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PAPER

How Virtual Reality Impacts Science Learning? A Meta-Analysis

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ABSTRACT

In recent years, virtual reality (VR) has gained popularity in aiding science education. There are variations in the results reported by the researchers on the effect of VR on student learning outcomes. This study aims to map the results of studies using VR on student science learning outcomes through meta-analysis. In addition, studies were also analyzed on the effects of years of publication, education levels, learning subjects, continents, immersive levels, and time of use of VR. There are 24 articles from international journals that deserve to be analyzed in the 2014–2023 period. The data were analyzed using Excel and JASP applications by presenting results in size effect values, forest plots, and published bias tests. The analysis showed that VR science learning improved learning outcomes compared to conventional learning. Analysis of moderator variables showed no significant effect at the level of education and time of use of VR. However, in education, the year of publication, the continent, and the immersive level showed a significant influence. These findings confirm that VR is an efficient technology that improves students' science learning outcomes. In further research, other researchers can investigate VR related to the teacher's role as a tutor or instructor, pedagogical approaches in VR, types of VR devices, and students' technological skills in using virtual reality.

KEYWORDS

immersive learning, learning outcomes, meta-analysis, science learning, virtual reality (VR)

1 INTRODUCTION

In this decade, the advancement of ICT technology has experienced a significant increase in graphics. Improving the quality of graphics on computer technology allows the presentation of the virtual world into the real world [1]. This development improves visual quality and allows users to enter a simulated environment generated by a computer. Technology that can mimic the real world or create an imaginary world entirely is known as virtual reality (VR). VR technology can show the form of the natural world within the virtual world [2]. This

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technology has become popular in presenting broad information simply [3]. Good information delivery will encourage understanding and avoid misconceptions in learning [4].

The presence of VR technology revolutionizes conventional learning. In conventional learning, face-to-face interaction must occur in the same place and time. Conventional learning has limitations in the flexibility of time and place to carry out the teaching and learning process [5]. In addition, there are other limitations in conventional learning related to resources in the form of limited learning equipment facilities such as experimental equipment and books. The presence of VR technology overcomes limitations that cannot be reached in conventional learning. With VR, it is possible to learn anytime and anywhere without the limitation of time and geographical location [6] [7]. Using learning media in the form of mobile applications encourages students' readiness to learn and practice it [8].

Virtual reality is a revolutionary technology that has changed how education is conducted, providing innovative teaching and meeting the needs of students in terms of technology [9] [10]. In this decade, VR technology has become a trend in learning [11] [12]. VR technology has been widely used in various health and science sectors. Implementing VR in science education has provided exciting opportunities to enhance interactive and immersive learning. Using VR technology, students can experience hands-on exploration in a virtual environment that resembles the real world. In a VR environment, students can interact with science objects, observe natural processes, and experience experiments on a scale impossible in real life [13]. In medicine, VR is used to simulate the dissection of human organs [14]. This technology can minimize the costs and risks of studying the surgical process [15]. Nuclear reactions can be studied more safely in a virtual environment [16]. This technology allows students to develop an in-depth understanding of science concepts and increase their motivation to learn.

Virtual reality technology supports a variety of learning options. Through VR, students can conduct repeated chemical titration experiments [17]. VR supports implementing STEM learning as a simulation medium [18]. The presence of VR can witness extraterrestrial phenomena like the real world [19]. In physics, VR is used to learn concepts of reality that are difficult to present in the real world [20]. Utilizing VR has many advantages over traditional learning. This technology can minimize the costs and risks of studying the surgical process [21]. Nuclear reactions can be studied more safely in a virtual environment [16]. This technology allows students to develop an in-depth understanding of science concepts and increase their motivation to learn.

In addition to advantages, VR has disadvantages when applied to learning. One of the main drawbacks is the high cost of utilizing the technology [22]. In addition, VR as a new technology requires adoption in the form of training before it can be used in learning [23]. The use of VR devices worn on the eyes can also have a negative impact on eye health [24]. Although it has limitations in the adoption process and availability, previous research reveals that this technology can be applied in learning with information related to the effect of VR applications on student learning outcomes.

Previous researchers have reported mixed findings on the influence of VR on science learning. Conventional learning outcomes are better than learning with VR when conducting chemistry learning experiments [25]. Another study showed positive results in using VR to improve student learning outcomes [26] [27] [28]. In the study of biology, the use of VR has a significant effect on improving learning outcomes [29]. In physics learning, supporting research helps improve students' learning ability [30] [31]. However, the study of biology applied in middle schools has a negative effect on the learning process [32].

Differences in the selection and number of samples and places of implementation influence the impact of VR in science learning. In addition, the implementation of diverse research methodologies encourages diverse results compared to the research results obtained by previous researchers. The application of VR at the level of primary, secondary, and university scopes provides different results in achieving learning outcomes. The varied designs and stages of the research require further review to conclude the application of VR in science learning. Such diversity requires limitations to obtain comprehensive results, seeing the effects of VR in general applied in science learning through meta-analysis reviews.

Various findings of the effects of VR use on learning outcomes in science learning require further analysis to obtain in-depth conclusions. Researchers provide study mapping solutions related to the influence of VR on science learning. Meta-analysis is a method of quantitative statistical analysis through various scientific studies that presents data in effect sizes to see the relationship of one variable with another. Previous researchers have analyzed 13 similar studies in middle and tertiary schools on the effect of immersive VR on learning outcomes [33]. Meta-analysis of 21 studies of 0.64 effect size from the range of 2010–2021 in primary education [34]. In addition, a systematic literature review of 23 studies from 2013–2020 on education [35].

A meta-analysis combines results from various studies to increase statistical power, expand generalizations, address variation between studies, reduce publication bias, and provide hypothesis testing and stronger identification of moderating factors. Although previous reviews have provided a basic understanding of VR in education, an in-depth investigation of VR studies is needed to obtain sharper results in VR research, especially in science learning. Therefore, it is imperative to conduct rigorous research to understand the limitations and best practices for integrating VR technology into science learning. Multiple databases are needed to ensure the completeness and actuality of the review, such as data from Science Direct, Dimensions, Google Scholar, Eric, and Springer, with quality articles with Q1, Q2, and Q3 quartile rankings. In addition, a deeper analysis related to the effect of using VR on student science learning outcomes. Also, analysis of several moderator variations consisting of years of publication, education levels, learning subjects, continents, immersive levels, and time of use of VR. Mapping the use of VR to science learning outcomes needs to be done to understand its impact, the challenges faced, and opportunities to be applied in science learning. This study aims to synthesize the findings from various studies in depth regarding the effects of VR on science learning. In addition, this study also aims to identify gaps in the research conducted regarding the impact of VR learning on various aspects such as the year of study, level of education, subjects, and geographical regions. Overall, the results of this study provide in-depth insights into the effects of using VR in science learning as well as its comprehensive implications.

2 METHOD

Meta-analysis is a statistical analysis of similar individual research results to integrate the findings [36], [37]. The preferred reporting items performed the meta-analysis procedure for systematic review and meta-analyses (PRISMA) [38]. The stages carried out to conduct meta-analysis are a) collecting studies, b) coding study features, c) calculating size effects, and d) investigating moderate effects of study characteristics [39].

2.1 Research question

In the context of the background already described, our research focuses on synthesizing articles discussing the interrelationship between VR and learning science.

1. How does VR affect science learning outcomes compared to students' traditional learning?
2. How does VR affect the years of publication, education levels, learning subjects, continents, immersive levels, and time of use of virtual reality?

2.2 Search article and inclusion criteria

Studies in this study were sourced from the databases Eric, Springer, Dimensions, Google Scholar, and Science Direct. Keywords used in the search process by combining "virtual reality" with "biology," "science," "chemistry," and "physics." Historical searches are limited to titles and abstracts following "Virtual reality" AND ("biology" OR "science" OR "physics" OR "chemistry"). Researchers use the Guidelines for PRISMA to conduct inclusion and exclusion processes. Some of the inclusion criteria used, namely:

1. Articles are between 2014 and 2023.
2. Articles written in English.
3. Articles are at the secondary school and university education level.
4. Articles come from international journals in Q1, Q2, and Q3 rankings from Schimago.
5. Published articles related to VR in learning physics, chemistry, and biology in titles and abstracts.
6. The article presents data on the number of samples, average value, and standard deviation (SD) of the control and experimental classes.

These keywords are selected based on previous literature, recent research trends, and relevance to the research topic. These keywords cover various important aspects of VR, science learning, and learning outcomes. The selection of the 2014 to 2023 deadline is due to the significant development in VR technology over the years. It ensures that the data analyzed is up-to-date enough for the relevance of the current research. ERIC, Science Direct, Dimensions, Springer, and Google Scholar are used as database sources due to their comprehensive data coverage, reliability, and specific focus on education and technology. This database is selected based on its credibility, accessibility, and relevance to the research topic. The total number of studies found is 78 articles in the Eric database; Science Direct has 11 articles; Dimensions has 251 articles; Springer has 145 articles; and Google Scholar has 298 articles. The inclusion and exclusion process in the study through the PRISMA procedure is shown in Figure 1.

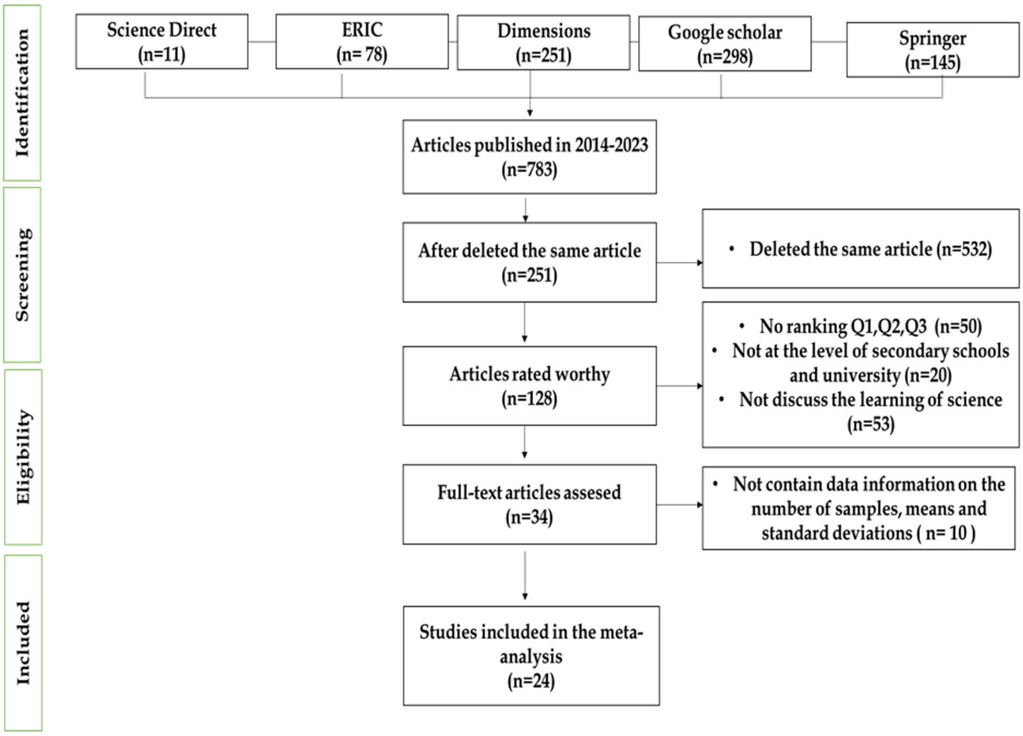

Fig. 1. PRISMA flow diagram

Figure 1 shows a PRISMA diagram in this meta-analysis. In each database, the same keywords are used to search for articles by combining the words "Virtual reality" with "biology," "science," "physics," and "chemistry" and utilizing filters from each search database. Articles relevant to these keywords are filtered according to the criteria determined by the article. According to the search keywords, the data is selected based on inclusion and exclusion criteria by recording all articles obtained from all databases. Duplicate articles are deleted, and selection is based on the category of article rankings from the publisher's journals, which are checked individually. Articles that meet the quartile rankings are re-selected to ensure conformity with the focus of discussion in the field of science and education level (university and secondary schools). The final selection stage is to check the availability of the data presented in the article to qualify as a source of meta-analysis data. Articles that met these criteria totaled 24 and were downloaded for coding. The coding of the article was carried out based on the order of year, quartile ranking, education level, research method, subject, country, continent, immersion level, duration of VR use, number of control groups and experimental groups, as well as learning outcome values in the form of average scores and SDs from both groups. The average value data and SD of the group were used to obtain the effect size of each study. To avoid potential bias, tests were conducted using the funnel plot technique to see the data distribution and conduct sensitivity analysis. Sensitivity analysis was performed by deleting one study at a time to see the impact on the overall heterogeneity test results. The meta-analysis results are considered stable and reliable if the results do not change significantly after eliminating individual studies. Sensitivity analysis was performed to ensure that extreme or low-quality individual studies did not affect the results.

2.3 Data analysis

The meta-analysis was conducted to combine quantitative data from various studies to estimate the impact of VR measures on student learning outcomes in measuring the effect. This effect is measured using tools such as Excel and JASP applications. Excel is used to process data to obtain the right effect size. JASP is used to analyze the results of meta-analyses, including forest plot presentation, heterogeneity analysis, funnel plots, and publication bias evaluation. To calculate the effect size, the average value (x), SD, and the number of samples (n) from the control class and experimental class [40]. The equation for calculating the size effect uses the following equation:

$$g = \frac{\bar{X}_E - \bar{X}_C}{SD_{whitin}}\left(1 - \frac{3}{4df - 1}\right) \tag{1}$$

$$SD_{whitin} = \sqrt{\frac{\left(n_E - 1\right)S_E^2 + \left(n_C - 1\right)S_C^2}{n_E + n_c - 2}} \tag{2}$$

The value of d is the effect size of the data obtained, and SD is the standard deviation. Researchers reportedly used Hedge's g for this effect size, which scored better than Cohen's d in adjusting for statistical bias [37]. To interpret the effect size values, we use the following classifications: g = 0.2 (small effect), g = 0.5 (medium), g = 0.8 (large), g = 1.20 (huge), and g = 2.0 (very huge) [41].

3 RESULTS

The articles used in the meta-analysis are scattered from ScienceDirect, ERIC, Google Scholar, Springer, and Dimensions databases. The data of articles found according to search keywords was 783. All data is filtered according to predetermined criteria. Twenty-four articles were eligible for mapping. All articles were coded and grouped into groups of years, education levels, learning subjects, continents, immersive levels, time of use of VR, effect size (g), number of samples (n), and standard error (SE). This aspect is characteristic of the results of the meta-analysis study. The results of the coding in the meta-analysis are shown in Table 1.

Table 1. Characteristics of a meta-analysis study

Author	Q	Years	Education Level	Methods	Subject	Country	Continent	Immersive Level	Time	N VR/control	g	SE
[25]	Q1	2021	University	TE	Chemistry	USA	America	IVR	10–25 minute	20/20	–1.14	0.34
[18]	Q1	2022	University	TE	Biology	Denmark	Europa	IVR	10–45 minute	41/38	1.59	0.26
[42]	Q1	2022	University	QE	Biology	Iran	Asia	IVR	60 minute	25/25	0.65	0.29
[43]	Q1	2019	University	QE	Biology	Scotland	Europa	SIVR	16 minute	50/62	0.15	0.19
[44]	Q1	2021	University	QE	Biology	Netherlands	Europa	IVR	90 minute	57/112	0.74	0.17
[45]	Q2	2019	University	QE	Biology	Saudi Arabia	Asia	NIVR	30 minute	59/48	0.8	0.2

(Continued)

Table 1. Characteristics of a meta-analysis study *(Continued)*

Author	Q	Years	Education Level	Methods	Subject	Country	Continent	Immersive Level	Time	N VR/control	g	SE
[30]	Q1	2021	Secondary Schools	TE	Physics	Turkey	Europa	IVR	90 minute	14/17	0.28	0.36
[46]	Q1	2022	University	QE	Chemistry	Belgium	Europa	IVR	30 minute	32/33	1.53	0.28
[47]	Q2	2020	Secondary Schools	QE	Physics	Oman	Asia	SIVR	30 minute	15/15	–0.71	0.37
[48]	Q3	2020	University	QE	Chemistry	USA	Europa	IVR	60 minute	50/50	1.11	0.21
[49]	Q1	2023	University	QE	Biology	Finland	Europa	NIVR	30 minute	35/35	1.28	0.26
[50]	Q2	2021	Secondary Schools	QE	Chemistry	Indonesia	Asia	SIVR	10–15 minute	34/34	0.99	0.26
[32]	Q1	2020	Secondary Schools	QE	Biology	USA	Europa	NIVR	90 minute	2020	–0.35	0.32
[29]	Q1	2021	University	D	Biology	China	Asia	IVR	90 minute	24/26	2.46	0.37
[51]	Q1	2019	Secondary Schools	D	Chemistry	China	Asia	SIVR	30 minute	36/36	1.21	0.26
[52]	Q2	2019	University	QE	Chemistry	USA	America	NIVR	30 minute	29/41	–0.25	0.24
[53]	Q1	2018	University	QE	Biology	USA	America	NIVR	7–8 minute	28/27	–1.1	0.29
[54]	Q1	2021	Secondary Schools	TE	Physics	Pakistan	Asia	IVR	30 minute	92/92	0.59	0.15
[55]	Q2	2021	University	QE	Biology	USA	America	IVR	30 minute	13/11	–0.19	0.4
[26]	Q2	2019	University	QE	Chemistry	China	Asia	IVR	20 minute	52/70	4.09	0.32
[56]	Q1	2021	University	QE	Chemistry	Germany	Europa	NIVR	60 minute	51/56	–0.16	0.19
[20]	Q1	2022	University	QE	Physics	China	Asia	IVR	30 minute	30/30	0.77	0.27
[57]	Q1	2019	University	QE	Physics	USA	America	IVR	30 minute	26/26	–0.1	0.28
[58]	Q1	2022	Secondary Schools	QE	Physics	UK	Asia	IVR	30 minute	25/25	0.18	0.28

Table 1 informs the distribution of articles analyzed in the quartile ranking Q1 as many as 17 articles, Q2 as many as six articles, and Q3 as many as one article. The journal articles used in this study are not based on the quartile value of the article published. However, the quartile ranking data in this study is based on Schimago data published in 2023. The articles analyzed were found in the 2018 to 2023 distribution. Researchers use three methods: quasi-experimental, true experimental, and development. The analyzed articles are spread across three continents and 15 countries. The technology used to observe the effects of VR on learning outcomes is grouped into immersive virtual reality (IVR), semi-immersive virtual reality (SIVR), and non-immersive virtual reality (NIVR). The sample size was grouped in the class by utilizing VR technology and the control class. The total sample size of all studies incorporated in this meta-analysis reached 1807 students. The time to use VR in learning is as low as seven minutes, and the longest is as long as 90 minutes in one learning session. The number of samples, the mean value, and the SD are used to obtain the value of the effect of size and standard error.

3.1 The effect of virtual reality on student science learning outcomes

Meta-analyses were performed using randomized effects to consider variations between studies incorporated in the analysis. Using random effects in research meta-analyses allows combining data from different studies by accounting for variation and heterogeneity and overcoming statistical biases [37]. The results of heterogeneity tests using random effects from 24 studies investigating the effect of VR on learning outcomes in science learning are presented in the form of forest plots. Code data information, point estimation, effect size (d), and 95% confidence interval (CI) as a forest plot are shown in Figure 2.

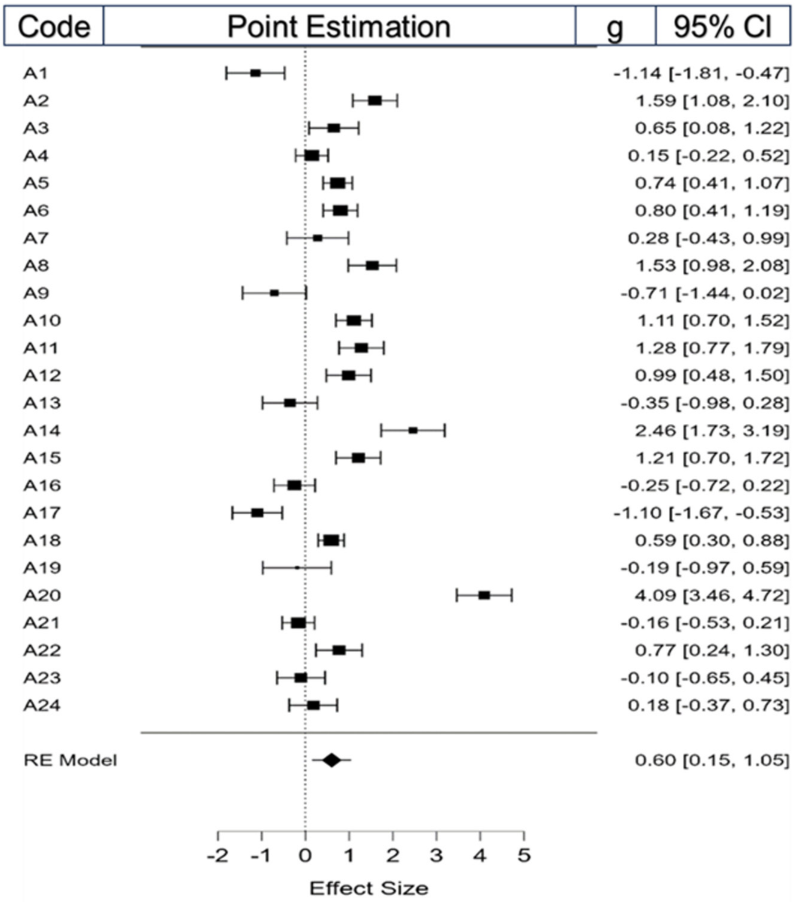

Fig. 2. Forest plot for effect size

Figure 2 shows the results of the distribution of size effect values from the study analyzed in the form of forest plots. The magnitude of the value of the effect of size on the level of confidence of 95% has a diverse distribution. Some studies show that the distribution is entirely on the right side of zero, while others are between the left side of zero. Studies on the right side of zero provide information regarding significant improvements. At the 95% confidence level, the effect size distribution interval range is from 0.15 to 1.05. The average effect size value of 0.6 is in the medium category. The heterogeneity test was conducted to determine the effect of VR on science learning outcomes. The heterogeneity test presents data in Q, p, and I^2 values. The value I^2 indicates the true heterogeneity of the data distribution [59]. Test result data from the values table so that it is visible in Table 2.

Table 2. Results meta-analysis

Variable	Overall	95% Confidence Interval (CI)	
		Lower	Upper
Number of Samples (K)	24		
Heterogeneity test (Q)	321.592		
p-value	< 0.001	0.152	1.053
Standard score (z)	2.621		
Effect Size (g)	0.602		
Heterogeneity test (τ^2)	1.190	0.693	2.486
Heterogeneity test (τ)	1.091	0.833	1.577
Heterogeneity test ($I^2\%$)	95.030	91.761	97.558
Heterogeneity test (H^2)	20.121	12.138	40.951

Note: If p-value > 0.05, No significant influence.

The results in Table 2 indicate differences in increased learning using VR compared to traditional learning in the randomized effects model ($g = 0.602$; 95% CI 0.152–1.053, $p < 0.001$; $I^2 = 95\%$). A sensitivity analysis was conducted to strengthen the data results through the heterogeneity test. This analysis is carried out by examining the changes if one of the articles is omitted. The assumption of elimination of one of the studies was based on the size of the smallest sample and the effect of the smallest size. The re-heterogeneity test is carried out with these two forms of assumptions. Assuming the data by eliminating the smallest sample, a random effect value ($g = 0.635$; 95% CI 0.170–1,100, $p < 0.001$; $I^2 = 95.26\%$). Assuming that the study with the smallest size effect was eliminated, a random ($g = 0.676$; 95% CI 0.231–1.21, $p < 0.001$; $I^2 = 94.77\%$). The results of the data obtained showed no significant change in the data from the results of the meta-analysis. This condition informs the data's stability and reduces the analyzed study's potential bias. Heterogeneity occurs due to differences in the year of publication of the study, the number of samples, regions, and variations in the methods used in each article. The implications of heterogeneity prompted the conduct of subgroup analysis to obtain more significant effects. This condition provides an analysis of the moderator effect on several categories of studies analyzed due to the influence of the heterogeneity of the studies investigated.

3.2 The effect of VR on the years of publication, education levels, learning subjects, continents, immersive levels, and time of use of VR

The heterogeneity test results allow the moderator effect of the study to be analyzed. The moderator effect analysis aims to understand the influence of moderator variables on independent and dependent variables. Analysis of VR moderator effects includes the years of publication, education levels, learning subjects, continents, immersive levels, and time of use of VR. The results of the VR moderator effect analysis are presented in Table 3.

Table 3. Moderator analysis

Moderator	k	Effect Size	95% CI		Qb	p-Value
			Lower	Upper		
Level of education					1.803	0.2
Secondary Schools	7	0.347	–0150	0.844		
University	17	0.717	0.113	1.320		
Learning subject					9.644	0.008
Physics	6	0.216	–0.183	0.616		
Chemistry	8	0.919	–0.159	1.998		
Biology	10	0.603	–0.021	1.227		
Years of publication					18.84	0.000
2018–2019	7	0.68	–0.549	1.909		
2020–2021	11	0.339	–0.235	0.913		
2022–2023	6	1.005	0.561	1.45		
Continents					90.78	0.000
Asia	10	1.098	0.296	1.900		
Europa	9	0.688	0.215	1.162		
America	5	–0.551	–1.003	–0.098		
Level immersion					38.92	0.000
NIVR	6	0.047	–0.636	0.729		
SIVR	4	0.432	–0.394	1.258		
IVR	14	0.898	0.242	1.553		
Time use VR					1.854	0.17
≤30 Minute	16	0.511	–0.098	1.12		
>30 Minute	8	0.78	0.157	1.403		

Note: If p-value > 0.05, No significant influence.

The data presented in Table 3 shows that there are 6 moderator variables of VR on science learning outcomes. At the education level, there are two levels analyzed, namely secondary schools and universities. For analysis, studies in the field of learning classified as science categories are grouped into physics, chemistry, and biology. The presentation analysis based on the publication year is grouped into 2018–2019, 2020–2021, and 2022–2023, analyzing the distribution of regions grouped into Asia, Europe, and America. Based on the immersion level of VR technology, analysis is grouped into NIVR, SIVR, and NIVR. In addition, the analysis of VR usage time was grouped into time ranges ≤30 and >30.

The analysis of the VR moderator effect based on education level showed different variations in results. The smallest effect size was found in secondary schools with a value of 0.347 in the small category, and this result was obtained from seven studies. Meanwhile, the largest effect size was found at the university level, with a value of 0.717 in the medium category, and this result was obtained from 17 studies. The lowest and highest interval scores at the 95% confidence level were –0.150 to 0.844 for secondary schools and 0.113 to 1.32 for university level. The results of the p-value test show a small value, which is 0.2. These findings indicate no significant differences in the use of VR between secondary schools and universities.

Analyzing the VR moderator effect by learning subjects revealed variations in results in each field. The lowest effect size was found in physics, with a value of 0.216 in the small category. This result was obtained from six studies. Meanwhile, the largest effect size was found in chemistry with a value of 0.919 in the large category, and this result was obtained from eight studies. The lowest and highest interval ranges at the 95% confidence level are –0.183 to 0.616 for physics, –0.159 to 1.998 for chemistry, and –0.021 to 1.227 for biology. The p-value test results show a small value, which is 0.008. These findings indicate significant differences in the use of VR in physics, chemistry, and biology subjects.

The results of the analysis of the VR moderator effect based on the year of publication of the study showed variations in the results. The largest effect size was found in the 2022–2023 range, with six studies and an effect size value of 1,005 in the large category. Meanwhile, the smallest effect size was found in the 2020–2021 range, with 11 studies and an effect size value of 0.339 in the low category. In 2018–2019, seven studies were found with an effect size value of 0.68 in the medium category. The lowest and highest interval values at the 95% confidence level are –0.549 to 1.909 for 2018–2019, –0.235 to 0.913 for 2020–2021, and 0.561 to 1.45 for 2022–2023. The results of the p-value test show a small value, which is 0.000. This finding indicates a significant difference in the findings of the publication of articles on VR between 2018 and 2023.

The analysis of the VR moderator effect based on the distribution of study areas showed significant variations in results. The lowest effect size was found in the Americas, with a value of –0.551 in the low category. This finding was obtained from five studies conducted. Meanwhile, the largest effect size was found on the Asian continent, with an effect size value of 1,098 in the large category. This finding was obtained from 10 studies conducted. On the European continent, there were nine studies with an effect size value of 0.688 in the medium category. The lowest and highest interval values at the 95% confidence level are 0.296 to 1.900 for Asia, 0.215 to 1.162 for Europe, and –1.003 to –0.098 for the Americas. The results of the p-value test show a small value, which is 0.000. This finding indicates a significant difference in publication findings in the area studied.

The analysis of the effects of VR moderators based on the immersive level of the technology used showed significant variations in results. The lowest effect size was found in NIVR, with a value of 0.047 in the low category. This finding was obtained from 14 studies conducted. Meanwhile, the largest effect size was found in IVR, with an effect size value of 0.898 in the large category. This finding was obtained from eight studies conducted. In SIVR, there were four studies with a value of 0.432 in the small category. The lowest and highest interval ranges at the 95% confidence level are –0.636 to 0.729 for NIVR, –0.394 to 1.258 for SIVR, and 0.242 to 1.553 for IVR. The results of the p-value test show a small value, which is 0.000. These findings indicate significant differences based on immersive levels in VR use.

The analysis of the VR moderator effect based on the time of use of VR showed a significant variation in the results. The smallest effect size was found in using VR in learning for ≤30 minutes, with a value of 0.511 in the small category. This finding was obtained from 16 studies conducted. Meanwhile, the effect size on the use of VR >30 minutes also had a value of 0.78 in the medium category, obtained from eight studies. The lowest and highest interval values at 95% confidence are –0.098 to 1.12 for ≤30 minutes and 0.157 to 1.403 for >30 minutes of use. The results of the p-value test show an insignificant value, which is 0.17. These findings indicate that there is no significant difference based on time.

3.3 Publication bias

All data used in the meta-analysis were tested for publication bias. The publication bias test aims to evaluate the conclusions of the meta-analysis results. In meta-analysis, publication bias can be caused by various factors [60]. If the research results used in the meta-analysis come from data studies with insignificant results, there will be a tendency for publication bias. Publication bias is associated with statistically insignificant effects [37]. Methods to detect publication bias include funnel plots, file drawer analysis, and Egger regression. The results of the publication bias test are presented in Table 4 and Figure 3.

Table 4. Results of publication bias test

Variable	Egger's Test	File Drawer Analysis	Funnel Plot Asymmetry
Fail-Safe N		1152.000	
Kendall's τ			–0.056
p-value	0.869		0.708
Z	–0.164		

Note: p > 0.05, no publication bias occurs.

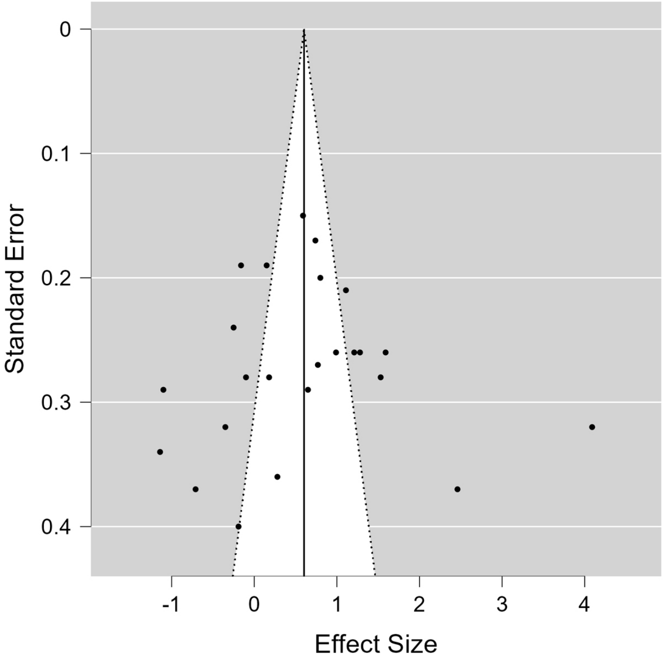

Fig. 3. Funnel plot

Table 4 presents the results of publication bias testing with the funnel plot method, file drawer analysis, and Egger regression. Meanwhile, Figure 3 displays a funnel plot visualization to see the balance of the study distribution in the form of dots. The results of the study distribution in the funnel plot inform the visualization of the symmetrical distribution of data. The symmetrical distribution of data in the funnel plot informs the absence of publication bias [37]. These results were strengthened by the p-values of the asymmetrical plot funnel and the Egger test of 0.78 and 0.869. The obtained p-value is greater than 0.05, the minimum threshold of data requirements in meta-analysis to prevent publication bias. These results indicate no publication bias in the asymmetrical plot funnel and Egger tests. Other bias test results are shown through the safe number file data, which is 1152,000, exceeding the required limit for publication bias tests. The safe number file limit requirement is measured by the formula 5k + 10, where “k” is the number of studies in the meta-analysis [61]. Based on the publication bias test results, there was no indication of bias in the studies conducted in this meta-analysis.

4 DISCUSSION

A meta-analysis of 24 articles investigating the effect of using VR in science learning found that VR had an effect size value of 0.6 in the moderate category. These findings suggest that VR use significantly affects learning outcomes. More interestingly, the value of the effects found in this study was higher than previous findings. A recent study by Akgun and Atici (2022) found that the effect of the size of VR influence in education has a value of 0.526 in the medium category [62]. These results support previous findings and show that using VR in learning has a significant effect.

Science learning by utilizing VR technology has also experienced a significant increase compared to conventional learning. Merchant et al. (2014) also found similar results that showed higher learning effects by utilizing VR [33]. As such, these results provide strong support for the benefits of using VR in the context of science learning. Behind the advantages of VR, as a new technology, VR has several disadvantages that need to be revealed. The availability of VR equipment that is still expensive is one of the constraints, and the higher the immersion rate, the more expensive the device will be [22]. In addition, VR learning interventions require practice before using the device [23]. VR devices attached to the eyes are also a weakness for eye health [24]. However, VR’s potential as an innovative learning medium has experienced rapid growth and development in the future, as shown by research aimed at overcoming current weaknesses. In general, the results of the VR meta-analysis study have a positive effect on improving science learning.

Analysis of moderator variables on education level and VR usage time showed no significant effect. These results align with previous research findings, explaining that differences may influence these factors in the types of learning and interventions used in the study [63]. However, variables such as the field of education, year of publication, continent, and level of immersion depth significantly influenced the use of VR in learning. The implications of this technology in education encourage practical learning in science learning. This technology is relevant to be implemented in learning at the secondary school and tertiary education levels. Limitations of interventions in learning are an important part of implementing this technology to support improving students’ learning ability. This technology is dominated by Asian, European, and American countries and provides opportunities for other countries to adopt the technology in science learning, supporting improving student learning outcomes. The use of VR technology with a higher level of immersion encourages a greater effect in supporting learning, so this is a consideration in the implications of being applied to support the optimal improvement of student learning outcomes.

The use of VR technology in educational contexts, especially in universities, has become dominant [64], [65]. Many universities are using VR to help simulate complex scientific phenomena in the learning process. In their research, Tarng et al. (2022) showed that the use of VR in a university environment can present a variety of scientific phenomena in the form of virtual environments, including in physics, chemistry, and biology learning [20]. Thus, complex experimental activities can be carried out more effectively and efficiently within a virtual environment.

Virtual reality in science learning also supports students' interest in learning and positively affects learning. A study by Lui et al. (2023) found that using VR in science learning can increase student interest and create a more enjoyable learning experience [66]. With the interactive simulations offered by VR, students can be more engaged in learning and develop a better understanding of complex science concepts. Simulation in learning encourages the formation of students' critical thinking skills [67] [68] [69]. In addition, using VR technology also supports creating more interactive learning in the classroom. Research by Zhao et al. (2020) revealed that VR allows direct interaction between students and learning content, such as three-dimensional objects, virtual environments, or simulations [63]. VR provides a more immersive learning experience and allows students to actively engage in learning, unearthing knowledge more interactively and engagingly.

Research publications related to VR technology have increased exponentially yearly [70]. Many publications on VR technology are found mainly in China and the USA, supported by significant technological advances in both countries [71]. The results of publications in the last two years indicate that VR has a large and significant effect. In addition, VR technology continues to experience improvements and changes from year to year, with a better immersion level than previous VR technologies. The results of publications in the last two years indicate that VR has a large and significant effect. In addition, VR technology continues to experience improvements and changes from year to year [63], with a better immersion level than previous VR technologies. Immersive VR technology is the most widely used technology in learning. This technology presents a more realistic environment compared to non-immersive and semi-immersive technologies. In terms of use, the equipment that is popularly used is Oculus, HTC Vive, and Samsung Gear VR. In non-immersive environments, using VR in learning is more likely to present the environment in 360-degree videos [49]. While in semi-immersive and immersive environments, users can move and control objects in the virtual environment.

In the learning process, exposure to VR use generally takes place in a short time, ranging from 7 to 30 minutes. However, there are exceptions when VR exposure lasts longer because participants are completing certain tasks, assessments, or procedures in a virtual environment [50] [53] [72]. Exposure to VR use over more extended periods can present opportunities for exploration and experimentation activities in learning and interaction in other virtual environments [73] [74]. Learning in VR provides opportunities for students to take advantage of learning time together in a virtual environment. Presenting 3D objects in VR encourages time efficiency in learning because students gain a better understanding quickly through simulation and collaboration in a virtual environment [75] [76].

Overall, the findings from these articles provide valuable insights for educators and curriculum developers in harnessing the great potential of VR technology. With its ability to create immersive and interactive virtual environments, VR technology has excellent potential to enhance students' learning experiences. Applications of VR in learning, including scientific simulations and interactions in virtual environments, can open up opportunities to design learning experiences that are more engaging and effective in understanding complex science concepts.

5 CONCLUSION

A meta-analysis of 24 articles showed that VR science learning improved learning outcomes compared to conventional learning (g = 0.602; 95% CI 0.152–1.053,

$p < 0.001$; $I^2 = 95\%$). The value of the size effect is in the medium category. The results of the publication bias test using the Egger test method, file drawer analysis, and funnel plot asymmetry showed no publication bias. Analysis of moderator variables showed that there was no significant effect at the level of education and time of use of VR. However, in learning subjects, the year of publication, the continent, and the immersive level showed a significant influence. In addition, the results of a meta-analysis. These findings confirm that VR is an efficient technology that improves students' science learning outcomes. VR is used as a medium for simulating and exploring phenomena in science learning. In science learning, VR is used to explore the mastery of concepts related to physics, chemistry, and biology. This technology is used in practice at the secondary and tertiary education levels.

Although the use of VR is known to have a very high influence on students' science abilities, the results are only based on research with certain criteria. Some studies For this study, only six research characteristics were studied, including the years of publication, education levels, learning subjects, continents, immersive levels, and time of use of VR. This meta-analysis has limitations on the database sources used that still need to be expanded; the variety of studies analyzed is still limited to the sciences, physics, chemistry, and biology groups. In addition, the quality of the studies can be expanded to obtain better results. Further analysis of the variation of other moderator variables provides greater opportunities for similar studies. Some others include the role of teachers as tutors or instructors, pedagogical approaches, types of VR devices, and students' technological skills. As a result, the conclusion does not reflect the effectiveness of the use of VR in science learning. These results provide an overview of opportunities and challenges for the implementation of technology in learning to other researchers.

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