to be trained in technology System instability System too slow Lack of user-friendly interface
Cascales, A. (2017)	X	X		X	Quasi-experimental study	Motivation	Applying knowledge	-
Chen, C.H. (2016)				X	Experimental design	Motivation Attitude	Understanding	-
Chen, C.P. (2015)	X			X	Mixed method (quasi-experimental study; interpretative study)	Enjoyment	Self-evaluate progress	-
Chiang, T.H. (2014)	X			X	Content analysis	Engagement Immersion	Creating knowledge	-
Cuendet, S. (2013)				X	Interpretative study	-	Understanding	-
Dünser, A. (2012)			X	X	Quasi-experimental study	-	Remembering information	-
Enyedy, N. (2015)	X			X	Case study	Engagement	Creating knowledge	-
Estapa, A. (2015)	X			X	Quasi-experimental study	Motivation	Remembering information	-
Frank, J.A. (2017)				X	Mixed method (experimental design; interpretative study)	Engagement	Remembering information	Difficult to use Students do not read
Gopalan, V. (2014)	X		X		Mixed method (quasi-experimental study; interpretative study)	Motivation Engagement Enjoyment	-	System too slow Interface is not intuitive
Gutiérrez, E. (2016)			X	X	Experimental study	-	Remembering information	-
Huang, T.C. (2016)	X			X	Mixed method (experimental design; interpretative study)	Engagement Interest	Remembering information	Students need to be trained in technology
Ibáñez, M.B. (2014)	X			X	Experimental design	Flow	Applying knowledge	-
Ibáñez, M.B. (2016)		X			Content analysis	-	Remembering information	Distraction
Kamarainen, A. M. (2013)	X			X	Mixed method (experimental design; interpretative study)	Self-efficacy Engagement Attitudes	Remembering information	Teachers need to be trained Novelty effect
Lin, H.C.K. (2015)		X	X	X	Mixed method (experimental design; interpretative study)	Attitude	Remembering information	-
Liou, W.K. (2016)				X	Quasi-experimental study	-	Remembering information	-
Martín, J. (2010)	X			X	Mixed method (quasi-experimental; interpretative study)	Satisfaction	Remembering information	-
Salmi, H. (2017)	X			X	Quasi-experimental study	Enjoyment Interest	Remembering information	-
Sommerauer,				X	Experimental design	-	Remembering	-

P. (2014)							information	
Tarng, W. (2015)	X			X	Quasi-experimental study	Motivation	Remembering information	.
Tarng, W. (2016)			X	X	Experimental design	-	Understanding	.
Wang, H.Y. (2014)				X	Content analysis	-	Creating knowledge	-
Yoon, S. (2017)				X	Mixed method (quasi-experimental study; interpretative study)	-	Remembering information	-
Zimmerman, H.T. (2016)	X			X	Mixed method (quasi-experimental study; ethnography)	Attitude	Remembering information	-

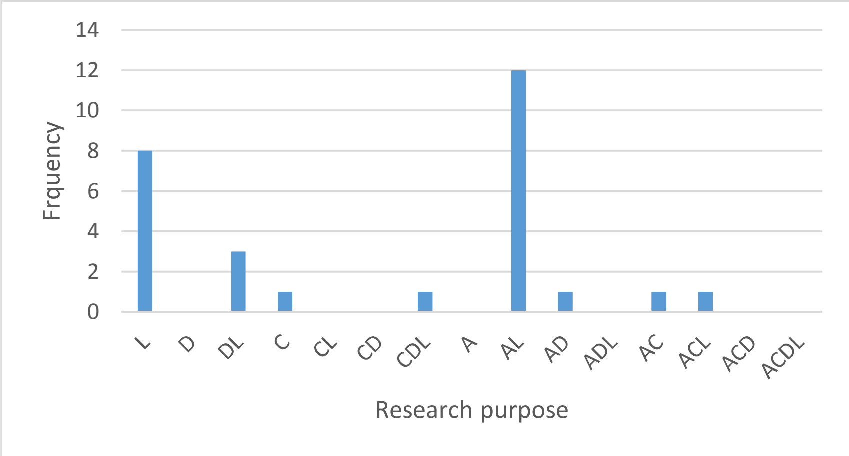
A: Investigating the affective domain during AR learning.

C: Evaluating the influence of learner characteristics in the AR learning process.

D: Designing an AR system for learning.

L: Evaluating the effects of AR learning.

Table 5. Research purposes, methods, and outcomes



A: Investigating the affective domain during AR learning.
C: Evaluating the influence of learner characteristics in the AR learning process.
D: Designing an AR system for learning.
L: Evaluating the effects of AR learning.

Figure 1. Research purpose frequency

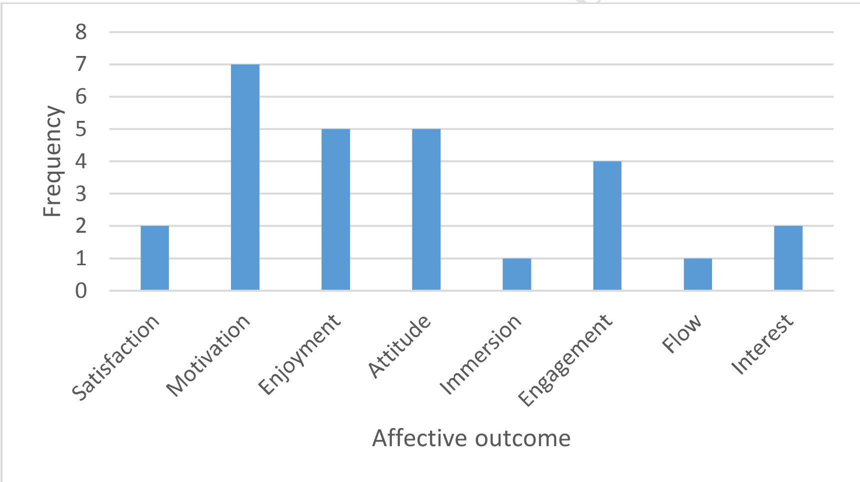


Figure 2. Frequency of affective outcomes

Research highlights

1. A review of the literature on AR technology to support STEM education is shown.
2. Most AR applications use trigger mechanisms to aid the consumption of information.
3. Some AR applications allow the exploration of digital assets to build knowledge.
4. AR STEM education research should focus on science skill-based outcomes.
5. AR STEM applications should offer metacognitive and experimental support.