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Review

Theory and Practice of VR/AR in K-12 Science Education—A Systematic Review

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Abstract: Effective teaching of science requires not only a broad spectrum of knowledge, but also the ability to attract students' attention and stimulate their learning interest. Since the beginning of 21st century, VR/AR have been increasingly used in education to promote student learning and improve their motivation. This paper presents the results of a systematic review of 61 empirical studies that used VR/AR to improve K-12 science teaching or learning. Major findings included that there has been a growing number of research projects on VR/AR integration in K-12 science education, but studies pinpointed the technical affordances rather than the deep integration of AR/VR with science subject content. Also, while inquiry-based learning was most frequently adopted in reviewed studies, students were mainly guided to acquire scientific knowledge, instead of cultivating more advanced cognitive skills, such as critical thinking. Moreover, there were more low-end technologies used than high-end ones, demanding more affordable yet advanced solutions. Finally, the use of theoretical framework was not only diverse but also inconsistent, indicating a need to ground VR/AR-based science instruction upon solid theoretical paradigms that cater to this particular context.

Keywords: virtual reality; augmented reality; K-12 science education; systematic review

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1. Introduction

1.1. Augmented Reality/Virtual Reality(AR/VR) Applications and Beliefs

Science education for primary and secondary school students are facing a variety of challenges nowadays. On the one hand, scientific knowledge often contains a large number of abstract and complex concepts [1], which is difficult for children and adolescents to internalize, even with the help of words and 2D images [2,3]. For example, food digestion has been documented as an essential topic in many countries' primary school science curriculums [4–6], but without vivid animation, it can be overwhelming for students to obtain accurate understanding with their pure imagination. On the other hand, implementing real scientific experiments is often bounded by reality conditions, such as a lack of materials, high cost for necessary equipment, safety risks, or difficulties in geographical distance [7].

To tackle the above challenges, researchers have resorted to computing technologies, which are suggested should play a crucial role in student learning [8], comprehension of science concepts, as well as scientific reasoning skill development [9,10]. This is especially true for Generation Z, who have been born in the digital era, and have technologies permeated into virtually every aspect of their lives [11]. The way Gen Z processes information requires educators to not only teach with basic technologies, but capitalize the full potential of e-learning 4.0 [12], which is more personalized, data-based, and gamified [13]. For instance, instead of viewing pictures of digesting organs, students may use Google Board to view food digestion in action, and see clearly how food is processed in each organ with the naked eye. Among all advanced computing technologies, virtual reality (VR) and augmented reality (AR) are increasingly capturing educators' and learners' attention. In particular, VR is defined as a real-time graphical simulation in which the user interacts with the system via analog control, within a spatial frame of reference and with user control of the viewpoint's motion and view direction [14]. It first appeared in 1966 and was used in the design of US Air Force Flight Simulator [15]. Developed from VR, AR is a technology used for improving users' perception of the real world by dynamically adding virtual elements to the physical environment [16]. It made its debut in the 1990s, which was initially proposed by scientists from Boeing, an aircraft manufacturer, where they mixed virtual graphics with real environment displays to help aircraft electricians assemble cables [17].

As VR and AR technologies mature, they are gradually being applied in other domains, including education. For example, in order to teach the basic concepts of electromagnetism, researchers created an AR application so that students could explore the effects of magnetic fields [18]. Another example is that the system developed by VR technology simulated the movement of the Earth around the Sun, which could enable learners to better understand how seasons formed [19]. Since then, the positive effects of AR/VR integration have been documented in numerous studies, mainly including improved authenticity, increased animation, elevated interaction, enhanced student engagement, as well as reduced costs [20–26].

First of all, VR/AR can mimic authentic conditions to great extent, such as touring spots, planets or even body organs. For instance, they can enable learners to "reach" places that are difficult to reach in reality [20], and present the structure of cells, molecules and other microscopic objects [21], or the motion of large-scale cosmic objects right in front of their eyes [19]. Secondly, VR/AR can vividly demonstrate the occurrence of phenomenon or a process that may not be visible to naked eyes [22], and help learners better understand abstract scientific concepts with little or no oral explanation [23]. For example, while magnetic lines of force are real but invisible, VR/AR can help learners visualize the magnetic field line, and be aware of its existence and possible effects on human beings or everyday objects. Thirdly, VR/AR allows learners to manipulate objects to reflect authentic outcomes without suffering from real danger or risks of conducting experiments with especially hazardous or explosive chemicals [24]. For example, students can view the consequences of chemical mixtures in the environment created by VR without worrying about the danger of explosion. Fourthly, VR/AR provides richer sensory experience that is more attractive and interesting than pure narrative, text or pictures [22]. For example, students may not feel as excited or thrilled when watching a video of undersea scenes as those who experience with VR/AR equipment to explore creatures under the sea. VR/AR may also be used as a tool for game-based learning, which can stimulate learners' learning interest by presenting interactive games that they can navigate through using hand gestures, body movement, and other types of interactions [25]. In this way, their learning motivation would be greatly enhanced. Last but not least, compared with purchasing reality objects, VR/AR technology can greatly reduce such costs in the long term by presenting students with similar or lifelike experience with meticulous design [26].

1.2. Research Questions

Despite the above-mentioned benefits, the mere use of VR/AR does not necessarily guarantee successful outcomes. As Radu has reminded us, AR applications can be eye-catching and distracting at the same time, due to their frequent motion and the great number of objects presented to keep learners engaged [27].

Given the evolving nature of emerging technologies like VR/AR, and the fundamental role science education plays in K-12, it is crucial to systematically examine how AR/VR has been integrated with K-12 science education on both theoretical and practical levels. It is expected that, with the findings of the review, interested researchers and educators can be more informed of the trending theory and practice in the use of AR/VR in K-12 science education, and become more confident in using VR/AR to enhance science teaching and learning. A preliminary search on this topic has yielded four similar literature reviews. The contrasted differences between the four papers are listed in the table below (Table 1).

Table 1. A comparative analysis of related reviews.

Reference	Covered Years	Research Topics	Technology Type	Grade Level	Analyzed Dimensions
[28]	2004–2011	Science learning	AR	Not specified	1. Learning outcomes 2. Learning experience 3. Learner characteristics 4. Technical features 5. Learning content
[29]	2003–2017	Informal science learning	AR	K-12 students and adults	1. Learning content 2. Learning outcomes 3. Technical features 4. Type of devices
[30]	2009–2019	STEM education	Immersive VR	K-12 education and higher education	1. Publication information 2. Instructional context 3. Learners' background. 4. Research methodologies 5. Learning outcomes 6. Technical features 7. Type of devices
[31]	2002–2016	STEM education	Three-dimensional multi-user virtual worlds	7–12 years old; 13–17 years old; 18 years old and above	1. Learning topics 2. Instructional design methods 3. Technical features 4. Instructional design workflow

As shown in Table 1, none of the current systematic reviews provided information on the generic trends, theoretical stances and practical applications of both VR and AR in K-12 science education. Therefore, the aim of the present paper was to bridge this gap by addressing the following research questions:

1. What were the research trends?
2. What theories were grounded upon or adopted?
3. What types of learning activities have been conducted?
4. What research designs were used?
5. What types of VR/AR technologies were employed?
6. What kind of science education content was involved?
7. What were the learning outcomes?

2. Methods

2.1. Data Collection and Processing

According to Hsu et al. and Hwang and Tsai [32,33], it is important to review based on high-quality publications. In this study, a preliminary search was performed in October 2021, with the application of Boolean logic (virtual reality or VR or augmented reality or AR in subject terms) AND ("science education" or "science teaching" or "science learning" in abstract) AND ("primary school" or "elementary school" or "primary education" or "high school" or "k-12" in abstract). To ensure both quality and accuracy, only peer-reviewed journal papers with full text available have been included. This paper establishes the following inclusion and exclusion criteria (Table 2), and reviews each paper to determine whether it is eligible for analysis.

Table 2. Inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Students used VR/AR devices to learn	Not using VR/AR treatment as an independent variable
The participants were primary or secondary school or high school students	For preschool children, special education, college students, teachers and other adult learners
Learning of science	Non-science subjects
Empirical studies	Literature reviews, commentaries or meta-analysis
Written in English	Written in other languages

On this basis, the researchers performed the PRISMA review process (Figure 1), including identification, screening, qualification and analysis. After several rounds of screening, 61 papers meeting the standard were eventually retained (listed in the Appendix A), labeling ID1-ID61 sequentially.

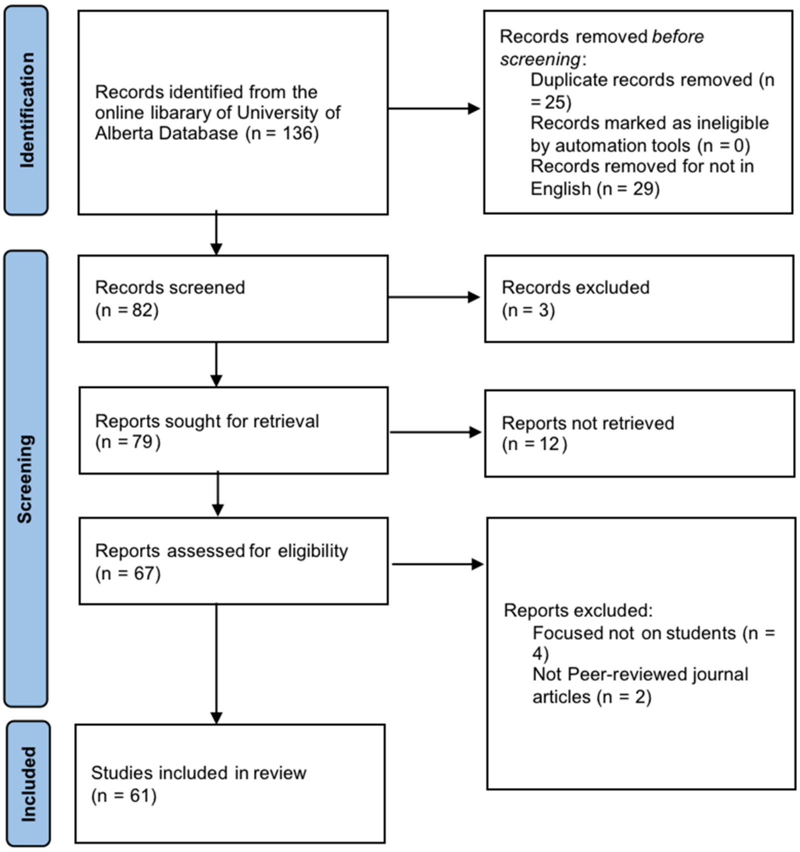

Figure 1. Literature selection process.

2.2. Coding Scheme

To better understand these studies, seven types of coding scheme were either adapted or developed as follows: (1) Codes for bibliometric analysis. In reference to Zou et al.'s [34], the bibliometrics information may be categorized by published years, distributed journals, involved disciplines and grades. (2) Codes for theories. Zydney and Warner propose that there are three theoretical types, namely the grounded theoretical foundations, cited theoretical foundations and theoretical foundations not provided [35]. (3) Codes for learning activities. Based on Luo's approach, learning activities can be analyzed from the perspective of learning mode, such as collaborative learning, inquiry-based learning, receptive learning and so on [36]. (4) Codes for research design. Luo also categorizes research design in six aspects, including the type of research, research method, number of experiments, study length, data collection method, and data analysis methods [36]. (5) Codes for VR/AR technologies and devices. According to Sun et al. and Chen [19,37], AR/VR technologies may be divided into four types, namely they are immersive VR, desktop VR, image-based (or tag based) AR and location-based AR. Meanwhile, Hwang et al. propose that devices of AR/VR refer to the hardware equipment they rely on, such as tablet computer, cameras, desktop computer, smart phone, etc. [38]. (6) Codes for content focus. In reference to Li and Tsai's classification of cognitive goals, we have coded the science learning content into six dimensions: scientific knowledge/concept, scientific reading, scientific process, problem solving, scientific thinking and scientific literacy [39]. It should be noted that scientific literacy is a comprehensive index, which includes the connotation of the first five indicators. (7) Codes for outcomes. Drawing upon Bloom's classification system [40], we have coded learning outcomes as one of the following: cognition, affection and behavior. Meanwhile, from the perspective of effectiveness, the papers were also classified as positive effect, negative effect or mixed effect. The positive effect means that the research results confirmed the research hypothesis; the negative effect means that the research hypothesis was refuted, and the mixed effect refers to having a positive effect in some of the variables and a positive effect in others.

3. Results

3.1. Research Trends

The distribution of publication per year is shown in Figure 2. It can be seen that the number of papers published per year has maintained relatively stable from 2002 to 2018, with no more than four papers every year. However, it surged up to eight in 2019, and 16 in 2020, indicating that more scholars have been paying attention to this field.

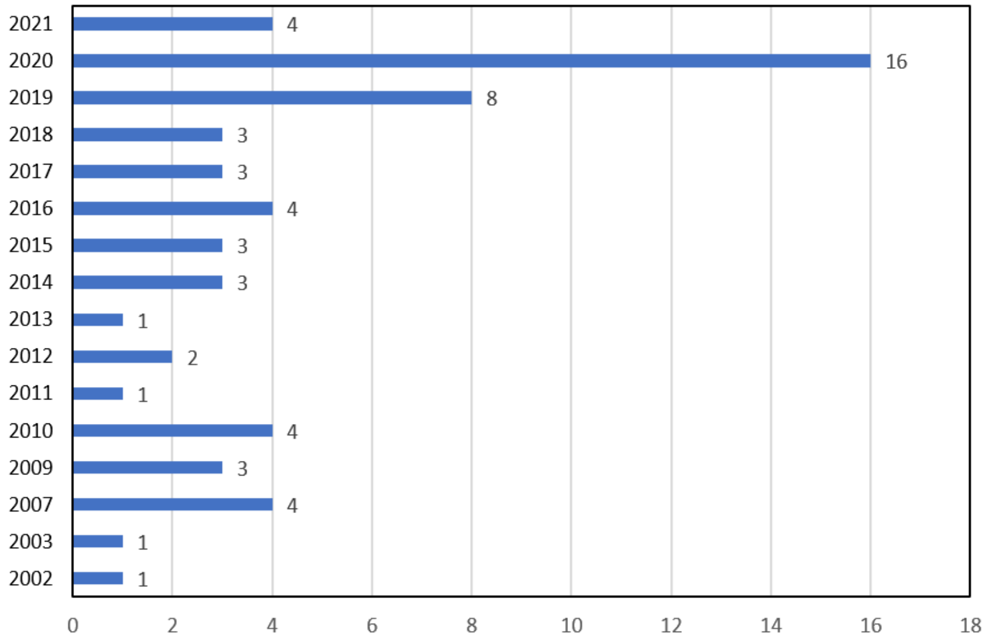

Figure 2. Number of published papers per year.

The journal distribution is shown in Figure 3. The most published journals were *Journal of Science Education and Technology* (9), *Computers and Education* (7) and *British Journal of Educational Technology* (6). Other less frequently published journals include *Journal of Educational Technology and Society*, *International Journal of Computer-Supported Collaborative Learning*, *Interactive Learning Environments*, and so on.

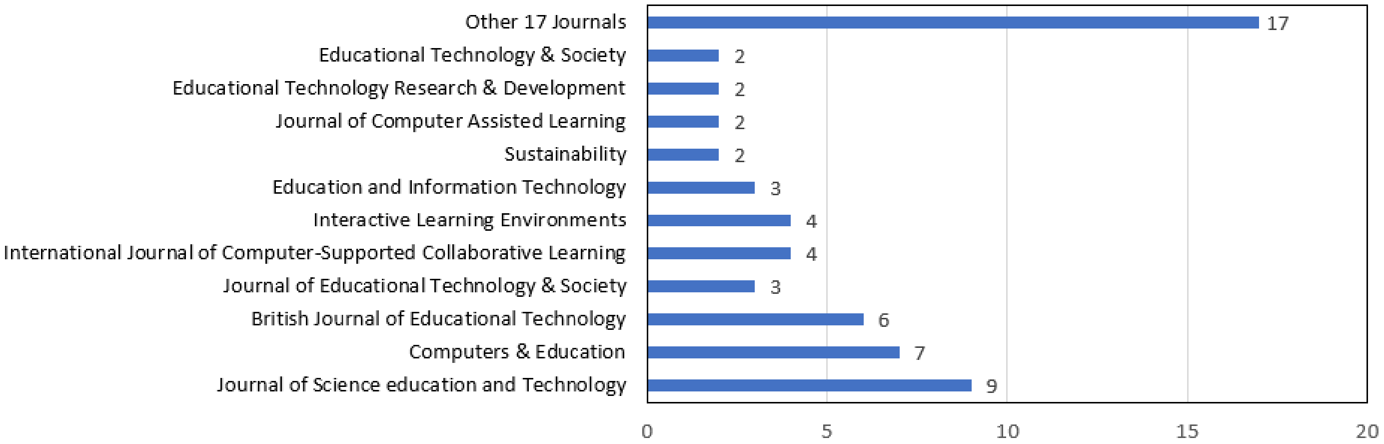

Figure 3. Number of papers published by each journal.

The cross-distribution by scientific discipline and level of education is shown in Table 3. The subjects were unevenly distributed across disciplines, with most focusing on Physics (23) and Biology (13). As for the participants, 50% were primary school students, 30.6% were junior students, and 19.4% were high school students.

Table 3. Discipline and level of education.

Discipline Classification	Primary School	Junior School	High School	Total
Astronomy	1	1	0	2
Biology	10	2	1	13
Chemistry	0	1	1	2
Environmental Science	1	1	2	4
Geography	6	3	2	11
Medical Science	0	2	3	5
Physics	13	7	3	23
Physiology	2	2	0	4
STEM	1	0	0	1
Science	2	3	2	7
Total	36 (50%)	22 (30.6%)	14 (19.4%)	72 [a]

Note: [a] Some studies involved multiple levels of education or disciplines, so the total number is more than 67.

3.2. Theories

With reference to Zydney and Warner, theories may be coded as one of three types: grounded theoretical foundations, cited theoretical foundations, and theoretical foundations not provided [35].

3.2.1. Grounded Theoretical Foundations

Grounded theoretical foundations refer to the explicit proposal to carry out research under the guidance of a certain theory. Among the 61 papers, 21 (34.4%) of them clearly indicated the theories they used, as shown in Appendix B. These theories cover a wide range of fields, including pedagogy, psychology, and learning science. This demonstrates that VR/AR research has integrated the latest developments of contemporary pedagogy, psychology, and learning science research. Meanwhile, it also shows that solid understanding of theoretical paradigms are perceived as critical for effective VR/AR instructional design.

3.2.2. Cited Theoretical Foundations

Among the 61 papers, 11 (18%) of them cited theories to analyze the research results. These theories were not directly applied to the design of VR/AR learning activities. Among the cited theories, constructivism was most frequently used (i.e., ID14, ID22, ID28, ID23, ID42, ID55), indicating that learners' active role and centrality were underlined in these studies. The second most cited theory was Mayer's cognitive theory of multimedia learning. Three papers (ID22, ID9, ID56) cited the continuous principle of the theory to demonstrate how learning materials designed according to the principle could effectively reduce the cognitive load of learners and improve learning performance. The other cited theories include cognitive load theory (ID22, ID56), cooperative learning theory (ID23, ID55), game-based learning theory (ID2), and so on.

3.2.3. Theoretical Foundations Not Provided

Thirty papers (49.2%) did not cite any theory to inform their learning or research design, but did mention certain terms closely related to particular theories. For example, Gnidovec et al. (ID36) studied 13- and 14-year-old students' technology acceptance of AR, which was a construct from the Technology Acceptance Model [41].

3.3. Learning Activities

The denotation of learning activities is shown in Appendix C. Among all the learning activities, inquiry-based learning was used the most (34 papers), followed by receptive learning (12 papers), problem-based learning (8 papers), game-based learning (6 papers), and collaborative learning (5 papers). It should be noted that in experimental research, only activities of the treatment group were accounted for, due to the inexplicit nature of the control group activity description.

The research using inquiry-based learning enabled learners to understand scientific concepts or phenomena through the operation and interaction of virtual things with the support of VR/AR. For example, Squire and Jan (ID2) required students to learn about polychlorinated biphenyls and mercury by exploring the cause of death of Ivan in VR games [42]. Sun et al. (ID6) built a VR model to simulate the movement of the Sun, the Moon, and the Earth [19]. Papers that adopted receptive learning used VR/AR to present virtual objects, so that learners could observe scientific things or phenomena in an intuitive way. For instance, Shim et al. (ID1) developed a VR system called VBRS simulating the iris and pupil of the human eye, through which students could see flowers of various shapes when they shifted between multiple viewpoints by pressing the number keys on the keyboard [43].

Three papers integrated collaborative learning, while they also adopted inquiry-based learning at the same time. That is to say, learners inquired about certain objects or phenomenon in collaborative ways. For instance, Chiang et al. (ID10) used location-based AR to assist students' investigation of the ecological environment of the pond near the school [44]; Fidan and Tuncel (ID23) developed an AR-based application, which used sound and animation to create an inspiring atmosphere [1].

There was one paper on flipped learning, topic-based learning and design-based learning respectively, as shown in Appendix C.

3.4. Research Designs

The research methods were combed in terms of six aspects, and the statistical results are shown in Table 4. First of all, the number of experimental studies (47 papers) was far more than that of investigation studies (14 papers). Secondly, the majority of studies employed quantitative design (31 papers) and mixed-research design (26 papers). Thirdly, most studies (24 papers) used VR/AR for teaching within 0–3 h, as compared to over three hours, and 25 papers reported teaching with AR/VR for only one class session. Furthermore, questionnaires (44 papers) and knowledge tests (32 papers) were used as major data collection methods. Finally, a t-test was the most frequently adopted statistical measure (34 papers).

Table 4. Classification of research design.

Research Type	Total (%)	Research Method	Total (%)
Experimental study	47(77)	Quantitative research	31(50.8)
Investigation research	14(23)	Qualitative research	4(6.6)
		Mixed research	26(42.6)
Learning time	**Total (%)**	**No. of class sessions**	**Total (%)**
0–3 h	24 (39.3)	1 time	25 (41)
3–10 h	14 (23)	2–3 times	4 (6.6)
Over 10 h	10 (16.4)	Over 3 times	19 (31.1)
Not reported	13 (21.3)	Not reported	13 (21.3)
Data collection method	**Total (%)**	**Data analysis method**	**Total (%)**
Questionnaire	44(72)	Independent/Paired sample *t*-test	34 (55.7)
Knowledge test	32 (52.5)	ANOVA [1]/ANCOVA [2]/MNOVA [3]	22 (36.1)
Interview	24 (39)	Qualitative material analysis	19 (3.1)
Observation/ethnography/student diary	8(13.1)	Wilcoxon statistical test	6 (9.8)
Video	4 (6.6)	Structural equation model	3 (4.9)
Sound recording	1(1.6)	Video analysis	3 (4.9)
Software records data	1(1.6)	Descriptive statistics	4 (6.6)
		Regression analysis	2 (3.3)
		Others	12 (19.7)

Note. [1] refers to Analysis of Variance; [2] is Analysis of Covariance; [3] is Multivariate Analysis of Variance.

3.5. Technologies and Devices

In terms of technologies, four types of VR/AR were identified (see Figure 4), including immersive VR, desktop VR, image-or marker-based AR, and location-based AR [28]. The immersive VR system surrounds the user with a 360-degree virtual environment; the desktop VR system is displayed to the user on a conventional computer monitor, whereas a 3-D perspective displays technology projects 3-D objects onto the 2-D plane of the computer screen [19].

Specifically, seven (ID6, ID16, ID27,ID43, ID48, ID51, ID56) of the 61 papers used immersive VR; 14 papers (ID3, ID20, ID4, ID1, ID5, ID24, ID41, ID42, ID49, ID52, ID55, ID59, ID60, ID61) used desktop VR; seven papers (ID9, ID10, ID21, ID30, ID46, ID53 ID54) used location-based AR, 31 papers used image-or marker-based AR, and two papers (ID14, ID18) used two kinds of VR or AR at the same time.

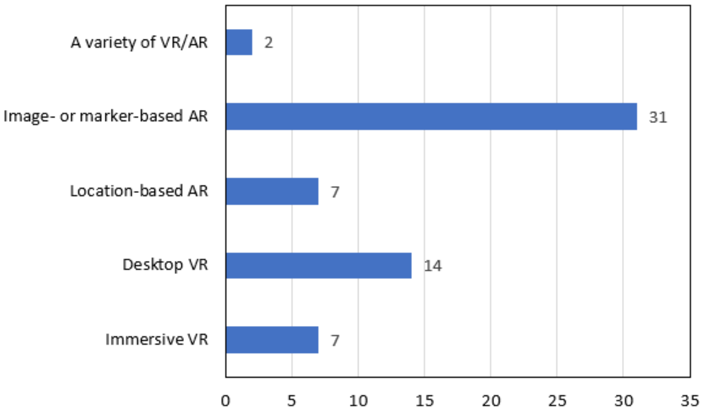

Figure 4. Technology types of reviewed studies.

As for the device or hardware equipment, it may be categorized as the following (Figure 5). It can be seen that tablet PC (24 papers), desktop PC (18) and smart phone (14) were the most frequently used devices, whereas devices like the puzzle set were least employed.

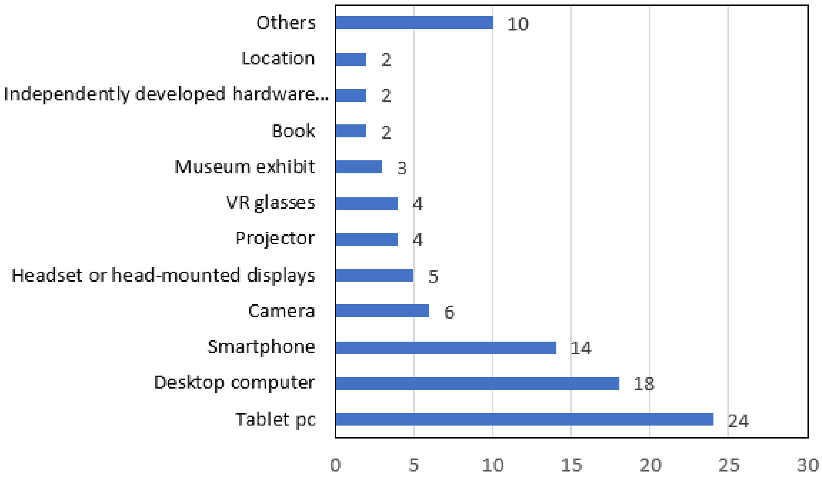

Figure 5. Number of times each device was used.

3.6. Content Focus

The first type of content was scientific knowledge/concept, which was also the most targeted among other types. Specifically, in 47 out of 61 papers, researchers used VR/AR technology to help learners understand scientific knowledge and concepts. For example, Wrzesien (ID5) used an immersive interactive virtual water world software called E-Junior to let learners play the role of Mediterranean residents or fish in the sea, participating in daily activities of the Mediterranean, and learning the concept and knowledge of marine ecology through exploration in the virtual world [20].

The second type of content was science reading. There was one paper on AR technology that supported scientific reading. In the research of Lai et al.'s (ID25), students used mobile devices equipped with an AR science learning system to scan the textbooks, and the relevant pictures would immediately and dynamically appear above them [45]. The experimental results showed that, compared with the traditional multimedia science learning method, the treatment significantly improved the students' academic performance and learning motivation, and also significantly reduced their perception of the external cognitive load in the learning process.

The third type of learning was scientific process, and two paper (ID15, ID61) focused on this. For example, Hsu et al. (ID15) used AR technology to build a surgical simulator to train students performing laparoscopic surgery and cardiac catheterization [46]. They found that students had positive cognition and high level of participation in AR courses and simulators, and their interest in learning greatly increased.

The fourth type was problem-solving (9 papers). For example, Kyza and Georgiou (ID21) used an AR application called TraceReaders, which allowed learners to write location-based AR applications for outdoor survey learning [47].

Three papers (ID2, ID37, ID44) embodied the fifth type of content, which was science thinking. For example, Chang et al. (ID37), with the support of mobile AR, aided students in contemplating about the dilemma of building nuclear power plants and using coal-fired power plants in virtual cities [48]. It is found that students' previous knowledge and beliefs had a certain impact on students' ability to participate in learning and reasoning.

Finally, there were also two papers (ID34, ID50) focusing on acquiring science literacy. Scientific literacy is the comprehensive embodiment of scientific knowledge, scientific thinking, and scientific ability [49]. Wahyu et al. (ID34) found that mobile AR assisted STEM learning could significantly improve students' scientific literacy than traditional learning methods [49].

3.7. Outcomes

The learning outcomes of 61 papers were classified according to the theory of Bloom's instructional objective classification [40]. As is shown in Figure 6, 46 papers set cognitive goals, and six of them reported mixed effects; 40 papers established affection goals, and five of them reported mixed effects. Three papers aimed to improve behaviors, all of which reported positive effects.

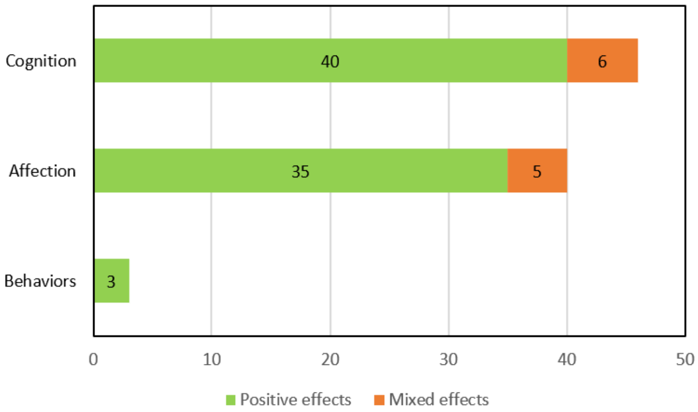

Figure 6. Number of times each dimension of learning goals appeared. Note. The total does not add up to 61 because one study could set multiple types of goals.

3.7.1. Cognitive Goals

There were 46 papers that focused on realizing cognitive goals. Most of them (40) concluded that VR/AR technology could effectively improve the academic performance of science courses, enhance the understanding of scientific concepts and phenomena (31 papers: ID1, ID4, ID6, ID7, ID8, ID9, ID12, ID13, ID14, ID16, ID17, ID18, ID19, ID20, ID21, ID22, ID23, ID24, ID25, ID28, ID29, ID30, ID32, ID36, ID40, ID41, ID43, ID44, ID55, ID57, ID58), promote students' knowledge construction (3 papers: ID10, ID40, ID51), improve their science thinking ability (6 papers: ID2, ID11, ID20, ID30, ID37, ID44), improve their problem-solving ability three papers: ID21, ID41, ID60), realize the comprehensive improvement of scientific quality (2 paper: ID34, ID50), or evaluate the effect of students' mastery of scientific process (1 paper: ID61). For instance, Çakıroğlu (ID40) found that the VR environment provided a variety of sensory stimuli, enabling students to observe things closely and pay more attention to details [50]. Moreover, VR materials could help learners better associate previous knowledge with new knowledge.

But there are still some studies (6 papers: ID3, ID5, ID33, ID38, ID49, ID52) concluding that VR/AR technology was no more effective than non-VR/AR technology in improving students' performance. For example, Chen et al. (ID3) developed an Earth VR motion system to help understand the changes of day and night and four seasons caused by the Earth's rotation. The researchers conducted a pre-test and a post-test on the students, and the scores of most post-test items were higher than those of pre-test. However, for the questions about the rotation of the Earth, the students' post-test score was significantly lower than the pre-test score due to the fact that the system did not provide sufficient information about the Earth's rotation [14]. Similarly, Wrzesien et al. (ID5) concluded that there was no significant difference in academic performance between the experimental group using VR technology and the control group using traditional learning methods [20]. A possible cause could be that the attraction of the virtual environment had diverted students' attention. They were more interested in operating virtual things than scientific concepts themselves. Wang (ID33) found that students who used e-Book learning materials had higher scores than students who used AR learning materials, although the difference was not statistically significant [51]. It may be inferred that well-designed AR content could limit students' thinking, because some students preferred studying directly based on the guidance of AR content as soon as they received the materials, and completed the tasks without thinking. E-books do not provide very detailed demonstration information, but the text information guided by graphics makes learners think first and then work. Chen (ID38) compared the differences between the game method and AR supported learning, and found that there was no significant difference between the two methods in improving academic performance [37]. It may be because several methods used in the experiment provided immediate reflection tips when students submitted wrong answers, while AR did not give full play to its advantages in multimedia learning.

3.7.2. Affective Goals

The 40 papers that examined affective goals could further be broken down into secondary dimensions, such as motivation (16 papers), attitude (15), engagement (8), technology acceptance (8), interests (7), self-efficacy (5), cognitive load (5), satisfaction (4), expectation of success (3), etc.

Among the 40 papers, most of them (35 papers) reached a relatively consistently positive conclusion, that is, the use of VR/AR technology could stimulate learners' motivation (15 papers: ID5, ID9, ID15, ID16, ID19, ID20, ID25, ID27, ID30, ID32, ID33, ID38, ID40, ID44, ID47), attitude (14 papers: ID2, ID4, ID6, ID14, ID16, ID23, ID26, ID28, ID29, ID31, ID34, ID35, ID45, ID61), and learning interest (7 papers: ID1, ID6, ID27, ID44, ID50, ID53, ID56), and then made students more engaged in learning (8 papers: ID5, ID11, ID14, ID15, ID21, ID37, ID43, ID49), so as to obtain better satisfaction (3 papers: ID5, ID22, ID40), expectation(1 paper: ID40), good mood (1 paper: ID42), more sustainable values and norms (1 paper: ID50), or to enhance students' flow states (1 paper: ID38), or to have a good perception of the authenticity (1 paper: ID59). Most of them drew conclusions that the use of VR/AR had a higher technology acceptance (7 papers: ID5, D18, ID26, ID33, ID36, ID43, ID47) than non-VR/AR technology, having lower cognitive load than non-VR/AR technology (1 paper: ID25) or the same cognitive load with non-VR/AR technology (4 papers: ID9, ID20, ID22, ID30).

This is mainly because the environment and virtual objects created by VR/AR provided students with experience that could replace the real environment [46], and provided opportunities for inquiry-based learning, so that students could experience pleasure and interest in the process of inquiry [52]. Moreover, unlike the extrinsic motivation stimulated by reward, praise or punishment, VR/AR attracted learners and stimulated their intrinsic motivation [20]. For example, Chang and Hwang (ID20) found that the AR-based flipped learning guiding approach not only benefited the students in terms of promoting their project performance, but also improved their group self-efficacy [53]. Chang et al. (ID30) concluded that the combination of VR technology and peer assessment learning method significantly improved students' self-efficacy [54].

However, there were still some studies that concluded with negative results in such dimensions as motivation (1 paper: ID32), technology acceptance (1 paper: ID46), self-efficacy (1 paper: ID48), satisfaction (1 paper: ID55), expectation (1 paper: ID56) and so on. It could be because that the use of VR/AR was too complex to operate appropriately and effectively, or that there was insufficient information provided, which could have resulted in learning difficulty. For example, Lu et al. (ID32) found that the experimental group using AR has lower learning motivation than the control group without AR. The author believed that the main reason was that learners were unfamiliar with materials and equipment, which posed certain learning challenges [55]. Lo et al. (ID46) found that the perceived usefulness of using AR was correlated with age. That is, older students tended to think that AR applications were not very useful. It was hypothesized by the authors that the older the students were, the harder it was for them to follow the teacher's instructions, or the more difficult for them to learn [56]. Shin (ID55) found that the learners did not enjoy the experience of desktop VR, because it did not generate a strong sense of immersion [57].

3.7.3. Behavioral Goals

There were three papers (ID11, ID54, ID57) that focused on realizing behavioral goals. These studies reached a consistent conclusion that the use of VR/AR could improve students' learning behavior. For example, Yoon and Wang (ID11) compared the time of interaction with devices and team cooperation between AR users and non-AR users. It was found that the former's time of interaction with devices was significantly higher than that of the latter, while the team cooperation was the opposite. This indicated that AR devices improved participation in learning, but also affected cooperation between teams to some degree [58].

4. Discussion

4.1. Trends in the Integration of VR/AR in K-12 Science Education

First of all, there is a growing number of studies in VR/AR's integration in K-12 science education, indicating researchers' and practitioners' interest in using VR/AR to enhance learning science. For instance, 20 out of 60 papers were published in the last two years. Despite this, the majority of studies were published much more in generic educational technology journals, such as *Computers and Education* and *Educational Technology and Society*, which accounted for 85% of all. Contrarily, only few domain specific science education journals (i.e., *Journal of Science Education and Technology*) published such studies. This may be due to the fact that for most K-12 science teachers, VR/AR is an emerging technology that seems novel and inaccessible, and its effects on students is still ambiguous without conclusive findings or universal instructional design models [59,60]. Therefore, in future research more attention should be paid to the exemplary integration of VR/AR into teaching specific science topics, foster deep integration and enumerate the particular effectiveness of VR/AR application on students' learning outcomes, so that science teachers become more receptive of VR/AR uses.

Secondly, the theories involved appeared very diverse. On the one hand, this diversity demonstrates VR/AR's capacity of accommodating a multitude of theories; on the other hand, it also indicates the lack of an over-arching theoretical paradigm that could guide AR/VR-based science instructional design. Such a paradigm would not be possible without the collaborative effort from learning scientists, science teaching experts, instructional designers and VR/AR specialists. The absence of any of the stakeholders may lead to an ineffective design framework. It should also be noted that 45% of the reviewed papers did not cite any theory, which could lead to unsubstantiated interpretation of obtained results.

Thirdly, inquiry-based learning was the most adopted learning model (87.5%) among the reviewed studies, which is consistent with previous findings that inquiry-based learning was one of the most commonly used learning models [28–31]. Regardless, this learning model was not entirely gauged with the measured learning outcomes in the reviewed studies. That is, although students indeed used VR/AR devices, teachers did not necessarily capitalize on the benefits of inquiry-based learning, beside providing students with immersive or lifelike experiences. Previous studies have shown that inquiry-based learning without sufficient guidance is not significantly better than traditional textbook teaching [61]. Thus, it must be cautioned that there is a fine line between inquiry-based learning and simply asking students to explore or view an VR/AR object or environment. For example, Salmi et al. (ID19) developed a mobile AR application to enable students to explore the different reactions between a number of atoms and molecules, within which students only needed to interact with the AR system to view the structure of atoms and molecules; thus, it could be hardly deemed as inquiry-based learning [62].

Fourthly, in terms of the research methods, there were more quantitative studies (50.8%) than qualitative or mixed-method studies (42.6%), more experimental designs (77%) than investigation designs (23%). The emphasis on experimental studies could be because that those experimental studies were practically more welcomed than investigative studies in nearly all academic journals, owing to their more advanced statistical analysis measures and illustrations. Meanwhile, experimental studies help teachers make more instant and precise adjustment to their existing science teaching, such as integrating a certain VR/AR software, or a device. On the other hand, investigation studies are more suitable for understanding students' perceptions, attitudes or satisfaction toward the generic VR/AR technologies, the results of which may not be directly applied to specific instructional design or adaptation.

Last but not least, there were a variety of VR/AR technologies employed, such as location-based AR, image-or marker-based AR, immersive VR, and desktop VR, but the ratio of using advanced VR/AR technologies was very low. This is in direct contrast to Pellas, Dengel and Christopoulos's finding that 60% of the studies used high-end immersive devices, while nearly 30% used low-end solutions [36]. One major reason could be that school teachers were unlikely to purchase higher-end technologies, for experiment's sake without school's financial support. Moreover, considering K-12 students' cognitive ability and psycho-motor skills, it is not only appropriate but also safe for them to use less-advanced and -expensive devices, so as to avoid the risks of under-utilization or damage. In other words, to increase the diffusion of AR/VR use in K-12 science education, there is a need to develop more affordable and portable devices that can be easily operated, so that both science teachers and students can utilize them effectively and efficiently. Also, given that there were only four papers (ID8, ID11, ID17, ID34, accounting for 10%) that focused on learning with AR/VR in informal environment, it may be suggested that VR/AR technologies that can be easily transported from one place to another be developed, so that students can learn with such technologies seamlessly in and out of class. For instance, students who were instructed to observe planets with VR/AR devices in class may continue to learn this topic at home by using both VR/AR technologies and their personal microscope.

4.2. Issues in the Integration of VR/AR in K-12 Science Education

Despite its apparent advantages, VR/AR also has its limitations or issues. The first type of issues reflected in previous studies are technical issues, which refer to either the inherent limitations of VR/AR technologies, or the associated technological glitches, such as lack of mobility and inconvenience of using, especially for immersive VR. For example, HMD, trackers and other VR-related utilities like the Cave Automatic Virtual Environment could often cause such difficulties [14].

The second type of issues are pedagogical issues. Teachers who use VR/AR to teach science may have problems in using it effectively and efficiently, including identifying the most suitable resources, designing the most appropriate activities, or conducting the most precise assessments. For instance, VR/AR has been reported as distracting and visually overloading. Wrzesien and Raya (ID55) found that there was no significant difference between the results of the experimental group using virtual devices and the control group without virtual devices. Learners were easy to get lost in the virtual environment, and a lack of sufficient learning information was the main reason for this phenomenon [20]. Teachers thus are obligated to sift through various VR/AR resources, and identify those that are age-appropriate, visually comfortable, and mentally congruent. Also, as Charsky and Ressler (2011) point out, the lack of teaching methods and objectives can make students confused and depressed, and even increase their knowledge overload and reduce their learning motivation [63]. Some studies noted the limitations of VR/AR technology and sought to overcome them with supplementary activities. For example, Yoon et al. (ID8) used knowledge prompts, a bank of peer ideas, working in collaborative groups, instructions for generating consensus, and student response forms for recording shared understanding [64]. These scaffolds could promote collaboration within the peer groups by encouraging students to discuss their observations and reflections of their experience. Another pedagogical issue lies in the comprehensive and accurate evaluation of student learning outcomes. For instance, students' cognitive and affective outcomes were mainly measured, whereas behavioral change was less emphasized.

The third type of issues can be categorized as social issues. For instance, the price of VR/AR devices is considered a social issue, rather than a technical issue, because the price is not solely determined by the technical complexity or sophistication, but its relative novelty among other technologies as well as the income level of its targeted consumers. Meanwhile, whether teachers can integrate VR/AR into science teaching is greatly dependent upon the social perceptions of such technologies, as well as their school support, both of which constitute the context for our topic. For instance, according to Chih et al., not all schools were willing to pay a high price for virtual display devices and real-world devices [14].

There are also several research issues. In terms of the research length, about 62% of the studies observed usage for less than 10 h. Under such circumstances, probability factors like the novelty effect could hardly be eliminated. Also, while a multitude of variables were examined, including scientific reading, scientific process, scientific problem solving, scientific literacy and so on, most studies still focused on low-level cognition through knowledge tests; high-level thinking ability has not received adequate attention. According to Bloom's goal classification, memory, understanding, and application correspond with low-order thinking abilities, whereas analysis, evaluation and creation belong to high-order thinking abilities [65]. Academic research shows that "injection" mode is usually used to cultivate high-level thinking ability in science learning; that is, the learning of thinking skills is integrated with the learning of the science curriculum. In this mode, students are fully involved in thinking practice, focusing on the learning process and understanding of meaning. After solving certain challenging problems, high-level thinking skills can be developed [65]. However, the emphasis on higher-order thinking has been absent in most reviewed studies in this paper. This is consistent with previous research that the application of VR/AR in science education mainly focuses on the understanding of scientific concepts and phenomena [28,29]. For example, 85% of the studies focused on students' mastery of scientific knowledge or concepts, without mentioning critical thinking, social reasoning ability, innovation tendency and other high-level thinking ability. Moreover, the data analysis methods relied mostly on *t*-test (55.7%), which would be insufficient to analyze more complex relationships or phenomenon.

4.3. Implications and Recommendations

Based on the issues identified above, we offer the following suggestions in both theoretical advancement and practical improvement of the VR/AR's integration in K-12 science education. As for science teachers, it is paramount to be familiar with both psychological and pedagogical theories, so that VR/AR-based activities can effectively and efficiently promote student learning interest as well as achievement. They should also be very selective in choosing the most appropriate and authoritative VR/AR apps or resources, so as to not only meet the learning demand of students, but also avoid foreseeable technical glitches. When designing learning activities, it is essential for teachers to target more advanced skills, such as critical thinking, in order to cultivate students' inquiry-based mindset. What's more, with the knowledge of trending VR/AR practices, teachers may embrace more learning models like collaborative learning and project-based learning into their science instruction. Researchers, on the other hand, are suggested to conduct more mixed-method studies, which offer a comprehensive and profound understanding of students' experiences and changes in cognition, affection and behavioral skills. They may as well include teachers as research participants, instead of focusing on students only, so that barriers in teachers' intention or proficiency of VR/AR integration could be identified and addressed at an early stage. When possible, studies that last longer and have repeated trials are strongly recommended. Longer interventions with repeated evaluation could help solidify the benefits of VR/AR-based science instruction, and boost teachers' confidence with its exemplary uses. Finally, technical experts or software engineers may be prompted to develop more affordable, portable and personalized subject-specific VR/AR technologies, and program more science-related immersive VR/AR environment that cater to different grade levels' needs. For instance, lower-grade level students may use AR/VR to gain new experience and direct observation, while higher-grade levels may use it to foster the ability to analyze, evaluate and even create.

4.4. Limitations

The current research also has its limitations. For example, the review was very selective, meaning that we intentionally chose journal articles from renowned databases only to ensure quality, rather than including also conference papers or theses. Another limitation was that the citation or reference network analysis were not included, in order to keep the paper more focused and tightened. Future research that aims to conduct a more comprehensive review could enlarge the scope and utilize knowledge mapping software to illustrate the trend and research hot spots with sophisticated displays.

5. Conclusions

VR/AR is advantageous in K-12 science education [18]. The purpose of this paper was to examine the theoretical and practical trends and issues in existing research on VR/AR's application in K-12 science education between 2000 and 2021, including the publication data, adopted theories, research methods, and technical infrastructure, etc. It was found that there has been a growing number of research projects on VR/AR integration in K-12 science education, but studies pinpointed the technical issues rather than the deep integration of AR/VR with science subject content. Also, while inquiry-based learning was most frequently adopted in reviewed studies, students were mainly guided to acquire scientific knowledge, instead of cultivating more advanced cognitive skills, such as critical thinking. Moreover, there were more low-end technologies used than high-end ones, demanding more affordable yet advanced solutions. In terms of research methods, quantitative studies with students as the sole subjects were mainly conducted, calling for more mixed-method studies targeting both teachers and students. Finally, the use of theoretical frameworks was not only diverse but also inconsistent, indicating a need to ground VR/AR-based science instruction upon solid theoretical paradigms that cater to this particular domain.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Details of the reviewed studies.

ID	Reference	Paper Title	Theories	Learning Activities
ID1	[43]	Application of virtual reality (VR) technology in biology education	Not provided	Receptive learning
ID2	[32]	Mad City Mystery: Developing scientific argumentation skills with a place-based augmented reality (AR) game on handheld computers	Game based learning theory	Game-based inquiry learning
ID3	[14]	A desktop VR earth motion system in astronomy education	The theory of experiential learning	Inquiry-based learning
ID4	[66]	An ethnographic comparison of real and VR field trips to Trillium Trail: The salamander find as a salient event	Grounded on theory of multiple intelligences	Inquiry-based learning

Table A1. *Cont.*

ID	Reference	Paper Title	Theories	Learning Activities
ID5	[20]	Learning in serious virtual worlds: Evaluation of learning effectiveness and appeal to students in the E-Junior project	Grounded on three theories: the experiential learning theory, theory of leisure, multiple intelligences theory	Game-based inquiry learning
ID6	[19]	A 3-D VR model of the sun and the moon for e-learning at elementary schools	Used the language related to learning attitude theory but did not cite it	Inquiry-based learning
ID7	[67]	Learning physics through play in an AR environment	Used the language related to cooperative learning theory but did not cite it	Inquiry-based learning and collaborative learning
ID8	[64]	Using AR and knowledge-building scaffolds to improve learning in a science museum	Grounded on knowledge construction theory	Inquiry-based learning
ID9	[52]	An AR-based mobile learning system to improve students' learning achievements and motivations in natural science inquiry activities	Cited Meyer's multimedia design theory and used the language related to inquiry learning theory but did not cite it	Inquiry-based learning
ID10	[44]	Students' online interactive patterns in AR-based inquiry activities	Grounded on knowledge construction theory	Inquiry-based learning and collaborative learning
ID11	[58]	Making the invisible visible in science museums through AR devices	Not provided	Inquiry-based learning
ID12	[68]	Employing Augmented-Reality-Embedded instruction to disperse the imparities of individual differences in earth science learning	Used the language related to learning style theory but did not cite it	Inquiry-based learning
ID13	[69]	Constructing liminal blends in a collaborative augmented-reality learning environment	Grounded on distributed cognitive theory	Inquiry-based learning and collaborative learning
ID14	[70]	Enhancing learning and engagement through embodied interaction within a mixed reality simulation	Grounded on embodied learning theory; cited constructivism theory; used the language related to learning attitude theory, self-efficacy theory, learning participation theory but did not cite them	Inquiry-based learning
ID15	[46]	Impact of AR lessons on students' stem interest	Used the language related to learning motivation theory but did not cite it	Inquiry-based learning
ID16	[71]	An augmented-reality-based concept map to support mobile learning for science	Used the language related to learning motivation theory, learning attitude theory but did not cite it	Inquiry-based learning and receptive learning
ID17	[72]	How AR enables conceptual understanding of challenging science content	Not provided	Receptive learning
ID18	[45]	The influences of the 2-D image-based AR and VR on student learning	Grounded on cognitive load theory; Used the language related to technology acceptance but did not cite it	Inquiry-based learning

Table A1. *Cont.*

ID	Reference	Paper Title	Theories	Learning Activities
ID19	[62]	Making the invisible observable by AR in informal science education context	Cited Self-determination theory; Used the language related to learning motivation theory but did not cite it	Receptive learning
ID20	[53]	Impacts of an AR-based flipped learning guiding approach on students' scientific project performance and perceptions	Used the language related to critical thinking theory, group self-efficacy theory, learning motivation theory, and psychological load theory but did not cite it	Flipped learning
ID21	[47]	Scaffolding AR inquiry learning: The design and investigation of the Tracereaders location-based, AR platform	Grounded on the theory of experiential learning and used the language related to the theory of inquiry learning but did not cite it	Inquiry-based learning
ID22	[73]	Impacts of integrating the repertory grid into an AR-based learning design on students' learning achievements, cognitive load and degree of satisfaction	Grounded on situated learning theory and cited constructivism theory, cognitive load theory, and cognitive theory of multimedia learning	Receptive learning
ID23	[1]	Integrating AR into problem based learning: The effects on learning achievement and attitude in physics education	Grounded on Situational learning theory; Cited constructivism theory, cooperative learning theory, Self-guidance theory, situational learning theory; Used the language related to learning attitude theory but did not cite it	Problem-based learning
ID24	[74]	Applying VR technology to geoscience classrooms	Not provided	Problem-based learning
ID25	[45]	An AR-based learning approach to enhancing students' science reading performances from the perspective of the cognitive load theory	Grounded on cognitive theory of multimedia learning and cognitive load theory; used the language related to learning motivation theory but did not cite it	Problem-based learning
ID26	[21]	A usability and acceptance evaluation of the use of AR for learning atoms and molecules reaction by primary school female students in Palestine	Not provided	Receptive learning
ID27	[75]	The effect of the AR applications in science class on students' cognitive and affective learning	Used the language related to learning motivation theory, learning interest theory, and meaningful learning theory but did not cite them	Receptive learning

Table A1. *Cont.*

ID	Reference	Paper Title	Theories	Learning Activities
ID28	[26]	The effect of using VR in 6th grade science course the cell topic on students' academic achievements and attitudes towards the course	Cited Piaget's learning theory and used the language related to learning motivation theory but did not cite it	Receptive learning
ID29	[76]	The effect of AR Technology on middle school students' achievements and attitudes towards science education	Used the language related to learning motivation theory but did not cite it	Topic-based learning
ID30	[54]	Integration of the peer assessment approach with a VR design system for learning earth science	Used the language related to learning motivation theory, critical thinking theory, creative ability theory, and cognitive load theory but did not cite it	Design-based learning
ID31	[77]	Students' motivational beliefs and strategies, perceived immersion and attitudes towards science learning with immersive VR: A partial least squares analysis	Used the language related to motivation theory, self-regulation theory, learning attitude theory but did not cite it	Inquiry-based learning
ID32	[55]	Evaluation of AR embedded physical puzzle game on students' learning achievement and motivation on elementary natural science.	Used the language related to learning motivation theory but did not cite it	Game-based inquiry learning
ID33	[51]	Integrating games, e-Books and AR techniques to support project-based science learning	Used the language related to learning motivation theory but did not cite it	Inquiry-based learning
ID34	[49]	The effectiveness of mobile AR assisted stem-based learning on scientific literacy and students' achievement	Not provided	Inquiry-based learning
ID35	[78]	Using AR to teach fifth grade students about electrical circuits	Used the language related to learning attitude theory but did not cite it	Receptive learning
ID36	[41]	Using AR and the Structure–Behavior–Function Model to teach lower secondary school students about the human circulatory system	Used the language related to technology acceptance but did not cite it	Receptive learning
ID37	[48]	Students' context-specific epistemic justifications, prior knowledge, engagement, and socioscientific reasoning in a mobile AR learning environment	Used the language related to situational cognitive theory, learning engagement theory but did not cite them	Inquiry-based learning
ID38	[37]	Impacts of AR and a digital game on students' science learning with reflection prompts in multimedia learning	Used the language related to situational learning theory but did not cite it	Inquiry-based learning
ID39	[79]	Use of mixed reality applications in teaching of science	Used the language related to learning motivation theory, learning attitude theory but did not cite them	Receptive learning
ID40	[50]	Perceived learning in VR and animation-based learning environments: A case of the understanding our body topic	Used the language related to constructing knowledge and so on but did not cite it	Receptive learning

Table A1. *Cont.*

ID	Reference	Paper Title	Theories	Learning Activities
ID41	[80]	Integrating spherical video-based VR into elementary school students' scientific inquiry instruction: Effects on their problem-solving performance	Not provided	Inquiry-based learning and problem-based learning
ID42	[81]	High school students' perceptions of affect and collaboration during virtual science inquiry learning	Used the language related to cooperation learning theory but did not cite it	Inquiry-based learning and collaborative learning
ID43	[82]	Effects of an immersive VR-based classroom on students' learning performance in science lessons	Not provided	Inquiry-based learning
ID44	[83]	Enhancing elementary school students' abstract reasoning in science learning through AR-based interactive multimedia	Not provided	Problem-based learning
ID45	[84]	Science Spots AR: A platform for science learning games with AR	Not provided	Game-based inquiry learning
ID46	[56]	The study of AR-Based learning for natural science inquiry activities in Taiwan's elementary school from the perspective of sustainable development	Grounded on Technology Acceptance Model	Inquiry-based learning
ID47	[85]	Effects of incorporating AR into a board game for high school students learning motivation and acceptance in health education	Grounded on the basic learning theories of situated learning theory, scaffolding theory, dual-coding theory, and over-learning and competition-based learning	Game-based inquiry learning
ID48	[86]	Scientific inquiry self-efficacy and computer game self-efficacy as predictors and outcomes of middle school boys' and girls' performance in a science assessment in a virtual environment	Cited self-efficacy theory	Inquiry-based learning and game-based inquiry learning
ID49	[87]	A multi-user virtual environment for building and assessing higher order inquiry skills in science	Grounded on inquiry learning theory	Inquiry-based learning
ID50	[88]	Augmenting printed school atlases with thematic 3-D maps	Not provided	problem-based learning
ID51	[89]	Investigating potential relationships between adolescents' cognitive development and perceptions of presence in 3-D, haptic-enabled, VR science instruction	Piagetian theory	Inquiry-based learning
ID52	[90]	Science learning in virtual environments: A descriptive study	Not provided	Inquiry-based learning
ID53	[91]	A mixed methods assessment of students' flow experiences during a mobile AR science game	Not provided	Game-based inquiry learning
ID54	[92]	Using epistemic network analysis to examine discourse and scientific practice during a collaborative game	Cited cooperative learning theory and knowledge construction theory	Collaborative learning and game-based inquiry learning
ID55	[57]	VR simulations in web-based science education	Not provided	Topic based learning

Table A1. *Cont.*

ID	Reference	Paper Title	Theories	Learning Activities
ID56	[93]	Can an immersive VR simulation increase students' interest and career aspirations in science?	Not provided, but cited terms of self-efficiency theory	Inquiry-based learning
ID57	[94]	Earth science learning in SMALLab: A design experiment for mixed reality	Grounded on theory of cooperation	Inquiry-based learning
ID58	[95]	SMALLab: virtual geology studies using embodied learning with motion, sound, and graphics	Grounded on theory of experiential learning	Inquiry-based learning
ID59	[96]	On location learning: Authentic applied science with networked augmented realities	Not provided	Game based inquiry learning
ID60	[97]	Investigations of a complex, realistic task: Intentional, unsystematic, and exhaustive experimenters	Cited item response theory	Problem-based learning
ID61	[98]	The impact of internet virtual physics laboratory instruction on the achievement in physics, science process skills and computer attitudes of 10th-grade students	Grounded on cognitive and social constructivism theory	Problem-based learning

Appendix B

Table A2. List of grounded theoretical foundations cited in reviewed studies.

Theories	Application Scenarios
Multiple intelligences theory	Students were asked to explore in the virtual environment, so their multiple senses were stimulated, and their ability to establish intellectual and emotional connections with their own world was enhanced. (ID4) The researchers attempted to stimulate primary school students' musical intelligence, bodily-kinesthetic intelligence, spatial intelligence, interpersonal intelligence, and intrapersonal intelligence in VR environment. (ID5)
The theory of leisure	A Serious Virtual World was constructed with VR, which enabled primary school students to find their potential and skills in the leisure environment, compare with other players in the game, and learn in the cooperative game. (ID5)
Knowledge construction theory	Learning scaffoldings, such as knowledge prompt and peer thinking database, were designed to support 6–8 grade students' knowledge construction in AR environment. (ID8) A location-based mobile device AR system was developed to help learners construct knowledge through discussing problems and sharing knowledge. (ID10) The virtual laboratory based on computer network provided learners with positive learning opportunities, increased communication with others, and helped to cultivate students' reflective and metacognitive ability. (ID61)
Distributed cognition theory	The author proposed a new theory named the Theory of Liminal Blends, which was based on the distributed cognitive theory to guide the research. (ID13)
Embodied learning theory	In order to understand how embodied interaction affects participation and immersion, researchers put forward a series of questions to explore the degree of participants' cognitive and perceptual participation in experiencing virtual environment. (ID14)
Cognitive load theory	The experimental group and the control group dealt with different multimedia objects, and gained different extraneous and germane cognitive load with different learning effects. (ID18) An integrated learning method of multimedia teaching materials based on AR was designed to reduce students' cognitive load. (ID25)

Table A2. *Cont.*

Theories	Application Scenarios
Multimedia learning theory	In this study, an AR-based science learning system was developed based on the contiguity principle of multimedia learning theory, which was used by students to interact with textbooks. (ID25) Based on the interactivity principle, students set up the AR experiment and observed the results. (ID35) According to the multimedia learning theory, an AR game was designed to test its learning efficiency. (ID38)
The theory of experiential learning	Students collected virtual elements to mimic reality experience. (ID5) The principle of experience continuum and interaction of experiential learning theory were used to design primary school student's learning activities of visiting outdoor space, motivate them to learn, and exert a positive impact on their cognitive and emotional outcomes. (ID21) The researchers developed a system with AR technology that allowed the learner's body to move freely in a multimodal learning environment to enhance embodied learning. (ID58)
Situated learning theory	An AR-based learning system called Mindtool was designed, which enabled students from fourth graders to explore concepts or solve problems. (ID22) AR environment was used to create heuristic problem situation, so that students aged from 12 to 14 could learn through PBL. (ID23) A health education board game applying AR was developed. This game included eight topics, such as health check, hospital, ambulance and so on, helping students learn health knowledge in a realistic situational environment. (ID47)
Theory of immersion	A research model to understand the learning perception of immersion was proposed, which tested the learning characteristics and evaluated the immersion variables through the individual's motivational beliefs and strategies. (ID31)
Technology acceptance theory	TAM theory was used to study users' adoption patterns from the perspective of perceived usefulness and perceived ease of use, and a blueprint for the research to be explored was constructed. (ID46)
Theory of inquiry learning	A VR system named Multi-User Virtual Environments was developed to enable multiple simultaneous participants to enact collaborative learning activities of various types. (ID49)
Piaget's cognitive theory	Research questions were put forward according to Piaget's cognitive theory and the Inventory of Piaget's Developmental Tasks was used in the study for learners to complete. (ID51)
Theory of collaborative learning	The learning activity was designed according to theory of collaborative learning, including three parts: (1) a new mixed-reality learning scenario, (2) a student participation framework, and (3) a curriculum. (ID57)
Other theories	Lin et al. (ID47) used five theories to design their AR health education board game. In addition to the situational learning theory mentioned above, other four theories are scaffolding theory, dual-coding theory, over-learning theory, and competition-based learning theory. In their AR health education board game, users needed to use the developed App to scan question card on the inspection report. Guidance and correct answers were provided at the back of the question card (scaffolding theory). pictures and text were added to the question card as study aids (dual-coding theory). To answer the question rightly, the users needed to repeat practicing again and again (over-learning theory), and the competition mechanism was used by the game to enhance the learning motivation of learners. (ID47)

Appendix C

Table A3. List of learning activities in reviewed studies.

Types	Corresponding Paper	Activity Summary
Inquiry-based learning	ID2, ID3, ID4, ID5, ID6, ID7, D8, ID9, ID10, ID11, ID12, ID13, ID14, ID15, ID16, ID18, ID21, ID31, ID32, ID33, ID34, ID37, ID38, ID41, ID42, ID43, ID46, ID48, ID49, ID51, ID52, ID56, ID57, ID58	Learners interacted with virtual environment or virtual objects created by VR/AR, and learned scientific knowledge and scientific concepts or phenomena by exploring.

Table A3. *Cont.*

Types	Corresponding Paper	Activity Summary
Receptive learning	ID1, ID16, ID17, D19, ID22, ID26, ID27, ID28, ID35, ID36, ID39, ID40	VR/AR could help learners better understand scientific concepts and phenomena by visualizing invisible things, simplifying complex things, concretizing abstract things, and combining real-world learning objectives with digital content.
Cooperative learning	ID7, ID10, ID13, ID42, ID54	Learners completed the learning activities through cooperating with each other (ID7, ID13), or sharing, and discussing (ID7, ID10, ID13) with others.
Problem- based learning	ID23, ID24, ID25, ID41, ID44, ID50, ID60, ID61	Researchers used the environment created by VR/AR as the basis for raising problems and the source of materials for solving problems.
Game-based learning	ID45, ID47, ID48, ID53, ID54, ID59	Learning activities were carried out in the form of games. Learners used scientific knowledge to solve problems through interaction with the environment or other learners. The main types of games are story game (ID45), health education board game (ID47), role playing games (ID48 and ID59), and collaborative role playing game (ID53 and ID54).
Flipped learning	ID20	Learners used AR-based flipped learning system, to watch videos in advance, finishing homework, and discussing in class.
Topic-based learning	ID29, ID55	The researchers developed an AR-based activity manual with 32 learning activities. In the experimental group, teachers used these activity manuals for theme teaching, and students completed learning activities according to the content of the manual. (ID29) The learning content was organized according to different topics, which indicated learning subjects of earth science education. (ID55)
Design based learning	ID30	Researchers developed a peer assessment approach and incorporated it into VR design activities, in which students designed their own VR projects to raise environmental awareness and cultivate earth science knowledge.

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