Interactive Learning Environments

ISSN: 1049-4820 (Print) 1744-5191 (Online) Journal homepage: https://www.tandfonline.com/loi/nile20

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Mustafa Sırakaya & Didem Alsancak Sırakaya

INTERACTIVE LEARNING ENVIRONMENTS
https://doi.org/10.1080/10494820.2020.1722713

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Augmented reality in STEM education: a systematic review

Mustafa Sırakaya and Didem Alsancak Sırakaya

Department of Computer Technologies, Kırşehir Ahi Evran University, Kırşehir, Turkey

ABSTRACT
This study aimed to systematically investigate the studies in which augmented reality (AR) was used to support Science, Technology, Engineering and Mathematic (STEM) education. In this framework, the general status of AR in STEM education was presented and its advantages and challenges were identified. The study investigated 42 articles published in journals indexed in SSCI database and deemed suitable for the purposes of this research. The obtained data were analyzed by two researchers using content analysis method. It was found that the studies in this field have become more significant and intensive in recent years and that these studies were generally carried out at schools (class, laboratory etc.) using marker-based AR applications. It was concluded that mostly K-12 students were used as samples and quantitative methods were selected. The advantages of AR-STEM studies were summarized and examined in detail in 4 sub-categories such as "*contribution to learner, educational outcomes, interaction* and *other advantages*". On the other hand, some challenges were identified such as teacher resistance and technical problems.

ARTICLE HISTORY
Received 4 August 2019
Accepted 24 January 2020

KEYWORDS
Augmented reality; STEM; science education; interactive learning environments; systematic review

1. Introduction

New methods and tools are constantly sought in order to enhance and increase student interest and improve the learning process. Among these tools, augmented reality (AR) is a technology that attracts attention with its various features (Wang, Callaghan, Bernhardt, White, & Peña-Rios, 2018). AR can be defined as a technology that allows virtual objects to be simultaneously superimposed on real images (Azuma, 1997). Thus, virtual objects are viewed in the same environment as the real world (Azuma et al., 2001). AR technology is used in many areas such as education since it enables perfect integration of virtual content with the real world (Azuma, Billinghurst, & Klinker, 2011). Studies reveal that AR provides many advantages in education. Thanks to the digital content it adds to the real image, AR enables students to have different and effective learning experiences. AR makes learning easier (Enyedy, Danish, & DeLiema, 2015; Martin-Gonzalez, Chi-Poot, & Uc-Cetina, 2016) by concretizing abstract concepts (Bujak et al., 2013; Ibáñez, Di Serio, Villarán, & Delgado Kloos, 2014; Laine, Nygren, Dirin, & Suk, 2016). Also, research shows that AR attracts student attention (Bressler & Bodzin, 2013; Bujak et al., 2013; Huang, Chen, & Chou, 2016) and increases motivation (Chang & Hwang, 2018; Ibáñez, Di-Serio, Villarán-Molina, & Delgado-Kloos, 2015). Lessons where AR is used are more fun (Gun & Atasoy, 2017) and enjoyable and student participation in class increases (Giasiranis & Sofos, 2017; Wojciechowski & Cellary, 2013). However, some challenges exist in relation to the use of AR in education. The fact that some AR equipment is expensive (Küçük, Kapakin, & Göktaş, 2016) and that interaction with others is negatively affected while using HDM (head-mounted displays) (Billinghurst, Belcher, Gupta, & Kiyokawa, 2003) can be listed among these challenges.

CONTACT Mustafa Sırakaya mustafasirakaya@gmail.com

Difficulty of developing AR educational materials (Chang, Chung, & Huang, 2016) and the time-consuming nature of this activity (Laine et al., 2016) create important challenges for teachers. Teachers may not have the skills (Gavish et al., 2015) and the time (Dunleavy, Dede, & Mitchell, 2009) to use AR in the classroom. In addition, the limited number of free AR authoring tools and educational AR materials that teachers can easily use is a limiting factor in the use of AR in education. Another important challenge is students need to learn about AR (Cai, Chiang, Sun, Lin, & Lee, 2017; Huang et al., 2016).

AR is a popular technology that has become the focus of educational research over the last decade (Akçayır & Akçayır, 2017; Bacca, Baldiris, Fabregat, Graf, & Kinshuk, 2014; Ibáñez & Delgado-Kloos, 2018; Sırakaya & Alsancak Sırakaya, 2018). AR is used at all levels of education, from preschool to university. In addition, studies exist in many different fields including mathematics (Lin, Chen, & Chang, 2015; Martin-Gonzalez et al., 2016), physics (Yoon, Elinich, Wang, Steinmeier, & Tucker, 2012), chemistry (Yang, Mei, & Yue, 2018), biology (Hwang, Wu, Chen, & Tu, 2016; Laine et al., 2016), astronomy (Chen & Wang, 2015), preschool education (Yilmaz, 2016), museum education (Huang et al., 2016; Sommerauer & Müller, 2014) and arts (Di Serio, Ibáñez, & Kloos, 2013). STEM education is one of the areas where AR can be used effectively. The disciplines that make up STEM education do not exist on their own in the real world, they coexist in a multidimensional and complex way and people face these multidimensional problems in their lives (Pimthong & Williams, 2018). Therefore, STEM education is offered in many countries to help people understand STEM and utilize it in their lives. STEM education enables people achieve educational goals by preparing them for daily life and work life (Pimthong & Williams, 2018). STEM education is an approach where students participate in engineering design or research and achieve meaningful learning experiences through the integration of science, technology and mathematics (Moore & Smith, 2014). STEM education is a meta-discipline defined as the creation of a new discipline as a whole based on the integration of information from other disciplines (Ceylan & Ozdilek, 2015). Features such as support for hands on learning (Hsiao, Chen, & Huang, 2012) and inquiry-based learning (Dunleavy et al., 2009), contribution to the development of spatial ability (Lin et al., 2015) and increased cooperation (Bressler & Bodzin, 2013) indicate that AR is an effective tool for STEM education. Bujak et al. (2013), Cheng and Tsai (2013) and Wu, Lee, Chang, and Liang (2013) emphasize that AR has educational potential which may be useful in STEM education. AR in STEM education is both an educational practice and an educational research field. Thus, this study focused on the use of AR in STEM education both as an educational practice and an educational research field. For this purpose, answers to the following research questions were sought:

(1) What are the general characteristics of AR-STEM studies?
(2) What are the advantages identified in AR-STEM studies?
(3) What are the challenges identified in AR-STEM studies?

2. Background research

Investigating the studies in a specific field is important in presenting the existing situation and providing guidance for future studies (Kucuk, Aydemir, Yildirim, Arpacik, & Goktas, 2013; Seo & Bryant, 2009). Various studies were conducted to present the current situation, advantages, challenges, limitations and tendencies in regards to the use of AR in education (Akçayır & Akçayır, 2017; Bacca et al., 2014; Cheng & Tsai, 2013; Ibáñez & Delgado-Kloos, 2018; Radu, 2014; Sırakaya & Alsancak Sırakaya, 2018). Akçayır and Akçayır (2017) systematically reviewed 68 research articles published in SSCI journals to demonstrate the advantages and challenges of AR use in education. In a meta-review, Radu (2014) revealed the positive and negative effects of AR on learning experiences. In another systematic review, Bacca et al. (2014) focused on the use, advantages, limitations, effectiveness, challenges and characteristics of AR in educational settings.

Sırakaya and Alsancak Sırakaya (2018) identified trends in educational AR studies (publication year, method, research subjects, sample level, number of samples, data collection tool, AR type, AR imaging tool). Unlike these studies, Cheng and Tsai (2013) focused on studies using AR in science education. After a thorough examination of affordances of AR in science education, the authors made suggestions for future studies. As can be seen, studies which evaluated the use of AR from different perspectives were carried out in educational settings. However, there is only one systematic review which examined the articles that focused on the use of AR in STEM education. By reviewing seven well known databases on education and technology (ACM Digital Library, ERIC, IEEExplore, ISI Web of Science, ScienceDirect, Scopus, and Springer), Ibáñez and Delgado-Kloos (2018) investigated 28 articles on the use of AR in STEM education. This study, which significantly contributed to the literature, listed the articles individually and categorized them based on the following features: "General characteristics of AR applications", "Instructional process" and "Evaluation of interventions". The reviewed articles were discussed under the following titles: "Design of augmented reality applications", "Instructional processes" and "Measures of student outcomes". The present review addressed the articles with an inductive approach. Thus, the purpose was to contribute to the literature by focusing on the current situation, advantages and challenges related to AR in STEM education.

3. Method

3.1. Article selection process

Different methods are used by researchers to select articles for review studies. Selecting articles published in journals that are significant in the field or indexed in specific databases (ERIC, ProQuest, EBSCHO, ScienceDirect) is one way to select articles. For this study, articles related to AR in STEM education which were published in journals indexed in SSCI database were selected. The Web of Science (WOS) web site was used to access these articles. Advance search option was used in the WOS web site with the following query string: "augmented reality AND (STEM OR science OR technology OR engineering OR mathematics)". The query came up with 564 articles when the timespan was selected as "end of 2018" (since 1980), the document type as "article" and language as "English" in search filters. When educational categories (education & educational research, education special, education scientific discipline, psychology educational) were selected in the search filter in order to access only educational articles, the number of articles that fit the search parameters was found to be 180. The last search was conducted on 22 February 2019. Full texts of these 180 articles were downloaded and their suitability for the present research was examined by the two researchers separately. Review of the suitability of the 180 articles was based on the inclusion and exclusion criteria (Table 1) prepared using the previous AR review studies (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018; Sırakaya & Alsancak Sırakaya, 2018). The opinion of a third field expert was sought for the articles on which the two researchers had disagreements. As a result of these evaluations, 42 articles out of 180 were found suitable for the purposes of this study.

Table 1. Inclusion and exclusion criteria.

Inclusion	Exclusion
Articles	Conference proceedings, book chapters, etc.
Available in full-text	Articles only available in summary
Empirical articles	Editorials, review articles and articles on application development
Articles focusing on AR	Articles that focus on environments such as virtual reality and mixed reality, although the term AR is used
Articles about STEM education	

3.2. Data coding and analysis

The articles which met the inclusion criteria were coded by the two researchers. Microsoft Excel program was used to encode the data. First of all, 12 randomly selected articles were coded separately in order to calculate coding reliability. Inter-rater reliability was calculated as 0.92 with Cohen's kappa analysis. The remaining articles were coded independently by the two researchers after coding reliability was ensured. After the completion of the coding process, consensus was reached by discussing the codes on which the researchers had disagreements.

Data were analyzed using content analysis method. Content analysis is a method that includes text organization, categorization, comparison and development of theoretical results (Cohen, Manion, & Morrison, 2005). The inductive approach suggested by Miles and Huberman (1994) was adopted in data analysis. First, the coding scheme was created by coding the expressions that were meaningful in themselves. Later sub-categories were formed by combining the codes and inductive categories were formed by combining sub-categories.

4. Results and discussion

4.1. What are the general characteristics of AR-STEM studies?

Studies that focused on the use of AR in STEM education were first conducted in 2012 (Figure 1). The increase in the number of studies by year is remarkable. In addition, it was observed that the majority of the 42 articles that were examined (26 articles) were published after 2015 (2016–2018). Similarly, Ibáñez and Delgado-Kloos (2018) states that the majority of 28 articles (24 articles) published between 2010 and 2017 on AR in STEM education were published after 2013. The increase in the number of AR-STEM studies in recent years may indicate that this topic will be popular in the coming years as well.

Quantitative methods (e.g. Hwang et al., 2016) were used in about half of the studies that focused on the use of AR in STEM education (52%). Studies that used quantitative methods were followed by studies conducted by mixed methods (43%) (e.g. Enyedy, Danish, Delacruz, & Kumar, 2012) and qualitative methods (5%) (e.g. Yang et al., 2018). Ibáñez and Delgado-Kloos (2018) also reached a similar conclusion and found that quantitative (46.4%), mixed (35.7%) and qualitative (17.9%) methods were

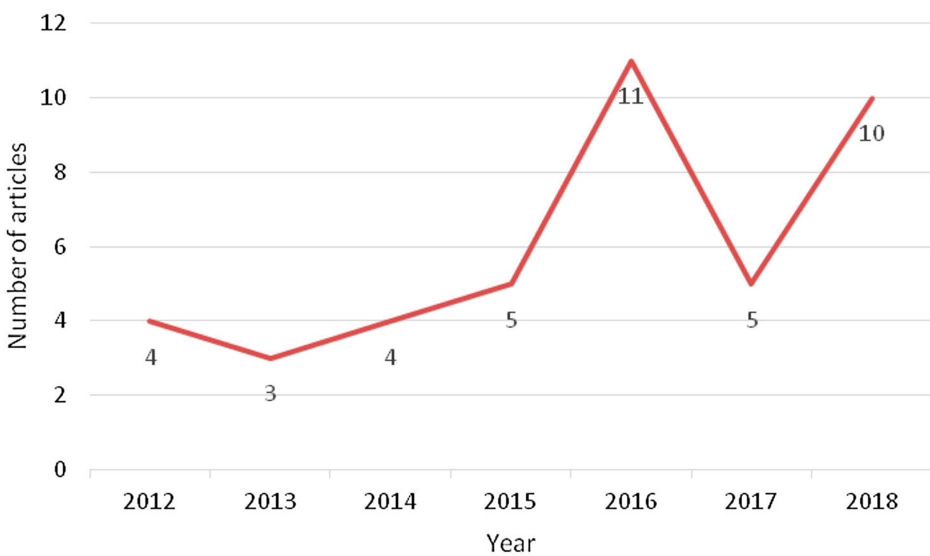

Figure 1. Number of articles by year.

used in AR studies in STEM education, respectively. Considering that AR-STEM studies increased significantly after 2015 (Figure 1), it is normal that experimental studies are conducted to determine the effectiveness of AR use in STEM education. Another reason for the predominance of quantitative studies may be related to the advantages of quantitative methods such as generalizability of results and the ease of working with large samples. It is seen that quantitative methods are mostly preferred in studies conducted in the field of educational technologies (Bond & Buntins, 2018; Kucuk et al., 2013; Ross, Morrison, & Lowther, 2010). The scarcity of studies where qualitative methods was utilized is noteworthy in this respect.

It was found that 74% (31 studies) of the studies were carried out in school settings (class or laboratory) while 26% (11 studies) were conducted in out-of-school settings (field trip, museum or campus). When it comes to studies carried out in school settings, it was found that 5 studies were carried out in the laboratory (e.g. Mejías Borrero & Andújar Márquez, 2012) and 26 were conducted in classroom settings (e.g. Turan, Meral, & Sahin, 2018). In terms of studies conducted in out-of-school settings, it was identified that 4 studies were conducted on field trips (e.g. Hwang et al., 2016), 5 in museums (e.g. Chen & Wang, 2018) and 2 on campuses (e.g. Chang, Hsu, Wu, & Tsai, 2018). Ibáñez and Delgado-Kloos (2018), who reached a similar conclusion, stated that 70% of the AR studies in STEM education are conducted in the classroom and 30% are conducted outside the classroom.

Pointer and reference to the user's location are used respectively in marker-based AR and the location-based AR to enrich the real image by adding virtual objects on it (Cheng & Tsai, 2013). Based on AR type, 88% of the articles included marker-based AR (e.g. Turan et al., 2018) and 12% included location-based AR (e.g. Chiang, Yang, & Hwang, 2014). Ibáñez and Delgado-Kloos (2018), who reached a similar conclusion, emphasized that 71.4% of AR studies in STEM education used marker-based AR and 25% used location-based AR. This result was also supported by the studies conducted by Bacca et al. (2014) and Sırakaya and Alsancak Sırakaya (2018) where marker-based AR was used in higher ratios compared to location-based AR. The fact that marker-based AR applications are easier to use (Thornton, Ernst, & Clark, 2012) and easier to develop (Lu & Liu, 2015) than location-based AR may be effective in this outcome. The facts that AR-STEM studies were mostly conducted on K-12 students (Table 2) and they mostly utilized marker-based AR may be related to each other. Marker-based AR may have been selected since it is easier to be used by K-12 students. The result that 73% of the marker-based AR articles investigated in this review study were carried out with sample groups at K-12 level supports this finding. However, location-based AR has a significant advantage of allowing students to learn outside the classroom (Chiang et al., 2014) and supporting scientific inquiry learning (Cheng & Tsai, 2013). This review determined that all location-based AR studies were conducted outside the school (during field trips, in museums or on campuses).

According to the Next Generation Science Standards Classification, AR-STEM studies are performed in the following disciplines: 38% physical sciences (e.g. Ibáñez et al., 2015) 36% life sciences (e.g. Huang et al., 2016), 12% earth and space sciences (e.g. Liou, Yang, Chen, & Tarng, 2017), 10% mathematics (Lin et al., 2015) and 5% engineering, applications and sciences (e.g. Giasiranis & Sofos, 2017). It is concluded that while studies on mathematics are mostly conducted in class and with marker-based AR, most location-based AR studies (60%) are conducted in life sciences. Marker-based AR was used in all physical studies. All studies conducted in physical sciences used marker-based AR. These results are parallel to the findings of Ibáñez and Delgado-Kloos (2018). While studies in life sciences were mostly conduced with primary and secondary school samples

Table 2. Distribution of sample levels.

Sample level	*f*	%	Sample research
Secondary school students	14	29.79	Yoon et al. (2012)
Primary school students	10	21.28	Chang and Hwang (2018)
High school students	8	17.02	Chao, Chiu, DeJaegher, and Pan (2016)
Undergraduate students	8	17.02	Moro, Stromberga, Raikos, and Stirling (2017)
Teachers	7	14.89	Ozdamli and Karagozlu (2018)

(59%), it was concluded that most of the physical studies were conducted with middle and high school samples (73%).

Table 2 demonstrates that the most preferred sample groups in AR-STEM studies were secondary school students (29.79%), primary school students (21.28%), high school students (17.02%), undergraduate students (17.02%) and teachers (14.89%). Ibáñez and Delgado-Kloos (2018), who reached similar results, listed the most common sample groups in AR studies in STEM education: middle school students (43%), higher education students (25%), elementary school students (11%), primary school students (7%) and others (14%). According to Piaget's cognitive stages of development, primary and secondary school students are in the stage of concrete operations. Students in this stage learn more about concrete concepts that they can perceive with their sensory organs. AR facilitates the understanding of abstract concepts by concretizing them (Bujak et al., 2013; Laine et al., 2016). The selection of secondary and primary school students as samples in AR-STEM studies may be related to this. The majority of AR-STEM articles (68.09%) were found to be conducted at K-12 level. The studies conducted by Akçayır and Akçayır (2017) and Sırakaya and Alsancak Sırakaya (2018) also concluded that the most common sample in AR articles was K-12 students.

According to Table 3, the most common sample size in AR-STEM studies was between 31 and 100 (69.05%) followed by studies with sample sizes between 101–300 (14.29%) and 11–30 (11.90%) respectively. Ibáñez and Delgado-Kloos (2018) reported that the sample size was 90 or below in 75% of the AR studies in STEM education. There was only one study conducted with a sample size of 1–10 and again, only one study with a sample size of more than 1000 (2.38%). In the investigated studies, the highest sample size was determined to be 1211 (Hsiao et al., 2012) and the lowest sample size was 10 (Ozdamli & Karagozlu, 2018). It was concluded that quantitative methods were the most common methods in these studies. The fact that the common sample size was 31–100 may be related to using quantitative (experimental) methods in AR-STEM studies. This finding is parallel to the studies of Bacca et al. (2014) and Sırakaya and Alsancak Sırakaya (2018) where it was concluded that the maximum sample size in AR studies was between 31 and 100.

The most common data collection tools used in AR-STEM studies were as follows (Table 4): achievement test (29.67%), survey / questionnaire (24.18%), interview (19.78%), attitude, personality or aptitude scale (16.48%), observation (7.69%) and other (2.20%). This finding is similar to the studies of Bacca et al. (2014) and Sırakaya and Alsancak Sırakaya (2018).

4.2. What are the advantages identified in AR-STEM studies?

The advantages of AR-STEM studies were collected in 4 subcategories: contribution to learner, educational outcomes, interaction and other advantages (Table 5).

4.2.1. Contribution to learner

The most important contribution to the learner was the increased success achieved by AR use in STEM education. Many studies concluded that AR increased achievement in education in STEM areas (e.g. Chen & Wang, 2018; Gun & Atasoy, 2017; Hwang et al., 2016; Ibáñez et al., 2014; Wu, Hwang, Yang, & Chen, 2018). Although AR was found to impact achievement positively, this impact varied for students with different achievement levels. For instance, Lin et al. (2015) reported

Table 3. Distribution of sample size.

Sample size	*f*	%	Sample research
Between 1 and 10	1	2.38	Ozdamli and Karagozlu (2018)
Between 11 and 30	5	11.90	Martin-Gonzalez et al. (2016)
Between 31 and 100	29	69.05	Hwang et al. (2016)
Between 101 and 300	6	14.29	Cheng (2018)
Between 301 and 1000	0	0	–
More than 1000	1	2.38	Hsiao et al. (2012)

Table 4. Distribution of data collection tools.

Data collection tool	*f*	%	Sample research
Achievement test	27	29.67	Chen and Wang (2018)
Survey / Questionnaire	22	24.18	Bressler and Bodzin (2013)
Interview	18	19.78	Laine et al. (2016)
Attitude, personality or aptitude scale	15	16.48	Turan et al. (2018)
Observation	7	7.69	Lin et al. (2015)
Other	2	2.20	Chiang et al. (2014)

that AR was effective at small and medium scale for students with average and low academic achievements while it was ineffective for students who demonstrated high academic achievement.

According to the studies investigated in the scope of this study, the use of AR in STEM education increased student motivation (e.g. Cai et al., 2017; Chang & Hwang, 2018; Cheng, 2018). For instance, Chang et al. (2016) emphasized that students experienced lack of motivation due to the lenght of time needed for plant growth and lack of opprtunities to observe changes in plant growth in the classroom. They reported that AR increased motivation since it enabled students to observe and manipulate (e.g. sunlight) these changes.

AR ensured development of positive attitudes towards learning (e.g. Cai et al., 2017; Chang et al., 2018; Chen et al., 2016; Hsiao et al., 2012; Kamarainen et al., 2013). It also increased student interest /willingness to learn (e.g. Bressler & Bodzin, 2013; Cai et al., 2017; Huang et al., 2016). AR provides significant contributions to students in STEM education. On the other hand, Ibáñez et al. (2014) and Bursali and Yilmaz (2019) pointed out that these contributions may be caused by the novelty effect, while Hsiao et al. (2012) stated that these effects can be diminished when AR is used in education in general. Kamarainen et al. (2013) suggest future research to measure the novelty effect by ensuring AR use during multiple field trip experiences in order to examine whether novelty attenuates, and engagement is sustained. Similarly, Ibáñez et al. (2014) emphasized the need for further research to eradicate the novelty effect.

Studies demonstrated that AR use in STEM education reduces cognitive load (e.g. Küçük et al., 2016; Liou et al., 2017; Turan et al., 2018) and facilitates learning (e.g. Chen et al., 2016; Martin-Gonzalez et al., 2016; Montoya et al., 2017). However, some studies indicated that AR use can result in excessive cognitive overload (Cheng & Tsai, 2013; Wu et al., 2013). This indicates that more detailed research is needed on cognitive load. That AR facilitates learning is a more distinctive finding. Reality that is enriched with elements such as tips and explanations make learning easier for learners. Montoya et al. (2017) studied static and dynamic content in AR technology in order to determine which one is more effective and reported that using dynamic content in AR facilitated learning to a higher ratio compared to static content.

The analyses conducted in the framework of this research demonstrated that the use of AR in STEM education increased satisfaction (e.g. Huang et al., 2016), improved spatial ability (e.g. Gun & Atasoy, 2017), developed cognitive abilities (e.g. Yoon et al., 2012) and provided permanent learning (e.g. Sommerauer & Müller, 2014). On the other hand, Ibáñez et al. (2015) reported that students had some learning problems when they had the freedom to discover information by using AR in STEM areas. Therefore, this practise should be supported by effective scaffolding mechanisms in order to assist the students in the discovery process.

4.2.2. Educational outcomes

According to results, the most important educational output provided by use of AR in STEM education was "increased participation in class" (e.g. Giasiranis & Sofos, 2017; Moro et al., 2017). AR gives students a fun and enjoyable learning experience (e.g. Chen et al., 2016; Gun & Atasoy, 2017). In addition, it helps students to learn cooperation skills (e.g. Bressler & Bodzin, 2013) and develops group self-efficacy (e.g. Chang & Hwang, 2018). These advantages highlighted in the studies

Table 5. Advantages of AR in STEM education.

Inductive categories	Sub-categories	Sub-categories codes	*f*	%	Sample research
Contribution to the learner	Increases achievement	Learning achievement	12	9.6	Chen and Wang (2018)
		Achievement	6	4.8	Turan et al. (2018)
		Learning performance	3	2.4	Montoya, Díaz, and Moreno (2017)
		Academic achievement	2	1.6	Gun and Atasoy (2017)
		Understanding of …	2	1.6	Chiu, DeJaegher, and Chao (2015)
		Knowledge phase	1	0.8	Ibáñez et al. (2014)
	Increases motivation	Learning motivation	5	4.0	Chang and Hwang (2018)
		Student motivation	4	3.2	Ibáñez et al. (2015)
	Develops positive attitudes	Student attitudes	7	5.6	Kamarainen et al. (2013)
		Learning attitude	2	1.6	Hsiao et al. (2012)
	Increases interest / willingness to learn	Interest	7	5.6	Chen, Chou, and Huang (2016)
		Willingness	2	1.6	Gun and Atasoy (2017)
	Makes learning easier	Facilitate / easier	7	5.6	Martin-Gonzalez et al. (2016)
	Reduces cognitive load	Cognitive load	5	4.0	Küçük et al. (2016)
	Increases satisfaction	Satisfaction	2	1.6	Ibáñez et al. (2014)
		Positive emotions	1	0.8	Chang et al. (2016)
	Develops spatial ability	Spatial ability	2	1.6	Gun and Atasoy (2017)
		Spatial perception	1	0.8	Lin et al. (2015)
	Develops cognitive abilities	Cognitive abilities	3	2.4	Yoon et al. (2012)
	Provides permanent learning	Retention of the knowledge	2	1.6	Sommerauer and Müller (2014)
	Increases class engagement	Engagement / participation	4	3.2	Moro et al. (2017)
Educational outcomes		Cognitive and emotional engagement	1	0.8	Chang et al. (2018)
	Visualization (object, event, etc. that cannot be seen with the naked eye)	Unobservable / invisible scientific concepts	4	3.2	Yoon, Anderson, Lin, and Elinich (2017)
	Fun learning	Fun learning	3	2.4	Gun and Atasoy (2017)
	Cooperative learning	Collaboration skills	2	1.6	Bressler and Bodzin (2013)
		Group self-efficacy	1	0.8	Chang and Hwang (2018)
	Individualized teaching	Individualized learning	3	2.4	Kamarainen et al. (2013)
	Provides in-depth learning	Deeper phases of knowledge construction	3	2.4	Chiang et al. (2014)
	Concretizes abstract concepts	Scientific concepts	2	1.6	Laine et al. (2016)
		Math operations	1	0.8	Gun and Atasoy (2017)
	Learning at desired time and space	Learning anywhere and at any time	2	1.6	Küçük et al. (2016)
	Student-centered learning	Student-centered learning	1	0.8	Kamarainen et al. (2013)
	Informal learning	Informal learning	1	0.8	Yoon et al. (2017)
Interaction	Provides real-time interaction	Real time interaction	3	2.4	Chen et al. (2016)
	Increases interaction between student and course content	Interactions between learners and AR system	3	2.4	Cheng (2018)
	Provides a sense of presence	Sense of presence	2	1.6	Ibáñez et al. (2014)
	Increases interaction among students	Interactions among students	2	1.6	Kamarainen et al. (2013)
Other advantages	Easy to use	Easy to use for students	2	1.6	Liou et al. (2017)
		System interface	1	0.8	Martin-Gonzalez et al. (2016)
	Enables safe application of dangerous experiments etc.	Safe environment	2	1.6	Yang et al. (2018)
	Reduces costs (laboratory equipment and supplies)	Virtual counterparts	2	1.6	Wojciechowski and Cellary (2013)
	Suitable for laboratory courses	Virtual / remote laboratory	1	0.8	Mejías Borrero and Andújar Márquez (2012)

investigated in the framework of this study may be effective in increasing students' affective and cognitive participation in classes (Chang & Hwang, 2018).

Advantages of AR use in STEM education are cited as "visualization" and "concretizing abstract concepts". AR allows visualization of concepts that cannot be visualized in class (e.g. Wojciechowski & Cellary, 2013), during field trips (e.g. Kamarainen et al., 2013) in museums (e.g. Yoon et al., 2017) and in laboratories (e.g. Chiu et al., 2015). It teaches abstract concepts -that are difficult to visualize- by concretizing them (e.g. Gun & Atasoy, 2017; Laine et al., 2016). Wu et al. (2013) stated that AR transforms invisible and abstract concepts into real and visible ones.

Other educational outcomes outlined in AR-STEM studies are: individualized teaching (e.g. Kamarainen et al., 2013), in-depth learning (e.g. Chiang et al., 2014), learning at desired time and space (e.g. Laine et al., 2016), student-cantered learning (e.g. Kamarainen et al., 2013) and informal learning (e.g. Yoon et al., 2017). These advantages give an idea about how AR can support learning outside the classroom.

4.2.3. Interaction

The advantages in regards to the interaction highlighted in AR-STEM studies were collected in 4 subcategories: real-time interaction (e.g. Chen et al., 2016), increased interaction between student and course content (e.g. Cheng, 2018), a sense of presence (e.g. Ibáñez et al., 2014), increased interaction among students (e.g. Kamarainen et al., 2013). AR enables the user to interact with virtual objects in the real time environment in which the user is located. The real time interaction with virtual objects positively affects students' sense of presence (Chang et al., 2018; Liou et al., 2017). Real-time interaction (Chen et al., 2016; Küçük et al., 2016) increases the interaction among students (Cheng, 2018; Kamarainen et al., 2013) and the interaction with the course content (Cheng, 2018). It is reported that AR facilitates *learning by doing* by increasing student interaction with the content. Additionally, Hsiao et al. (2012) also reported that AR ensured that students could engage in more physical activities compared to other learning activities via higher interactions with AR.

4.2.4. Other advantages

AR use in STEM education has advantages such as ease of use (e.g. Martin-Gonzalez et al., 2016), the opportunity of safe application of dangerous experiments (e.g. Yang et al., 2018), reduction of costs and suitability of use in laboratory courses (e.g. Wojciechowski & Cellary, 2013). AR reduces costs by exchanging virtual counterparts with expensive laboratory equipment and consumables (Wojciechowski & Cellary, 2013). It also allows safe application of potentially hazardous tests (Wojciechowski & Cellary, 2013; Yang et al., 2018). In this respect, AR can be used in STEM education as preparation for the experiments that the students need to do in real laboratory settings (Yang et al., 2018). The fact that AR is a technology that can be easily used by today's students (Di Serio et al., 2013; Liou et al., 2017; Martin-Gonzalez et al., 2016) is an important advantage for its use in STEM education.

4.3. What are the challenges identified in AR-STEM studies?

While the articles on the use of AR in STEM education highlighted numerous advantages of AR, some of the challenges associated with its use were also emphasized (Table 6). The most common challenge found in the articles was "Problems in detecting the marker". The device camera must continuously detect the marker in order to display the digital content in marker-based AR applications. Lack of appropriate amount of light in the class (more or less light than necessary) (e.g. Chang & Hwang, 2018; Hsiao et al., 2012) may cause that problem. Gun and Atasoy (2017) suggest careful monitoring of light in classroom settings. Similarly, internet connection (e.g. Küçük et al., 2016), GPS problems (e.g. Bressler & Bodzin, 2013) and lack of sufficient features in student devices (e.g. Küçük et al., 2016) were among the challenges encountered in AR-STEM studies. However, technological advances of mobile devices and cheaper prices for these devices may eliminate these problems in the coming years.

Table 6. Challenges of AR in STEM education.

Sub-categories	Sub-categories Codes	*f*	%	Sample research
Problems in detecting the marker	Lack of appropriate amount of light in the class	4	33.3	Gun and Atasoy (2017)
Time consuming content development phase	Preparation of realistic graphics or 3D models	2	16.7	Laine et al. (2016)
Teacher resistance towards AR use	Teacher resistance	2	16.7	Hsiao et al. (2012)
Technical problems	Internet connection problems	1	8.3	Küçük et al. (2016)
	GPS problems	1	8.3	Bressler and Bodzin (2013)
Lack of enough features in student devices	Student devices	1	8.3	Küçük et al. (2016)
Reduces imagination	Reduces imagination	1	8.3	Cheng (2018)

Teachers' resistance to the use of AR in STEM education is a problem that needs to be overcome. Hsiao et al. (2012) indicated that teachers displayed more resistance than students and that this resistance was related to the fact that teachers who wanted to increase student achievement were not willing to spend time on exploring new tools. Another challenge encountered in the use of AR in STEM education was "the time-consuming content development" phase (e.g. Chang et al., 2016; Laine et al., 2016). Preparation of realistic graphics and 3D models require an especially long time. To solve this problem, Chang et al. (2016) suggested developing a modular AR system and Laine et al. (2016) planned to found a library consisting reusable media assets, screen templates and 3D models. Cheng (2018) was stated that AR decreased the imagination of students. Apart from these challenges, it should be remembered that there are other challenges cited in literature regarding the use of AR in education.

5. Conclusions and future research

With its characteristic features, AR technology provides important opportunities for STEM education. This study aimed to identify the current situation, advantages and challenges related to AR usage in STEM education.

The first study question focused on the general characteristics of AR-STEM studies. It was determined that AR-STEM studies, first explored in 2012, have become very popular especially in recent years. Based on this conclusion, we can argue that AR use in STEM education will be an important research topic for researchers in the coming years. Other results obtained in this study can guide future AR-STEM studies. Accordingly, future studies that will be designed in the qualitative method, that will be conducted outside the school and that will use location-based AR applications may fill in the gaps in the scope of AR use in STEM education in the current literature. In this context, studies can be carried out to determine the effectiveness of AR in informal education. It was found that some sample groups (such as preschool, special education, vocational training) were not involved in STEM education studies. Future studies may include these sample groups to contribute to literature.

The second research question aimed to reveal the advantages of AR use in STEM education. Research results show that the use of AR in STEM education supports the learning and teaching process. However, it should be kept in mind that novelty of innovation can be a contributing factor as well. Researchers are advised to take measures to eliminate impact of innovation when planning AR-STEM studies (piloting prior to actual implementation, prolonging the implementation period). In addition, it is observed that there are not enough studies to test the effect of AR according to individual characteristics. Studies to compare the impact of AR use on groups with different individual characteristics (such as gender, age, achievement, motivation, spatial ability) can produce interesting results. A notable feature of AR is its support for learning outside the classroom. AR technology can be used to support out-of-class activities in blended learning methods such as flipped learning. This research focused on the current situation, advantages and disadvantages in AR-

STEM studies. Further research can be carried out on issues such as pedagogical approach, teaching strategies and teaching techniques used in AR-STEM studies.

Challenges encountered in AR-STEM studies were generally related to technical problems. In the coming years, advances in mobile technologies, may help overcome these technical problems such as problems in the detection of the marker, GPS problems and internet problems. However, there are other challenges such as teacher resistance to AR and the necessity of prolonged time periods to develop content. High quality professional development is crucial to provide the necessary knowledge and skills for effective use of AR in STEM education and to counter teacher resistance. Studies can be conducted on how to support teachers and provide professional development on using AR in STEM education. Educational AR materials and AR authoring tools that can be used by teacher without any charges can be developed. Both application developers and researchers can conduct additional research to overcome these challenges. It is suggested that other challenges in regards to AR mentioned in the literature should be taken into consideration in future studies.

6. Limitations of the study

The articles reviewed in this research are limited to the journals indexed in the SSCI database. Articles published in journals indexed in the SSCI database are important for the field. However, other databases such as ERIC, ProQuest, ScienceDirect, Springer can also be used. This research is limited to experimental studies presented in article format.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Mustafa Sırakaya is an assistant professor at the Vocational School of Technical Sciences at the Kırşehir Ahi Evran University. His research interests focus on augmented reality (PhD. thesis subject), technology in education, computational thinking, instructional design and vocational education and training (VET).

Didem Alsancak Sırakaya is an assistant professor at the Vocational School of Technical Sciences at the Kırşehir Ahi Evran University. Her research interests are in the flipped learning, augmented reality, gamification, distance education, instructional design and research methods.

ORCID

Mustafa Sırakaya http://orcid.org/0000-0002-7964-4399
Didem Alsancak Sırakaya http://orcid.org/0000-0002-1821-5275

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