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A systematic literature review of mixed reality environments in K-12 education

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Abstract
Various studies have widely utilized mixed reality (MR) in primary and secondary (K-12) education. Nevertheless, there has been relatively no explicit focus on a substantial amount of studies that are reviewed systematically in order to present and suggest the educational benefits of MR technology for the development of learning environments. The present systematic literature review describes the current state of knowledge and practices using MR in K-12 education and provides guidance for educators and scholars focusing on instructional design contexts by critically appraising and summarizing the existing research. It also outlines a wide range of results yielded by quantitative, qualitative and mixed-method studies to investigate potential benefits, difficulties, and effectiveness of MR environments across various learning subjects. Overall, 21 studies published from 2002 until 2018 in 18 international peer-reviewed journals were analysed, with 11 and 10 studies regarding primary and secondary education, respectively. This review informs educators and scholars about insights and evidence gained by prior findings on the current state-of-the-art research so that provide a contribution of scientific knowledge and innovation using MR environments in different learning subjects. Implications for practice and research are discussed in detail, as MR has the potential to influence students' engagement, participation, skill acquisition, and embodied learning experience for knowledge transfer within well-structured instructional design contexts.

Keywords Mixed reality · Interactive environments · Instructional design · Systematic review · K-12 education

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1 Introduction

Contemporary digital technologies associated with head-mounted display (HMD), cardboards, mobile devices (e.g., tablets, smartphones), in combination with embodied simulations generated by Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR) deliver highly interactive user experiences with various applications that transform the way that people work and educate (Du, Li and Varshney, 2019; Pellas et al. 2018). Such technologies have made substantial progress into everyday practice settings and have become more accessible to the broader public due to three factors that can enhance the user experience. These are interaction, immersion, and information intensity (Heim 1998). AR, VR, and MR technologies have the potential to "augment" the user experience (Benford et al. 1998; De Lima et al. 2014), giving users the opportunity to embody, modify, act out or physicalize a considerable number of subjects based on their personal needs and demands (Chen and Duh 2018).

However, there is a distinctive difference among VR, AR and MR technologies that need to be referred. Unlike VR that allows users to be fully immersed into a completely computer-assisted virtual environment (CAVE), or AR, which layers digital content on top of physical objects usually through computing devices (e.g. smartphones), MR is generated entirely by merging digital and real-world objects together in certain contexts. MR also encompasses a mixture of reality with elements and features generated by AR and VR technologies that takes place into the physical world (Chang et al. 2010; Xiao et al. 2018). In particular, AR and *"augmented virtuality"* between physical and virtual elements are included in the general term of MR (Milgram and Kishino 1994). In the former, digital objects are added to "augment" the natural world, while in the latter, physical objects are those which are added into a virtual world (Pellas et al. 2018).

MR promises to be today a genuinely innovative technology that becomes more prominent in everyday life. MR concerns the combination of real and digital settings, which produces a rich and flexible "canvas" for users' mental and conceptual representations, where physical and digital objects coexist and respond on users' actions in real-time (Milgram et al. 1995). The origins of MR as a term can be traced back in 1994 and was pioneered by Milgram and Kishino (1994). The same researchers supported the opinion that MR is provided *"...anywhere between the extrema of the virtuality continuum"* (p. 1322), where the virtual contexts extend from real to virtual environments using such a technology that can "augment" the user experience. Fig. 1 depicts an extension of MR term adapted by Milgram and Kishino's (1994) *"reality-virtuality continuum"*.

MR as real-time multimedia and interactive technology can be utilized for the development of "augmented" environments inside real-world settings, in which users can add/embed virtual information within it (Tamura et al. 2001). The very nature of MR allows the development of an intuitive mapping between a visualized and an abstract or a fictional environment (Pan et al. 2006). By linking the physical with the digital "world" when browsing or consuming information, MR technology offers a more realistic and intuitive way of providing contextual and location-specific information to users (Benford et al. 1998). In MR environments, the data are being processed usually by several different input devices, such as smart glasses, tablets, sensors or personal computers (PC), which are combined with output devices, such as projectors,

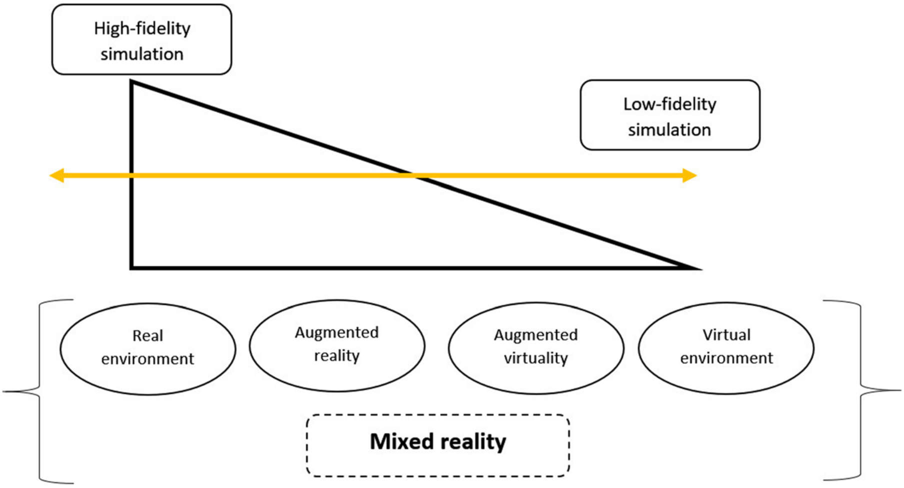

Fig. 1 An illustration of the MR reality extension

interactive walls or PC monitors to display the processing results. All input and output devices have to be integrated inside a physical environment enhancing the user's sense of "presence" (Ponto et al. 2006).

To date, several studies have already utilized MR environments in K-12 education. Some of the most popular in primary education have utilized MR to support different learning subjects in science, divided into three branches/ scientific fields (Boutellier et al. 2011; Gauch 2003) that consists of formal (Rowe 2014; Sugimoto et al., 2011), natural/physical (Enyedy et al. 2015; Kitalong et al. 2009; Palaigeorgiou et al. 2018; Yoon et al. 2012; Rogers 2002), and social science (Bayon et al. 2003; Han et al. 2015; Kalpakis et al. 2018; Zhou et al. 2008). Likewise, in secondary education, MR has been widely exploited in formal (Chang et al. 2010; Leonard and Fitzgerald 2018; Lindgren et al. 2016; Mateu and Alaman 2013; Mateu et al. 2014), natural/ physical (Birchfield and Megowan-Romanowicz 2009; Chao et al., 2016; Johnson-Glenberg et al. 2014; Tolentino et al. 2009), and social scientific fields (De Lima et al. 2014). Within such contexts, the "augmentation" of learning content into real-world contexts can essentially assist students to create conceptual anchors by which new knowledge can be built (Johnson-Glenberg et al. 2014; Lindgren et al. 2016) through engaging and immersive experiences (Palaigeorgiou et al. 2018; Tolentino et al. 2009). In other words, the use of MR technology can assist users not only to entail a visually-rich environment with virtual objects inside real-world contexts but also allows them to interact with those objects and their physical counterparts in well-defined instructional settings. Therefore, MR environments for educational purposes are learning spaces that enable the development and utilization of representationally-rich and highly-interactive "tools" by merging different computing devices for various activities. Students and instructors are embodied within a shared-space "hybrid" reality within specific spatially-located virtual and physical contexts in order to achieve certain learning goals.

There is a broad agreement that MR is quickly gaining momentum in primary and secondary education with various potentials in teaching and learning. The diffusive use of MR technology in the last few years seemed to benefit students' problem-solving skills and motivation (Chang et al. 2010; Mateu and Alaman 2013), participation and learning satisfaction (Chao et al., 2016; Leonard and Fitzgerald 2018), as well as learning performance through tangible (Mateu et al. 2014; Zhou et al. 2008), embodied (Kalpakis et al. 2018; Palaigeorgiou et al. 2018; Sugimoto 2011) or sensory-based learning activities (Chao et al., 2016; Enyedy et al. 2015; Han et al. 2015). MR provides remarkable opportunities for students' participation through collaborative problem-solving learning tasks using real-world objects (e.g., maps, books, or robots); thus, it adds a layer of utilizing several interactive applications inside classrooms (e.g. Johnson-Glenberg et al. 2014; Rogers et al. 2002) or outside in museums or field trips (e.g. Kitalong et al. 2009; Yoon et al. 2012). MR environments are perceived to provide more fun and engaging activities compared to "conventional" teaching approaches and seem to influence students' intentions positively so that participate in many learning subjects (Bayon et al. 2003; Rowe 2014; Tolentino et al. 2009).

To the best of our knowledge, there are no previous works to outline and present instructional contexts in order to convey information about the educational uses of MR technology in different K-12 learning subjects. According to the analysis from previous studies' results that literature studies have clearly missed (Chen and Duh 2018; Stretton et al. 2018), this review seeks to provide instructional design considerations, best practices and trends that educators or scholars can be informed so as to develop a learning environment within specific educational contexts using MR technology in the future. Overall, the present study systematically reviews and synthesizes previous studies and their instructional settings related to the use of MR technology in terms of providing a comprehensive analysis based on the reviewed articles. The overarching research question for this review is "*Can the educational uses of MR technology support different learning subjects in K-12 education?*" and divided into the following three sub-questions:

• *RQ1: What MR environments have been utilized in favour of improving students' learning outcomes/achievements and under what instructional conditions has this experience taken place?*

• *RQ2: What is the main technological equipment (input and output computing devices) comprised in each of the proposed MR environments?*

• *RQ3: What are the potential benefits or difficulties according to the methodological approaches applied by assessing the use of proposed MR environments in teaching and learning?*

The purpose of this systematic literature review is to investigate the potential use of MR environments in different K-12 (primary and secondary) learning subjects by summarising selected studies available in the relevant literature published from 2002 to 2018. Thence, reaching the following three goals will create a pathway to address the purpose of this review:

a) to outline the educational uses of MR environments, including the scientific fields, in which they were applied, the main technological equipment and computing devices exploited, the learning subjects involved, the research designs and methodologies conditions under which these studies were conducted;

b) to present the effects of using MR technology on students' learning achievements and outcomes, and lastly;
c) to synthesise the potential benefits and difficulties regarding the development of MR environments within different formal (inside the classroom) or informal (outside the classroom) instructional settings.

2 Method

This study aims to review the collected studies systematically. A systematic literature review provides several potential benefits both to support further research efforts as it is usually conducted to present an unbiased synthesis and interpretation from findings that previous works have presented in a balanced manner (Kitchenham et al. 2010). To achieve such an attempt, relevant evidence that fits the pre-specified eligibility criteria can give answers to specific research questions and need to be collated the following specific steps (Moher et al. 2009). For the purposes of this study, the review process was divided into three steps reported by Kitchenham (2007): a) planning, b) conducting the review, and c) reporting the review. The former stage was guided by the principles of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Moher et al. 2009). The PRISMA methodology was utilised in order to describe adequately all eligibility criteria for study collection, information sources, remove duplicates, screen records, data collection process, and finally synthesize the results. In essence, the current review aims to provide any foundation for knowledge accumulation that can assist any potential theories' expansions and improvements, identifies and closes research "gaps", unveiling further areas where previous research that has not thoroughly been addressed yet. Section 2.1 (planning), 2.2 (conducting the review) and section 3 (reporting the review), describes all necessary steps which are documented below.

2.1 Planning

2.1.1 The need for a systematic review

So far, previous literature reviews (Chen and Duh 2018; Stretton et al. 2018) have advocated that MR environments have gained ground within various educational contexts and most of the technology maturity problems seem to be addressed. Stretton et al. (2018) have included studies addressing the use of mobile MR technology in healthcare tertiary (higher) education and more specifically on user mobile MR to teach procedural skills, anatomy, and clinical assessment. According to the same review, tertiary students demonstrated better performance and skills towards the future use of mobile MR environments. In addition, Chen and Duh (2019) have conducted a review by applying text mining method to 4296 MR research articles published in the last two decades. After classifying the studies, six clusters of trends were revealed, one of which was education. This cluster included studies which either monitored students' performance or their experience issues (e.g., usability). The same authors have broadly provided a wide range of recommendations, including the need to be further clarified the theoretical aspects and characteristics for the development and creation of MR environments, in align with their underlying pedagogical approaches. Both previous reviews have suggested that MR seems to promote better students' learning achievements and outcomes.

However, as literature on the field grows, we are clearly missing studies analysing and presenting the potential benefits of MR technology in specific age groups in primary and secondary education. Students of different ages have distinct technological expectations, learning demands, personal interaction skills and attitudes which also change a lot throughout their development. There are no studies providing a systematic synthesis of relevant studies focused on the use of MR technology so that delve into a critical look at the pedagogical approaches, the scientific fields, the research methods, the different environments' setup descriptions, and the participants' experience or achievements in different K-12 learning subjects. Additionally, it is also important in this context to review studies that are presented in international scientific journals in order to avoid superficial conclusions based more on in-progress or weak scientific works.

The current review seeks to address the aforementioned "gap" and provides evidence that builds upon previous works conducted on the field of using MR environments in K-12 education. Understanding this "gap" requires a deeper knowledge of how the school contexts are governed, so that uncover the dynamics that create and sustain MR environments for K-12 learning subjects. This review serves as a useful and timely addition to what is already known by previous studies that have utilized the MR technology in K-12 education. The results can inform educators and scholars with effective advice, and suggestions on how to incorporate an MR environment and under what instructional conditions the combination of several computing devices can be utilized properly for different learning subjects. In this investigation, we also present possible combinations of computing devices and technological equipment which were utilized to create MR environments having an impact on students' engagement, knowledge gain, skill acquisition, and participation in different learning subjects.

2.1.2 Inclusion and exclusion criteria

Considering the three research questions of this review, the general inclusion ad exclusion criteria for the studies of this review were agreed to be the following:

General Criteria:

a. Studies that published between 2002 and the fourth quarter of 2018.
b. Studies that presented and utilized system setup description of MR environments across various K-12 learning subjects.
c. Studies that provided results of educational potential that was particularly based on research design (or on robust) method using MR environments (prototypes).
d. Studies that have an abstract and full-paper written in English.

Specific Criteria:

a. Studies that reported the potential benefits, difficulties and/or effectiveness of MR environments across various learning subjects within specific instructional design contexts.

b. Studies that adequately described the design of MR environments and outlined the combination of computing devices used.
c. Studies that presented assessment methods about the learning experience and effectiveness in learning approaches using MR in various educational scenarios for K-12 school-context learning subjects through formal or informal instructional settings.

Exclusion Criteria:

a. Studies that are not identified as *"articles"* and not included in any of the selected journals (e.g., books, chapters, colloquiums, etc.).
b. Studies that either mentioned the term *"mixed reality"* to support learning or mentioned the term *"mixed reality learning"*; however, there was not any match with MR.
c. Studies that did not provide sufficient data for effect size calculation or did not have clear summarisation or aggregative findings from their qualitative and/or quantitative data.
d. Articles that have not presented any evidence retrieved by any well-structured research method and evaluation process (e.g., case studies, empirical, etc.).

2.2 Conducting the review

2.2.1 Search strategy

For a full-fledged review, all the selected databases that were searched for this study's objectives were as relevant if they were referred to educational technology, computers science and social science. These searched databases were from ERIC, ESCBO, SCOPUS, IEEEXplore, ScienceDirect, JSTOR, Web of Science, and Wiley. All searches were made separately to each database. Branching searches were performed using forward and backward search procedures from the reference lists of previous literature reviews (Chen and Duh 2018; Stretton et al. 2018), which were consulted at earlier stages of this review. Appendix Table 9 presents the main protocol that was followed for each database search.

The search process was a manual search for peer-reviewed international journal articles during the last fifteen years. The search terms (keywords) that were used for the purposes of this review included terms related to MR in conjunction with several terms that could describe possible outcomes, impacts or effects of utilizing this technology in K-12 education. Several search terms helped the authors to determine the scope of the definition of digital games since many of the terms include the word *"mixed reality"* such as *"mixed reality environment", "mixed reality instruction" and "mixed reality learning"*. Additionally, more specific terms were also included such *as "Augmented Reality learning", "Augmented Reality"* and *"Augmented Reality environment"*, since many titles in their system overview largely describe the integration of AR technology inside MR environments (e.g. De Lima et al. 2014; Han et al. 2015). This suggestion comes in align with Milgram et al. (1995) who defined the concept of AR within the context of the *"reality-virtuality continuum"* that is projected by displaying the learning content on interactive walls or large screens within specific instructional contexts. The same authors have also pointed out the importance arising from the degree of immersion and the tendency towards *"augmented virtuality"* to support MR technology. This suggestion comes in align with the term of *"MR environment"* for teaching and learning purposes as determined above (see *Introduction*).

For the purposes of this review the most relevant journals which are methodologically and scientifically relevant were finally chosen. The Google Scholar h5-index for the large category of *"Engineering and Computer Science"* and its separated categories related to *"Computer Science"* and *"Educational Technology"* were a starting point. This decision was deemed as necessary since the two sub-categories are more relevant to the *"Education and Educational Research"* and "*Human-Computer Interaction"* from the *Journal Citation Report Social Science Citation Index* (JCR SSCI) and the *Journal Citation Report Science Citation Index* (JCR SCI), respectively. On the one side, most of the journals relating to educational technology are indexed together into the JCR SSCI list with journals about educational research in general, offering a too broad foundation from which to start the literature search. On the other, many journals indexed in the JCR SCI list have published articles, which were completely focused on educational purposes. A specific list produced from the international peer-reviewed journals according to the Google Scholar h5-index was initially validated through an iterative double-check process from all authors in order to review studies that could be potentially relevant and consistent with this literature review's quality. This feature is defined in the JCR by considering the citation relationship of the journals and is based on the number of citations from one journal to the other and the total number of articles.

Standards were summarized by following Kitchenham's guidelines (2004), since such a search process is one of the most useful procedures in practice. All the selected journals in which previous studies referred in primary and secondary education, providing empirical or case studies, are shown in Tables 1 and 2. The coordination of the data extraction and checking tasks were performed by the first author; however, all authors together discussed differences and issues in case of disagreement until the final decision would be reached. In particular, the first author of this study conducted all of the content analysis results and finally, the data was validated by the other two authors who are experienced researchers in topics relating to *"Education and Educational Research"* and *"Human-Computer Interaction"*. Moreover, the other two authors conducted the screening tasks and discussed with the first author the overall decisions based on the prescribed selection rules. All authors had access the full-text of the articles included, in order to decide the appropriateness of each one to this review's objectives and criteria, which described above. Finally, all of them decided which study need to be kept with the first one always following the overall consensus according to the described selection rules.

2.2.2 Study quality assessment

To ensure the quality of all the included studies from a methodological-design perspective, special focus was given to articles which have presented their results based on

Table 1 Number of MR studies for primary education published in international journals

	JCR-SSCI Journal (Publishers)	Analysed studies	Research studies
1.	Computer-Supported Collaborative Learning (Springer)	2	Enyedy et al. 2015; Yoon et al. 2012
2.	IEEE Transactions on Learning Technologies (IEEE)	1	Sugimoto 2011
3.	Educational Technology Research and Development (Springer)	1	Han et al. 2015
4.	Virtual Reality (Springer)	1	Bayon et al. 2003
5.	Presence (MIT Press)	1	Rogers, 2002
6.	International Journal of Emerging Technologies in Learning	1	Kalpakis et al. 2018
7.	Technical Communication Quarterly (Taylor & Francis)	1	Kitalong et al. 2009
8.	InteractiveTechnology and Smart Education (Emerald)	1	Palaigeorgiou et al. 2018
9.	Digital Creativity (Taylor & Francis)	1	Rowe 2014
10.	Journal of Virtual Reality (Online)	1	Zhou et al. 2008

qualitative and/or quantitative data analysis, as such studies are considered to be the most accurate forms of experimental research to prove or disprove a hypothesis (Punch 1998). For an experiment to be classified as a valid experimental design, the following criteria must be fulfilled (Russell and Gregory 2003):

a. Studies provided and substantiated research question(s).
b. Studies presented their results by a sample of students and should also be relevant to the research question(s) and/or the instructional design method(s) that were followed.

Table 2 Number of MR studies for secondary education published in international journals

	JCR-SSCI Journal (Publishers)	Analysed studies	Research studies
1.	Journal of Science Education and Technology (Springer)	2	Chao et al., 2015; Tolentino et al. 2009
2.	Computers and Education (Elsevier)	2	Chang et al. 2010; Lindgren et al. 2016
3.	Journal of Universal Computer Science (Online)	1	Mateu and Alaman 2013
4.	International Journal of Computer-Supported Collaborative Learning (Springer)	1	Birchfield and Megowan-Romanowicz, 2009
5.	Research in Learning Technology (ALT publications)	1	Leonard and Fitzgerald 2018
6.	Entertainment Computing (Elsevier)	1	De Lima et al. 2014
7.	Journal of Educational Psychology (APA)	1	Johnson-Glenberg et al. 2014
8.	International Journal of Human-Computer Interaction (Taylor & Francis)	1	Mateu et al. 2014

c. Studies with data (qualitatively and/or quantitative) that were analysed adequately.
d. Studies provided an analysis of their findings using either quantitative and/or qualitative data.
e. Studies analysed and rationalized clearly why were conducted and presented some implications for practice and research.

All the selected reviewed articles for qualitative analysis that were finally chosen and had purposeful sampling (case studies or empirical studies), based on a conscious selection of a small number of data sources. Additionally, to strengthen further a total weight of evidence, each study was calculated by adding the scores on each of the abovementioned criteria. To assess the inter-rater reliability with respect to the quality coding of the selected articles, a sub-sample of 9 of a total 21 articles (43%) from the articles related to K-12 education which included and coded independently by the two authors of this review. The inter-rater reliability (r) for the total scores was 0.87, showing a good agreement between the authors regarding the quality of the final chosen articles which finally included.

2.2.3 Data collection

The present literature review considered the JCR SCI list and the same process with the iterative double-check for the JCR SSCI list was repeated. From the fifteen ($n = 18$) indexed peer-reviewed international journals overall, fifteen ($n = 15$, 83%) have an impact factor up to 1.05, according to 2017 data metrics as reported by Thomson Reuters Journal Citation Reports (2018). The fact that important journals within their field published articles about the educational uses of MR technology indicates that it is an emerging approach to learning, and thus, it is of great interest to those researchers and educators who aspire to enrich their students' learning experience. A total of twenty-one ($n = 21$) articles meeting the inclusion criteria that decided above and were coded after considering previous studies (Chen and Duh 2018; Stretton et al. 2018), which categorised MR and the impact of this technology in relation to several learning subjects. In terms of studying the educational potential of MR environments from the reviewed studies the following categories should be identified:

a. the instructional design settings, and research methodologies that measured the successful implementation of learning objectives for a specific subject.
b. the purposes of previous studies in align with their scientific construction and understanding of knowledge related to different learning subjects.
c. the impact and/or effectiveness that any MR environment had on student engagement and participation.
d. the learning gain measurement in different educational subjects within formal or informal instructional school-contexts on their learning outcomes and achievements.
e. the components/computing devices that students had to utilize in order to participate in several learning tasks, e.g., mobile devices, robots, Microsoft HoloLens, etc.

2.2.4 Data analysis

The analysis of data is tabulated as follows:

a) Table 1 presents 10 journals indexed in the JCR-SSCI and JCR-SCI lists that contained a total of 13 articles selected for this study, discussing the use of MR technology in primary education.
b) Table 2 presents 8 journals indexed in the JCR-SSCI and JCR-SCI lists which contained a total of 10 articles discussing MR technology the use of in secondary education.

Since the number of articles seemed to appear limited, an analysis of the publication year of each article shows that the number of published studies relating to MR in primary and secondary education has progressively increased year-by-year, particularly during the last five years. These results make clear that MR technology in secondary education is emerging in a variety of learning subjects; however there still more to be done for its boarder acceptance (Chen and Duh 2018; Stretton et al. 2018) for its general acceptance and appropriateness for different K-12 learning subjects.

The main criteria for each study are provided below as a coding scheme. These are the following:

a. the instructional design method that was implemented in relation to any proposed MR environment usage.
b. the components and features or elements that were used in support of every MR environment.
c. the formal and/or informal instructional settings which were followed.
d. the instructional design conditions which were utilised in order to improve students' learning experience and participation concerning different learning subjects.

Figure 2 presents a flowchart that was followed regarding the article selection process using the PRISMA diagram adapted by Moher et al. (2009).

The content analysis tool to collect and aggregate the data was the *Nvivo* (ver. 10) software for content processing and analyzing the data and assess the reliability of the results from every reviewed article.

2.3 Reporting the review

2.3.1 Overview

The last step of this systematic review includes two interrelated aspects (Kitchenham 2007): a) to circulate the results to potentially interested parties and b) to write up the results of the review. Therefore, the first subsection (*3.1. Overview*), gives an overview of how this review seeks to answer the research questions and the second one (*3.2. Results*), disseminates the results from the reviewed studies. In specific, the current subsection outlines how the main research questions are aligned with the results from the reviewed studies, specifying the dissemination strategy in order to communicate the results of this review. This review was not possible to have an accurate meta-analysis as

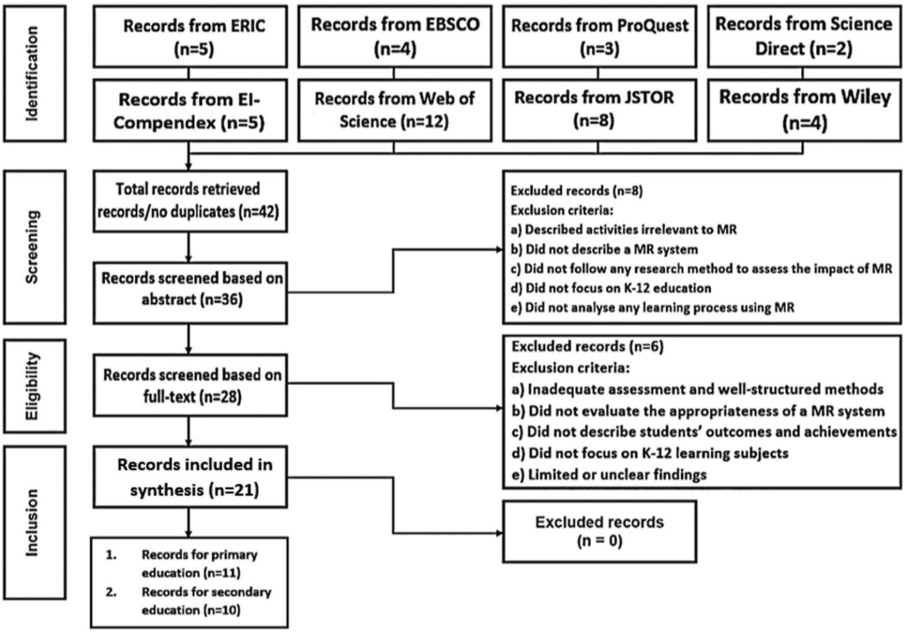

Fig. 2 Flowchart for article selection process

the research methods used for instructional design methods and the research design with data collection differed significantly. Overall, the results were synthesised by extracting the main themes under which the findings of this review are identified and presented. The data coding process was performed according to the categories described above (see *subsection 2.2.4*).

A list of categories for the analysis is informed by this review's questions. These are the following:

• Respecting *RQ1*, this review considers the type of learning approaches and students' outcomes/achievements of each study by developing and utilizing a variety of MR environments.

• Regarding *RQ2*, this review considers the technical equipment including the type of computing devices used (e.g., web cameras, large screens, laptops, etc.), and where each study took place (e.g., in-class, field trips, museums, etc.).

• Concerning *RQ3*, this review takes under serious consideration each study's purposes, research methods which were followed, alongside with learning subjects, advantages or difficulties on students' performance, and any possible negative perceptions using the MR technology.

2.3.2 Results

The results in this review are presented and disseminated to give answers in regard to the three research questions (*RQ1-RQ3*). With respect to *RQ1*, an important aspect of this review is to separate that each MR environment uses considering the following learning subjects:

a) formal science (e.g., mathematics, theoretical branches of computer science, robotics, information theory),
b) natural/physical science (e.g., including physics, chemistry, astronomy, earth scientific learning subjects, such as geology, geography, and biological sciences related to the scientific study of life, plants and organisms), and
c) social science (e.g., anthropology, archaeology, communication studies, economics, history).

An interesting note that emerged from the data in Table 3 below is that four studies (36.4%) were applied to social science subjects, particularly in storytelling (Zhou et al. 2008; Bayon et al. 2003), dramatic play (Han et al. 2015), and history (Kalpakis et al. 2018). Five studies were related to the natural/physical science with 45.5% (Enyedy et al. 2015; Kitalong et al. 2009; Palaigeorgiou et al. 2018; Rogers et al. 2002; Yoon et al. 2012) and two (18.2%) covered formal science subjects (Rowe 2014; Sugimoto 2011).

Likewise, half of the reviewed studies (50%) in secondary education presented results in regard to formal science learning subjects (Chang et al. 2010; Leonard and Fitzgerald, 2018; Lindgren et al. 2016; Mateu and Alaman 2013; Mateu et al. 2014), four (40%) covered natural/physical science subjects (Birchfield and Megowan-Romanowicz, 2009; Chao et al., 2016; Johnson-Glenberg et al. 2014; Tolentino et al. 2009). Lastly, one study (10%) addressed a learning subject related to social science (De Lima et al. 2014).

A synopsis of instructional and learning approaches using MR environments, as well as the results and most important observations for each reviewed study, with chronological order, appear in Tables 4 and 5 for primary and secondary education, respectively. An important observation that supports the opinion regarding the MR technology usage for collaborative instructive guided settings is that nine (82%) studies in primary (Bayon et al. 2003; Kalpakis et al. 2018; Enyedy et al. 2015; Han et al. 2015; Palaigeorgiou et al. 2018; Rogers et al. 2002; Sugimoto 2011; Yoon et al. 2012; Zhou et al. 2008), and seven (70%) studies in secondary education (Birchfield and Megowan-Romanowicz, 2009; Chang et al. 2010; Mateu and Alaman 2013; Mateu et al. 2014; Leonard and Fitzgerald, 2018; Johnson-Glenberg et al. 2014; Tolentino et al. 2009) have applied collaborative problem-solving learning tasks.

As shown above, in Table 4, many studies used tangible and embodied user interfaces in order to create immersive learning experiences. In particular, Kalpakis

Table 3 MR environment uses according to the scientific field

Primary education	Number of studies	Percentage (%)
Formal Science	2	18.2
Natural/Physical Science	5	45.5
Social Science	4	36.4
Secondary education	Number of studies	Percentage (%)
Formal Science	5	50.0
Natural/Physical Science	4	40.0
Social Science	1	10.0

Table 4 An overview of studies in primary education which utilized MR environments

Research studies	Instructional environment ➢ Learning approaches	Study results and observations	Number of participants [n] and the duration of instruction [t]
Rogers et al. (2002)	MR environment enables students to experiment and interact with different media and representations while they engaged from simple to more complex activities. Students have tried to mix colours through four conditions of physical and digital transformations (physical action - physical effect, physical action - digital effect, digital action - digital effect and digital action - physical effect). ➢ An exploratory collaborative problem-solving approach in technology.	Students were most interested in manipulated physical artifacts (coloured blocks) to create digital artefacts	$n = 20$ t = 4 h
Bayon et al. (2003)	*KidPad* is a desktop collaborative drawing application with Multiple Input Devices metaphors were used to allow students to form "non-linear"" narrative structures via zooming/navigation, so as to create, construct, tell and re-tell stories. ➢ Computer-supported collaborative learning through storytelling.	a) Students benefit by using KidPad since they seemed to elaborate and recall by means of the production of a more complex story structure b) Increase students' motivation and interest c) The final set-up allowed students to produce story content dynamically, to create basic narrative structures and to retell their stories in a collaborative and adaptable physical space	$n = 42$ t = 3 h
Zhou et al. (2008)	*wIzQubes*™ is a pair of cubes with markers on their sides that trigger augmentations for interactive storytelling ➢ Problem-solving learning tasks using interactive storytelling construction.	a) Kids prefer an interactive storytelling system than a traditional storybook. b) wIzQubes™ interface "was loved" by the kids	n = 20; t = 10 min for 4 weeks
Kitalong et al. (2009)	*Journey with Sea Creatures (JwSC)* is a MR multimodal informal learning environment of a science museum. It consists of a podium surrounded by styrofoam painted to resemble a cave. A curvilinear projection screen, mounted to the underside of the podium, served as a window into a microworld. Interaction with the user, Narrative mapping with the aid of two virtual personas ".	a) Increased students' interest in the Cretaceous period b) Students had fun and enjoyed interacting with the JwSC kiosk. c) Students felt engaged with the learning experience	$n = 56$ t = 3 h

Table 4 (continued)

Research studies	Instructional environment ➢ Learning approaches	Study results and observations	Number of participants [n] and the duration of instruction [t]
	➢ Problem-solving learning tasks in natural science through narrative mapping		
Sugimoto (2011)	*GENTORO* is a system for student support in story creation and expression. It is comprised by a robot and a handheld projector. Students can collaborate and make robots interact according to their story in a physical space augmented by the handheld projectors ➢ Collaborative problem-solving storytelling in robotics education.	a) Engage students in storytelling activities b) Support student in creating and expressing their own original stories	*n* = 25 t = 3 h
Yoon et al., (2012)	Learning science using the device "Be the Path" that utilized electrical circuits and augmented reality ➢ Collaborative problem-solving tasks in a science museum	a) Better learning performance b) Instructors help is required when students face more complex problems	*n* = 119 t = 30 min for 3 weeks
Rowe (2014)	*Mixed Reality Bugs* project utilizes projection mapping and camera-based interaction to project digital bugs and insects, into physical environments, of which they are 'aware' from camera-derived feedback in real-time. ➢ Problem-solving learning tasks in natural science for organisms (Glowing pathfinder bugs) through projection mapping interactive tasks	a) High levels of participants' immersion and engagement b) Immediate and spontaneous interaction, attempting to fulfill a desire to touch and communicate with the creatures	n = 2 t = 3 h
Enyedy et al. (2015)	*Learning Physics through Play (LPP)* system is composed of a) an AR system that records and displays the students' actions, b) a software that generates a visual display based on the recorded data and c) an augmented carpet. ➢ Collaborative problem-solving in physics.	a) Help students revise their misconceptions b) Increased cognitive gain c) Help students to explore foundational physics concepts	*n* = 43 t = 43 weeks
Han et al. (2015)	Students wear a QR code hat and choose on a set of QR images while a iROBIQ robotwith build-in camera and monitor provides them with augmented experiences in order to support them in story telling	a) Increased interest in dramatic play, interactive engagement, and media recognition b) Younger-aged children liked more the experience than their older fellows	*n* = 81 t = 1 h

Table 4 (continued)

Research studies	Instructional environment ➢ Learning approaches	Study results and observations	Number of participants [n] and the duration of instruction [t]
	➢ Collaborative learning in robotics education.		
Kalpakis et al. (2018)	A MR environment based on Makey Makey, Scratch and projections to present historical information and allow students to interact through embodiment in order to help them improve historical thinking. ➢ Collaborative embodied problem-solving exploration in history education	a) Increased students' satisfaction and enjoyment b) Increased student's engagement c) Better historical understanding	$n = 66$ t = 20 min for 6 sessions
Palaigeorgiou et al. (2018)	FingerTrips is an interactive augmented three-dimensional tangible map on which students interact with their fingers. ➢ Collaborative embodied problem-solving exploration in geography	a) Students enjoyed learning b) Learning was effective c) Students learn faster with the aid of FingerTrips	$n = 58$ t = 25 min in 24 sessions

et al. (2018) and Palaigeorgiou et al. (2018) have utilized tangible interfaces, using the *Makey Makey* board, augmented by an overhead projector based on students' actions. Zhou et al. (2008) have also utilized tangible interfaces to exploit a pair of cubes, tracked by computer vision in order to control the storytelling process. The first cube was used to navigate through different scenes of the story, with the numbers printed on fiducial markers pasted on the six sides. The second cube was used to choose different items needed in the story, with the cartoon symbols on the six sides. Other studies (Bayon et al. 2003; Rogers et al. 2002; Yoon et al. 2012) have also provided different MR interactive environments that included tangible interfaces to allow students explore and interact collaboratively with their peers. In many studies, students were being part of the MR environment using sensing motion devices. For example, Enyedy et al. (2015) have tried to teach physics through an MR environment tracked by students' motions and locations so as to generate a visual display that simulates forces and friction of a virtual ball. Additionally, Han et al. (2015) have used cubic hats that the students were wearing to support AR-infused tracking and mapping with multiple angles of characters embodied as robots in order to increase the degree of reality of dramatic play through physical sensory and multimodal immersion.

Many studies in secondary education have utilized embodied simulation to enhance student experience using multimodal interaction with several augmented objects of the MR environments in learning subjects related to formal science. As described in Table 5, Chang et al. (2010) have presented *Robostage,* a MR environment for authentic learning tasks that extends a vertical screen using many multimedia features to improve the realistic nature of the simulation. In particular, the operation of the learning system was changed from keyboard and mouse on a flat-screen combined with

Table 5 An overview of studies in secondary education which utilized MR environments

Research studies	Instructional environment ➢ Learning approaches and learning subject	Study results and observations	Number of participants [n] and the duration of instruction [t]
Tolentino et al. (2009)	Situated Multimedia Arts Learning Laboratory (*SMALLab*) presents a recent teaching experiment for high school chemistry students. ➢ Socio-collaborative learning (distributed cognition) for chemistry	a) Learning while exercising was equally effective with *SMALLab*, hands-on activities, role-play had a significant impact on students' performance b) Computer-assisted instruction and instructors feedback increased the quality of students' achievements, as it seemed to keep all students' interest and motivation at a higher level with less anxiety c) Students improved their thinking and reasoning skills, collaborative learning, and shared conceptual knowledge of chemical equilibrium and titration reactions.	*n* = 136 t = 8 h
Mateu and Alaman (2013)	The *Cubica* system uses tangible interfaces to combine the real world with a virtual world of OpenSimulator to improve students' interest and motivation and their active participation in programming. ➢ Collaborative problem-solving in programming and theoretical computer science concepts.	a) Students achieved a better understanding of sorting algorithms by using virtual worlds and the tangible interface b) While students said they would like to participate again in a similar session; some teachers have found it to be insufficient: many activities were developed in a fairly short period of time c) The focus was on teaching computer science, in particular, "sorting algorithms" in order to simplify the abstract concept of an array, and the inside OpenSim to deliver students' explanations	n = 42 t = 3 h
Johnson-Glenberg et al. (2014)	*Embodied Mixed Reality Learning Environment (EMRELE)*. It uses motion-capture and a highly collaborative pedagogy for science learning. It is based on SMALLab's infrastructure that engages the major modalities (i.e., sensing systems including visual, auditory, and kinesthetic) that students use to learn. ➢ Collaborative embodied learning in physical science	a) Support for face-to-face and collaborative tasks among students using digital objects. b) Embodied learning conditions seemed to be effective for instructive guided collaborative learning tasks inside the classroom c) The sense of immersion within embodied learning tasks led to sensorimotor activation, and congruency with the learning material	*n* = 69 t = 6 days

Table 5 (continued)

Research studies	Instructional environment ➢ Learning approaches and learning subject	Study results and observations	Number of participants [n] and the duration of instruction [t]
Birchfield and Megowan-Romanowicz (2009)	*SMALLab* was utilized to afford face-to-face interaction among students. ➢ Computer-supported collaborative learning in earth science subjects.	a) Collaborative learning tasks are provided. b) Potential benefits to be used by schools and families to raise daily physical activity c) Significant learning gains and positive impact on collaborative learning instructional settings	*n* = 72 t = 3 h
Chang et al. (2010)	RoboStage. provides many multimedia features to improve the realistic nature of the simulation by extending authentic learning tasks inside a vertical screen. ➢ Collaborative problem- solving learning for physics to understand human-robot interaction in robotics education.	a) Supplemental learning material for technology courses were provided. b) Effective for low-achieving students to control the robot and a virtual character are used in the authentic learning activity c) Students' learning performance was improved in the authentic learning environment with a robot more than with a typical book	*n* = 36 t = 7 h
De Lima et al. (2014)	MR prototype based on the *"Swords and Dragons"* genre allows a sketch-based interaction that has been used in engineering, education, and 3D modelling for recognition of hand-drawn sketches. ➢ Problem-solving learning in learning in writing dramas using interactive storytelling.	a) Positive effect on students' motivation and engagement during an interface with a sketch-based interaction interface can offer an attractive environment for developing interactive narratives b) Students showed that the use of hand drawings as a form of interaction can improve user satisfaction and experience	n = 21 t = 5 h
Chao et al. (2016)	*Gas Frame* is a sensor-augmented Virtual Labs, in which students utilize physical interactions with science simulations to promote and understand gas laws. ➢ Problem-solving learning with physical controls in chemistry subjects.	a) Students had enhanced flow experience inside discovery-based learning tasks, and they achieved higher performance b) Mobile physical controls assisted students to understand better gas laws and to develop an understanding of almost all aspects of science concepts	*n* = 30 t = 3.5 h
Mateu et al. (2014)	*VirtualTouch* is a new tool that combines virtual worlds and tangible interfaces using OpenSim and Kinect technologies, providing a MR experience in computing education. ➢ Hands-on collaborative problem-solving in	a) Students significantly increased their conceptual understanding of electrostatics b) *VirtualTouch* was considerably less costly to deploy due to the use of OpenSim that is free of charge	n = 42 t = 3 h

Table 5 (continued)

Research studies	Instructional environment ➢ Learning approaches and learning subject	Study results and observations	Number of participants [n] and the duration of instruction [t]
	programming and theoretical computer science concepts.	c) Learning effectiveness performed significantly together with a "trial and error" method	
Lindgren et al. (2016)	*MEteor* offers an interactive simulation of planetary astronomy that is projected on a large floor surface. The simulation presents an accurate representation of gravitational forces that affect astronomical objects such as asteroids. The embodied learning tasks were about gravity and planetary motion in an immersive, whole-body interactive simulation. The same authors compared students' learning and attitudes about science with another number of counterparts who used a desktop version of the same simulation. ➢ Problem-solving learning in earth science subjects.	a) Students presented sufficiently concepts and experiencing with their critical ideas in physics. They used whole-body activities in order to achieve significant learning gains, engagement, and more positive attitudes towards science b) Full-body interactions and embodied metaphors with MR can maximize the educational impact on astronomy courses	$n = 113$ t = several days
Leonard and Fitzgerald (2018)	*Microsoft HoloLens* is a MR device that was utilized inside schools and an educational design research stance was taken to explore the researchable and designable aspects of the technology overall. ➢ Collaborative exploration with problem-solving in technological innovations.	a) Development of environments for high-quality products in order to understand better all students several technological aspects b) Attention and confidence factors from both students and teachers were high when the impact of the MR environment was analysed and found to be highly successful and well-respected	$n = 73$ t = 3 h

physical objects in a virtual world which could be remotely controlled to move and to make sounds. Leonard and Fitzgerald (2018) have utilized *Microsoft HoloLens* so as to integrate digital content into real-time visually-rich contexts. Students interact using body gestures and voice commands with both real-world artefacts and virtual artefacts in the form of receiving each eye individually a stereoscopic image by adding the illusion of three-dimensionality to holograms displayed by smart glasses. Another indicative MR environment is *MEteor*. Lindgren et al. (2016) have developed *MEteor* that is an interactive simulation of planetary astronomy that is projected by a large floor surface that presents an accurate representation of gravitational forces affecting astronomical objects such as asteroids. It is accompanied by an adjacent wall projection that offers laser scanning technology to precisely track a students' position within the simulation and enables them to play the role of an asteroid moving within the simulation space.

An interesting point of view is that MR technology was utilized in different natural/ physical and formal scientific fields. A possible explanation is that MR provides various abilities that can bring to life invisible, abstract, and complex concepts that might be difficult to view in conventional instructional settings. First, students do not have to rely only on their imagination to envision what is happening (Johnson-Glenberg et al. 2014; Han et al. 2015; Rowe 2014) because MR can "augment" the physical world by computer-generated perceptual information and integrate immersive sensations that are perceived as parts of the real-world environment. In particular, embodied interaction within a MR environment was recommended by several studies as it provides students a better learning experience (e.g., Chao et al., 2016; Kitalong et al. 2009; Lindgren et al. 2016). Second, the most well-referenced "tools" seemed to be the use of tangible (e.g. Kalpakis et al. 2018; Zhou et al. 2008) and Microsoft Kinect sensors (e.g., De Lima et al. 2014; Mateu et al. 2014) inside MR environments which are still promising in educational settings into formal science subjects (60% in primary and 40% in secondary education). This is of great importance because tangible objects appear to provide some advantages to users in mapping and registering real-world objects with simulated MR components and features. Such environments have the potential to support several learning approaches due to the availability of sensors in mainstream computing devices that allow users' spatial location and position to enhance their learning experience (Palaigeorgiou et al. 2018).

In addition to the above, it is also important to present where the reviewed studies took place. In primary education, eight studies utilized MR environments inside their classrooms (Bayon et al. 2003; Enyedy et al. 2015; Han et al. 2015; Rowe et al., 2014; Palaigeorgiou et al. 2018; Rogers 2002; Sugimoto et al., 2011; Zhou et al. 2008) and three studies were conducted outside "conventional" classrooms, such as in a history museum (Kalpakis et al. 2018), in a natural science museum (Kitalong et al. 2009) or in a physical science museum (Yoon et al. 2012). In contrast to studies conducted in primary education, all studies (Birchfield and Megowan-Romanowicz 2009; Chang et al. 2010; Chao et al., 2016; De Lima et al. 2014; Johnson-Glenberg et al. 2014; Leonard and Fitzgerald 2018; Lindgren et al. 2016; Mateu and Alaman 2013; Mateu et al. 2014; Tolentino et al. 2009) in secondary education were conducted inside classroom settings.

In regard to *RQ2*, the organization of the data regarding the technological equipment of each MR environments with the appropriate Appendices was formed as tables in Appendices Table 10 and Table 11. Each Appendix includes all the appropriate information tabulated for the presentation of the data referring the combination of computing devices that was utilized for the development of MR environments. More specifically, the results in Appendices Table 10 and *C* revealed that various studies followed embodied/authentic simulation MR (50% in primary and 40% in secondary education). Also, the use of embodied simulations with real objects allows MR designers to use low-cost components, having a more cost-effective simulation-based environment was detected by previous studies (Kalpakis et al. 2018; Mateu and Alaman 2013). This can be explained as reasonable since students more easily map out any process in authentic simulations that are more effective and stable compared to mobile tracking techniques, which are widely used in AR applications. In this perspective, many studies have utilized MR technology and computing devices either in-class or outside. Nonetheless, the implementation of marker-based AR is ease-to-use if there are appeared the right conditions and the availability of laboratories inside school contexts (Han et al. 2015; Lindgren et al. 2016) or through informal laboratories which could support the development process (Chang et al. 2010).

To categorize the computing devices and technological equipment that is being utilized by several MR environments, it is imperative first of all to divide the "tools" for designing and developing several "augmentations" within K-12 scientific fields. Most of the studies in K-12 education have used projectors to apply the "augmentations" over the real objects (Bayon et al. 2003; Kalpakis et al. 2018; Lindgren et al. 2016; Palaigeorgiou et al. 2018; Rowe 2014; Rogers et al. 2002; Sugimoto 2011) or in large displays (Bayon et al. 2003; Enyedy et al. 2015; Kitalong et al. 2009) or either in monitors (De Lima et al. 2014; Zhou et al. 2008) or a monitor on a robot (Chang et al., 2010; Han et al. 2015). Furthermore, students needed to scan the physical world through web cameras or Microsoft Kinect inside MR environments (De Lima et al. 2014; Mateu et al. 2014). The interaction between users and the system was provided by using tangibles (Kalpakis et al. 2018; Mateu and Alaman 2013; Palaigeorgiou et al. 2018; Kitalong et al. 2009; Rogers et al. 2002; Sugimoto 2011; Yoon et al. 2012), AR cards (Bayon et al. 2003; Han et al. 2015; Zhou et al. 2008), motion-sensing devices (Enyedy, 2015; Johnson-Glenberg et al. 2014; Rowe 2014), or HMD Microsoft Holonens (Leonard and Fitzgerald 2018).

Motion sensing input devices to support embodied interaction referred as the second most extensively used category of "tools". This could be attributed to the fact that field trips are less frequent in secondary education, which could explain why most of the selected studies took place inside classrooms, where mobility is less than or equal as an important aspect. A further possible explanation for the advanced use of "static" tools can be the fact that most of the reviewed studies have been exploited inside school contexts or inside buildings and laboratories, such as science museums, where MR environments can be easier integrated (Johnson-Glenberg et al. 2014; Mateu and Alaman 2013). In this perspective, fewer reviewed studies covered natural/physical science and took place outside of the conventional classroom or during field trips, where mobile devices are more convenient. Nonetheless, it remains to be seen whether innovative technologies such as *Microsoft HoloLens*, which have yet to reach the mainstream computing devices, are going to change the field of MR and become the dominant technologies in the future (Leonard and Fitzgerald 2018; Xiao et al. 2018).

In concern with *RQ3*, Table 6 shows the research methods that were applied to the reviewed studies which have conducted in primary and secondary education. It is quite obvious that most research designs were mainly explorative, and this reveals that the educational MR is still in its infancy in regard to assessing its real learning value. A significant observation is that many studies used medium-sized research samples (between 30 and 80 participants). Most studies used mixed methods by collecting both quantitative and qualitative data with close-ended questionnaires, interviews, and tests. In primary education,

Table 6 Research methods, design, and brief analysis of instrumentation

Studies in primary education	Research method design	Assessment methods and instrumentation
Bayon et al. (2003)	Qualitative	- Students' collaboration and MR system utilization - Observations of students' interactions
Enyedy et al. (2015)	Qualitative	- Students' opinions/perceptions about the provided MR system - Students Interactions video recording analysis
Rogers et al. (2002)	Qualitative	- Evaluation of explorative instructional settings - Students' interactions with video recording analysis
Palaigeorgiou et al. (2018)	Mixed	- Students attitudes towards the proposed tangible environment - A questionnaire regarding environment effectiveness and efficiency and for comparison to traditional learning; Interview for student experience
Kalpakis et al. (2018)	Mixed	- Students historical understanding and attitudes - The use of open-ended questions for historical understanding, a closed-type questionnaire about the easiness the enjoyment and the effectiveness of the environment. Lastly, the group interviews about the overall experience
Kitalong et al. (2009)	Qualitative	- Students' satisfaction, experience, and attention. - Observations regarding students' attention and interactions, written survey, interviews for comments and suggestions
Han et al. (2015)	Quantitative	- Students' perception toward AR-mediated dramatic play - A questionnaire to measure the students' perception of the AR-infused dramatic play; interviews with the children
Rowe (2014)	Qualitative	- Student engagement - Observations of museum visitor actions in the proposed interactive exhibit
Yoon et al. (2012)	Mixed	- Students' cognitive gains, user interactions, and experience - Conceptual knowledge questionnaire; interviews; observation notes; students' interactions with video recordings
Sugimoto (2011)	Quantitative	- Students' embodied participation, engagement in storytelling activities - Post-experimental inquiries and video analyses of students inquire with the Simplified Creative Product Semantic Scale (CPSS) questionnaire
Studies in secondary education	**Research method design**	**Assessment methods and instrumentation**
Birchfield and Megowan-Romanowicz (2009)	Mixed	- User experience into collaborative instructional contexts. - A coding rubric and statistical analysis to classify the types of teacher-to-student utterances in the audio/video data
Chang et al. (2010)	Quantitative	- The degree of familiarity of the 25 new words (10 using the robot, 10 using the non-robot, and 5 for robot commands). - Two questionnaires regarding the vocabulary familiarity evaluation and learning experience with virtual characters.
Chao et al. (2016)	Quantitative	- Students' learning performance in physical interactions between traditional and MR- supported instructional settings - Pre-and-post-tests about students' knowledge of science concepts.
De Lima et al. (2014)	Quantitative	- MR system's usability for interactive storytelling - IRIS Evaluation Toolkit to evaluate the system usability, the correspondence of system capabilities with user expectations

Table 6 (continued)

		(user satisfaction), the interaction effectiveness and the user experience (curiosity, flow, and enjoyment).
Johnson-Glenberg et al. (2014)	Mixed	- Students' learning performance in science learning subjects (chemistry) - Pre-mid-post-tests about students' knowledge and achievements.
Leonard and Fitzgerald (2018)	Mixed	- Users' experience and engagement - A questionnaire to explore whether there were patterns in the way students responded to the MR apps that went beyond simple enjoyment and engagement.
Lindgren et al. (2016)	Quantitative	- Students' general understanding in regard to physics concepts across the whole-body (experimental group) and desktop conditions (control group). - Questionnaires regarding Force Concept Inventory (FCI), physics in space, attitude and efficacy, presence and engagement
Mateu and Alaman (2013)	Quantitative	- The usefulness of the Cubica MR environment - A questionnaire about system usability, the correspondence of system capabilities with user expectations (user satisfaction).
Mateu et al. (2014)	Qualitative	- User experience and easy-to-use learning on gestures and tangible artifacts - Evaluation of a case study based on CS teacher observations
Tolentino et al. (2009)	Mixed	- Conceptual knowledge of chemical equilibrium and titration reactions - Pre-post test samples on science concepts knowledge

three studies (27%) followed mixed research methods and presented results from quantitative and qualitative data (Kalpakis et al. 2018; Palaigeorgiou et al. 2018; Yoon et al. 2012), six studies (55%) presented qualitative data from semi-structured interviews inside or outside classroom observations alongside with the analysis of transcripts from students' discussions demonstrating their capability to produce something meaningful (Bayon et al. 2003; Enyedy et al. 2015; Kitalong et al. 2009; Rogers et al. 2002; Rowe 2014; Zhou et al. 2008). Other two (18%) quantitative data based on experimental-comparative methods (Han et al. 2015; Sugimoto 2011). Nevertheless, in primary education, Rowe (2014) has presented the achievements and observations with a limited number of participants, such as two to conduct a preliminary experiment before conducting another one with a large sample.

Similarly, half of the reviewed studies (Chang et al. 2010; Chao et al., 2016; De Lima et al. 2014; Lindgren et al. 2016; Mateu and Alaman 2013) in secondary education presented quantitative data (50%). The other four studies (Birchfield and Megowan-Romanowicz, 2009; Johnson-Glenberg et al. 2014; Leonard and Fitzgerald, 2018; Tolentino et al. 2009) have conducted mixed methods research designs (40%). Lastly, only one study (Mateu et al. 2014) has discussed the results retrieved by qualitative data from students' interviews (10%). According to Table 6, in secondary education, only one longitudinal study was conducted (Birchfield and Megowan-Romanowicz, 2009) to assess users' experience, and four studies (Chao et al., 2016; Johnson-Glenberg et al.

2014; Lindgren et al. 2016; Tolentino et al. 2009) were conducted in order to measure students' learning performance using (quasi-) experimental studies to compare students' learning performance and concept knowledge with any potential learning gain using the MR technology.

Table 7 presents the main results from prior works only one study (10%) concerning the category *"learning performance and/or learning gains"*. As a single study can report more than one sub-category in regard to improvement, each one can also fulfill other sub-categories. For instance, three studies (27%) suggest an improvement in both *"engagement and participation"* and *"positive perception and attitudes"* issues. The vast majority of primary education four (36%) of the reviewed studies reported that MR environments led to *"student interaction/socialisation/ collaboration"* among students.

In secondary education, four (40%) studies reported a *"learning performance and/ or learning gains*". Additionally, two (20%) studies identified an increase in "*positive perceptions and attitudes",* an improvement within contexts that support *"interaction and collaboration"* among students, respectively and 10% an increase in *"engagement and participation"* issues.

However, almost all of the reviewed studies have also reported several difficulties. Table 8 presents the data collected on the difficulties of MR technology in educational settings. The first most observed difficulty in the reviewed studies was *"studying and utilizing the same learning materials to other educational subjects"* which could cause difficulties (45.5% in primary and 30% in secondary education). This may cause difficulties in using MR environments to interdisciplinary programs, in which for example students could take part in experiential exercises in STEM courses. Students may feel frustrated when some applications did not track or display data properly, or when they

Table 7 The improvements of using MR technology in K-12 education

Primary education	Studies	Number of studies and percentage (%)
Learning performance and/or learning gains	Yoon et al. 2012	1 (10%)
Engagement and participation	Bayon et al. 2003; Han et al. 2015; Yoon et al. 2012	3 (27%)
Positive perceptions and attitudes	Enyedy et al. 2015; Kitalong et al. 2009; Rowe 2014	3 (27%)
Interaction and collaboration	Palaigeorgiou et al. 2018; Rogers et al. 2002; Sugimoto 2011; Zhou et al., 2008	4 (36%)
Secondary education	Studies	Number of studies and percentage (%)
Learning performance and/or learning gains	Chao et al., 2016; Johnson-Glenberg et al. 2014; Lindgren et al. 2016; Tolentino et al. 2009	4 (40%)
Engagement and participation	De Lima et al. 2014; Mateu et al. 2014	2 (20%)
Positive perceptions and attitudes	Birchfield and Megowan-Romanowicz, 2009; Leonard and Fitzgerald 2018	2 (20%)
Interaction and collaboration	Chang et al. 2010; Mateu and Alaman, 2013	2 (20%)

Table 8 Difficulties to utilize MR technology in educational settings

Primary education	Studies	Number of studies and percentage (%)
Studying and utilizing the same learning materials to other educational subjects	Kitalong et al. 2009; Sugimoto 2011; Yoon et al. 2012; Rogers et al. 2002; Enyedy et al. 2015	5 (45.5%)
Focusing on the use or production of virtual information		0 (0%)
Merging virtual or real objects is required to be developed learning materials in favour of supporting MR environments	Kalpakis et al. 2018; Palaigeorgiou et al. 2018 Zhou et al. 2008	3 (27%)
Combining computing devices so as to develop MR systems may create a modest learning curve to students who do not have access to to such devices	Bayon et al. 2003; Han et al. 2015	2 (18%)
Measuring student learning performance and/or effectiveness of MR environments in limited time periods	Rowe 2014	1 (9.5%)
Secondary education	Studies	Number of studies and percentage (%)
Studying and utilizing the same learning materials to other educational subjects	Chang et al. 2010; Lindgren et al. 2016; Tolentino et al. 2009	3 (30%)
Focusing on the use or production of virtual information	Chao et al., 2015; De Lima et al. 2014	2 (20%)
Merging virtual or real objects is required to be developed learning materials in favour of supporting MR environments	Leonard and Fitzgerald 2018	1 (10%)
Combining computing devices so as to develop MR environments may create a modest learning curve to students who do not have access to such devices	Birchfield and Colleen Megowan-Romanowicz, 2009; Johnson-Glenberg et al. 2014	2 (20%)
Measuring student learning performance and/or effectiveness of MR environments in limited time periods	Mateu and Alaman 2013; Mateu et al. 2014	2 (20%)

sometimes struggle to use the computing devices to view any "augmented" information. To overcome such difficulties, improvements to the algorithms and/or hardware used for image tracking and processing must be made. As both easy-to-use and intuitive embodied realistic simulated tasks are instrumental for rewarding the learning experience inside MR environments, it seemed to be also crucial factors for students' performance (Birchfield & Megowan-Romanowicz, 2009; Lindgren et al. 2016) and engagement (De Lima et al. 2014; Sugimoto 2011).

The second most reported difficulty was *"focusing on the use or production of virtual information"*. It seemed that the novelty factor was crucial for students' engagement and participation (27% in primary and 20% in secondary education). The appropriateness of using MR in order to become adequate for educational purposes still needs more empirical studies to be conducted in several learning subjects, such as social sciences. The third observed in "c*ombining computing devices so as to develop MR environments may create a modest learning curve to students who do not have access to specific ones"* (18% in primary and 20% in secondary education). In addition, other referred difficulties included several *"measuring student learning performance and/or effectiveness of MR environments in limited time periods"* (9.5% in primary and 20% secondary education), and the fact that in case of having to change any learning material, teachers did not have such a chance with the view to *"merging virtual or real objects is required to be developed learning materials in favour of supporting MR environments*" (27% in primary and 10% secondary education).

More specifically, several difficulties in using "tools" properly was reported by several studies. A distinctive difficulty that has been observed is that students could not easily understand how to operate the controls or interact with the MR environments in primary education. For example, Sugimoto (2011) has reported that some students' groups could not control the robot stably because they had difficulty in holding the handheld projector. Bayon et al. (2003) have mentioned that students found it challenging to plan interactive story structure within the proposed MR environment. Moreover, there were also some difficulties from the technical-operational perspective that has been reported. Two studies in primary education (Sugimoto 2011; Zhou et al. 2008) have reported the unstable recognition of visual objects as a problematic situation that many MR environments have to deal with. Sometimes such a problematic situation is easily overpassed when are existed adequate light conditions. Nevertheless, other times the same problem required from the user to limit his/her actions so as to be able to interact with other components inside a proposed MR environment smoothly. Another important technical difficulty is reported by Rogers et al. (2002), where a pen was the main MR interactive "tool" that allowed only one student to perform one action at a time. This difficulty can be potentially passed with the use of better or more expensive infrastructures; however, many times the lack of financial resources leads to such problems. For this reason, two studies (Kalpakis et al. 2018; Palaigeorgiou et al. 2018) have advocated that there is a need to build low-cost and easily constructible MR environments.

Equally, in studies referred to learning subjects in secondary education, there have been also noticed several difficulties. For instance, some studies (Chang et al. 2010; De Lima et al. 2014) have admitted that due to the limited number of devices, only a few participants each time allowed to proceed with specific learning tasks inside a MR environment, and thus this situation was boring for other peers. Also, space and time constraints created limits in collaborative problem-solving tasks, in which students could not so easily define more so the way that provided a pathway on how that tried to solve the main problems that projected in large screens (Birchfield and Megowan-Romanowicz, 2009) or in HMD (Leonard and Fitzgerald 2018). Prior works (Chao et al., 2016; Mateu et al. 2014) have refereed that MR environments were developed by merging several sensing tracking sensors such as tangible ones, which allow a limited manipulation of learning content and feedback from one or two variables. Such a process restricts possible ways in which students can physically interact with the simulation in case of having the participation of more than one student.

A variety of studies followed collaborative instructive guided settings. In most studies, students were free to enter and exit in such learning spaces and support collaborative tasks with up to 30 to participate together, while the maximum number of them separated in teams of less than five at the same time in order to use any MR environment (e.g., Chao et al., 2016; Johnson-Glenberg et al. 2014). Particularly interesting is the fact that in their study, Johnson-Glenberg et al. (2014) have described a limited number of four students who could be tracked simultaneously and collaboratively with their peers. Even within simulation designs and subsequent research efforts (Lindgren et al. 2016; Tolentino et al. 2009) have applied embodied interaction learning tasks, it was revealed an improvement on students' engagement when embodied metaphors which were also utilized were fairly literal in the sense that the motion of one student's body represented the motion of an asteroid. Thus, an effective embodied interaction among students inside MR environments requires improved reasoning by using less literal and more abstract metaphors, such as body movement representing changes to more complicated processes such as physics laws. The consequence is that studying with haptic devices focuses on relatively simple conceptual domains related to macroscopic or microscopic phenomena but not with a combination of both.

According to all the aforementioned, the MR integration required by the developers and educators to be advised with specific design guidelines and rationale which could be meaningful for all students' experience regardless of gender and background for a variety of learning subjects into K-12 education (Leonard and Fitzgerald 2018). Since instructional contexts supported by MR can significantly affect students to participate in different subjects, the learning material should be clear, relevant to the learning objectives that curriculums provide. Empirical and case studies focused on the needs of specific learning subjects would help students to identify the most suitable elements to use them reasonably. The development of more intuitive and user-friendly MR environments is required today that relies on several objects and features to be utilized by the instructional developers so that create their learning content more accurately according to the scope of any scientific field.

3 Discussion

The current systematic literature review underlines specific learning subjects related to natural/physical, formal and social scientific fields in K-12 education using MR environments which have not yet been investigated. Educators and scholars who may find MR technology integration within their courses more challenging are those who have experience in the use of computing devices, such as tangible or tablets. Based on the results from the reviewed studies analysis, researchers and software developers have integrated learning content by merging real-world and digital contexts together, with the goal to transform the educational process with fun and engaging learning activities. For instance, a variety of studies have considered that the use of MR environments can support different learning subjects, as results from previous studies revealed improvements on students' learning experience with MR in subject understanding, participation, and motivation (e.g., Khoo et al. 2008; Panet al. 2006). To this notion, students in K-12 education participated in learning tasks reflected on the emergent landscape that enables higher-order thinking skills (e.g., technology literacy, creativity, problem-solving, critical thinking, and collaboration), as indicated by previous studies related to social science (De Lima et al. 2014; Kalpakis et al. 2018; Palaigeorgiou et al. 2018), natural/physical science (Chao et al., 2016; Kitalong et al. 2009), and formal science learning subjects (Chang et al. 2010; Lindgren et al. 2016; Sugimoto 2011).

The advancement in hardware and software in align with the widespread use of computing devices can provide the opportunity to rapidly increase students' learning participation with hands-on experiences (Kitalong et al. 2009; Sugimoto 2011; Tolentino et al. 2009). A substantial body from previous studies (Leonard and Fitzgerald 2018; Xiao et al. 2018) has presented several MR environments generated by cutting-edge computing devices, such as smart glasses that display holograms or embodied interactive environments for various learning subjects. The use of MR technology by combining several computing devices have prompted educators to harness the power of VR and AR technological advances in order to provide immersive and interactive applications in different instructional settings either inside or outside classrooms (Huang et al., 2018; Lindgren et al. 2016). Applications created inside MR environments capable of providing information on a specific object or location using visual markers were mostly utilized in museums (Bayon et al. 2003), art exhibitions (De Lima et al. 2014), and field studies related to chemistry (Chao et al., 2016). Furthermore, MR provides a landscape that enables students in K-12 education to be engaged with concepts which are not so easily accessible in their real life. MR allows these difficult conceptions to be taught so that students can try to solve complex problems, by providing information related to a learning subject from the real world with virtual information (Chao et al., 2016; Huang et al., 2018). Previous studies (Chang et al. 2010; Khoo et al. 2008; Weng, et al., 2018) have also presented great potential and advantages in different learning subjects, like the manipulation and visualization of abstract, complex or digital-oriented content that can offer alternative ways of self-discovery and constructivist learning processes (Johnson-Glenberg et al. 2014). Such learning approaches could shift away from lecture-style and more traditional teaching pedagogy towards active learning. Beyond having the opportunity to learn through interactive activities with clear goals, MR environments need to provide immediate feedback to the players' actions in favour of giving a positive effect on students' learning performance (Han et al. 2015). This would assist students to understand and develop new knowledge, as well as gained from their previous knowledge with the use of computing devices, which in turn will enable them to connect the correct usage of such devices with the twenty-first century's demands and needs.

The development of MR environments based on the reviewed studies inevitably varied, since many of them encompassed the narrative aspect of creating interactive-multimedia applications to support problem-solving tasks related to formal scientific fields (e.g., Chao et al., 2016; de Lima et al. 2014) or informal instructional settings, in museums (Bayon et al. 2003; Rowe 2014; Yoon et al. 2012). MR technology is valuable for teaching different scientific fields, as it offers the ability to bring to life invisible, abstract, and complex concepts (Tolentino et al. 2009). Even if fewer studies conducted in regard to storytelling (Bayon et al. 2003; De Lima et al. 2014), dramatic play (Han et al. 2015) or history (Kalpakis et al. 2018) can become more engaging when MR is combined with location-triggered and spatialized contextual information to students. For example, an interactive paper and pencil interactive storytelling (dramatization) tools with a sketch-based AR interface allowed an easy and more natural way to influence any ongoing story running through inquiry/ discovery learning. Within such contexts, the use of MR seemed to have a significant impact on students' learning experience and emotional-social development (De Lima et al. 2014). Additionally, projection mapping created by using projectors and camera-based interaction for the development of intuitive and engaging interactive experiences (Rowe 2014). Nevertheless, more studies in social science are required in order to assist instructional developers to understand how to design more effective MR experiences for different subjects such as events from ancient history that students could describe by interacting with real and digital objects.

Another important aspect is that the technologies utilized by previous studies have provided a variety of different "tools" including robots (Chang et al. 2010; Sugimoto 2011), HMD (Leonard and Fitzgerald 2018), computers with webcams (De Lima et al. 2014; Zhou et al. 2008), MR books with sensors (Chao et al., 2016; Mateu et al. 2014), tangible interfaces (Kalpakis et al. 2018; Palaigeorgiou et al. 2018), and barcode readers (Bayon et al. 2003). All these different technologies suggest a broad and diverse consideration of MR within classroom settings; however, it is still unclear if smart glasses such as *Microsoft HoloLens* can become a success in the near future since such a statement should be further investigated inside school contexts. Experimentation and simulation tools can potentially become appropriate for MR environments so that students can provide embodied representational fidelity to physical objects and a visually appealing environment in which they can use to interact with their peers or their instructor (Lindgren et al. 2016).

This review suggests that interactive learning challenges using MR needs to be designed in terms of supporting different activities in various instructive guided approaches beyond in-school classrooms, such as field trips, and museums which would support supplementary learning approaches. The improvement on students' learning experience appeared to be succeeded by merging well-known computing devices, which can lead to enjoyment, knowledge gain, interaction, increased engagement, and enhanced collaboration (e.g., Johnson-

Glenberg et al. 2014; Mateu and Alaman 2013). With the use of MR technology, students improved their learning achievements (Chang et al. 2010; Yoon et al. 2012), increased their motivation (Leonard and Fitzgerald 2018; Lindgren et al. 2016), particularly improved their positive attitudes towards the learning process. Additionally, a large body of contemporary research (Chang et al. 2010; Leonard and Fitzgerald 2018) has reported a need to use learning theories/ theoretical underpinnings such as Constructionism in order to inform the teaching methods considering any interactive learning experience that can be provided inside MR environments.

To sum up, the reviewed studies in secondary education revealed an improvement on student learning performance and/or learning gains, albeit studies in primary education reported an improvement mostly on students' engagement and participation. While many evaluations were made over a short period of time, usually on the same day of each intervention, it is important for other works to investigate whether students in K-12 education preserved the same positive results in a long-term basis e.g. several months after the intervention. Some of the reviewed studies were focused on the quantity of learning gain during the intervention without analysing further the learning mechanism and transformations. Additionally, there is also a lack of data that creates difficulties in identifying whether the benefits of the learning experience into specific computing devices, features or approaches in using MR environments need to be investigated. Hence, further studies need to propose new design techniques in a way that allows educators to be able to analyse learning mechanisms and measure the results of their interventions in long-term.

3.1 Implications for research and practice

The present review is in the line of reasoning from future outlook or difficulties which have been mentioned by previous literature reviews (Chen and Duh 2018; Stretton et al. 2018), in terms of integrating MR technology to K-12 education. From an instructional design perspective, two are the most notable implications. First, features and elements of MR environments appeared to become useful by merging different computing devices such as sensors or tangible devices which can assist students to map out subparts within problem-based learning contexts. Students were able to explore and understand the consequences arising from choices made in every MR environment given the appropriate feedback to their actions. Second, the natural intuitive multimodality for user interaction in embodied real-time learning tasks assisted also students to think on how to solve problems through interactive learning tasks in order to understand more accurately some theoretical and/or abstract concepts. In particular, the representational fidelity of visual and/or real elements and features combined with real-world counterparts within specific time and space contexts can enhance students' awareness and achievements mostly in (collaborative) problem-solving learning tasks.

However, from a methodological-educational perspective, many experimental setups had several downfalls regarding the use of MR multimedia-interactive environments. First, testing activities by just triggering or pushing any static content or real-world objects need to be included and organized into well-structured instructional settings in order to be properly tested and be proposed by any design development method. Second, the use of static objects cannot always assist students to avoid the *"steep learning curve"* due to the high novelty effect on the use of computing devices and their applications that are produced. Third, any further test criteria for timeliness and robustness need to be based on pre-defined points that can be visually appealing and can lead students to generate test cases as sequences by triggering events automatically so that execute their personal augmentations. Therefore, a significant consequence of all the referred downfalls is that any suggested "augmentations" should be sufficiently validated in practice and mostly into real school-age context (e.g. inside or outside classrooms), with respect to ensure further the applicability of MR environments.

From a research design perspective, fewer studies were conducted in order to present findings of what students finally learn using MR. Many elicitation studies were conducted to measure user experience mostly in a short period of time. For instance, Rowe (2014) has clearly referred a small number of participants in order to introduce students in different learning subjects, due to the use of MR environments outside the typical classroom, e.g., inside museums. Nevertheless, such studies have also pointed out some good experience gained to all those students who wanted to be engaged and participated even in any future experiment. Up until now, prior efforts did not contribute to the effects of using MR environments on low-and high-achieving students and their experience of the pursuit of learning performance excellence in different subjects. For instance, Lindgren et al. (2016) have concluded that the lower academic achievement of students led to better learning gains; albeit some others with high academic achievement did not thoughtfully benefit. Another significant point of view was the fact that fewer studies (e.g. Chao et al., 2016; Johnson-Glenberg et al. 2014) have followed quasi-experimental (pre-and-post-tests) research method designs to compare any potential learning gains or an improvement on science concepts knowledge; thus, it was provided a difficulty for educators and scholars to understand further how a MR environment and its technological equipment can be utilized so that contribute to any learning subject. Despite the appropriateness of using several computing devices for the development and creation of MR environments, fewer studies have also paid attention so as to investigate the effects on students' learning in relation to analytics tools which are in nowadays widely utilized, and therefore it is difficult to be recognized the potential integration of such multimedia-interactive environments inside or outside K-12 school-age contexts.

This literature review also highlights some practical implications, specifically for developers and instructors who want to use MR environments in different scientific fields through in−/formal school contexts. Innovative design methods about the development and creation of interactive learning content inside MR learning environments are still required (Chang et al. 2010; Han et al. 2015; Rogers, 2002). The development of MR authoring tools can become very useful to those instructors and educators who do not have a strong background in programming in such tasks so that produce content capable to assist and enhance further the learning subject. Further research is therefore required for improving the user experience and knowledge construction processes in MR environments in order to enhance the students' learning experience. The consequence is that educators and MR designers need to understand how to create tasks and environments by taking into serious consideration students' needs and demands to each learning subject, in which such a technology can be utilized. As previous works (Chao et al., 2016; De Lima et al. 2014) indicated, various MR environments were developed with products that everyone use daily, and thus it can be argued that such a technology has the potential to reduce the financial cost of learning activities which may tend to involve easier advanced technological tools to support students' participation. To be achieved such a goal in practice, it is also needed a shift in the quality culture of schools which will value or reward any further innovative teaching process, in which educators and instructors would probably remain reluctant to adopt MR, as this may add to the heavy workload that they have to overcome.

3.2 Limitations and recommendations for future research

This review has several worth noting limitations. It includes a process-based analysis, focusing on the constituting design components benefits and difficulties on the use of several MR environments regarding specific research methods with a breadth of studies examined in different learning subjects. Consequently, the discussion of the content and results (system setup description) related to each MR usage has been brief because of analyzing studies presented in international peer-reviewed journals. This process was useful in providing an exceptionally thorough, rigorous method to categorize articles, not only for achieving the main goals of this review but also for extracting intricate information about individual studies that developed MR environments and are briefly presented in Appendices Table 10 and Table 11.

In addition to the above, there has been identified a considerable number of other studies which cannot be included because it was determined by the query method employed and the criteria of selection that have unquestionably constrained the sample into ways that may not be easily assessed at the time of writing this review. On the one side, some of the criteria for selection of articles are focused on full-papers, written in English and published in international journals. On the other, possibly further studies that may be significant for developers and scholars will be conducted but could not be included because such studies were published in proceedings from international conferences or some of were avoided to describe in detail a research method and students' learning outcomes. Thus, a consequence is that this review did not broaden the range of studies to these domains for reasons of motivation leading to an inflation of surveys. Any inadequacy on the appropriateness of MR environments would lead someone to not clearly understand the effects of such systems/prototypes on students' engagement, participation or even their performance in different K-12 learning subjects.

Further research addressing any potential validity and reliability concerns should consolidate the role of MR environments in terms of enhancing students' learning experience. In particular, future works are still required into different facets of interactive learning through formal and informal instructional settings, including the development of instructional design frameworks underpinned by learning theories such as Constructivism that can become more valuable for a teaching approach. Also, theoretical design frameworks to elaborate on any potential design rationale, guidelines and design criteria that MR technology needs to be provided for learning tasks within K-12 school-based contexts. Additionally, longitudinal studies are necessary to be conducted with long-term analysis of students' learning experiences in primary and secondary education courses alongside a larger sample to provide additional evidence based on their solutions for real-world problems. Such an effort can also provide important insights regarding the suitability of interactive environments for learning even into interdisciplinary subjects. All the reviewed studies in this study provided results that were analyzed by taking into consideration data retrieved by a qualitative and/or quantitative method(s). This is of great importance since instructors and educators could be informed a lot about the effect of MR inside classrooms, but not regarding students' learning achievements or skills of each at an individual level. Due to the surge of computing devices in several domains of educational technology, learning analytics can be suggested as an additional "tool" focus on both the quantitative and the qualitative data retrieved by measuring the effects of MR environments, and thus there is a need to be incorporated in future research works. Last but not least, there was not identified any MR to be considered as appropriate in various learning subjects for students with special needs, and this challenge may be of great importance for future works in the future.

4 Conclusion

The current systematic review of research that is focused on the use of MR in K-12 education is timely as the widespread integration of innovative technologies on students' everyday life, such as VR and AR have gained popularity amongst scholars and educators. Thus, there is a broad agreement that first of all it is imperative to understand the current practices made by using MR, and its components in order to shed light on future implementations. A total of 21 articles were finally included in this systematic literature review framed by the following perspectives:

- The findings from this review indicated a widespread adoption in different learning subjects that utilized MR by merging computing devices in order to develop interactive and immersive learning experiences.
- The results from previous studies revealed that the majority of students achieved significantly better learning gain, outcomes, and performance using MR than their counterparts in traditional instructional (lecture-style) formats.
- MR technology provides several potential benefits but also brings some challenges for both scholars and students. By synthesizing the relevant literature on the use of MR in different K-12 learning subjects, this review provides recommendations for researchers, practitioners, or policy-makers who want to develop research-based

Appendices

Table 9 The specific protocol that was executed in each database

Database	Protocol	Note
JSTOR	((((learn or learning or engagement or learning outcomes or learning achievements) <in>ab) <and > ((Mixed reality or Mixed reality games or Mixed reality environments) <in>ab)) <in>ab) <and > ((qualitative or quantitative)) <and > ((school or K-12) <in>ab)) <and > (pyr > ΄O 2000 <and > pyr < ΄O 2018)	Search on the field "Abstract".
SCOPUS	ab: ((teaching or learning or education or educational) and (Mixed reality games or Mixed reality environments) and (middle school or Primary or Secondary)) Content Type >Journal Articles Publication Date >Between Saturday, January 01, 2008 and Thursday, December 30, 2018	Search on the fields "Abstract", "Title" and "Keywords".
Science Direct	(learning OR teach OR learn OR education OR educational) <in> Smart Search AND (Mixed reality game-based learning or Mixed reality environments) <in> Smart Search AND (Primary OR Secondary OR k-12) <in> Smart Search AND Date: between 2012 and 2017 AND Limited to: PEER_REVIEWED In Education Full Text	Search on the field "Abstract". - Term K-12 replaced by high school or middle school by restriction of the database. - Terms "teach" and "learn" suppressed limiting quantity of terms used to search the database. Variations to the terms removed were used and can be identified that did not compromise the result.
ESCBO	Publication Type: "Journal Articles" and Full-Text Available	Search on the field "Keywords (all fields)".
ERIC	(Publication Date: 2012–2018) ((Keywords: teaching OR Keywords: teach OR Keywords: learn OR Keywords: learning OR Keywords: education OR Keywords: educational) and (Keywords: Augmented reality OR Keywords: Mixed reality OR Keywords: 3 Mixed reality games OR Keywords: prototypes and Mixed reality OR Keywords: a qualitative and quantitative research method OR Keywords: K-12)	Search on the field "Keywords (all fields)".
Wiley	((learning or engagement or educational) <in>ab) <and > ((Mixed reality or mized reality supported environments) <in>ab)) <and > ((Primary or Secondary or Higher education) <in>ab)) <and > (pyr > ΄O 2000 <and > pyr < ΄O 2013)	- Search on the field "Abstract".
Web of Science	((learning or K-12 education) <in>ab) <and > ((Mixed reality environments) <in>ab)) <and > ((Primary or Secondary) <in>ab)) <and > (pyr > ΄O 2000 <and > pyr < ΄O 2013)	- Search on the field "Abstract".

Table 10 Technological equipment and components of MR supported environments in primary education

Research studies	Description of technological equipment
Rogers et al. (2002)	a) Two coloured building blocks, with a different colour displayed on each of their six students' faces allowing them to mix digital colours. b) Each face of the block was embedded with a hidden RFID tag so as to enable physical actions to trigger virtual effects c) When a face of the block was placed on the RF tag reader, an animation mirroring the color of the identified face was triggered and projected onto an adjacent vertical display d) Digital pen to mix digital colours in "digital-to-digital" transform
Bayon et al. (2003)	a) KidPad desktop collaborative drawing application based on the concept of Zooming User Interface (ZUI), 'Local Tools' and Multiple Input Devices metaphors b) Barcode printer to allow students to print barcodes that are connected to specific parts of a story c) Barcode readers that allow the system to zoom at the barcode corresponding part of the story d) Magic Carpet which was composed of 12-floor sensors organised in four rows to assist students to move around a story by jumping on the sensors e) A web camera was added to the environment so that students could take f) Instant images which were imported directly to KidPad g) PDA as another media that allow students to draw and beam their images directly to KidPad h) A projector that displays students' paintings as part of the story according to the barcode readers or the students' movements over the Magic Carpet
Zhou et al. (2008)	a) The user interacts wIzQubesTM in a physical 3D reality. wIzQubes™ have markers on all their sides, b) Web camera that captures the tabletop area where the two cubes are manipulated by the user c) A PC program that renders 3D graphics according to the storyline and the cubes' events that triggers different segments of the 3D Animation d) PC Monitor that displays the MR environment
Kitalong et al. (2009)	a) The physical installation of the JwSC experience consisted of a podium surrounded by Styrofoam painted to resemble a cave b) Projector along with a curvilinear projection screen (dome), mounted to the underside of the podium, served as a frenetically busy window into the microworld. c) Joystick and trackballs controllers to allow users to interact with JwSC
Sugimoto (2011)	a) The GENTORO system is consisted of a robot that is a character in the students' stories where they draw detailed sketches and specify the behavior of the robot. b) Handheld Projector that allows students to control the movement of a robot in their storytelling. c) The robot is controlled by the mobile PC connected to the projector, to make the robot follow a path drawn on the projected image. d) Wii controller to control scene changes e) WiFi communication is used to send control commands from a mobile PC to the robot via the server and between the server and the Wii controller, uses Bluetooth communication.
Yoon et al., (2012)	a) Tangibles that students touch in order to close a circuit. b) When the circuit was completed, a lit bulb triggered the projection of an animated flow of electricity on the visitor's hands, arms, and shoulders—showing the complete loop and visualizing the flow of electricity through the completed circuit.
Rowe (2014)	a) Microsoft Kinect sensor is used to analyse depth-map information. b) PC with software allows the digital creatures to react to physical interference within their own digital space. c) Projector used to augment physical objects and spaces, (projection mapping)

Table 10 (continued)

Research studies	Description of technological equipment
Enyedy et al. (2015)	a) A carpet with AR Markers where the students are moving b) A camera mounted directly above the carpet space and pointing downward. c) The camera feed is projected onto a whiteboard where the students can see themselves moving around, creating a mapping between their own first-person perspective and the camera's third-person perspective— d) incidentally, the same perspective one takes when looking down at a physical game board.
Han et al. (2015)	a) Marker in the form of a three-sided cubic hat that all students wear b) Robot iROBIQ with a monitor and a camera which captures students c) The monitor screen embedded in iROBIQ simultaneously shows students physical actions represented in a virtual dramatic play with the real story characters (i.e., three pigs) and backgrounds d) Large screen display (widescreen TV) where the AR scenes presented on the robot screen are also broadcasted so as to be visible by the other students
Kalpakis et al. (2018)	a) Low cost - low fidelity handmade objects such as two pairs of human steps that allow students' embodied actions or paintings. b) Two Makey Makey circuit boards that provided the sensors connected to the objects so as to understand students' actions c) The augmentations and the interactions were programmed with MIT's Scratch Projector d) Two computers that were running the Scratch scripts
Palaigeorgiou et al. (2018)	a) Tangible 3D maps that were augmented with the aid of a projector b) Makey Makey cirquit board to convert conductive materials to interactive elements, and enable students and instructors to easily design and program fingertips with a variety of events and activities over the augmented map c) MIT Scratch software to program the student's interactions d) Students move their fingers over the map and when touch specific places projector provides more information according to the predefined scenario on Scratch

action plans so that design, develop and evaluate MR environments as potential learning spaces to enhance students' learning experience and outcomes.

- The paucity of research about the use of theoretical design frameworks with specific guidelines both for the development and evaluation in regard to the appropriateness of utilizing MR in different learning subjects. Assessment methods have been mostly limited to quantitative or qualitative data drawn from course evaluation and surveys. Moreover, there is a scarcity in empirical research design to understand how students learn in-depth and within specific contexts to investigate relevant issues with larger sample sizes and longer time experiments.

Table 11 Technological equipment and components of MR supported environments in secondary education

Research studies	Description of technological equipment
Tolentino et al. (2009)	a) A set of "glow balls" and wireless peripherals to interact all students in real- time with each other and with dynamic visual, textual, physical and sonic media through full-body 3D movements and gestures. b) An open cube-shaped space with the following sensing and feedback equipment: a 3D object tracking system. c) A top-mounted video projector providing real-time visual feedback, four audio speakers for surround sound feedback, and an array of tracked physical objects (glow balls) across the floor. d) A networked computing cluster with custom software drives the interactive system.
Mateu and Alaman (2013)	a) The virtual world of OpenSim server was installed within the high school local area network (LAN) to overcome bandwidth and firewall restrictions combined with tangible interfaces (cubes) focused on teaching computer science, in particular, "sorting algorithms" using the LSL programming language. b) A Non-Player Character (an avatar controlled by a program) was created inside OpenSim to be in charge of sending and receiving messages between the virtual world and the tangible interface. c) Cubes (dices) were used to represent the values of the elements of the array. Such devices act as a mediator among the physical devices and the virtual world: when somebody modifies the state of the tangible interface d) One LCD display that showed auxiliary messages, such as the number of iterations during a sorting process.
Johnson-Glenberg et al. (2014)	a) A kinesthetic and scalable place with 12 infrared OPTITRACK motion-tracking cameras that send information to a computer about where a student holding a tracked object is in a floor-projected environment b) An open-ended on all sides environment that has a floor space that is 15 × 15 ft (4.572 × 4.572 m) with integrated tracking sensors in which students step into the active space and grab a "wand" (a rigid body trackable object) that allows the physical body to now function like a 3D cursor. c) Trackable objects are used to select virtual molecules from the edge of the floor and the system uses the height of the object to serve as the release mechanism.
Birchfield and Megowan-Romanowicz (2009)	a) Six-element camera array for object tracking, a top-mounted video projector providing real-time visual feedback, four audio speakers for surround sound feedback, and an array of tracked b) Physical objects (glowballs). A networked computing cluster with custom software drives the interactive system.
Chang et al. (2010)	a) The virtual scene is presented on the two perpendicular screens (the diagonal of each measured 80 in.). b) The operation of this MR supported environment made by using a keyboard and mouse on the flat screen to voice and physical objects in the virtual world. c) A robot which could be remote-controlled to move and to make sounds. d) Bluetooth wireless connection and the sense inputs of the robot through the built-in sensors are used.
De Lima et al. (2014)	a) Paper and pencil are combined to be created an interactive storytelling system in which tasks include a sketch-based interface with an AR visualization interface. b) An ordinary sheet of paper with a fiducial marker printed on it, and a common pencil.

Table 11 (continued)

Research studies	Description of technological equipment
	c) A webcam is used for the sketch recognition interface and the AR dramatization system. The story planner handles the actions of several virtual autonomous characters whose behavior may, however, be redirected via user interactions. d) The sketch recognition system comprises of a vector machine (SVM) classifier in order to be recognized a set of sketches when users draw on a sheet of paper, which is then captured by a camera.
Chao et al. (2016)	a) A streamlined, flexible, and scalable mixed-reality science learning solution using probe ware and sensors. b) A variety of sensors (i.e., temperature, force, and pressure sensors) that are located such that in their actions appeared to directly impact a virtual world. Instead of clicking or touching icons on a computer screen, students interact through physical actions with everyday objects. c) The use of sensors enables students to interact with the Frame through a variety of physical objects, such as hair dryers, hot jars, or pushing on springs using haptic devices such as a glove or joystick or visual images of a flame or pump.
Mateu et al. (2014)	a) Virtual worlds and tangible interfaces using OpenSim and Kinect technologies. b) Natural User Interfaces (NUI), which are based on gestural interaction, and Tangible User Interfaces (TUI), which are based on interaction with physical objects. c) The middleware includes some bots populating the virtual world, which are part of the mechanism for communicating OpenSim with the Kinect using Microsoft Visual Studio 2012 was used as the programming environment, using the C# programming language.
Lindgren et al. (2016)	a) An interactive simulation of planetary astronomy that is projected onto a large (30 × 10 ft) floor surface. The simulation presents an accurate representation of gravitational forces that affect astronomical objects such as asteroids. b) An adjacent wall projection that offers basic instructions and presents data on a learner's performance within the simulation that can be reviewed and used to inform subsequent activity. c) Laser scanning technology allows MEteor to precisely track a learner's position within the simulation to play the role of an asteroid moving within the simulation space projected on a wall display.
Leonard and Fitzgerald (2018)	a) *Microsoft HoloLens* allows students to learn how to use digital content and interact with both real-world and virtual artefacts in the form of holographic-like images. b) The device places images onto a transparent near-eye screen so as to create the illusion of a holographic image in real space.

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