A meta-analysis of the impact of AR and VR technologies on mathematics learning

Longwei Cao*

Department of Mathematics and Information Technology, The Education University of Hong Kong, Hong Kong, China

*Corresponding author: 377173221@qq.com

Abstract. Using Augment reality (AR) technologies and Virtual reality (VR) technologies in education is a new tendency. The aim of this study is to test the effect of AR and VR technologies on the development of students' mathematics learning. Articles that met the inclusion criteria from a systematic database like Web of Science were included in the meta-analysis. A total of 18 research articles published from 2010 to 2023 were included in this study. The overall result showed that AR and VR technologies had a large positive impact (SMD=0.882, p<0.001) on students' mathematics learning. Sub-group results showed that the effect were significantly moderated by outcome, school level, content area, but were not significantly moderated by technology and experimental period. According to the results, some suggestions were given for the future studies.

Keywords: Mathematics education, Augment reality, Virtual reality, Technologies on education, Meta-analysis.

1. Introduction

With the development of the technology and the rapid changes in information, communication and wireless technology [1], language [2], management [3], the mobile devices become widely prevalent, affordable and convenient. Generally, augmented reality (AR) and virtual reality (VR), as one part of the mobile devices, had been used in well-known fields like medical [4]. They also had made great processes in theory and practice of the education area [5]. Mathematics can be seen as an essential cognitive tool that we possess, and it is also the foundation of many disciplines and the advancement of the modern social civilization [6]. For most students, math is a boring and difficult discipline [7]. Effective teaching of mathematics just like science needs not only a lot of knowledge, but also the ability to attract students' attention and foster their learning interest [8]. Some experts indicated that some of the educational methodologies which were still in using were old – fashioned, but VR and AR would transform it [9]. Although more researches show the interests in this field, it is still hard to say the overall impact of AR and VR on mathematics learning [10]. Some researchers believe that not all students have ability to apply this method, it depends on their experience and age [11]. Besides, the cost of AR and VR technologies is also a challenge [5]. On the other hand, some researchers consider that it can provide students with nice visual experience [12] and reduce the cognitive burden on the students, because it can visualize complicated functions [5].

In this essay, we will concentrate on providing an analysis of the articles published from 2010 to 2023 to summarize the effects of AR and VR technologies in academic achievements, learning motivations, together with the mathematics abilities in mathematics through a meta-analysis.

2. Literature review

2.1. VR and AR in education

Technologically speaking, VR is a mediated graphical tool, with a spatial frame of reference that user can control the viewpoint's motion and view direction, this allows the users to interact with the system by using the analog control [13]. The idea of VR exists a long time, while this term first appeared in 80s and VR technologies which had been produced are based on the key ideas in 1800s [9]. One of the strengths is to promote the immersive experience [5].

Compared with the VR, the idea of Augmented Reality (AR) just came out in recent decades. And it is a technology which developed from VR for enhancing the perception of the users by adding some virtual elements to the physical world [14]. Because of the interaction with the real world, it is able to deploy both indoor and outdoor [5]. Until 1990, the term "Augmented Reality" was introduced by a Boeing researcher whose name was Tom Caudell [9].

The earliest literature about this study can date back to 2002, it became more popular in recent years. VR and AR technologies are commonly used in many education fields like science [15], language [2], mathematics [16], engineering [17], chemistry [18] and physics [19]. These technologies are going to provide students with opportunities of learning in an impressive interactive way, so that they will get better retention than just by learning using textbooks. In terms of results, students who used AR technologies had better performance, motivation and less anxiety than those who did not use AR technologies [12]. Yousef [20] believed that AR technologies had been quite helpful for enhancing the desire of learning and re-motivating the intention in learning.

2.2. AR and VR in mathematics learning

Nowadays, VR and AR technologies are also starting to be used in mathematics learning. With a 360 - degree view of information provided by VR technologies, students can use a more realistic approach to experience the knowledge in a virtual environment [21]. These technologies are more likely to provide in the geometry [22] or algebra [23] as visualization tools. For promising advantages, Demitriadou et al. [24] found that the interactivity and students' interests in mathematics education had been improved successfully by AR and VR technologies. Su et al. [22] showed that students who applied VR technologies had showed better learning outcomes by completing the tasks. However, some undesired negativity outcomes probably be generated from AR and VR technologies, due to the health problem like headache or dizziness [25]. In addition, current meta-analysis studies present a focus on STEM education rather than the mathematics domain (e.g., [26]).

Considering all these factors, this essay is going to fill the above gaps, guiding by the following research questions:

(1) What is the effect of the AR and VR technologies, compared with the education without these technologies?

(2) What can impact the effect of the technologies on the students' learning mathematics?

3. Methodology

3.1. Data sources and search strategy

The purpose of this meta-analysis study is to reveal the effect level of AR and VR teaching technologies on K-12 students' individual mathematics development, and compare to the learning outcomes without AR or VR technologies.

The data resource of this study was Web of Science. Key descriptors or root forms of AR and VR technologies terms (i.e., AR, VR, Augmented reality, Virtual reality) were used on searching for relevant articles, together with main mathematical terms (mathematics, mathematics education mathematical education, STEM education, Algebra, Geometry, Statistics, calculus, probability). A pool of 1367 records was retrieved from the databases. After deleting duplicate records, 719 articles were considered for further screening.

3.2. Inclusion and exclusion criteria

We applied selection criteria to refine the search results (Table 1). All articles included in this study were written in English and published in journals or online. In order to extract the relevant data, the essay selected the following information from the studies, based on the conceptual framework: study authors; year of publication; sample size; content area; design method; language and measurements of result.

Table 1. The criteria of the inclusion and exclusion

Criteria	Inclusion	Exclusion
Time period	published from 2010 to 2023	published not in period
Language	English	Not English
Literature	published in journals or online	Non-published
Research design	Study had pre-test and post-test	Study did not have pre-test and
	or experimental test and control	post-test, experimental test and
	test between AR or VR based and	control test or the study did not use
	non-AR or VR based	AR or VR technologies
Results of research	Enough quantitative data for calculating	No quantitative data for calculating
Educational outcomes	Cognitive learning outcome	Not cognitive learning outcome

3.3. Screening process

As showing in the Figure. 1, the flow chart illustrates the process that current study produced from the screening to the determination of the studies to be included in the analysis. Before the screening stage, the pre-selected process was done.

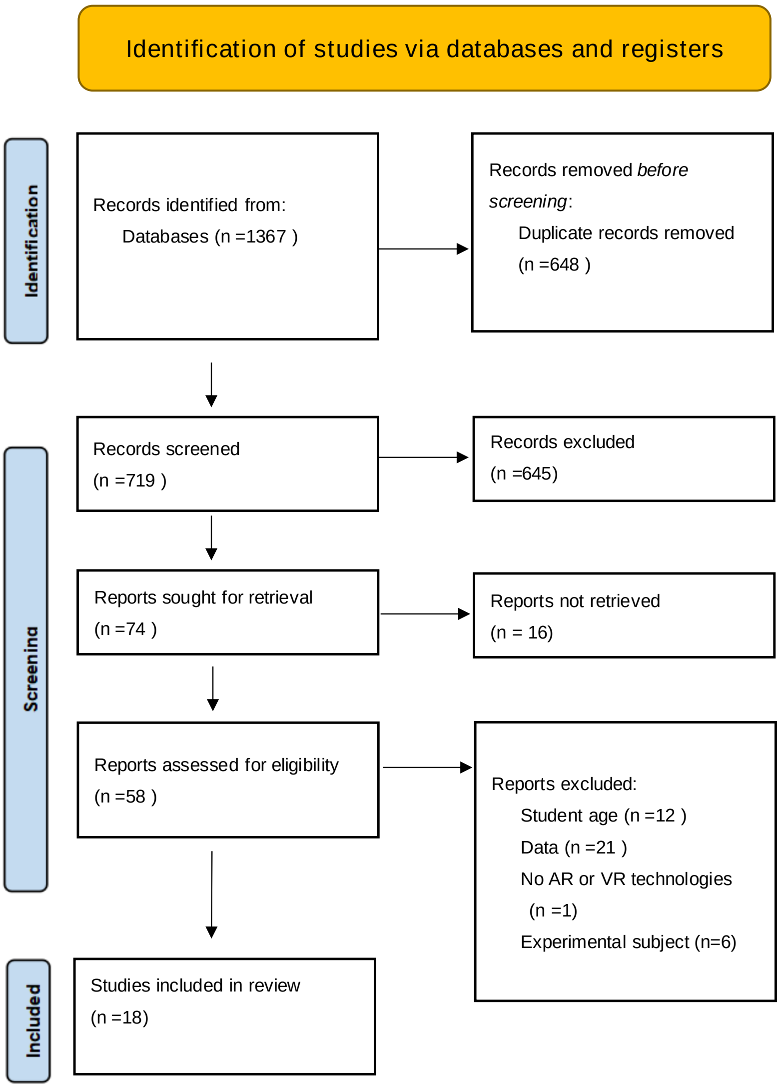

Fig. 1 PRISMA flow diagram of the article screening process

We removed 648 duplicate articles. Afterwards, titles and abstracts of the articles were located, 645 mathematics-education unrelated articles were deleted. It was followed by the second stage, selected the articles that cannot be retrieved (16 articles). For the last stage, articles which did not contain sufficient statistical values, did not have an experimental or control group, the experimental subjects were not K-12 students, and did not include the AR or VR technologies were eliminated by reading the full texts of the articles.

In the end, 18 eligible articles associated with 33 outcomes (Some independent studies include multiple outcomes) were included in the final meta-analysis.

3.4. Coding and data analysis

Before doing meta-analysis, it is necessary to encode the feature values of the research literature. The encoding in this study included school level, publication year, technologies, experimental period, content area and sample size. The specific coding instruction is shown in Table 2.

In addition, an overview of identified studies can be found in Table 3.

Table 2. Characteristic value coding table

Characteristic	Mark or description
School level	Preschool=1, Primary school=2, Secondary school=3
publication year	From 2010 to 2015=1, From 2015 to 2020=2, From 2020 to present=3
Technologies	AR=1, VR =2, AR and VR=3
Content area	Geometry=1, Algebra=2, Probability=3, Numbers=4
Experimental period	NA=1, Within 4 weeks=2, From 2 to 6 weeks=3, Over 6 weeks=4
Sample size	Up to 30=1, From 30 to 60 =2, Over 60=3

Table 3. The basic elements of the 18 articles included in the study

Number	Study(year)	Nationality/ Region	School level	Content area	Technology	Sample size	Experimental period	Outcomes
1	Poçan et al. (2023)[6]	Turkey	Secondary school	Algebra	AR	73	6 weeks	achievement, Motivation
2	Chen, Y. (2019)[12]	Chinese Taiwan	Primary school	Algebra, Geometry	AR	82	3 weeks	Achievement
3	Akman & Çakır. (2023)[16]	Turkey	Primary school	Numbers	VR	64	4 weeks	Achievement, Memory retention
4	Yousef et al. (2021)[20]	Egypt	Primary school	Geometry	AR	62	3 weeks	Achievement
5	Su et al. (2022)[22]	Chinese Taiwan	Secondary school	Geometry	VR	40	5 weeks	Achievement, Motivation
6	Demitriadou et al. (2020)[24]	Cyprus	Primary school	Geometry	AR, VR	30	NA	Achievement
7	Abdul Hanid et al. (2022)[27]	Malaysia	Secondary school	Geometry	AR	124	4 weeks	Achievement, Ability
8	Bhagat et al. (2021)[28]	China	Secondary school	Geometry	AR	27	NA	Achievement
9	Cai et al. (2020)[29]	China	Secondary school	Probability	AR	68	6 weeks	Achievement
10	Cetintav & Yilmaz. (2023)[30]	Turkey	Secondary school	Geometry	AR	40	6 weeks	Achievement, Ability, Motivation
11	del Cerro Velázquez & Morales Méndez. (2021)[31]	Spain	Secondary school	Algebra	AR	48	3 weeks	Achievement, Ability
12	Gargrish et al. (2022)[32]	India	Secondary school	Geometry	AR	54	2 months	Memory retention
13	Gecu-parmaksiz & Delialioglu (2020)[33]	Turkey	Preschool	Geometry	AR	72	6 weeks	Achievement, Ability
14	Gecu-parmaksiz & Delialioglu (2019)[34]	Turkey	Preschool	Geometry	AR	72	6 weeks	Achievement

15	Hwang & Hu, (2013)[35]	Chinese Taiwan	Primary school	Geometry	VR	58	8 weeks	Achievement
16	Ibáñez et al. (2020)[36]	Mexican	Secondary school	Geometry	AR	93	2 months	Motivation
17	Koparan et al. (2023)[37]	Turkey	Secondary school	Geometry	AR	98	9 days	Achievement
18	Lin et al. (2015)[38]	Chinese Taiwan	Secondary school	Geometry	AR	68	NA	Achievement

This study used meta-analysis software (CMA software) as the main tool of data processing and analysis. The original data from the independent study included the number of samples (N), the mean (Mean) and the standard deviation (SD) of the experimental group and control group. was used to evaluate the statistical heterogeneity. Besides, this study took the school level, technology, content area and experimental period as the sub-groups.

4. Finding

4.1. Publication bias

In systematic review and meta-analyses, there is a serious problem, publication bias, which can have a large extent of negative impact on the validity of the conclusions [39]. In order to detect and reduce the risk, several effective methods can be used. For instance, the method of the visual inspection of a funnel plot, the trim-and-fill approach [40] and Egger's linear regression test [41]. In this study, we used both methods to measure the effect of publication bias.

As you can see in the Figure 2, the funnel plot showed that most of the effect size of the study samples included in the meta-analysis were in the effective region of the funnel plot and relatively disturbed in the both sides of the average effect quantity, symmetrically. So there were no obvious outlier outcomes (z score above 3.0 or g ≥ 2.34). The probability of publication bias was relatively low.

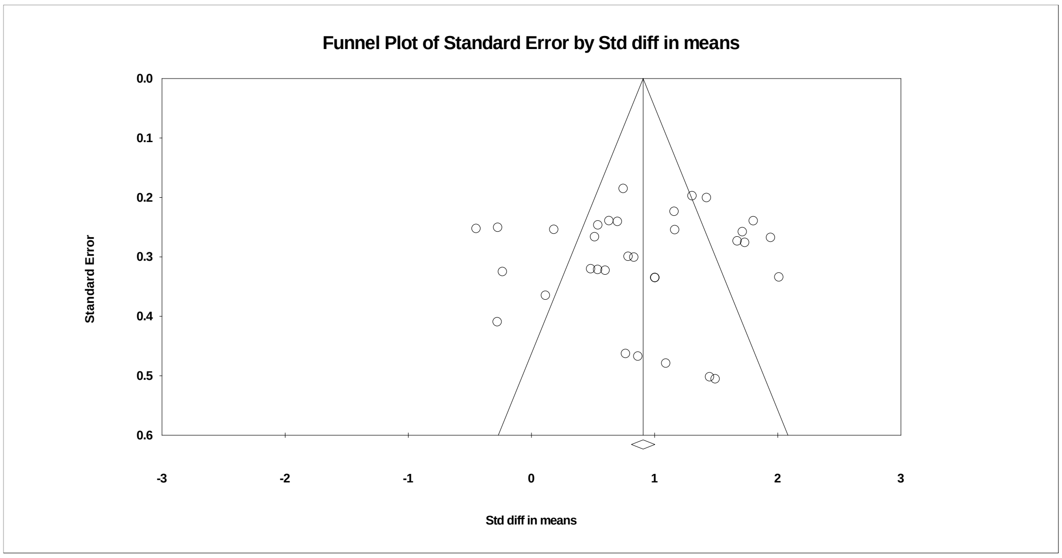

Fig. 2 Funnel plot of standard error by Hedges's g

To verify this assumption, the study also took the Egger's regression test. The result was that both p-value were more than 0.05. Thus, there was no significant evidence of publication bias. The obtained analysis results were highly reliable(Table 4).

Table 4. The result of the Egger's regression test

Intercept	95% lower limit	95% upper limit	P-value (1-tailed)	P-value (2-tailed)

	(2-tailed)	(2-tailed)		
-0.87285	-4.33296	2.58725	0.30528	0.61056

4.2. Heterogeneity test

Higgins et al. [42] suggested that when $I^2 = 0\%$, it indicated that there was no heterogeneity; when $I^2 < 25\%$, it was considered to have mild heterogeneity; when $25\% \le I^2 \le 50\%$, there was moderate heterogeneity; when $I^2 > 50\%$, the high heterogeneity could be found. As Table 5 demonstrated, in this study, I^2=81.977% which meant that there was high heterogeneity in this study. Region, publication time, experimental period and research object, etc. can be considered as the factors of its occurrence. In order to ensure the reliability of the research, the study will use the Random Effects Models to analyse the data at the overall effects level (Table 5).

Table 5. The result of the heterogeneity

Model			Effect size and 95% confidence interval		Heterogeneity		
Model	Number studies	SMD	Lower limit	Upper limit	I^2	df	p
Fixed	33	0.907	0.811	1.002	81.977	32	0.000
Random	33	0.882	0.652	1.113			

4.3. The overall effect test result of the AR and VR technologies in mathematics education

To investigate the overall impact of AR and VR technologies, Figure. 4, the overall effect included in the study, SMD, was calculated to be 0.882, the 95% confidence interval (CI) was from 0.652 to 1.113, Z-value was 7.509 and p-value was less than 0.001.

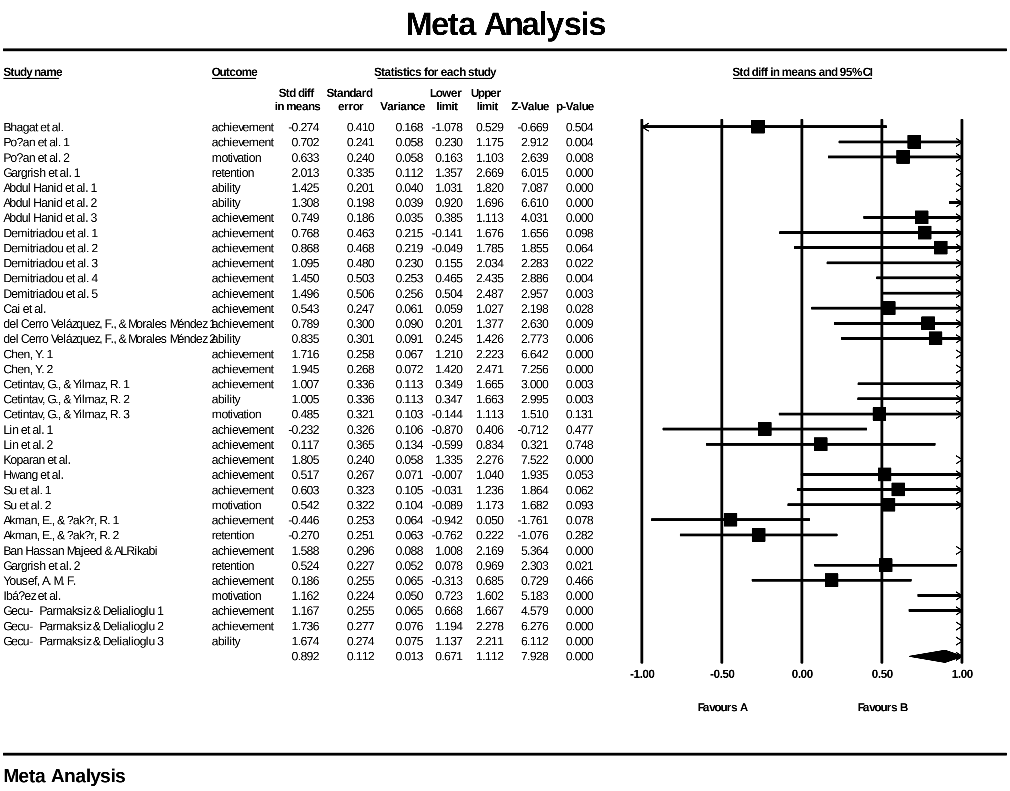

Fig. 4 Forest plot of all included effect sizes

According to the Cohen's role [43] and Sawilowsky's suggestion [44], when d=0.2, it indicated that the impact was very small; when d was between 0.2 and 0.5, it was a medium degree of influence; when the effect amount was ≥ 0.8 but less than 1.2, it was large impact; when the d=1.2, the impact was very large; and when the d=2.0, it could be seen as very huge effect. Hence, in this study, the overall effect of AR and VR technologies on the overall development of students was SMD=0.882>0.8, representing that AR and VR technologies had the positive effect on the individual development of students. About this study, it mainly measured the specific role of AR and VR technologies in students' development from four dimensions - Learning achievement, Learning ability, Motivation and Memory retention. Learning ability included computational think, visualization skill, self-Regulated Learning skill and spatial skill.

For learning achievement, AR and VR technologies for the effect size on students' learning achievement was SMD=0.828, p<0.001, reaching a statistically significant level indicates that these technologies can promote students' learning achievement. About learning ability, the SMD was 1.295, p<0.001, which showed that these had very large impact on the field of students' learning ability. Considered about the SMD of motivation, SMD was 0.751, p<0.001 showed the positive impact beyond the medium level. For memory retention, SMD was 0.861, but p>0.05, it meant that the effect on memory retention was not significant and the role of AR and VR technologies in this field still had a lot of room to improve. There were also statistical differences between different outcomes, p<0.05 and Q=8.557. It showed that AR and VR technologies greatly improved the learning ability. The detail was in Table 6.

Table 6. The effect of AR and VR technologies on students' development

Group			Effect size and 95% confidence interval		Test of null (2-Tail)		Heterogeneity			
Group	Number studies	SMD	Lower limit	Upper limit	Z-value	p-value	Q-value	df	p	I^2
Learning ability	5	1.295	1.040	1.550	9.946	0.000				
Learning achievement	22	0.828	0.528	1.128	5.411	0.000				
Motivation	4	0.751	0.420	1.083	4.445	0.000				
Memory retention	2	0.861	-1.377	3.098	0.754	0.451				
Total between							8.557	3	0.036	
Overall	33	1.009	0.842	1.176	11.830	0.000				

As mentioned above, students had a lot of benefits from the AR and VR technologies. However, in order to check if there were any differences in the effect of these technologies on the students' development in terms of the type of technology, the level of school and the content area. The study had conducted further analysis.

4.4. Subgroup analysis

4.4.1 Differences in effects of AR or VR technologies on students' development

Both AR and VR technologies provide learners an opportunity to allow themselves to get systematic knowledge in an immersive environment [45]. To verify which technology played a dominant role in the education, the study made a further investigation.

As Table 7, it was obvious that the AR technologies had the quite large impact on the student mathematics education, which SMD was 0.993, p<0.001. While that of VR technologies was just 0.460 and p>0.01. There was no significant difference between the AR and VR (Q=3.552, p>0.01). There are two possible factors. First, AR educational environment is a blend of the virtual reality and physical objects in the real world. And secondly, the articles that met the criteria were relatively few, resulting in data being affected by extreme values. In the end, the overall effect of the technologies, SMD, was 0.901, p<0.001, the AR or VR technologies presented the positive effect on student education.

Table 7. Difference in the AR or VR technologies

Group			Effect size and 95% confidence interval		Test of null (2-Tail)		Heterogeneity			
Group	Number studies	SMD	Lower limit	Upper limit	Z-value	p-value	Q-value	df	p	I^2
AR	26	0.993	0.763	1.222	8.472	0.000				
VR	7	0.460	-0.043	0.964	1.792	0.073				
Total between							3.552	1	0.059	
Overall	33	0.901	0.692	1.110	8.452	0.000				

4.4.2 Difference in the effect of the AR and VR technologies on different content area.

To measure the effect of AR and VR technologies in different content areas of the mathematics education, the study has got the following results (Table 8). Throughout the whole content area, with the exception of the probability and the numbers, the result showed that these technologies had the significantly positive effect on student education to learn geometry and algebra. For algebra, the SMD was 0.935, p<0.001. For geometry, the SMD was 0.997, p<0.001. And Q=41.543, p<0.001, there was significant difference between the effect of AR and VR technologies in different content area. But when we eliminated the data of the numbers and probability, there was no significant difference between algebra and geometry (Table 9). It was probably because AR and VR technologies can greatly visualize the abstract mathematics concepts, graph of functions and geometric figure. The 2-D images can be converted into 3-D models under the application of these technologies, which helped fostering the students' mathematical thinking. And the articles that included some different content area were relatively few so that the result may be affected.

Table 8. Differences in the different content area

Group			Effect size and 95% confidence interval		Test of null (2-Tail)		Heterogeneity			
Group	Number studies	SMD	Lower limit	Upper limit	Z-value	p-value	Q-value	df	p	I^2
Algebra	5	0.935	0.531	1.339	4.537	0.000				
Geometry	25	0.997	0.752	1.243	7.951	0.000				
Numbers	2	-0.354	-0.707	-0.008	-2.004	0.045				
Probability	1	0.543	0.059	1.027	2.198	0.028				
Total between							41.543	3	0.000	
Overall	33	0.615	0.447	0.784	7.149	0.000				

Table 9. Difference in the different content area without Numbers and Probability

Group			Effect size and 95% confidence interval		Test of null (2-Tail)		Heterogeneity			
Group	Number studies	SMD	Lower limit	Upper limit	Z-value	p-value	Q-value	df	p	I^2
Algebra	5	0.935	0.531	1.339	4.537	0.000				
Geometry	25	0.997	0.752	1.243	7.951	0.000				
Total between							0.066	1	0.797	
Overall	30	0.981	0.771	1.191	9.151	0.000				

4.4.3 Difference in effects of AR and VR technologies on students of different grade levels

In here, we can find that the AR and VR technologies were used for teaching students in preschool, primary and secondary education. Looking at the Table 10, the effect of these technologies on students' development in different school level was ranked - preschool (SMD=1.513, $p<0.001$), secondary school (SMD=0.832, $p<0.001$) and primary school (SMD=0.819, $p<0.01$), based on the effect size. And Q-value=9.936, $p<0.01$. It presented that AR and VR technologies had the significant difference on the individual development of preschool, primary school and secondary school students. This can be explained as the characteristic of the student. For preschool and primary school students, their cognitive abilities were not very mature, so that it was easy for them to be influenced by the teaching environment. For secondary school students, their cognitive abilities became more stable, which can make them adept at receiving new knowledge. Thus, AR and VR technologies had positive impact on the K-12 education.

Table 10. Differences in different school level

Group			Effect size and 95% confidence interval		Test of null (2-Tail)		Heterogeneity			
Group	Number studies	SMD	Lower limit	Upper limit	Z-value	p-value	Q-value	df	p	I^2
Preschool	3	1.513	1.152	1.874	8.214	0.000				
Primary school	11	0.819	0.267	1.372	2.910	0.004				
Secondary school	19	0.832	0.588	1.076	6.681	0.000				
Total between							9.936	2	0.007	
Overall	33	1.019	0.829	1.209	10.518	0.000				

4.4.4 Differences in the effects of the length of experimental period on students' development

In order to test differences in the length of experimental period on students' development, the study divided it into three stages, short-term (within 4 weeks), medium-term (from 4 to 6 weeks) and long-term (over 6 weeks). Because some articles did not indicate the exact experimental period, this study excluded this part of articles.

In Table 11, the overall effect showed that the SMD was 0.945, $p<0.001$, reaching a significant level. It meant that AR and VR technologies had the large promoting effect on students' mathematics education regardless of the length of the experimental period. To be specific, the effect of the long-term experiment was the largest, which SMD was 1.207, $p<0.01$. It was followed by the medium-term experiment (SMD=0.922, $p<0.001$). And the short-term experiment's SMD was 0.916, $p<0.001$. However, there was no significant difference among students of the different lengths of the experimental periods, Q=0.498, $p>0.01$. The reason may be that students need time to adapt to the new teaching method, with the prolong of the experimental period, students' adaptability to AR and VR technologies became better, while the experimental period was too long, students may feel fatigue, resulting in the less significant effect on promoting individual development.

Table 11. Differences in the length of the experimental period

Group			Effect size and 95% confidence interval		Test of null (2-Tail)		Heterogeneity			
Group	Number studies	SMD	Lower limit	Upper limit	Z-value	p-value	Q-value	df	p	I^2
Long term	3	1.207	0.445	1.970	3.103	0.002				
Medium term	11	0.922	0.651	1.193	6.668	0.000				

Short term	11	0.916	0.448	1.383	3.838	0.000				
Total between							0.498	2	0.780	
Overall	25	0.945	0.721	1.169	8.266	0.000				

5. Conclusion and limitation

This study conducted a meta-analysis of 18 experimental or quasi-experimental studies on the effect of AR and VR technologies on students' mathematics education, then based on the results of the meta-analysis, objective analysis and evaluation were drawn. After the analysis of the overall effect, the study divided it into four dimensions: Learning achievement, Learning ability, Motivation and Memory retention. Lastly, it used sub-group analysis to verify differences in the effect of the school level, technology, content area and experimental period on students' mathematics education. The existence of the abstract concept is one of the difficulties in learning mathematics, and it is necessary to use a tool to explain abstract concept [46].

The result of the meta-analysis presents that the overall effect was that SMD=0.882, which meant AR and VR technologies had large impact on students' mathematics education. It proves our above mentioned hypothesis that AR and VR technologies have the potential to become a promising tool that can visualize concepts and models in mathematics education, which makes knowledge easier for students to understand. However, some negative effect data illustrate that the traditional teaching methods cannot be completely abandoned. The result of the sub-group also provided the information that there were boundary conditions for AR and VR technologies on students' development in mathematics education. The study presented some factors, the school level, technology, content area and experimental period. For school level, the preschool students received the greatest impact, SMD was 1.513. For technology, the effect of AR was more than VR, SMD was 0.993. For content area, technologies maximized the effect in geometry, SMD was 0.997. And with the increase of the experimental period, the positive effect of the technologies became more significant.

Although the current study has presented that AR and VR technologies have large positive effects on the mathematics education from preschool students to secondary school students, there are still some limitations should be mentioned. Among the all limitations, the most critical limitation is the existing database. So further studies may include more databases. Moreover, additional moderator variables such as publication year and region can be examined and find the reasons of the differences or the similarities. Also, the learning approaches like game-based, problem-based, collaborative, interactive and the rest of the approaches may influence the effect of the AR and VR technologies. The engagement of students is a moderator that can be analyzed. However, because the number of studies included the above moderators is small, the study could not conduct a sub-group on these factors. In conclusion, future studies may have the chance to include these moderators, when the quality of the studies is high enough, we can obtain more precise effects on AR and VR technologies on mathematics education.

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