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Augmented reality in teaching about physics: first findings from a systematic review

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Augmented reality in teaching about physics: first findings from a systematic review

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Abstract. Augmented reality (AR) makes it possible to overlay digital content onto our view of real-world phenomena. This potentially facilitates learning of physics by visualizing connections between concrete physics phenomena and abstract physics formalism. Here we present a part of our systematic review of earlier research on the use of augmented reality (AR) in school and university teaching physics topics. Our systematic review includes 60 articles published between 2012 and 2020, indexed in the Scopus and Eric databases. We analyzed the technological properties of AR for different content areas of physics as well as various methodological aspects of earlier AR research in physics education (e.g., educational level of participants, sample size, and research design). It has been shown that AR becomes increasingly popular in the physics education research community.

Keywords: augmented reality, physics education, systematic review.

1. Introduction

During the times when schools, universities and laboratories are closed due to force majeure, virtual reality and augmented reality science labs become essential. Thereby augmented reality (AR) can be defined as "a real-world context that is dynamically overlaid with coherent location or context-sensitive virtual information" [1]. When it comes to types of AR applications, we distinguish: marker-based (camera and designated printed markers are used to activate AR content), location-based (AR technology uses information about the user's geographic coordinates), motion-based (AR content is triggered by the change in the movement) and markerless applications (AR content is activated without external world triggers, i.e. printed markers). Many believe that augmented reality has considerable potential to enhance the quality of the learning process [2-4]. This can be explained from the perspective of Mayer's cognitive theory of multimedia learning, particularly by the multimedia principle, principle of spatial contiguity, temporal contiguity, and the segmenting principle [5]. Consequently, it is no surprise that many earlier studies found positive effects of AR on the cognitive domain of learning. Concretely, it has been shown that using AR technology in teaching science topics could improve students' conceptual understanding, spatial skills, and practical skills [1,6-8. Besides potentially positive effects on the cognitive domain of learning, AR could also facilitate affective learning. In fact, technology has become an important part of students' everyday lives, and many believe that the use of technology in the classroom is very important to their overall performance. Consequently, they enjoy using videos and animations while learning [9,10]. Ibáñez and Delgado-Kloos (2018) reported that AR technology has positive effects on motivation, engagement and attitudes toward STEM subjects. Finally, it is important to note that although in many empirical studies a wide range of benefits has been detected, some authors reported certain shortcomings related to the use of augmented reality. These shortcomings are often related to suboptimal hardware and software solutions, as well as to inadequate training of students or teachers and the need to invest more efforts in the preparation of instructional materials [11-13].

1.1. Study purpose and research questions

The purpose of this study is to provide an overview of high-quality papers on the use of AR technologies in teaching and learning about physics topics. Here it should be noted that in this paper we use the term "physics education" to include all learning about physics, regardless of the context (e.g., formal, informal) and educational level (e.g., primary school, secondary school, university) in which learning happens. Concretely, "physics" was operationally defined as "concepts and procedures that physicists develop or use in their study of natural phenomena, as described in physics textbooks at various levels of education". Consequently, all AR education articles in whose titles, keywords or abstracts we recognized concepts and procedures that are covered in physics textbooks at various educational levels were classified as "physics-related articles" and included in this review.

Based on the analysis of a pool of physics-related AR articles, we aimed to answer the following research questions:

RQ1: What instructional techniques and strategies were used for AR-based learning of physics?
Significance: The effectiveness of any learning technology depends on how it is used. Answering this research question could help us identify instructional techniques and strategies that are more or less effective in utilizing the positive, inherent features of AR technology.

RQ2: Is the number of studies related to AR in teaching about physics increasing over time?
Significance: Answering this question could help us identify some important trends when it comes to the popularity of AR technologies in physics education.

RQ3: How are the articles on AR in teaching physics topics distributed geographically?
Significance: Answering this question might help us to find out whether AR physics education research is a global phenomenon or whether it is limited to a few developed countries.

RQ4: What types of participants and how many of them were included in earlier AR physics education research?
Significance: Answering this question could help us identify populations for which more AR physics education research is needed.

RQ5: In what learning environments was the AR physics education research situated?
Significance: Answering this research question could help us identify learning environments that are particularly suitable for the use of AR technologies, as well as to identify environments for which further research is needed.

RQ6: What are the most popular software development and hardware technologies for AR-based teaching about physics?
Significance: Answering this research question could help us identify a whole spectrum of software and hardware possibilities that could be potentially useful for physics educators.

RQ7: What physics topics were covered through earlier AR physics education articles?
Significance: Answering this research question could help us identify physics topics that physics educators and researchers found to be particularly convenient for AR use, as well as identify physics topics for which further AR research may be needed.

2. Methods

For our systematic review, we first had to identify earlier research relevant to answering our research questions. We decided to look for these papers in the Scopus and ERIC databases, which are known for indexing a wide spectrum of high-quality educational research papers. A brief overview of the criteria for inclusion of articles is provided in Table 1.

Table 1. Inclusion criteria.

Inclusion criteria
Published between January 2012 and November 3, 2020.
Peer reviewed journal article.
Related to using AR in teaching physics.
Written in English.
Original publication

Concretely, we searched for articles describing augmented reality-based learning about physics. To identify such articles, we used the search terms "augmented reality" and "mixed reality" with the Boolean operator "OR". Only peer-reviewed studies in English published between 2012 and 2020 were included. Augmented reality review articles were excluded.

An ERIC search by the first author of this manuscript resulted in 763 articles that met the specified search criteria, compared to 7790 articles found by searching Scopus. The last search was performed on November 3, 2020.

After carefully reading the titles, keywords and abstracts for the 8553 search results, the first author of this manuscript concluded that 86 search results were related to teaching physics topics. However, through a closer inspection of these 86 search results, 21 duplicates were identified and removed. Thus, based on the initial selection process conducted by the first author of this paper, 65 articles about augmented reality-based learning about physics were identified. In the second round of review, these 65 articles were analyzed for shortcomings in their research methodology. This process resulted in the exclusion of an additional 5 articles. Finally, 60 articles remained in our pool for systematic review of augmented reality-based learning about physics. 45 of these articles were empirical research articles and 15 were non-empirical articles. This is the reason why the number of articles relevant to answering individual research question varied. For answering RQ1, RQ4 and RQ5 only the 45 empirical research articles were regarded as relevant. In contrast, for answering RQ2, RQ3, RQ6, and RQ7 we had to consider all 60 identified articles. Our workflow was based on the guidelines of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)[14].

For purposes of estimating some measure of objectivity in the inclusion of articles, the second author of this paper was asked to independently review a sub-pool consisting of 25% randomly selected, initially identified articles and to decide whether these articles meet the inclusion criteria. It was found that the initial agreement between the first and second author of this paper amounted to 94.4%, and after discussion, complete agreement could be established. At the time of the study, each of the two coders had at least ten years of experience in physics teaching.

3. Results and discussion

In this section, we present and discuss our findings for each of the research questions.

3.1. What instructional techniques and strategies were used for AR-based learning of physics?

To further explore the literature on AR based learning of physics, we have created a Table 2 that provides information on the sample size and educational level of the study participants, as well as descriptions of the instructional techniques and strategies from the 45 empirical research articles. Here we will only discuss the instructional techniques and strategies, while educational level and sample size of participants will be discussed later.

Table 2. Sample characteristics and instructional aspects of using augmented reality technology in teaching about physics; 45 empirical research articles are included.

Researchers	Educational level	Number of participants (teachers-(N_t); students-(N_s))	Instructional techniques	Instructional strategies
Abdusselam and Karal [15]	K-12	$N_s = 70$ $N_t = 1$	Inquiry	Discovery
Akçayir *et al.* [1]	Higher education students	$N_s = 76$ $N_t = 1$	Inquiry	Discovery
Altmeyer *et al.* [16]	Higher education students	$N_s = 50$	Inquiry	Discovery
Amelia *et al.* [17]	K-12	$N_s = 37$	Unknown	Unknown
Baran *et al.* [18]	K-12	$N_s = 31$ $N_t = 1$	Observation, Inquiry	Cooperative/ Collaborative and Discovery
Cai *et al.* [19]	K-12	$N_s = 50$	Inquiry	Discovery
Cai *et al.* [20]	K-12	$N_s = 42$	Inquiry	Cooperative/ Collaborative
Cai *et al.* [21]	K-12	$N_s = 98$	Inquiry	Discovery
Chang and Hwang [22]	K-12	$N_s = 111$	Inquiry	Cooperative/ Collaborative
Daineko *et al.* [23]	K-12	$N_s = 50$; $N_t = 5$	Unknown	Unknown
Echeverría *et al.* [24]	K-12	$N_s = 45$	Game	Cooperative/ Collaborative
Enyedy *et al.* [25]	K-12	$N_s = 43$	Game	Cooperative/ Collaborative
Faridi *et al.* [26]	Higher education students	$N_s = 80$	Inquiry	Discovery
Fidan and Tuncel [27]	K-12	$N_s = 91$	Inquiry	Discovery
H. Y. Wang *et al.* [28]	Higher education students	$N_s = 40$	Inquiry	Cooperative/ Collaborative
Huang and Lin [29]	K-12	$N_s = 104$	Observation	Presentation
Ibáñez *et al.* [30]	K-12	$N_s = 60$	Structured observation	Discovery
Ibanez *et al.* [31]	K-12	$N_s = 40$	Structured observation	Discovery
Kirikkaya and Başgül [32]	K-12	$N_s = 120$	Observation	Discovery
Lin *et al.* [33]	Higher education students	$N_s = 40$	Inquiry	Cooperative/ Collaborative
Lindgren *et al.* [34]	K-12	$N_s = 113$	Game	Discovery
Liou *et al.* [35]	K-12	$N_s = 54$	Inquiry	Cooperative/ Collaborative
Majid and Majid [36]	K-12	$N_s = 25$	Inquiry	Discovery
Matcha and Rambli [37]	K-12 Higher education students	$N_{s(K-12)} = 6$ $N_{s(HE)} = 10$	Inquiry	Cooperative/ Collaborative
Montoya *et al.* [38]	Higher education students	$N_s = 41$	Observation	Presentation
Oh *et al.* [39]	K-12	$N_s = 20$	Game	Cooperative/ Collaborative
Phon *et al.* [40]	K-12	$N_s = 34$	Structured observation	Cooperative/ Collaborative
Restivo *et al.* [41]	K-12	$N_s = 21$	Inquiry	Cooperative/ Collaborative
Reyes-Aviles and	Higher education students	$N_s = 60$	Inquiry	Discovery

Aviles-Cruz [42]				
S. A. Yoon and Wang [43]	K-12	$N_s = 70$	Unknown	Unknown
S. A. Yoon *et al.* [44]	K-12	$N_s = 119$	Unknown	Cooperative/ Collaborative
S. Yoon *et al.* [45]	K-12	$N_s = 58$	Inquiry	Discovery
Sahin and Yilmaz [46]	K-12	$N_s = 100$	Observation	Presentation
Strzys *et al.* [47]	Higher education students	$N_s = 52$	Inquiry	Discovery
Suprapto *et al.* [48]	K-12	$N_s = 33$	Observation	Presentation
Tarng *et al.* [49]	K-12	$N_s = 56$ $N_t = 1$	Observation	Discovery
Thees *et al.* [50]	Higher education students	$N_s = 74$	Inquiry	Discovery
Tian *et al.* [51]	Higher education students	$N_s = 20$	Observation	Discovery
Tomara and Gouscos [52]	K-12	$N_s = 13$	Inquiry	Cooperative/ Collaborative
Tscholl and Lindgren [53]	Parents and children pairs	N = 194	Game	Cooperative/ Collaborative
Urbano *et al.* [54]	Higher education students	$N_s = 433$	Inquiry	Cooperative/ Collaborative
Xiao *et al.* [55]	K-12	$N_s = 36$	Observation	Presentation
Y. H. Wang [56]	K-12	$N_s = 52$ $N_t = 1$	Inquiry	Discovery
Yau *et al.* [57]	K-12	$N_s = 39$	Inquiry	Discovery
Zhang *et al.* [58]	K-12	$N_s = 200$	Observation	Discovery

First, it is important to note that any educational technology is only effective to the degree it is used effectively by the learner or teacher [59]. In analyzing the instructional strategies, an approach suggested by Akdeniz [60] was used. Specifically, the articles in our sample were categorized with respect to the variable "instructional strategy" as follows: Instruction through presentation, Instruction through discovery or Collaborative learning. In a presentation strategy, the application first gives students some general information about the topic, followed by a detailed explanation. Discovery is an instructional strategy in which students acquire knowledge by independently discovering certain phenomena, i.e., it is characterized by self-regulated learning. In earlier AR research, discovering was implicitly guided through students' interaction with the AR environment. Finally, collaborative learning is realized by dividing students into small groups in which they interact with the AR application to perform specific activities. In our sample of research articles, the discovery strategy was most frequently suggested, while the presentation strategy was far less popular.

In analyzing the instructional techniques, an approach proposed by Gündüz [60] has been followed. Specifically, with respect to the "instructional technique" variable, the articles in our sample were categorized as follows: Observation, Inquiry or Game. Observation is an instructional technique in which students are relatively passive learners whose role is mainly to observe information such as image, text, video or animation (e.g., they activate the AR-based tool and observe what happens). In contrast, inquiry is an instructional technique in which students actively construct their knowledge by exploring the physical phenomena at hand. Inquiry usually involves some of the following activities [61]: generating hypotheses, designing comparisons, collecting observations, analyzing data or constructing interpretations. Finally, an instructional technique is identified as a game when a format typical for games is used, such as rewards for correctness or immediate feedback in response to student interactions.

From the Table 2 we can see that the most commonly used instructional technique is inquiry (N = 23), while the most prevalent instructional strategy is discovery (N = 21). This is certainly due, at least in part, to the popularity of the constructivist approach to learning in the science education research community. In fact, by allowing for interactivity and learning through multiple representations [16,70], augmented reality applications are very handy for learning physics by inquiry.

3.2. Is the number of studies related to AR in teaching about physics increasing over time?
Table 3 shows how the 60 identified AR articles were distributed over the nine year period.

Table 3. Number of studies per year.

Year of publication	2012	2013	2014	2015	2016	2017	2018	2019	2020
Number of articles	3	3	7	2	6	5	8	8	18

From Table 3 it can be seen that augmented reality is becoming increasingly popular in physics education. The first studies on the use of AR in teaching about physics topics appeared in 2012 and since then the number of studies has been increasing. Specifically, among the 60 chosen articles, 70% were published between 2012 and 2019. From Table 3, we can also see that the largest increase in the number of studies relevant to the augmented reality in teaching physics topics occurred in 2020.

Our findings are consistent with the predictions of Horizon Reports from the year 2011 which states that augmented reality technology will become widespread to the many educational fields, in the near future [64].

In fact, the general development of technology has contributed to the more frequent usage of technological devices in the today's classrooms. Specifically, mobile phone is the predominant device used by almost all school students on a daily basis, and AR technology is increasingly available for mobile devices [72,73]. In general, statistics show that the majority of adults own more than one mobile device and the largest number of mobile-phone users are in the age range of the typical college student (18-29 years old) [67]. This could also potentially explain why it is much easier to use AR in class today than it was nine years ago. We can also argue that in recent years, software development kits and a wide range of hardware or mobile devices suitable for implementing augmented reality-based learning have become widely available and affordable for teachers and students.

3.3. How are the articles on AR in teaching physics topics distributed geographically?
Table 4 provides an overview of geographical distribution of the 60 articles from our sample. The country of origin was determined based on the location of the research site or affiliation of the first author (for non-empirical articles).

Table 4. Number of articles by country of origin.

Country	Turkey	Germany	USA	Taiwan	Malaysia	China	Japan	Spain	Singapore	Portugal
Number of articles	9	8	7	6	6	4	3	2	2	2
Country	Korea	Mexico	India	Indonesia	Kazakhstan	Greece	Colombia	Chile	Australia	
Number of articles	2	1	1	2	1	1	1	1	1	

From Table 4 we can see that articles on AR in teaching physics topics have been published by authors from almost every continent. Specifically, most articles were published by authors from Turkey (N = 9), closely followed by Germany (N = 8) and the USA (N = 7). From these findings, it follows that the general level of physics education research in a given country, the specific research interests in the physics education research community of a given country (i.e., research tradition), and the economic development factor are important predictors of the frequency of AR physics education articles. Concretely, a Scopus search, dated from November 11th 2021, with "physics education" as a search term (all fields) showed that most found articles have USA (991 results), Indonesia (288), Turkey (184) and Germany (156) as their country of origin. This indicates that these countries are at the top when it comes to publishing physics education articles. Three out of four of these countries are also at the top when it comes to publishing AR physics education articles. The reason why Indonesia is not at the top in publishing AR articles may be related to the fact that AR technologies are somewhat less accessible to teachers and students in Indonesia than in more economically developed countries such as USA, Germany and Turkey.

3.4. What types of participants and how many of them were included in earlier AR physics education research?

Tables 5 and 6 give us insight into the characteristics of the participants and the size of the participant samples in the 45 empirical research articles included in our review.

Table 5. Number of studies by types of participants; non-mutually exclusive categories have been used because some studies included more than one type of participants (e.g., they included students and teachers/parents).

Type of participants	K-12	Higher education students	Teacher	Parents
Number of studies	33	12	6	1

From the Table 5 we can see that most studies included K-12 participants (N = 33). Deeper analyses show that 10 out of these 33 studies included primary school students (grades 1 through 5), 12 studies included lower-secondary school students (grades 6 through 9), and 11 studies included upper-secondary students (grades 10 through 12). In addition, 12 studies included higher education students. Finally, there were 6 studies that included teachers/lecturers as participants. In general, it is important to note that some of the studies included more than one type of participants (Table 2). For example, in the study by Tscholl and Lindgren [53] the participants were parents and students. A similar distribution of participant types has also been observed in earlier AR systematic reviews [13,21]. This is probably related to the mere fact that the K-12 age group is the largest of all the groups mentioned above. We can also argue that students in K-12 education have their first contact with learning physics topics and it is important that this first contact is not too abstract which makes AR an attractive teaching technology. Pujol *et al.* [69] and Lee *at al.* [70] reported that many students spend a lot of time playing digital games or using the AR environment, which means they are skilled in using game consoles and mobile devices. This makes the K-12 population suitable for conduction of AR educational research.

Table 6. Distribution of studies according to size of the participant sample; non-mutually exclusive categories have been used because some studies included more than one type of participants (e.g., student-sample size was big, but teacher sample size was small).

Size of the participants sample	1 – 5	6 - 15	16 - 30	31 - 50	51 – 100	100 >
Number of studies	6	3	4	15	16	8

When it comes to participant sample sizes, from Table 6 it is evident that in previous AR physics education research, student samples mostly included between 30 and 100 students. However, there were also 8 studies with more than 100 participants, and one of these studies included more than 400 participants [54]. In addition to students, some of the studies included also teachers who were asked about their thoughts on the AR approach to physics teaching. In such studies conclusions were often drawn based on the opinion of a single teacher. This might be related to the fact that some populations are more accessible to researchers (e.g., university students) than others (e.g., teachers) [71]. It would be interesting to conduct some multi-level design experimental studies on AR physics teaching, in which multiple schools, teachers and students would be included.

3.5. In what learning environments was the AR physics education research situated?

Learning about physics topics takes place in different types of learning environments. It is useful to point out that learning environments may differ regarding how individuals interact with each other (social aspects), as well as regarding some of the material characteristics of the environment [72]. On the other hand, the effectiveness of learning methods and educational media may largely depend on the type of learning environment in which they are used [79,80]. Therefore, it is useful to describe findings on the applicability of AR in different learning environments.

In 41 of our 45 empirical research articles, AR-based learning took place exclusively in a classroom, while in 4 studies AR-based learning took place exclusively in an out-of-school environment.

It is obvious that AR was mainly used in a classroom. Considering that such a learning environment is the most typical, this finding is not surprising. In this learning setting, AR may be used by the teachers for facilitating whole-classroom demonstrations of physics phenomena, as well as for organizing guided group learning and individual learning.

AR might be particularly useful for skill development in a laboratory environment. This is because laboratory equipment is often insufficient to allow individual students to experiment independently with physical objects. This is where AR technology could provide a solution, as it is relatively easy to prepare AR experiments for multiple students. In fact, in science education research, augmented reality is effectively used to enhance learning in laboratory environments [81,82]. These types of labs can also provide students with the opportunity to conduct dangerous, costly and complex experiments that are very challenging to implement in vivo. Studies have proven that combining hands-on and virtual labs leads to better learning outcomes compared to independent use of hands-on experiments or virtual labs [83,84].

Finally, it is useful to note that in four studies AR-based learning took place exclusively outside the school setting. In two studies, Yoon *et al*. [52,53] investigated students' learning during a field trip to a science museum and Oh *et al*. [39] explored students' learning in a research lab setting. Similarly, Tscholl and Lindgren described how AR-based learning of physics can be implemented in a Science center as a research environment [53].

We could conclude that, taking into account the compatibility of AR with mobile devices which are omni-present, the AR technology could be a tool of choice to facilitate learning outside-of-school (e.g., in museums), in environments which lack the traditional teaching and learning aids, such as the blackboard. The potential of using AR technologies in outside of the school settings is currently clearly underutilized.

3.6. What are the most popular software development and hardware technologies for AR-based teaching about physics?

An overview of software development technologies that authors of the 60 identified articles used in their AR applications is presented in Table 7.

Table 7. List of studies by AR software technology.

AR software technology	Not specified	Unity 3D and Vuforia	Other
Number of studies	31	16	13

It can be seen from Table 7 that for a significant portion of the earlier articles, the authors did not explicitly state which software development tool was used for development of the AR application at hand. This practice should obviously be changed if we want the AR research to be replicable and informative. Next, it should be noted that in the papers from our sample, where the software development tool was explicitly stated, the most popular tool was Unity3D which was most often combined with Vuforia. This could be explained by the fact that Unity3D is an easy to use, multi-platform game development software with a large community of online users. In addition, Unity3D is an increasingly popular software for developing augmented and virtual reality experiences. It is particularly convenient for simulating physics problems because it has an embedded gravity and object collision system. Unlike many alternative software development tools, it is free to use. Researchers often combine it with the Vuforia plugin because this plugin is free for development of prototype AR applications and supports a wide range of phones, tablets, and eyewear. Its relative strength lies in the fact that it can be easily used for augmented reality applications, i.e., to detect and track images and 3D objects in real time. However, to publish Vuforia AR applications it is required to pay a license fee.

Additionally, to develop AR applications, researchers used a wider range of software packages (which were merged into the category "Other"): JSARtoolKit and Blender3D, ARwithWPF, Meta One SDK, Metaio Creator, Apple Integrated Development Environment Xcode with Vuforia SDK, GeoGebra, 3DS and Java3D, Android SDK and Java.

Next, it is also useful to provide some information about the AR hardware technologies used in the 60 identified AR-articles (Table 8).

Table 8. List of studies by AR hardware technology; non-mutually exclusive categories have been used because in some studies multiple technologies have been combined.

AR hardware technology	Mobile device (Android)	Mobile device (Not specified)	Smartglasses	Motion sensor	Desktop computer (camera)	Projector	Mobile device (IOS)	Other	Not specified
Number of studies	24	11	7	7	7	3	3	2	1

From Table 8 it is evident that in most of the identified articles, the authors use/recommend mobile devices for implementing AR-based learning about physics. Thereby, they most frequently use Android devices, which is a very practical choice since Android operating system is the most popular among students for playing mobile games [79]. Besides mobile devices, some authors use/recommend auxiliary hardware such as smartglasses, motion sensors, and projectors.

The most common augmented reality smartglasses are the HoloLens, which use sensors and advanced optics to display information about the real world or project virtual objects into the real world. They are particularly useful for education and business environments. For example, they have been successfully used to visualize the relationship between magnetic field, electric current and Lorentz force[80]. The most widely used motion sensor is *Kinect,* which allows users to interact with the AR environment through body gestures. It was effectively used for learning about magnetic fields in the study by Cai *et al.* [20]. When it comes to projectors and laser scanning motion sensors, they are particularly practical for room sized interactive augmented reality simulations from astronomy, as shown by Tschool and Lindgren [53].

Another technical aspect of AR educational research is the use of AR target features. Table 9 provides an overview of AR target features used/recommended in the 60 identified AR-articles.

Table 9. Number of studies by AR features; non-mutually exclusive categories have been used because in some studies multiple AR features have been combined.

AR features	Marker-based	Not specified	Location-based	Motion-based	Other
Number of studies	39	8	6	5	3

From Table 9 it can be seen that marker-based augmented reality was used/recommended in most of the articles from our sample. This could be explained by the fact that marker-based AR allows the creation of printed materials with interactive AR media, which can greatly facilitate the organization of physics learning in the classroom. Unlike location-based AR, where AR content can sometimes only be activated in a fixed location, marker-based AR allows users to use interactive AR simulations in their own learning environment. For example, marker-based AR was used in Majid and Majid's study [36] where students learned from a 3D model of atoms and from videos of real experiments in the augmented reality environment. On the other hand, location-based AR applications can be particularly useful for learning topics such as astronomy, because by using this technology students can see the targeted celestial bodies from the geographical location where they are located, regardless of weather conditions. For example, this has been recognized by Kirikkaya and Başgül [32] who used the location-based method for learning about meteorites, meteors, star clusters and galaxies. In contrast to the marker-based and location-based AR, a comparative strength of the motion-based AR is that it enables whole body learning, as in the case of asteroid movement simulation in the study by Tschool and Lindgren [53]. Finally, the markerless AR approach allows students to open simulations without the printed material, which was used by Reyes-Aviles and Aviles-Cruz [42] to show how DC circuits are working. This approach differs from traditional simulation-based learning in the point that students can observe related augmented reality data (3D objects, text or videos) presented directly over the real-world scenery.

3.7. What physics topics were covered through earlier AR physics education articles?

In general, the effectiveness of visualizations depends on the extent to which they are tailored to reflect the most important aspects of the target concepts [81]. Thus, there are good theoretical reasons for claiming that the AR effectiveness also depends on the nature of physics topics and that different physics topics may require different AR-learning approaches and different characteristics of the AR-applications. Consequently, AR studies are needed for a wide range of physics topics. For this reason, it is useful to see which physics topics have been covered in previous AR physics education articles. An overview of the physics topics covered through the identified 60 AR-articles is presented in Table 10.

Table 10. Number of articles by physics topic; non-mutually exclusive analysis categories have been used because some articles were related to multiple topics.

Physics topics	Electromagnetic waves	Ray optics	Electrostatics	Thermodynamics and heat	Atomic and molecular physics	Magnetism	Mechanics and mechanical waves	Astronomy	Electrical circuits
Number of articles	1	3	4	4	5	9	10	15	19

Table 10 shows that the most prevalent physics topic in our sample of AR-articles was "electrical circuits". Within this topic, the majority of articles was related to DC electrical circuits. This could be explained by the fact that for learning about electrical circuits it is very important to combine reasoning about microscopic processes with observable macroscopic phenomena, which is relatively easy to visualize with AR technologies [42]. The next most common topic is astronomy, where learning often requires spatial reasoning about the trajectories of planets and asteroids, which can be effectively facilitated by the use of AR technologies, as they inherently enable 3D visualization of phenomena [9,41,63].

There have also been a considerable number of studies that included learning about mechanical phenomena, from kinematical graphs, through forces, pressure, energy, work and collisions to fluids and mechanical waves [32,36,37,53]. Considering that mechanical phenomena are the most common in physics education research, this finding is not surprising. Again, AR technologies are typically used to relate macroscopic to microscopic phenomena (e.g., frictional forces in the study by [25]), as well as to visualize physical changes in space in real-time (e.g., dynamics of fluids, in the study by Sanderasagran *et al*. [82], and to facilitate simultaneous reasoning about spatial and temporal aspects of physical phenomena (e.g., mechanical waves, in the study by Daineko *et al*. [23]).

A considerable number of studies were related to magnetism, which again can be explained by the fact that this physics topic requires a lot of spatial reasoning (e.g., right and left hand rules, field lines), which can be facilitated by the 3D visualization features of AR. The same is true for electrostatics and atomic and molecular physics. For thermodynamics and ray optics, more important is the AR feature to simultaneously visualize macroscopic and relevant microscopic/abstract processes/entities (e.g., conduction of heat through solids or accounting for images by showing relevant characteristic rays)[58,89].

Although many physics topics have been covered in earlier research, it is useful to point out that some topics need further research. For example, there are not many studies on electromagnetic waves and wave optics, although these topics are very demanding when it comes to reasoning about spatial and temporal variables, and relating abstract mechanisms to macroscopic phenomena [81].

4. Conclusions

In this paper, we have provided a systematic overview on the state of the current scientific literature on the use of AR in teaching about physics. To this end, we included in our analysis all papers indexed in Scopus or Eric databases describing AR in the teaching about physics phenomena and published between January 2012 and November 2020.

We structured our systematic review around seven research questions which were related to: learning strategies and techniques used with AR, popularity of AR physics education research from 2012 to 2020, geographic distribution of AR research, student populations included in earlier research, learning environments in which AR has been used, popular software and hardware solutions and physics topics covered.

In answering RQ1 we concluded that majority of researchers used the discovery method as the learning strategy of choice to facilitate learning physics with AR technologies. The most commonly used learning technique was inquiry, followed by observation and game.

In relation to RQ2, we could conclude that augmented reality is becoming increasingly popular among physics education researchers, with the greatest increase in the number of studies in 2020. The recent development of hardware and software, as well as the availability of AR technologies have certainly influenced the rise in AR-popularity over the past year.

In answering RQ3 we concluded that sampled AR articles were from nineteen countries, spread over almost all continents. Most of the physics-related AR articles were from Turkey, Germany or the USA. These findings can be explained by the general level of physics education research in a country, followed by the level of economic development and the specificity of research traditions.

As for RQ4, we have shown that most of the earlier AR studies have included students from the K-12 educational level, which may be related to mere fact that this group was the largest of all included groups in our analytic categories. In addition, this population may be particularly suitable for conducting AR research, as young students are exposed to similar digital gaming technologies on a daily basis. There was approximately an equal number of studies for primary, lower-secondary and upper-secondary education. Relatively little research exists for education at the university level.

RQ5 referred to the identification of learning environments in which AR was used to facilitate learning of physics topics. It can be concluded that AR can be effective in a wide range of different environments. Most of the earlier studies were conducted in the classroom environment. In general, AR technology has the potential to provide individual students with an alternative to expensive laboratory equipment. It appears that use of AR technologies in outside-of-school environments is not sufficiently explored, although it is particularly suited for such environments where traditional teaching equipment is lacking.

In answering RQ6 our goal was to identify the most popular AR development software and hardware solutions. The majority of the studies used the marker-based augmented reality approach, which can be explained by the fact that it is compatible with the popular Unity and Vuforia software environment. This approach allows the creation of printed materials with interactive AR media, which is very important for combining AR with traditional learning media (e.g., textbooks). The most popular hardware devices that researchers have used in their studies are mobile devices, which can be explained by their wide spread and availability.

RQ7 referred to the identification of physics topics covered in the identified physics-related AR-articles. We could conclude that most of the studies were conducted for the electrical circuits topic. This could be explained by the fact that for learning about electrical circuits it is very important to combine reasoning about abstract microscopic processes with observable macroscopic phenomena, which is relatively easy to visualize with AR technologies. The next most common topic is astronomy, where learning often requires spatial reasoning about the trajectories of planets and asteroids, which can be effectively facilitated by the use of AR technologies because they inherently allow 3D visualization of phenomena. It is interesting to note that AR-based learning about electromagnetic waves and wave optics is underrepresented in earlier articles. This is especially true for the topic of light polarization, where 3D reasoning is very important for learning the topic.

In the end, we can conclude that AR technologies could be a potentially useful tool that can supplement traditional educational technologies, provided that they are carefully designed and implemented, as well as being consistent with the corresponding learning objectives. In addition, we included into our review only journal articles from the Scopus and Eric databases so future review studies should include articles from other databases such as Web of Science and ProQuest.

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