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The Future of Augmented Reality Immersive Technology-Based Mathematics Learning: A Meta-Analysis Study

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ABSTRACT

Immersive technology with augmented reality (AR) as a didactic support has gone global and enriched the learning process with various packages of advantages. Although there have been many meta-analyses to test the aggregate effect of AR on students' academic performance, few have considered the duration of treatment as a moderator variable and also the comparison of the effect of AR in mathematics learning with other subjects. This study was conducted to. This random effect meta-analysis study was conducted to test the effectiveness of the application of immersive AR technology in learning by considering the duration of treatment and subject matter as research features and specifically identifying data from the Scopus database. This objective was achieved by examining 73 independent comparisons (n = 2822) that met the requirements and were identified from the Scopus database. The results of the CMA software-assisted analysis showed that the integration of immersive augmented reality technology in learning had a moderate effect ($g = 0.75$, $p < 0.005$) compared to learning conditions without AR. These results also add empirical validity to the relationship between categorical variables and the size of the research effect, as needed to understand research in the context of the application of AR in mathematics learning in the future. By clarifying the impact of AR implementation in mathematics learning, this study contributes to teachers to improve teaching effectiveness, enrich interactive learning media, and arouse students' interest and understanding of mathematical concepts in a more concrete and visual way. These findings also provide new directions for teachers, lecturers, stakeholders, and professionals in their efforts to develop a didactic framework by considering the duration of treatment in future AR applications.

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A. INTRODUCTION

Augmented Reality (AR) driven learning has become a new trend, incorporating technology into specific learning topics (Ashwini et al., 2022; Bower et al., 2014; Nordin et al., 2022; Pathania et al., 2023). AR technology is utilized as an interactive tool and media that connects digital information with the real world (Monfared et al., 2016). AR is considered an efficient and promising technology that can improve the education sector. AR is a visualization technology that enables human interaction by providing users with a perception of reality using virtual information (Oueida et al., 2023). AR is the latest innovation that can expand sensory perception through digital objects (Buchner & Kerres, 2023), so that it has the potential to be widely applied in the world of education (Sural, 2018; Yilmaz & Batdi, 2021). Virtual objects through AR interfaces help teachers to visualize 2D and 3D geometric objects (Demitriadou et al., 2020; Kan & Özmen, 2021; Leitão et al., 2014).

The use of AR supports accessibility achieved through mobile devices and dynamic switching of gesture recognition (Sun et al., 2019). The use of AR allows students to interact with virtual objects easily and naturally, thus supporting their understanding of what is being learned and improving the quality of education. AR is seen as a valuable educational tool and has great potential for future learning in supporting students' academic abilities (Bower et al., 2014). This AR integration also supports increased perception of existing materials (Yadav & Gupta, 2023). AR can even be a convenient and efficient alternative to replacing risky and expensive physical laboratories (Mukhtarkyzy et al., 2022). In line with that Romano et al. (2020) detailed the advantages of AR, namely helping to explain processes, assisting simulations, gaining attention, describing abstractions, explaining spatial concepts and replacing experiments.

The advantages of AR have triggered a flurry of studies, namely those that specifically test its effectiveness in learning. However, various previous empirical studies have provided varying and inconsistent results. Several research results reveal that augmented reality based learning (ARBL) can increase students' motivation and interest in learning, thereby supporting the improvement of their academic abilities (mis Al-nawaiseh, 2020; Aldalalah et al., 2019; Cahyana et al., 2023; Eldokhny & Drwish, 2021; Safar & Al-jafar, 2017; Setiawan et al., 2023; Silva et al., 2022; Whang et al., 2021). In contrast, several other individual studies show conflicting results that the use of AR has no or only a small effect on students' academic abilities (e.g. Chang et al., 2020; Chien et al., 2017; Putra et al., 2021; Yilmaz & Goktas, 2017). Even in the latest study, Buchner & Kerres (2023) found that the impact of AR technology on students' academic abilities is still unclear or inconsistent.

Meanwhile, in reality, teachers, lecturers, stakeholders and professionals need accurate information about how much influence AR has in improving students' academic abilities. This information is needed to consider the integration of AR in education. This hope is achieved by conducting a meta-analysis study because with this work we can integrate the findings of primary studies, and investigate the reasons for the inconsistency of the results from all primary studies to then consider its implementation (Franzen, 2020; Juandi, Suparman, et al., 2022; Juandi, Tamur, et al., 2022; Tamur, Ndiung, et al., 2023).

Related to this, in the current literature there have been many meta-analyses that specifically aim to find the overall effect of AR use in education. Meta-analyses conducted by Tekedere & Göker (2016); Ozdemir et al. (2018) and Lin & Yu (2023) for example only consider limited moderator variables. Likewise, meta-analyses conducted by Yilmaz & Batdi (2021) and Altinpulluk (2019) have also analyzed the overall effect of AR technology in education, but did not continue by analyzing categorical variables that might clarify the variation between the results of the primary studies. Of the various meta-analyses that have been conducted, none have specifically considered the duration of treatment as a moderator.

In addition to aiming to analyze the overall impact of AR integration in education, this study fills the gap from previous studies by considering the duration of treatment or learning as a categorical variable. Thus, in detail, the objectives of this study are: first, to determine the overall effect of mathematics learning supported by AR integration. Second, to analyze the variability among primary research results regarding the duration of learning provided. This contributes to the literature, teachers, lecturers, and stakeholders considering future AR use in education..

B. METHODS

This study uses meta-analysis as an approach to find the overall effect of AR integration in education. This is because meta-analysis provides a more objective procedure in drawing conclusions or decisions when various primary studies provide varying results (Cooper, 2017; Schmidt & Hunter, 2015). In general, meta-analysis research begins with the formulation of research problems and hypotheses, followed by literature searches, then variable coding, then statistical analysis, and ends with the interpretation of the same findings(Borenstein et al., 2009). The following describes the details of these stages.

1. Literature Search

Online databases were selected as the location for searching for documents or journal articles from research results that would be included in the analysis. Furthermore, the Publish or Perish (PoP) program was used to retrieve data related to the influence of AR use in education.

2. Literature Inclusion Criteria

The primary studies collected using the PoP application were then selected. Regarding this selection process, (Baashar et al., 2022) suggested using the PICO framework (Population, Intervention, Comparison, Outcomes). Based on the PICO framework, the inclusion criteria in the study are as follows:

a. Populasi

   In accordance with the research objectives, the studies included in this study specifically analyzed students from various levels of education as the population. The study reports included were in the form of journal articles written in English and indexed by Scopus. Studies outside these provisions were excluded from the analysis (e.g. Kan & Özmen, 2021). The studies analyzed must include statistical information to obtain the effect size. Studies that do not meet these requirements will be excluded from the analysis (e.g., Nordin et al., 2022; Oueida et al., 2023; Tezer et al., 2019).

b. Intervention

   Experimental research using AR technology as a treatment in the field of education or teaching. Meanwhile, meta-analysis studies such as (Baashar et al., 2022; Tekedere & Göker, 2016) were excluded from the analysis because they did not conduct experiments or did not use AR as a treatment. Research conducted by (Whang et al., 2021) dan (Tao et al., 2023) was also excluded from the analysis because the AR effectiveness experiments they studied were conducted outside the educational domain.

c. Comparison

   Experimental research and must involve a control group as a comparison. Development research that only uses one sample or uses a qualitative approach is excluded from the analysis (eg; Karagozlu et al., 2019; Ratnawati et al., 2022; (Hidayat et al., 2021). In addition, research that involves a control group as a comparison but uses structural equation modeling or survey research is excluded from the analysis (eg; Jiang et al., 2021; Yuan et al., 2021).

d. Outcomes

The studies analyzed examined the effect of AR on students' academic abilities (including knowledge, confidence, motivation, and skills). Studies that did not directly address these were excluded from the analysis (Chi et al., 2013; Osadchyi et al., 2021). Furthermore, in this study, the suggestion from Pigott & Polanin (2020) namely using the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) protocol was considered as a data filtering to produce transparent and high-quality meta-analysis stages. Figure 1 presents the data filtering process.

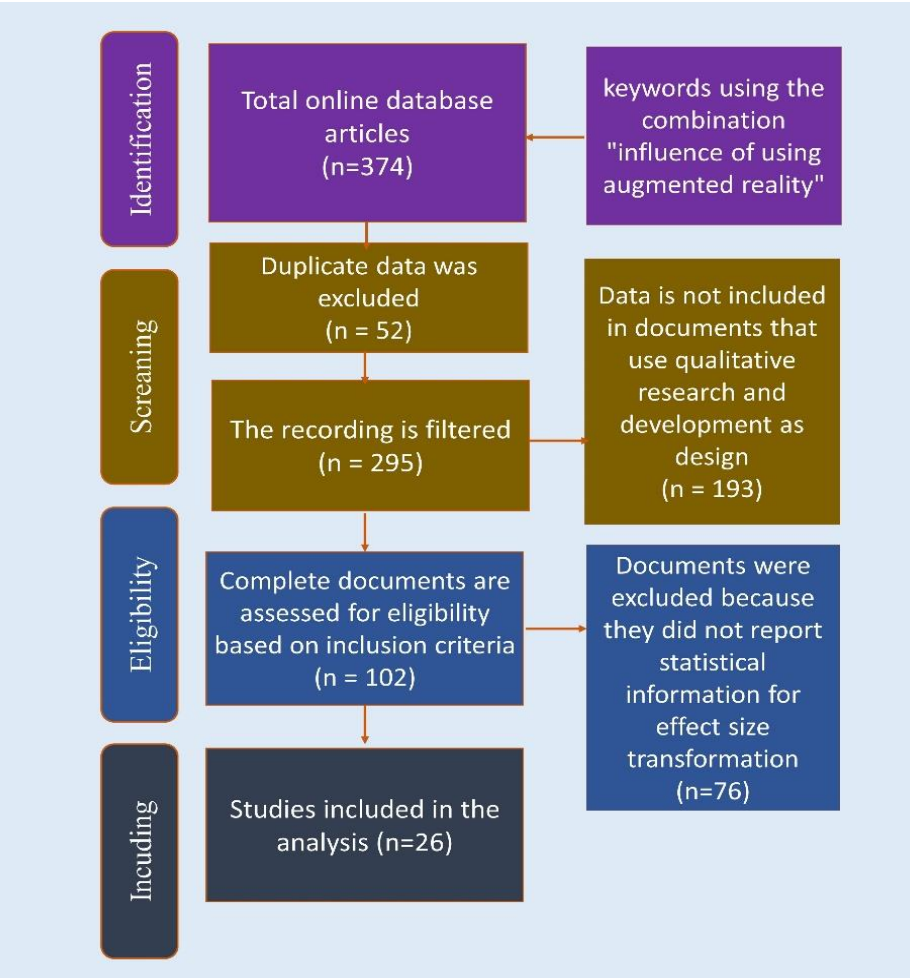

Figure 1. PRISMA procedure

Based on Figure 1 there are 26 primary studies that meet the inclusion criteria for analysis. However, some studies include more than one independent sample or comparison. As a result, in this study there are 73 independent samples in the analysis.

e. Coding Process

This study used a coding sheet as a research instrument developed to extract information from individual studies into numerical data. With this instrument, all data were coded separately by two coders according to the guidelines (Cooper, 2017). The level of agreement between the two coders was determined by randomly taking 5 of the 27 primary studies duplicated and distributed to them. The level of agreement between the two coders was determined using the Cohen's Kappa formula carried out by (McHugh, 2012) formulated in equation 1.

$$k = \frac{Pr(a) - Pr(e)}{Pr(e)} \quad (1)$$

In equation (1) the actual observed agreement is represented by Pr (a), and the agreement due to chance is represented by Pr (e). An index of 0.85 or greater has been previously determined to be considered high (McHugh, 2012). From the calculation results, the index k = 0.97 was obtained. This indicates that both coders reached substantial agreement and the developed instrument is valid.

f. Statistical Analysis

Effect size is chosen as a parameter to estimate the population. The effect size here is defined as the magnitude of the influence of AR integration in education on student learning outcomes. In this study, the CMA version 3 (Comprehensive Meta-Analysis) program was used to assist in calculating the effect size of each study, including finding statistical data such as p-values, Q statistics, and confidence intervals, funnel plots, and stem-leaf graphs. The Hedges' g equation was chosen because some samples were considered small in size. The interpretation of the effect size is based on the classification (Cohen et al., 2017) namely, less than 0.2 (negligible), 0.2 to 0.5 (small effect), 0.5 to 0.8 (moderate effect), 0.8 to 1.3 (large effect), and more than 1.3 (very large effect). The random effects model was chosen after meeting the heterogeneity requirements. The decision was made by observing the p value. If the p-value <0.05 the effect size of each study is heterogeneous, meaning that the effect size between studies or groups of studies may not measure the same population parameter (Borenstein et al., 2009). The next step is to check for publication bias to prevent misrepresentation of findings (Siddaway et al., 2019). This publication bias is possible due to the scientific fact that 6% of researchers rarely publish non-significant research (Cooper, 2017) so that the aggregate effect size can be overestimated (Park & Hong, 2016; Juandi, Kusumah, et al., 2022). This publication bias examination is carried out by examining the funnel plot, and the trim and fill procedure is used to assess the impact of publication bias (Borenstein et al., 2009).

C. RESULT AND DISCUSSION

1. Result

This study analyzed the overall effect of AR use in education, where the effect size is the research parameter. Then, this study was continued by examining the relationship between categorical variables and the study effect size. This will answer the variation in results between studies moderated by categorical variables. Table 1 presents the studies that meet the analysis requirements.

Table 1. Studies included in the analysis

Author, Year	Brief description	County
Setiawan et al., 2023 (Setiawan et al., 2023)	Analyzing the effect of using Augmented Reality media on elementary school students' science processing abilities	Indonesia
Putra et al., 2021 (Putra et al., 2021)	Comparing the effect of mobile augmented reality in a digital encyclopedia on problem solving abilities in first year students.	Indonesia
Chien et al., 2017 (Chien et al., 2017)	Analyzing the results of experiments using AR on elementary school students' scientific literacy	China
İbili et al., 2020 (İbili et al., 2020)	analyze the influence of geometry learning supported by the use of AR on students' three-dimensional thinking abilities.	Turkey
Chang et al., 2019	Analyzing learning supported by AR technology on students' knowledge, skills and motivation	Taiwan
Yilmaz et al., 2017	Analyzing the effect of learning supported by AR technology on students' creative abilities in language.	Turkey
Cahyana et al., 2023 (Cahyana et al., 2023)	Analyzing students' scientific literacy and numeracy who are given learning with the support of AR technology	Indonesia
Bursali et al., 2019 (Bursali & Yilmaz, 2019)	The focus of the research is to analyze the effect of applying AR technology on reading comprehension, learning permanence, and elementary school students' attitudes	Turkey
Aldalalah., 2019 (Aldalalah et al., 2019b)	Analyzing the influence of AR on students' mathematical and visual thinking abilities.	Saudi Arabia
Eldokhny et al., 2021 (Eldokhny & Drwish, 2021)	Comparing the academic achievements of students supported by AR technology with students taught traditionally	Egypt
Hanid et al., 2022 (Hanid et al., 2022)	Analyzing the influence of AR technology support on computational thinking, visualization, and geometric concepts.	Malaysia
Safar et al., 2017 (Safar & Al-jafar, 2017)	Analyzing the effectiveness of AR support in learning on students' English learning achievement in the State of Kuwait.	Kuwait
Önal., 2021 (Önal & Önal, 2021)	Analyzing the effect of teaching astronomy through AR support on student achievement and interest in learning.	Turkey
Al-nawaiseh et al., 2020 (Al-nawaiseh et al., 2020)	Analyzing the impact of using AR on tenth grade students' chemistry learning achievement and motivation.	Jordan
Silva et al., 2023 (M. Silva et al., 2023)	Analyzing the effect of AR technology support on students' academic levels, motivation and technology acceptance.	Mexico
Tarng et al., 2022 (Tarng et al., 2022)	Analyzing the effect of using the AR system on high school students' mastery of chemical equilibrium material.	Taiwan
Huang et al., 2023 (Huang et al., 2023)	Analyzing student learning outcomes that integrate AR technology	Taiwan

Author, Year	Brief description	County
Ibáñez et al., 2014 (Ibáñez et al., 2014)	Testing the impact of using AR on physics learning outcomes in middle schools	Spain
Abdusselam et al., 2020 (Abdusselam & Karal, 2020)	Analyzing the effect of AR-based teaching materials on academic achievement and student learning processes	Turkey
Weng et al., 2020 (Weng et al., 2020)	Analyzing the effect of AR technology support on students' biology learning outcomes	Taiwan
Karagozlu, 2018 (Karagozlu, 2018)	Analyzing the impact of AR applications on students' science achievement and problem-solving skills.	Cyprus
Chen et al., 2020 (Chen & Liu, 2020)	Analyzing the impact of using AR on students' understanding of chemistry concepts and interest in science.	China
Kirikkaya et al., 2019 (Kirikkaya & Başgül, 2019)	Examining the impact of AR-supported teaching on students' academic success, motivation, and attitudes towards science subjects	Turkey
Binhomran et al., 2021 (Binhomran & Altalhab, 2021)	Analyzing the usability of AR technology and its influence on EFL vocabulary mastery.	Saudi Arabia
Zhang et al., 2014 (Zhang et al., 2014)	Analyzing the effect of applying AR technology on learning outcomes in the field of astronomy	Taiwan
Ali et al., 2023 (Ali et al., 2023)	Menganalisis pengaruh AR terhadap kemampuan akademik siswa pada mata pelajaran matematika	Malaysia

The results of the variable coding presented in Table 1 show that 11 countries have conducted experiments to test the effect of AR on student learning outcomes. The top five countries that conducted the most experimental studies were Turkey (24%), Taiwan (20%), Indonesia (12%), China (8%), and Saudi Arabia (8%). The rest were spread across 6 other countries, namely Egypt (4%), Malaysia (4&), Kuwait (4%), Jordan (4%), and Mexico (4%).

a. Overall Analysis Results

First, the general results are described to achieve the first objective. From the data filtering results, 73 independent comparisons are included in the analysis. The research forest plot explored from CMA is in Appendix 1. From the analysis of the research forest plot, it can be seen that the effect size of each study is not on one vertical line, indicating variation in effect size between studies. Table 2 presents a summary of the results of the analysis.

Table 2. Results Summary of Data Analysis Results

Model	N	Hedges's g	Standard error	Test of null		Heterogeneity	
				Z-value	P-value	Q	P
Fixed-effects	73	0.73	0.03	26.087	0.00	362.97	0.00
Random-effects	73	0.75	0.06	11.572	0.00		

Based on Table 1, the P value <0 means that the effect size of each study is heterogeneous. This means that the selected estimation method is in accordance with the random effect model. From these results, the overall effect size of the study is 0.75 with a standard error of 0.06 which is accepted as a moderate effect according to the category (Cohen et al., 2017). Furthermore, publication bias examination was carried out using a funnel plot. Figure 2 presents a funnel plot of the study extracted from the CMA application.

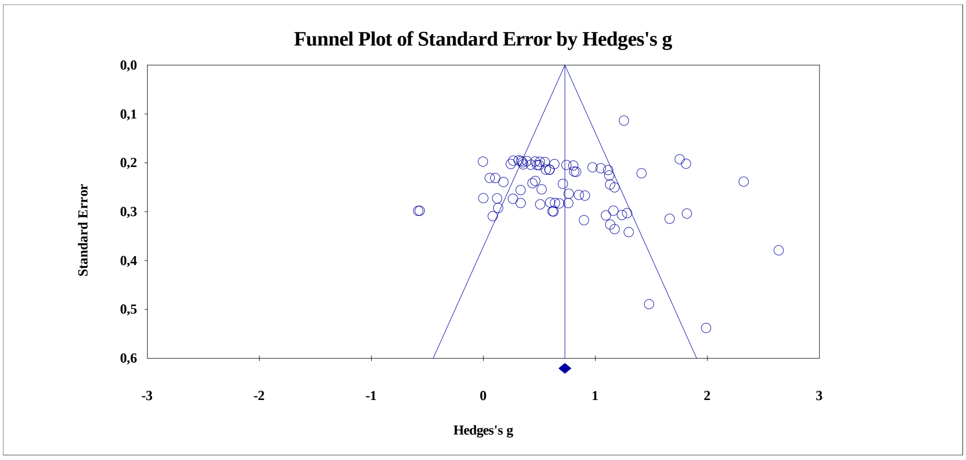

Figure 2. Research Funnel Plot

Based on Figure 2, it can be seen that the distribution of the effect size is less symmetrical. Therefore, the procedure for examining the impact of bias needs to be carried out by examining Trim and Fill. Table 3 presents the results of Trim and Fill.

Table 3 . Trim and Fill Results

	Studies Trimmed	Random-Effects			Q Value
		Point Estimate	Lower Limit	Upper Limit	
Observed values		0.75	0.61	0.86	362.97
Adjusted values	0	0.75	0.61	0.86	362.97

Table 3 includes the results of the trim and fill tests from the left and right according to the random effect model. The calculation results based on the random effect model show that no studies need to be trimmed. The observed and adjusted values do not change. This indicates that there is no impact caused by the indication of publication bias on the results of this study. Thus, the overall effect size of the study found as 0.74 is acceptable for estimating the population. According to the category (Cohen et al., 2017), this effect size can be classified as a medium effect. A graphical representation of this value is shown in Figure 3 below.

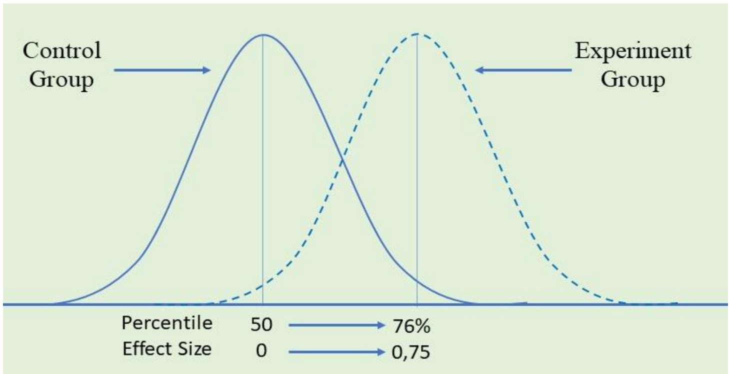

Figure 3. Visualization of effect size

Figure 3 is prepared based on the estimated point of 0.75 which covers the area corresponding to the 76th percentile under the standard normal curve. If the same performance measure is applied to both groups then the "average" student taught in the usual way who scored at the 50% level would score at the 76% level if taught using AR. The number of subjects in this study was 2786 and 72 comparisons. The average sample size for each class was 36 students. Thus a standardized score of 0.74 can be interpreted that the average student is ranked 18th in the experimental group, equivalent to a student who is ranked 9th in the control group.

b. Results of Study Characteristics Analysis

The results of the heterogeneity analysis have found high variability in the ES sample. This underlines the importance of analyzing moderating variables or what are often referred to as study characteristics (Garzón & Acevedo, 2019). Table 4 presents the results of the moderator analysis for the treatment duration variable.

Table 4. Results of the study moderator analysis

Moderator Variables	Category	N	Hedge's g	Heterogeneity		
				(Qb)	df(Q)	P
Duration of Treatment	1-3 weeks	33	0.98	82.07	1	0.00
	4 weeks or more	40	0.50			
Subject Matter	Biology	11	1.35	51.46	4	0.00
	Chemistry	16	0.87			
	Mathematics	18	0,64			
	Natural science	20	0,67			
	Physics	8	0,55			

2. Discussion

The results of the analysis gave an overall effect size of 0.74 which is categorized as a medium effect according to (Cohen et al., 2017). These results are not much different from previous studies where the average effect size of studies on the influence of AR use in education is in the range of 0.6 to 0.8 (Baashar et al., 2022; Lin & Yu, 2023; Tekedere & Göker, 2016; Yilmaz & Batdi, 2021). This study also supports previous studies that the integration of AR into educational environments helps improve students' academic achievement in collaborative learning environments, as well as increase their retention and ability to translate it into other environments (Cahyana et al., 2023; A. C. Silva et al., 2022; Whang et al., 2021). The results of the analysis also prove the superiority of the experimental group in general not only in terms of cognitive but also in terms of student motivation (Atalay, 2022; Djibril & Çakir, 2023; Gopalan et al., 2015), cognitive development (Yildiz, 2022), student collaboration (Costa et al., 2020), and their learning experience (Jesionkowska et al., 2020; Reeves et al., 2021). Thus, these results support previous theoretical assumptions that immersive augmented reality technology can improve the quality of education (Djibril & Çakir, 2023; Yadav & Gupta, 2023). AR can also help students to improve their focus through fun activities and immersive experiences (Cardenas-Valdivia et al., 2023; Samala & Amanda, 2023). AR integration also provides satisfaction to students with various interesting contents (Karagozlu et al., 2019).

Previous meta-analyses related to the effects of AR technology have considered variables such as students' educational level, attitudes, motivation, and self-confidence (Tekedere &

Göker, 2016; Ozdemir et al., 2018; Lin & Yu, 2023). Previous studies have also compared the use of AR applications using textbooks (Atalay, 2022; Gopalan et al., 2015), mobile learning (Aydoğdu & Kelpšiene, 2021; Delgado-Rodríguez et al., 2023; Djibril & Çakir, 2023), interactive books (Reeves et al., 2021; Yildiz, 2022), and game applications (Costa et al., 2020). Other meta-analyses did not consider moderator variables due to the estimation method used Yilmaz & Batdi (2021); Altinpulluk (2019) have also analyzed the overall effect of AR technology in education, but did not continue by analyzing categorical variables that might clarify the variation between the results of the primary studies. Furthermore, Garzón & Acevedo (2019) has conducted a meta-analysis by comparing AR applications with traditional lectures as a moderator. Until now, no one has compared the effectiveness between countries, and the effectiveness between subject matters as a categorical variable.

This study discusses the variable of treatment duration and its relationship with the effect size of the main study. Based on the summary of the results included in Table 4, it appears that the effect sizes of the two study groups in terms of treatment duration are significantly different (P-value on the total between= 0.00<0.05). This indicates that the difference in effectiveness between studies can be explained by the difference in treatment duration. This study highlights the importance of considering the treatment duration in implementing AR. The trend of the analysis results suggests preferring the 1-3 week duration option when implementing AR in the future. This is related to the Hawthorne effect that students will get bored if given the same model or treatment for a long time (Juandi & Tamur, 2021; Tamur et al., 2021; Tamur, Juandi, et al., 2023).

This study has provided scientific information that contributes to the decision to integrate AR in learning. In addition, this study is useful for knowing the position and development of the effectiveness of AR technology integration in education between countries. Further research is needed to examine other moderator variables such as the type of material applied to AR, differences in applications such as the comparison between using textbooks and images and barcodes as custom markers.

D. CONCLUSION AND SUGGESTIONS

The results of the study indicate that the overall effect of AR implementation in learning has a moderate effect on students' academic achievement. The results of the analysis also show that differences in treatment duration clarify differences in effect sizes between individual studies. The results of this study provide scientific information that contributes to integrating AR into learning, including considering its use in the future. However, this study could not include data from paid databases such as IEEE and Sage Publication. Therefore, further work is needed to collaborate with universities affiliated with documents in paid databases so that more articles can be included in the analysis. Further research is needed to test other moderator variables, such as the type of material applied to AR and the differences in its application, such as comparing textbooks and images and barcodes as customary markers.

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