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Review

Augmented Reality in K–12 Education: A Systematic Review and Meta-Analysis of the Literature from 2000 to 2020

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Abstract: With its capacity to support student-centered learning through digital transformation and shared experience, augmented reality (AR) has received increasing attention from both researchers and practitioners as an emerging technology to achieve innovative and sustainable education. Therefore, this study systematically reviewed the literature on the application of augmented reality in K–12 education settings between 2000 and 2020. After two stages of screening, 129 articles were selected, and the key research results were analyzed and integrated by adopting a coding scheme including basic information, instruction contexts, technical features, instructional design, and research results. The results revealed interesting findings regarding the augmented reality literature in terms of publication patterns, application fields, technological affordances, instructional designs, and methods. Furthermore, a meta-analysis was conducted to examine the effectiveness of augmented reality-based instruction, and the results showed a large overall effect size (g = 0.919) with three significant moderators. Finally, the practical significance of AR-based instruction and a future research agenda are discussed.

Keywords: augmented reality; K–12 education; systematic literature review; meta-analysis; technology features

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1. Introduction

Augmented reality (AR) is a technology that allows virtual objects to be interactively overlaid on real-time images [1]. According to Azuma et al. (2001), an AR system is a combination of real and virtual objects based in a real environment that interact and align with each other in real time [2]. These virtual objects can take the form of text, still images, video, 3D models, audio, or any other digital media. In contrast to immersive virtual reality, AR interfaces allow users to see the real world while viewing virtual imagery attached to real-world locations and objects. That is, unlike virtual reality, the concept of augmented reality is not replacing the real world with the virtual, but rather augmenting it by superimposing synchronous virtual objects on top [3,4]. Collectively, AR enhances the users' experience in the real world.

Over the past two decades, AR applications have received increasing attention and have been successfully applied in several fields, including engineering [5,6], tourism [7,8], medical education [9,10], sports [11], and general education [12–14]. AR technology bridges the gap between the virtual and real worlds, opening new avenues for teaching and learning and having a significant impact on the field of education [15]. AR technology has been used extensively in teaching, particularly during the time of the COVID-19 pandemic [16–18]. As stated in the Horizon report, new technologies such as augmented reality (AR) will result in a redesign of learning and teaching, making mobile learning more active and collaborative, resulting in an infinite number of learning experiences [19].

There is a substantial body of literature on the use of augmented reality in educational settings. According to a review of the literature, AR technology is used in education at almost all levels, from kindergarten to graduate school [20]. The literature has identified the benefits of AR in educational environments, such as increased achievement [21,22], enhanced motivation [23,24], and decreased cognitive load [25,26]. Despite the numerous learning benefits and positive findings associated with AR-based instruction, it has yet to be implemented on a large scale. Specifically, it was not widely used in K–12 classrooms during the COVID-19 pandemic. The use of AR for educational purposes has some limitations. Lu and Liu (2015) considered the technical problems encountered when using AR to be the main and most important limitation [21], whereas Leighton and Crompton (2017) considered the pedagogy to be a limitation of applying AR for educational purposes [27].

Previous research on the use of AR technology in K–12 education can be used to guide future research. Therefore, a systematic review is essential to present the current state of the art and to shed light on future studies. Although there have been many systematic reviews of the use of AR technologies in education in the literature, several caveats should be noted when interpreting their findings. For example, some reviews did not specify the target context (e.g., K–12, higher education, private sector, military, etc.) [15,20,28,29]. Some systematic reviews in the literature focused on articles on AR related to education in a specific field [30,31]. There are also some systematic review studies that reviewed AR and virtual reality (VR) altogether in one study, although they differ in terms of immersion and presence [32,33]. It is evident that these systematic reviews usually focus only on the advantages and limitations of AR applications in education and lack a focus on technology and pedagogy; in other words, there is still a lack of an up-to-date systematic review of the literature that focuses specifically on implementation of AR in K–12 education from a technological and educational standpoint.

To address this research gap, this study reviewed 20 years of literature (2000–2020), on AR-based instruction in K–12 educational settings and conducted a systematic analysis from the perspectives of publication trends, application contexts, technology features, and instructional design, and identified the overall effectiveness of AR and its moderators through a meta-analysis. According to Wang and Hannafin (2005) [34], those perspectives and their intertwined relationships are essential for understanding technology-enhanced learning environments. Consequently, the following five research questions guided our systematic review and meta-analysis:

1. What are the trends in the types of publications and research in AR-supported K–12 education?
2. What instructional settings in K–12 education have applied AR technologies to facilitate teaching and learning and how is this done?
3. What are the essential technical features and affordances of AR-supported K–12 education and how have they evolved over time?
4. What instructional strategies have been used in AR-supported K–12 education?
5. What is the overall effect of AR applications in K–12 education and what are the moderating factors?

2. Methods

Following the standardized protocol recently proposed by Yu and Maria (2019) [35], this study followed a systematic review approach to gain insights into the application of AR in K–12 settings. This systematic review consisted of three main stages: an initial literature search, manual screening, and analytical coding. We analyzed the relevant AR literature published between 1 January 2000 and 31 December 2020 to answer the questions proposed above. In addition, a meta-analysis was also conducted to examine the overall effectiveness of AR-supported instruction and its moderators, which consisted of three parts: (a) calculation of effect sizes, (b) homogeneity analysis, and (c) moderator analysis. Effect size for each independent study was estimated based on sample size, mean, standard deviation or *t*-test, F-test, and *p*-value using Comprehensive Meta-Analysis (CMA) software (version 3.0).

2.1. Initial Literature Search

Nowadays, electronic databases are a typical first stop in a literature search [35]. We chose to conduct an initial literature search in Scopus' literature database. Scopus was chosen because it is a widely used peer-reviewed literature database, recognized for the comprehensiveness and reliability of its indexed publications. In the Scopus database, we used a list of search strings for the initial search, which consisted of two clusters of key phrases. The first cluster comprised two items, 'augmented reality' and its abbreviation 'AR'; the second cluster indicated the educational context, including phrases such as 'education', 'class *', 'teach *', 'learn *', 'K–12', 'elementary', and 'middle school'. Consequently, commonly searched strings included 'augmented reality OR AR AND education OR teach * OR learn *' and 'augmented reality OR AR AND K–12'. Our initial literature search yielded 3184 articles that were downloaded for subsequent manual screening.

2.2. Manual Screening

This study's inclusion and exclusion criteria set the boundaries and scope for the scholarly publications that were included in the final review. These criteria were determined after establishing and refining the research themes and objectives. The manual screening process is depicted in Figure 1. Only articles that satisfied the following criteria were included in the final library. First, the articles had to be focused on AR. Articles about VR or mixed reality were removed. Second, the research had to be conducted in the context of K–12 education. Articles about other educational contexts, such as higher education, special education, and professional training, were excluded. Lastly, to ensure the quality of selected articles, only peer-reviewed empirical studies were included in this phase and publications such as reports and dissertations were excluded. Additionally, the research team had carefully read each article to ensure its academic rigor and relevance. In the case of divergent classifications, the authors discussed the article until an agreement was reached. After merging our results, a total of 129 articles were chosen for systematic review. The key metadata information of those articles is listed in Appendix A, which is accessible at: https://www.doi.org/10.17632/4rkrhngzm4.1 (accessed on 16 July 2022).

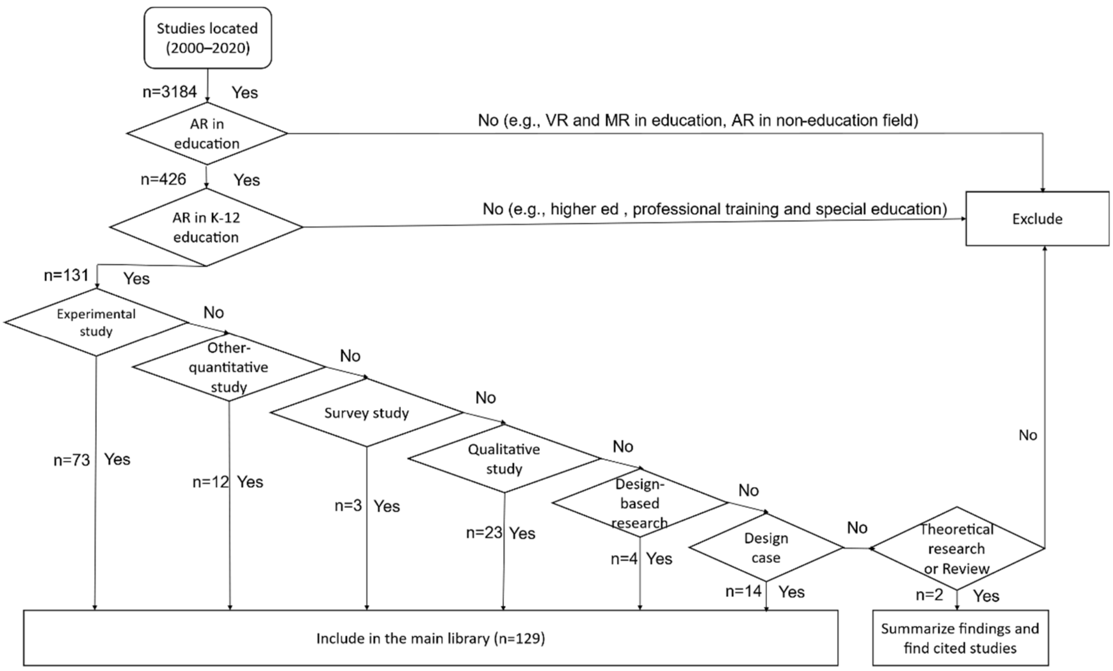

Figure 1. Decision diagram of the manual screening process.

2.3. Analytical Coding

After finalizing the master database, we carried out an in-depth reading of the selected articles, and the content of the selected articles was analyzed using the coding scheme shown in Table 1. The coding scheme was based on the work of Wang and Hannafin (2005) [34] and focused on the key aspects of the technology-enhanced learning environment. The final coding scheme included five interrelated aspects of AR-supported instruction in K–12 settings: basic information, instructional context, technology features, instructional design, and research findings.

Table 1. Lists of codes for the analysis of the selected articles.

Category	Code	Description
Basic information	Title	The full title of the study
	Authors	Complete list of author names
	Year	Publication year
	Source	Information about the journal/book/URL
	Research type	Empirical/theoretical/synthesis
	Empirical study type	Experimental/quantitative/qualitative/mixed method/survey research/design-based research
Instructional context	Disciplines	Basic science/social science/engineering/language/health and medicine/mathematics
	Grade level	Elementary/middle/high school/mixed
Technology features	Input	Voice/magnet/motion/haptic/GPS/mouse and keyboard/scanner/other
	Output	Monitor/video/optical
	Computing devices	Desktop/laptop/tablet/mobile phone/other hand-held/wearable device/cloud
Instructional design	Pedagogy	Inquiry-based/game-based learning/collaborative/trial-and-error/direct direction/experiential learning
	Instructional function	Attention grabber/content delivery/practice/assessment/engagement/other
	Scaffolding	No scaffolding/teacher/computer
	Rounds of practice	One single round/two or more rounds
	Learning outcomes	Knowledge/behavior/skill/affective
Research results	Sample size	Number of total participants
	Data source	Test/survey/interviews/video captures/field notes/other
	Statistical results	Difference (t-test/ANOVA/MANOVA/ANCOVA, non-parametric), associational (SEM/regression/factor analysis), meta-analysis
	Effect size	Record if mentioned

As shown in Table 1, the basic information codes record the main metadata for each article, including its year of publication, title, author, source, and type of study. Instructional context revealed the common use of AR in K–12 settings. The technical features focused on the three basic technical characteristics of the AR intervention, i.e., inputs, outputs, and computing devices. The design codes are based on the work of Luo et al. (2021) [36] and specify the pedagogical features of AR, the pedagogical scaffolding design, rounds of practice, and learning outcomes. The research codes focus on the empirical findings, such as the sample size, data sources, statistical results, and effect sizes for AR-supported instruction in K–12 settings. Both researchers were trained before coding the articles, and during the coding process, they would discuss any uncertainty with another expert in a weekly meeting [37]. The complete coding scheme and results are accessible at https://doi.org/10.17632/zbnx8m77v3.1 (accessed on 16 July 2022).

3. Results and Analysis

3.1. Publication Trends

As illustrated in Figure 2, publications related to AR-based instruction in the K–12 settings showed an upward trend overall across the last two decades, indicating that AR has received increasing acceptance in K–12 education. It is worth pointing out that the application of AR in K–12 education did not receive much attention until 2006, which is consistent with the findings of Li et al. (2021) [38]. The Horizon report forecasted in 2006 indicated that AR would be a promising technology in the long term and that AR would show a significant impact and gain attention in the coming years (2009–2010) [39]. As forecasted, AR has indeed become increasingly popular. Due to the technology being in its infancy, there were relatively few articles related to AR applications in K–12 education before 2014.

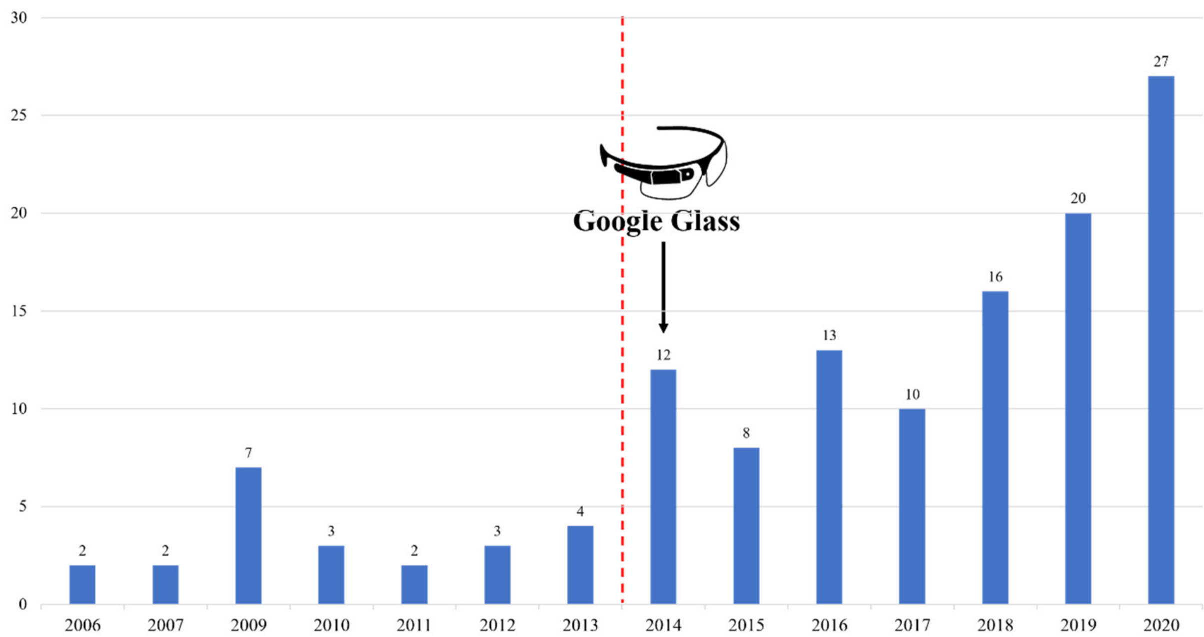

Figure 2. Publications on AR-based instruction in K–12 settings from 2000 to 2020.

In addition, Figure 2 shows a significant increase in 2014. This striking increase may be related to the advent of Google Glass. This new technology ensures the flexibility of education and the accessibility to learners. It can influence the way students are taught, adopting a learner-driven approach rather than a teacher-driven one [40]. Since then, AR has been increasingly adopted and experimented with in educational contexts as AR technology has matured and media hype about it has grown. On the basis of the development of AR technology, we took the time of the launch of Google Glass as the boundary and ensured that the two periods had an equal length and then compared the two research periods: one from 2000 to 2013 and the other from 2014 to 2020.

3.2. Research Design

Three categories of research studies were published from 2000 to 2020: empirical research, synthesis, and design cases. As illustrated in Figure 3a, our review shows that 88% of the studies were empirical research and 11% of the studies were design cases, only one theoretical research study (1%) was found in 2008, which discussed a representative sampling of past and current HIT Lab research [41]. Figure 3b presents the distribution of the types of empirical studies in the last 20 years. The most widely used method in studying AR-supported K–12 education was experimental research, accounting for 56% of all studies. Both the quantitative research method and the qualitative research method accounted for 9%. Surprisingly, mixed-method approaches were also used fairly frequently, accounting for 8% of all studies. The mixed-method design is currently the most advocated approach, as it has the advantages of being data-rich, objective, and reliable [42]. For example, a recent study by Wen (2020) conducted a mixed-methods study to investigate whether and in what ways AR features promote young learners' cognitive engagement with vocabulary learning [43]. Some design studies explored the feasibility of AR through case study designs, whereas some relied mainly on survey results to draw conclusions.

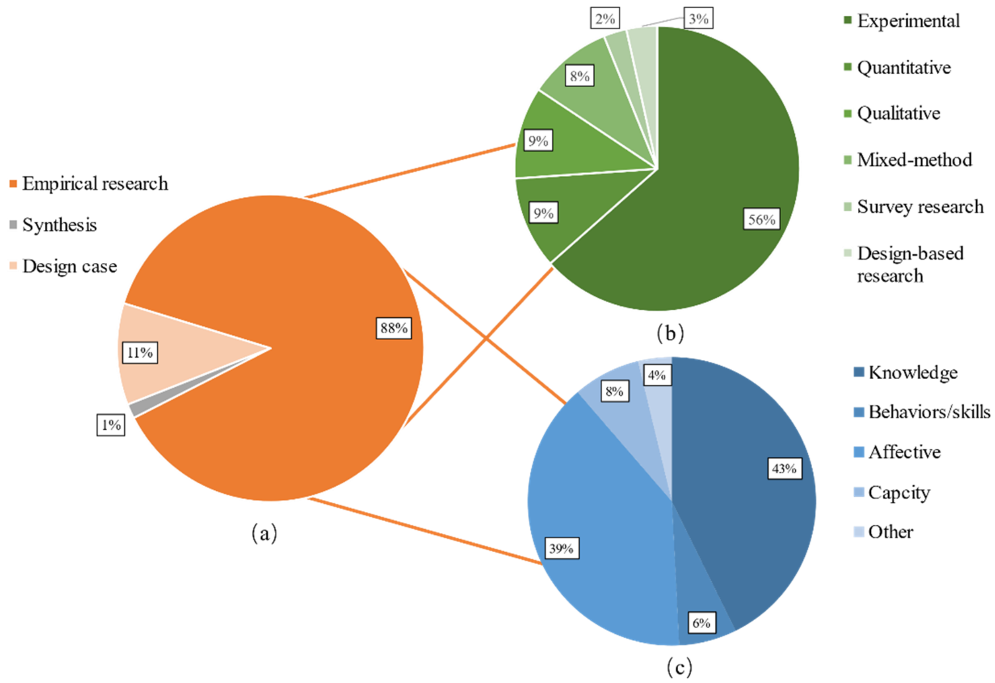

Figure 3. (**a**). Types of research studies (**b**). Types of empirical studies (**c**). Types of learning outcomes.

Figure 3c reveals the learning outcomes from AR-supported instruction in K–12 settings. Note that some of the reviewed articles focused on multiple learning outcomes at the same time, resulting in the sum of the outcomes exceeding the sum of the articles. From the graph below, we can see that the main types of learning outcomes for AR usage in K–12 settings are knowledge acquisition and affective learning, accounting for 43% (n = 83) and 39% (n = 76) of total outcomes evaluated. In addition, relatively few learning outcomes were related to skill mastery (n = 14), and these were concentrated in some basic science disciplines (primarily physics and science). For instance, Karagozlu (2018) designed an augmented reality application to improve students' problem-solving skills in science subjects [44].

3.3. Instructional Contexts

As seen in Figure 4, we tallied the number of studies for each disciplinary field and school setting. Elementary school students were the most common type of learners. The second most common preferred learner type was middle school students. One potential explanation for this occurrence is that according to Piaget's theory of cognitive development, elementary school students and early adolescents are in the concrete operational stage where they must see, hear, or otherwise use their senses to learn [45]. Thus, AR plays an important role in the learning of students at this stage with its powerful visualization capabilities. For instance, Kerawalla et al. (2006) conducted a comparative study on the use of an AR virtual mirror interface and traditional science teaching methods for 10-year-old children [4]. The study found that AR technology effectively helped the 10-year-old students understand how the Earth and sun interact in three-dimensional space to form day and night.

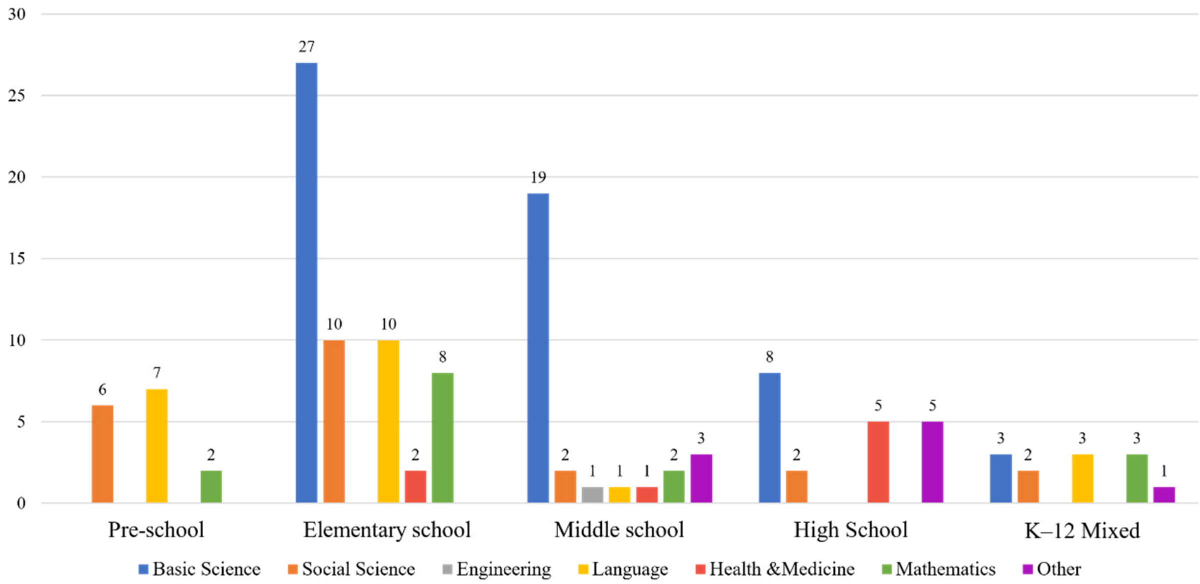

Figure 4. Number of publications by disciplinary field and school setting.

AR-based instruction was commonly used to teach subjects in two fields: basic science (e.g., physics, chemistry, biology, geology, etc.) and social science (e.g., liberal arts, history, sociology, education, culture, etc.). AR-based instruction is most often used for teaching subjects in the field of basic sciences. One possible reason is that AR is effective for students learning things they cannot see in the real world or without a specialized device and for activities that involve learning abstract or complex concepts (e.g., electrons, chemical elements). Another potential explanation is that AR technology provides a real-time interactive manipulation pathway that allows learners to engage in contextualized learning. An empirical study by Liu (2009) developed RFID as a tool based on AR technology to help students conduct outdoor field trips [46]. According to Chen et al. (2017), AR has been widely used in the social sciences due to the possibility of augmenting information and combining it with contextual information to provide new experiences [47]. It is noteworthy that AR-based instruction was also used several times to teach subjects in language fields [48,49].

3.4. Technological Features and Affordances

3.4.1. Input and Output

As shown in Figure 5, we focused on the input and output devices of AR technology. Scanners (e.g., images or QR code readers) were predominant input devices in the past two decades, accounting for nearly half of the empirical studies in our review. In addition, motion trackers (e.g., gestures, gait, and motions perceived by motion sensors such as Kinect), haptic sensors (e.g., haptic stimuli synthesized using force feedback or tactile devices), global positioning systems (GPS) (e.g., location-based mobile applications), and mice and keyboards have also been common types of input devices in the past twenty years. It is worth noting that with the development of technology, there are some other input devices available (e.g., voice-input devices, button-pressing controllers, styluses, etc.) An example of this is the study carried out by Dalim et al. (2020), in which the researchers used augmented reality with voice input for non-native children's language learning [50].

Closer inspection of Figure 5 shows there are several important differences between the two periods. Position coordinates acquired from GPS were one of the main inputs (25%) in the period from 2001 to 2013. This may have been due to the availability of sensors in mobile devices such as accelerometers, gyroscopes, and digital compasses, as well as the possibility of using GPS. These applications know the user's location and use this information to display information based on geographic location and/or directions [51].

This percentage decreased to 5% in the period from 2014 to 2020, indicating the decreasing popularity of location-based AR learning environments. Contrary to that, haptic input significantly increased (from 7% to 18%). According to Bermejo & Hui (2017), since visual and auditory channels are insufficient to create a seamless user experience in the AR/VR ecosystem, haptic ecosystems can generate the interaction complexity required for real-time information transfer [52]. Haptic devices can provide a two-way communication channel between humans and machines. It creates a strong sense of immediacy.

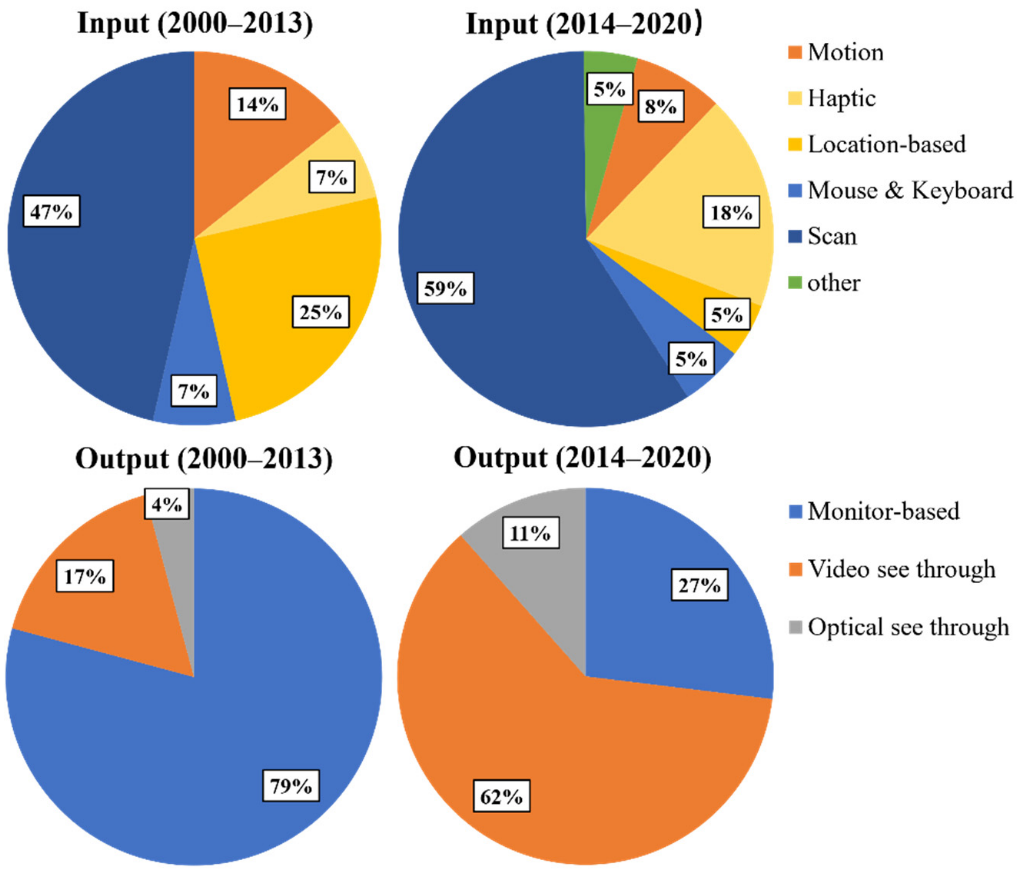

Figure 5. Input and output devices of AR-supported instruction from 2000 to 2020.

The output devices for AR-based instruction are simpler than the input devices for AR-based instruction and include three common types: output through a monitor, videos, and optical output. As shown in Figure 5, an obvious change is that the use of monitor output witnessed a sharp decrease from 79% to 27%; on the contrary, the use of video output significantly increased (from 17% to 62%). The results indicate that the most prevalent delivery technology was mobile devices, which was also shown by previous studies [20,53]. Further analysis showed that both periods involved optical output devices. Optical see-through augmented reality is a variant of AR in which graphics are superimposed on a user's view of the real world through an optical rather than a video combiner [54]. This output offers the unique advantage of direct elevated access to information. For example, Cai et al. (2019) used AR optical output technology to show virtual content that is invisible in the real world to help middle school students understand abstract mathematical concepts [55].

3.4.2. Computing Devices

We also focused on the computing devices of AR technology and plotted the results of this analysis in Figure 6. Unlike input and output devices, the function of a computing device is mainly to store and process data. It reads data from the input device, accesses the task-related database, performs the real-time calculations required by the task, and feeds the results to the output display device. In our study, data in AR systems were stored and processed by six types of devices: desktops or laptops, tablets, mobile phones, other hand-held devices, wearable devices, and the Cloud. Based on the division of the study period mentioned above, the most interesting aspect of this graph is that the main computing devices in the two periods are very different.

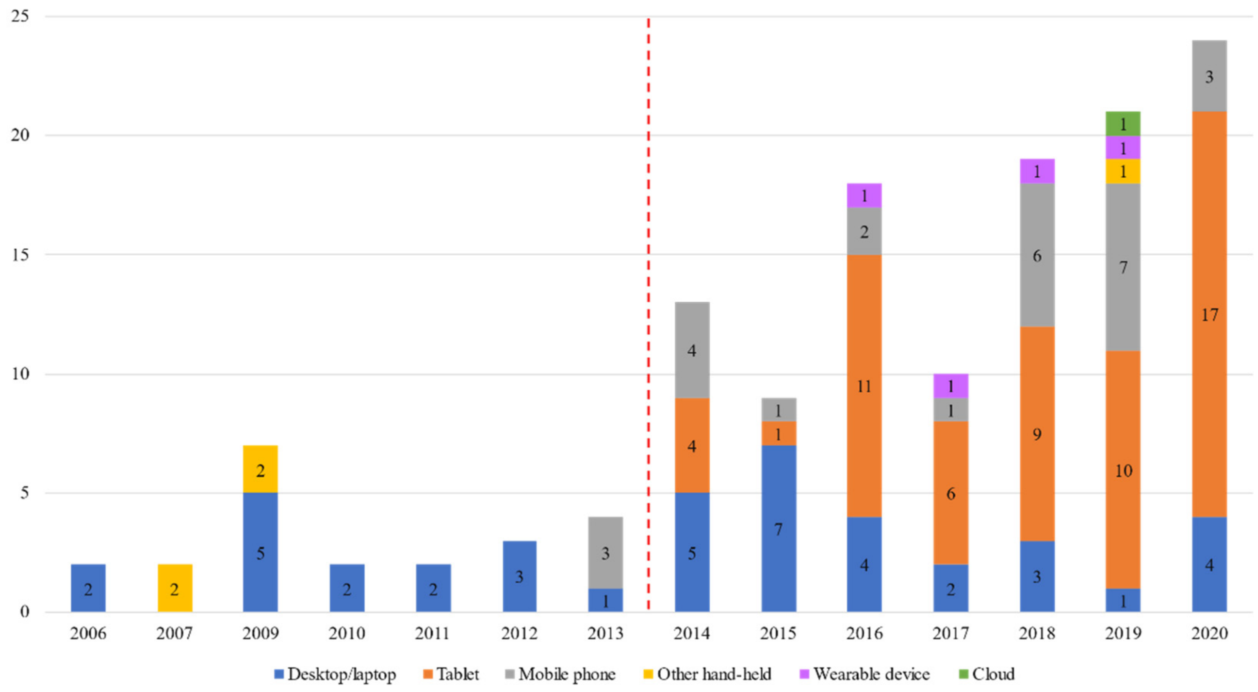

Figure 6. Computing devices for AR-supported instruction from 2000 to 2020.

As seen in Figure 6, desktop/laptop computers had an overwhelming advantage over other computing devices during the 2000–2013 period because they can perform complex mathematical operations for simulated and computational AR systems. Although desktop computers can support AR applications, they are not portable due to hardware limitations [56]. In contrast, mobile devices such as mobile phones and hand-held devices are portable and have many advantages, such as encouraging high levels of social interactivity and independent operation [57]. We noticed that hand-held devices (n = 4) were used more often than mobile phones (n = 3) in K–12 education before 2013. One possible reason is that earlier versions of mobile phones were not functionally advanced to support AR technology and lacked suitable AR applications for education. Consequently, hand-held devices such as RFID readers were popular substitutes for mobile phones to engage students in AR activities in earlier times due to their functionality and low cost [46].

With the development of technology, tablets witnessed a significant increase in the period from 2014 to 2020. This change confirms the predictions of the NMC Horizon Report, namely, that tablet computing technology has grown by leaps and bounds in recent years [58]. Compared with mobile phones, tablets have larger screens and higher performance than mobile phones, supporting a range of input combination formats that provide high-quality visualizations [59]. Since 2016, wearable devices have been used as computing devices in AR instruction. Wearable devices bring a higher level of engagement and immersion, while the applications of wearable technologies have the "potential to support situated, embodied learning in real-world contexts" [60]. For example, Hung et al. (2017) studied the learning effects of students wearing HMDs to read AR novels and showed that AR provided learners with more opportunities to acquire knowledge [61]. Surprisingly, only one article reported the use of the Cloud as a computing device in our review study [62]. Aurasma, a cloud-based application, was applied to provide a seamless AR learning experience for students in this study.

3.5. Instructional Design

As shown in Figure 7a, we classified the pedagogies used in the literature according to the school settings. AR technology mainly served two pedagogical purposes: direct instruction and inquiry-based instruction (i.e., problem-based learning, case-based learning, and project-based learning), which are related to the features of AR technology. AR technology promotes realistic sensory stimuli and diverse learner–computer interactions suitable for direct instruction in AR environments. In addition, AR technology can help students learn things they cannot see in the real world or without specialized equipment, as well as provide activities to learn abstract or complex concepts, making it suitable for inquiry-based instruction, where teachers create the context and students discover the learning for themselves. For instance, Chiang et al. (2014) developed an AR learning environment that support elementary students' knowledge construction through the 5-stage inquiry cycle of "ask," "investigate," "create," "discuss" and "reflect" [56]. It was found that AR-based inquiry-based learning activities engaged students in more interactive knowledge construction than traditional inquiry-based mobile learning activities.

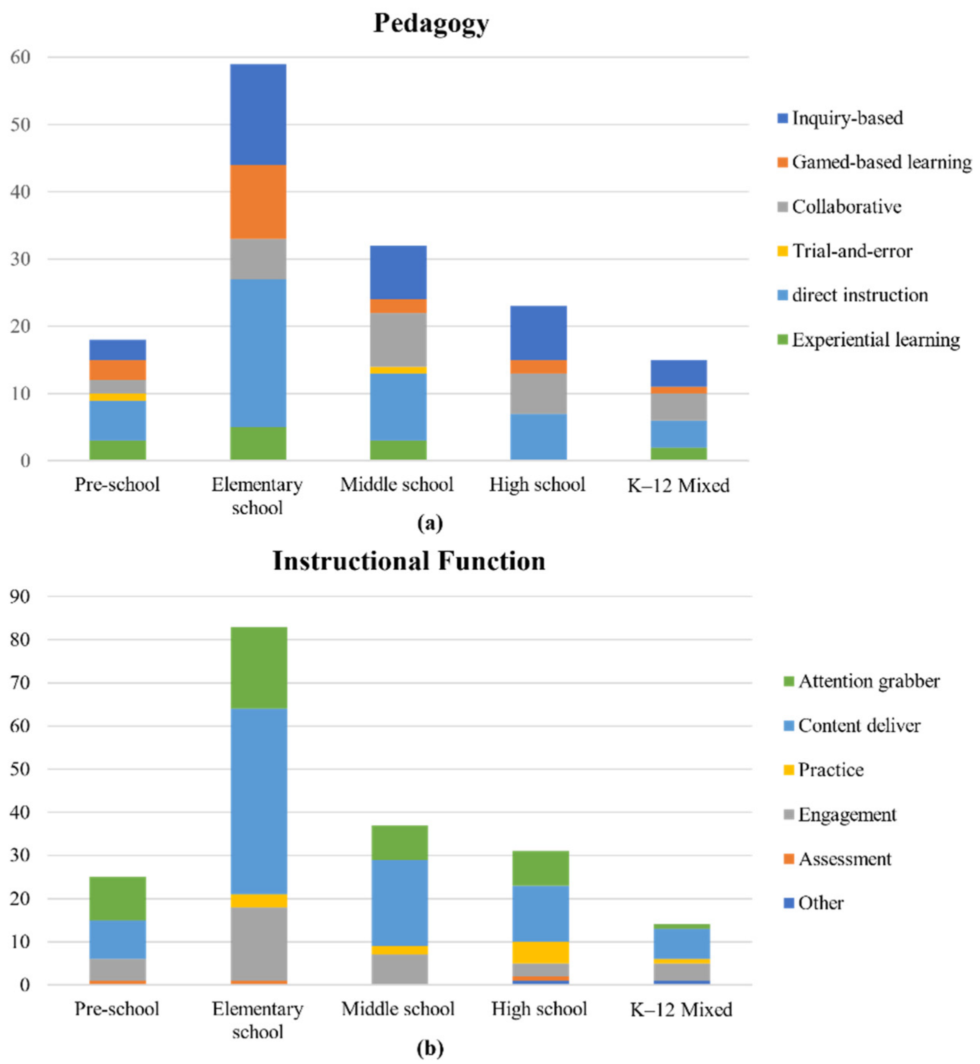

Figure 7. Pedagogy and instructional function by school setting. (**a**) Pedagogy by school setting; (**b**) instructional function by school setting.

Figure 7b shows the instructional functions of AR in different school settings. It is worth noting that multiple functions of AR technology were included in one study, resulting in a different total. As seen in Figure 7b, AR is more commonly used as an attention grabber and for content delivery. We also found that practice is a common pedagogical function at the high school level, which may be due to the experimental requirements of some important subjects (e.g., physics, chemistry, STEM, etc.), considering that AR is able to visualize content that is not normally seen, allowing learners to learn in a realistic context and facilitating safe and effective practice. A good example can be found in Abusselam and Karal's (2020) study, where students learned the physics of magnetic fields through independent practice in an AR learning environment [63].

By further comparison, we found an interesting correlation between pedagogy and instructional function. Although content delivery was the primary instructional function, direct instruction was also the most popular teaching pedagogy used by educators. Similarly, the advanced novelty of the new technology also makes it possible to attract learners' attention when teaching with AR technology. Educators often use games to engage students to help them easily grasp classroom concepts. In contrast to engagement as an important instructional function of AR, experiential learning is less used in AR-based instruction. According to Yuen et al. (2011), AR has a strong potential to provide powerful contextual, situated learning experiences, and serendipitous exploration while simultaneously promoting the discovery of the connected nature of information in the real world [64]. However, we need to re-examine some pedagogies that do not apply the educational function of AR well.

3.6. Meta-Analysis

Among the 73 reviewed experimental research articles, only 28 publications with 38 studies provided the required statistical data (e.g., mean, standard deviation, and sample size) for the meta-analysis. We calculated standardized effect sizes such as Hedges' g [65] from the means and standard deviation of the student learning outcome data (e.g., performance, cognitive load, and emotion) using Comprehensive Meta Analysis (CMA) software and a random effects model (REM). The REM results revealed an overall large effect size of AR-supported instruction for learning outcomes (g = 0.919, SE = 0.136, CI = [0.653, 1.185], p = 0.000). To determine if the effect size was sufficiently homogeneous across studies, a heterogeneity test of the effect sizes was performed. The Q-value was 463.835, with $p < 0.001$, and $I^2 = 92.02$, indicating that one or more existing moderators could account for this heterogeneity [66].

A mixed effect analysis (MEA) was performed to explore the potential moderators influencing the effectiveness of AR-based instruction. The results are shown in Table 2. To avoid statistical heterogeneity and biased results, one article was excluded from the calculations [67]. This table is quite revealing in several ways. First, the Q-statistics revealed no significant variance in effect size in terms of the grade level of the participants as a moderator variable ($Q_B = 0.871$, $p > 0.05$), whereas a large effect of AR-based instruction was reported in middle schools (g = 1.103) and the smallest effect in pre-schools (g = 0.493). Discipline was identified as a significant moderator of AR learning effectiveness ($Q_B = 22.512$, p = 0.000), with a large effect found for disciplines such as basic science, language, and health and medicine and an insignificant effect for engineering.

Second, regarding the technology of AR intervention, the Q-statistics revealed no significant variance in the effect sizes of AR-supported instruction for input devices ($Q_B = 1.262$, $p > 0.05$) compared with output models ($Q_B = 0.055$, $p > 0.05$) and computing devices ($Q_B = 1.096$, $p > 0.05$). In terms of input devices, although scanners were the most popular (n = 26), their effect (g = 0.862) was largely similar to that of the mouse and keyboard input (g = 0.806), both being lower than that of the location-based input (g = 1.209). In terms of output devices, both the monitor-based (g = 0.968) and video (g = 0.899) output produced the largest effect size. Regarding computing devices, desktops and laptops yielded the largest effect size (g = 1.185), whereas mobile phones generated the smallest effect (g = 0.666). Such findings support the idea of Spector (2020), namely, that advances in educational technology do not guarantee improved learning, and "the focus should be on learning, not on technology" (p. 835).

Table 2. Moderator analysis of selected experimental studies.

Moderator	k	g	95% CI	Q_B	p-Value
Grade level				0.871	0.832
Pre-school	3	0.493 [b]	[−0.760–1.746]		
Elementary school	22	0.933 [a]	[0.611–1.255]		
Middle school	7	1.103 [a]	[0.588–1.618]		
High school	6	0.908 [a]	[0.029–1.786]		
Discipline				22.512 ***	0.000
Basic science	24	1.150 [a]	[0.797–1.504]		
Social science	6	0.420 [b]	[0.071–0.769]		
Engineering	3	−0.045	[−0.429–0.339]		
Language	3	0.996 [a]	[0.267–1.725]		
Health and medicine	2	0.838 [a]	[0.442–1.233]		
Mathematics	3	0.578 [b]	[−0.717–1.873]		
Input				1.262	0.738
Scanners	26	0.862 [a]	[0.510–1.214]		
Mouse and keyboard	3	0.806 [a]	[0.548–1.064]		
Haptic	5	1.060 [a]	[0.200–1.921]		
Location-based	4	1.209 [a]	[0.484–1.934]		
Output				0.055	0.815
Monitor-based	11	0.968 [a]	[0.492–1.444]		
Video see-through	27	0.899 [a]	[0.573–1.225]		
Computing devices				1.096	0.778
Desktop/laptop	7	1.185 [a]	[0.438–1.931]		
Tablet	25	0.900 [a]	[0.585–1.215]		
Mobile phone	5	0.666 [a]	[0.516–1.486]		
Pedagogy				2.026	0.567
Inquiry-based	12	0.902 [a]	[0.441–1.363]		
Gamed-based learning	6	1.020 [a]	[0.300–1.740]		
Experiential learning	7	0.547 [a]	[−0.062–1.156]		
Direct instruction	13	1.113 [a]	[0.602–1.603]		
Instructional function				0.261	0.967
Content delivery	13	0.786 [a]	[0.417–1.155]		
Engagement	7	0.877 [a]	[−0.337–2.351]		
Practice	3	1.168 [a]	[0.038–2.713]		
Mixed	15	0.998 [a]	[0.088–2.247]		
Scaffolding				9.947 **	0.007
No scaffolding	12	1.525 [a]	[1.012–2.038]		
Computer	15	0.778 [a]	[0.357–1.198]		
Teacher	11	0.485 [b]	[0.084–0.886]		
Rounds of practice				10.023 **	0.002
One single round	33	1.039 [a]	[0.763–1.316]		
Two or more rounds	5	0.120 [c]	[−0.377–0.617]		

Note: k, number of independent studies; g, mean effect size; Q_B, between-group homogeneity. Effect sizes of 0.2, 0.5, and 0.8 were treated as small, medium, and large, respectively (Cohen, 1992). ** $p < 0.01$; *** $p < 0.001$. [a] Large effect; [b] medium effect; [c] small effect.

From the perspective of research design, no significant variance was found for the effect sizes of pedagogy (Q_B = 2.026, $p > 0.05$) and instructional function (Q_B = 0.261, $p > 0.05$), but there was significant variance in the scaffolding model (Q_B = 9.947, $p < 0.05$) as well as in the rounds of practice (Q_B = 10.023, $p < 0.05$). On average, compared with the teacher scaffolding model (g = 0.485) or the computer scaffolding model (g = 0.778), better learning outcomes can be achieved without scaffolding (g = 1.525). This result is somewhat counterintuitive. Further inquiry revealed that these no-scaffolding instruction methods commonly occurred in some types of informal learning. This result corroborated the ideas of Yoon et al. (2013), who suggested that as scaffolds increased, informal learning behaviors decreased [68]. Regarding rounds of practice, most of the practice rounds were performed only once, and one single round (g = 1.039) showed a much larger effect size compared with two or more rounds (g = 0.120).

4. Summary and Implications

This study conducted a systematic literature review and meta-analysis of 129 studies focused on AR applications in K–12 education over the past 20 years and analyzed the context, technology, design, and effectiveness of AR-supported instruction. Our findings revealed the following:

- Over the last two decades, there has been an overall increase in publications on AR-supported instruction in K–12 contexts;
- AR was more commonly used in elementary schools;
- AR is most widely applied in the teaching of basic science (e.g., physics, geology, and biology) and social science (e.g., history and culture), followed by language;
- Mobile devices have become the most commonly preferred delivery device for AR technology, with the advantages of convenience, high interactivity, and standalone operation;
- Tablet devices integrate the advantages of mobile phones and computers, with larger screens and higher performance, leading them to become the most dominant computing devices;
- Most AR applications aim to present factual and conceptual knowledge. Consequently, direct instruction has been the most popular pedagogy;
- The function of practice, despite its infrequent usage in AR instruction, yielded the best effects on learning;
- Overall, AR usage has a large effect on learning outcomes, with discipline, scaffolding, and rounds of practice as the significant moderators.

Based on those findings, we envision that an ideal AR application for K–12 context would acquire the following features: (1) portability to be implemented in various learning contexts, (2) flexibility to facilitate learning in diverse domains, (3) high interactivity to promote student-centered learning and hands-on practice, (4) high fidelity to support content delivery and display, and (5) sustainability featured by low cost and increased convenience and accessibility.

4.1. Implications for Future Practice

This study has provided a deeper insight into the application of AR in the K–12 education setting. In order to optimize the existing AR applications and technologies in education, some recommendations based on our research findings are presented below.

First, the usage of AR needs to fully consider the grade level and the application field. From our results, AR research in K–12 education is typically conducted in elementary, secondary, and high school. However, preschool education is a largely neglected area. The meta-analysis results did not show significant differences in effect sizes for each level of K–12 education. This may therefore be an important sample group for future research, especially in the teaching of basic science concepts. Apart from that, most studies were applied in the broad field of basic science and social science, and fewer studies focused on other disciplines, such as mathematics, health, and medicine, which are recommended to be explored in future research. It is worth noting that the application of AR in engineering disciplines has not been effective. One possible reason is that AR promotes distraction and increases the cognitive load of students.

Second, the choice of AR device can be more diverse than before. The results of this study indicate that the advancement of technology has made a huge change in the input and output devices of AR. The high performance, portability, and independent operation of mobile devices make them the most dominant delivery devices in AR. How to further create a two-way communication channel between humans and machines and improve the immersion and timeliness of users is an important direction for future technology development. In addition, although tablets are currently the most used computing devices, their effect is not the best, so we also suggest that wearable devices and cloud computing could be added as computing devices for AR in the future to improve portability and flexibility to achieve better teaching and learning results. Of course, the results of the meta-analysis showed no significant differences among devices, so we should be aware that we can choose the most suitable device within the cost constraints.

Third, an appropriate pedagogy should be selected, and the instructional function of AR should be fully utilized to promote learning. The results show no significant differences in the effect sizes for each pedagogy, and this implies that there may not be "a guideline for integrating AR with learning theory" [69] and "a model of factors that may maximize the use of AR for learning" [70]. We therefore suggest that researchers should not limit themselves to a single pedagogy when attempting to teach with AR, and that the flexible use of multiple strategies may yield better instructional outcomes. Similarly, although the results showed no significant difference in terms of instructional function, the practice function of AR worked best. One possible reason for this is that AR technology provides a real-time interactive way for learners to learn in context, which undoubtedly helps learners to practice safely and effectively. Current research in the context of K–12 education rarely reflects the practice functions of AR. Therefore, we suggest that AR could be applied to practice in future teaching to improve students' learning.

Lastly, the use of scaffolding and the number of rounds of practice need to be considered in actual instruction. The findings of this study suggest that AR programs in informal learning environments is best taught without scaffolds because informal learning behaviors decrease as scaffolds increase. In addition, our results show that practicing for one round in AR-based instruction is more effective than practicing for two or more rounds; this may be due to the novelty effect. Therefore, when designing AR instruction, educators should try to avoid the pedagogical impact due to the novelty of the technology. Further research and more extensive implementations of educational AR should be conducted to determine whether the findings regarding engagement and motivation are robust once the effects of novelty have been removed.

4.2. Implications for Future Studies

Based on our findings, we propose several implications for future research to address the limitations of the current literature. First, although researchers have been interested in assessing the learning effect of AR instruction, the literature lacks a systematic and in-depth analysis of different types of learning effects (e.g., cognitive, meta-cognitive, emotional, etc.). Many questions remain unanswered, such as why AR can have this learning effect, under what circumstances, for which populations, and how it works.

Second, assessment of student performance in AR activities becomes a challenge when AR becomes an integral part of the overall instructional process, especially in standard-based and educational experiences using high-stakes assessments. Therefore, future research on the impact of AR-based instruction should be further expanded.

Third, some empirical studies lacked sufficient statistical information to calculate the effect size. Therefore, they could not be included in the meta-analysis, which may have affected the results. In future studies, the complete range of summary statistics required for meta-analysis should be properly reported to calculate the combined effects.

Lastly, we recommend a cost analysis of augmented reality education programs, especially the labor costs. Gavish et al. (2015) reported that users in an AR training group required much longer mean training times than their non-AR-using peers due to the lack of familiarity with the technology [71]. According to Kraft (2020), effect size alone does not reflect the cost of a program [72]. As a result, it is necessary to examine the cost-effectiveness of AR programs to make sound decisions about their adoption in the K–12 educational context.

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Appendix A Key Metadata Information for the 129 Selected Articles

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