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Enhancing Mathematics Achievement through Virtual Manipulatives: A Meta-Analysis of K–9 Intervention

Lisda Fitriana Masitoh[1], Enggar Prasetyawan[2]

[1] Universitas Pamulang, Banten, Indonesia; dosen01928@unpam.ac.id
[2] Universitas Pamulang, Banten, Indonesia; dosen01927@unpam.ac.id

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ABSTRACT

Virtual manipulatives (VMs) have emerged as innovative tools in mathematics education, yet their overall effectiveness remains unclear. This study aims to synthesize existing evidence on the impact of VMs on K–9 students' mathematics achievement. A meta-analysis was conducted following PRISMA guidelines. A systematic literature search identified 23 experimental studies published between 2012 and 2022 that investigated the effectiveness of VMs in mathematics learning. Inclusion criteria required studies to provide sufficient statistical data and include control groups using either traditional methods or concrete manipulatives. Data were analyzed using the random-effects model via OpenMEE, and moderator analyses were performed based on education level and control group type. The overall effect size was strong and statistically significant (Cohen's $d = 1.603$, 95% CI [0.881, 2.324], $p < 0.001$), indicating that VMs significantly improve mathematics achievement. Subgroup analyses revealed larger effects at the secondary level ($d = 1.810$) than at the primary level ($d = 1.280$), and greater effectiveness when compared to traditional methods ($d = 1.979$) than to concrete manipulatives ($d = 1.473$). Despite some heterogeneity ($I^2 = 97.95\%$), publication bias was not evident. Findings affirm that VMs are effective tools for enhancing mathematics achievement across K–9 settings. Educators are encouraged to integrate VMs, especially in secondary classrooms. Further research should explore long-term impacts and broader contextual variables.

Corresponding Author:
Lisda Fitriana Masitoh
Universitas Pamulang, Banten, Indonesia; dosen01928@unpam.ac.id

1. INTRODUCTION

Mathematical achievement among students in many countries, including Indonesia, remains a significant and persistent challenge, as evidenced by low scores in international assessments such as Programme for International Student Assessment (PISA) and Trends in International Mathematics and Science Study (TIMSS). In response, the role of technology in education has become increasingly crucial. Technology integration facilitates easy access to global educational resources. The use of technology in education has influenced learning and enabled learning to be more effective (Nurzhanova et al., 2024;

Karim & Zoker, 2023;Gamit, 2023). In addition, integrating technology in learning can encourage students to be more confident when studying (Emata, 2023; Rocha, 2023; Arida et al., 2022; Ismail et al., 2023). The presence of online learning applications, interactive platforms and virtual manipulatives has provided students more dynamic and relevant learning experience. One of them is in mathematics learning.

Students feel comfortable using technology because it allows them to learn math more accurately (Emata, 2023). This is because technology can visualize abstract mathematical objects into concrete objects that are easy for students to understand (Pagau & Mytra, 2023). In the context of mathematics learning, one of the technological innovations that has developed quite rapidly is the use of virtual manipulative. There are two types of virtual manipulative in mathematics, namely concrete and virtual (Bassette & Bouck, 2023). Concrete manipulatives are three-dimensional objects used in direct activities, while virtual manipulatives are computer-based visual representations (Pappas, 2013). For example, marbles and ice cream sticks are concrete manipulative that can be used when students learn addition operations. Virtual props that can be used on the same material are computer-based images of marbles or ice cream sticks that can be manipulated on the screen by pointing, clicking, dragging and so on. Since the digital platform has now developed rapidly, mathematics lesson should emphasize the use of virtual manipulative (Arida et al, 2022). A virtual manipulative is one form of technology application that can create visual and interactive simulations, helping students understand mathematical concepts more concretely. A virtual manipulative is an interactive visual representation that is programmed and allowed to be manipulated, as well as providing opportunities to build mathematical knowledge (Istiandaru et al., 2018; Hidayah & Prayoga, 2021).

Teachers employ virtual manipulatives in mathematics learning in order to achieve the learning objectives. Virtual manipulatives in mathematics education have proven effective in increasing understanding of mathematical concepts and student involvement in the learning process (Luis & Soto, 2023). Based on research by (Moyer, Salkind, & Bolyard, 2008), the majority of virtual manipulatives were used in learning about geometry (32%), numbers and operations (35%), measurement (13%), data analysis and probability (7%), and algebra (13%). The implications of virtual manipulatives for mathematics learning bring new challenges and opportunities. This is because technology has become inseparable from students' daily lives in recent years, and the use of virtual tools is expected to improve students' mathematics learning outcomes. Mathematics learning achievement refers to the success attained by an individual after studying mathematics, in accordance with the competencies of the mathematics subject matter learned. (Elastika, Sukono, & Dewanto, 2021).

A number of previous studies give information about the effectiveness of virtual manipulatives in improving students' mathematics learning outcomes. In their research, Ocampo et al (2023) employed virtual manipulatives in mathematics instruction through interactive media. The findings showed that this media could improve students' mathematics achievement. The results of research conducted by Ngozi et al. (2017) revealed that virtual manipulative was an effective strategy for learning geometry. These results are supported by Senyefia (2017), who stated that the use of virtual manipulatives proved to be relatively more effective in increasing student achievement in transformation compared to traditional methods. However, research by Zacharia and Constantinou (2008) found that when the virtual manipulative was compared with a concrete teaching manipulative, both were equally effective in mathematics learning or did not differ significantly. Several research results show that the use of virtual manipulatives is effective in learning mathematics. Although numerous studies have investigated this topic, there is no synthesized evidence (meta-analysis) summarizing the overall effectiveness of virtual manipulatives on mathematics learning outcomes. This is important for providing insight and recommendations, especially for teachers.

The results of existing research encourage an analysis to determine how effective the use of virtual manipulatives is in actual mathematics learning. This case is addressed through a meta-analysis. Meta-analysis was carried out to compile a holistic of all existing research, with the aim of gaining a deeper understanding of the effectiveness of virtual manipulatives in the context of learning, particularly in mathematics learning achievement. Meta-analysis facilitates comparisons between quantitative studies by bringing them together on a standard metric called effect size (Cohen, Manion, & Morrison, 2018). This research aims to provide a quantitative view of the contribution of virtual manipulatives to mathematics learning achievement. To achieve this, the study specifically addresses the questions: What is the overall effect size of virtual manipulatives on mathematics achievement? How do educational level and the type of control group moderate this effect?

2. METHODS

This research was a systematic review and meta-analysis conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. It aimed to reveal the effect of using virtual manipulatives on mathematics learning achievement. Meta-analyses serve as a roadmap for relevant research, a basis for designing new studies, and a guide for creating institutional policies and educational curricula (Funa & Prudente, 2021). A meta-analysis study is a study that allows general conclusions to be reached from the results of different studies carried out on the same problem (Oztop, 2023). This general conclusion is shown through an effect size. For educational research, effect sizes can be more meaningful in providing conclusions regarding certain topics (Cohen et al., 2018). Meta-analysis involves rigorous statistical integration of reported findings from several primary research studies (Cohen et al., 2018).

In a meta-analysis of experimental research, the effectiveness or influence of the results of these studies is examined to obtain stronger conclusions. This meta-analysis tried to reach general conclusions about the effectiveness of using virtual manipulatives in mathematics learning. The experimental class is a learning activity using a virtual manipulative, while the control class uses a traditional approach or a concrete manipulative. Borenstein et al (2009) explain the stages in meta-analysis, first, procedures for collecting empirical data and determining inclusion criteria for the studies being analyzed. Second, variable coding, third, statistical analysis to determine effect size, fourth, findings and interpretation. Meta-analysis uses explicit protocols to increase consistency and objectivity throughout all stages (Cohen et al., 2018).

2.1 Data Collection

Following the guidelines of the PRISMA protocol (identification, screening, eligibility, and included) to ensure a systematic and transparent process, this meta-analysis included quantitative primary studies on the effectiveness of virtual manipulatives in mathematics learning, which were published between 2012 and 2022. The inclusion criteria used in this meta-analysis are:

a. Research published in English.
b. The primary research objective was to determine the effectiveness of mathematics learning using virtual manipulatives.
c. The primary research was experimental research with a control class.
d. The control class uses a traditional approach or concrete manipulative.
e. Primary research articles present the statistical information necessary for meta-analysis, namely, sample size, mean, and standard deviation
f. The research subjects of primary research were primary and secondary school students.

Primary research publications were accessed in November - December 2023 from journal articles and obtained through three literature searches, namely SAGE Publishing, ScienceDirect and Google Scholar. Data searches were carried out using keywords such as "virtual manipulative", "mathematics", mathematics achievement, "effectiveness", “impact”, which produced a list of 37 primary studies. Next, the results were filtered to meet the predetermined inclusion criteria.

After inspection, there were 23 primary study results data that met the inclusion criteria. The research used in this meta-analysis was from Turkey (Ukdem & Cetin, 2022), America (Packenham & Suh, 2012; Rana, 2015; Packenham et al., 2012; Kabel et al., 2021), Malaysia (Doias, 2013), Saudi Arabia

(Alshehri, 2008), Nigeria (Ngozi et al., 2017), Taiwan (Lee & Chen, 2014; Hwang & Hu, 2013) and Ghana (Senyefia, 2017).

The PRISMA flow diagram illustrates the study selection process. It details the number of records identified, screened and ultimately included in the meta-analysis . The diagram is presented below:

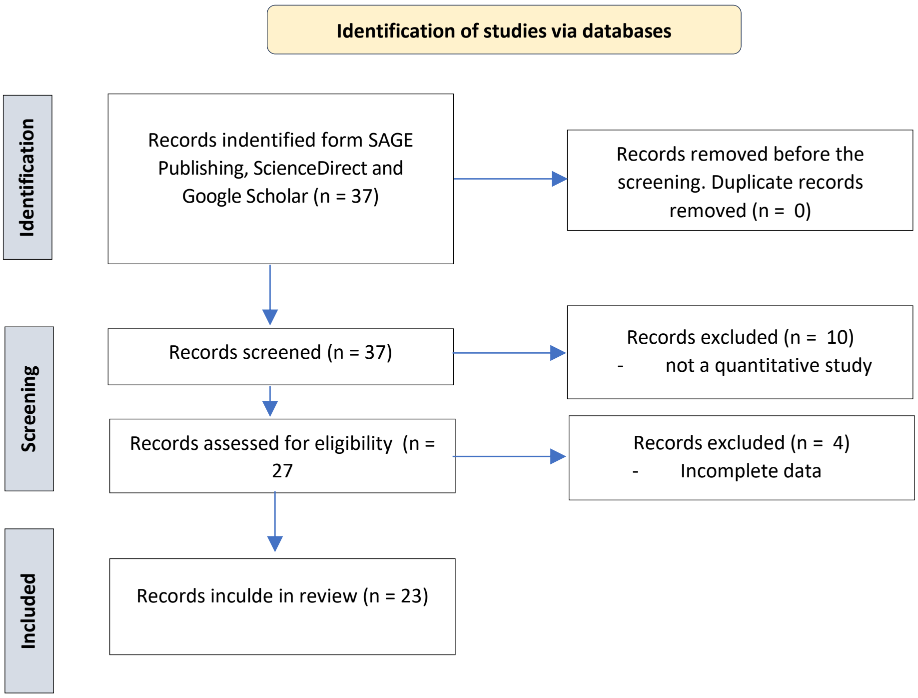

Figure 1. PRISMA Diagram

2.2 *Data Coding*

Research data tables must be created after the appropriate research has been determined and a quality review has been conducted. (Sen & Yildirim, 2020). Therefore, the instrument used in this research was a variable coding sheet that contains a data table. The data table contains information about the author and year, research title, education level, dependent variable, type of control class (traditional/concrete) and statistical information about the group which includes mean, standard deviation, and sample size. Covidence software was used for this process. Starting from importing references to data extraction to ensure the primary studies used comply with the predetermined inclusion criteria.To ensure that the data entered was correct, the coding stage was carried out twice. As a result, the coefficient of agreement between the coders was 1. In other words, the coding process has been completed.

2.3 *Data Analysis*

After coding, the data were analyzed. Data analysis was carried out using the standardized mean difference method to determine the effect size based on the Cohen's *d* coefficient (Mcgough & Faraone, 2009). Effect size is often conceptualized as a z-score (Renova, 2022). In this context, changes in mathematics learning achievement were expressed using test results for the experimental and control classes. Cohen's *d* was calculated from two average values and their standard deviation (Mcgough & Faraone, 2009). In this research, an analysis was carried out to determine the overall effect size (summary effect size) and the influence of primary study characteristics on the meta-analysis results. The primary study characteristics that are thought to influence effect size and will be analyzed are the level of education (primary and middle school) and the type of control class or control group (traditional or concrete manipulative). Estimation of the effect size at the 95% confidence interval was carried out with the help of OpenMEE software. The recommended interpretation of effect size according to Cohen et al. (2018) is:

Table 1. Interpretation of Effect Size

Range of Effect Size (ES)	Interpretation
ES ≤ 0.20	Weak effect
0.20 < ES ≤ 0.50	Modest effect
0.50 < ES ≤ 1.00	Moderate effect
ES > 1.00	Strong effect

Additionally, it must be decided whether to use a fixed-effects model or a random-effects model (Sari, Juandi, Tamur, & Adem, 2021). The fixed-effects model indicates homogeneous effect sizes across study groups. In contrast, the random-effects model is used when effects are heterogeneous. Heterogeneity testing is conducted to determine which model to apply.

3. FINDINGS AND DISCUSSION

First, a heterogeneity analysis was performed to determine whether random-effects or fixed-effects would be used. The heterogeneity test is presented in Table 2 below:

Table 2. Result of Heterogeneity Test

Tau^2	Q (df = 22)	Het. P - Value	I^2
2.970	1075.480	< 0.001	97.954

The heterogeneity tests were conducted using the Cochran's Q statistic and the corresponding p-value (Sari et al., 2021). The null hypothesis is that all studies are homogeneous. If p-value is less than 0.05, the null hypothesis is rejected, indicating significant heterogeneity among the studies. In this case, a random-effects model should be used. As shown in Table 2, the Q-value is 1075.480 with a p-value of < 0.001. Because the p-value is less than 0.05, the null hypothesis of homogeneity is rejected. This indicates that the observed differences in effect sizes across the studies are not due to chance alone, and the data are highly heterogeneous.

Additionally, the I^2 statistic provides a more intuitive measure of heterogeneity. The I^2 value of 97.954% confirms a substantial level of heterogeneity, meaning that almost all (98%) of the total variation in the effect sizes is due to true differences between the studies, rather than sampling error. Based on these results, a random-effects model was used to estimate the pooled effect size, which accounts for the high level of heterogeneity present in the included studies.

Next, using the OpenMEE software, the researcher calculated the effect size of mathematics learning with a virtual manipulative on student mathematics achievement for each primary study. The results of the effect size calculations from each study can be seen in Figure 2 below:

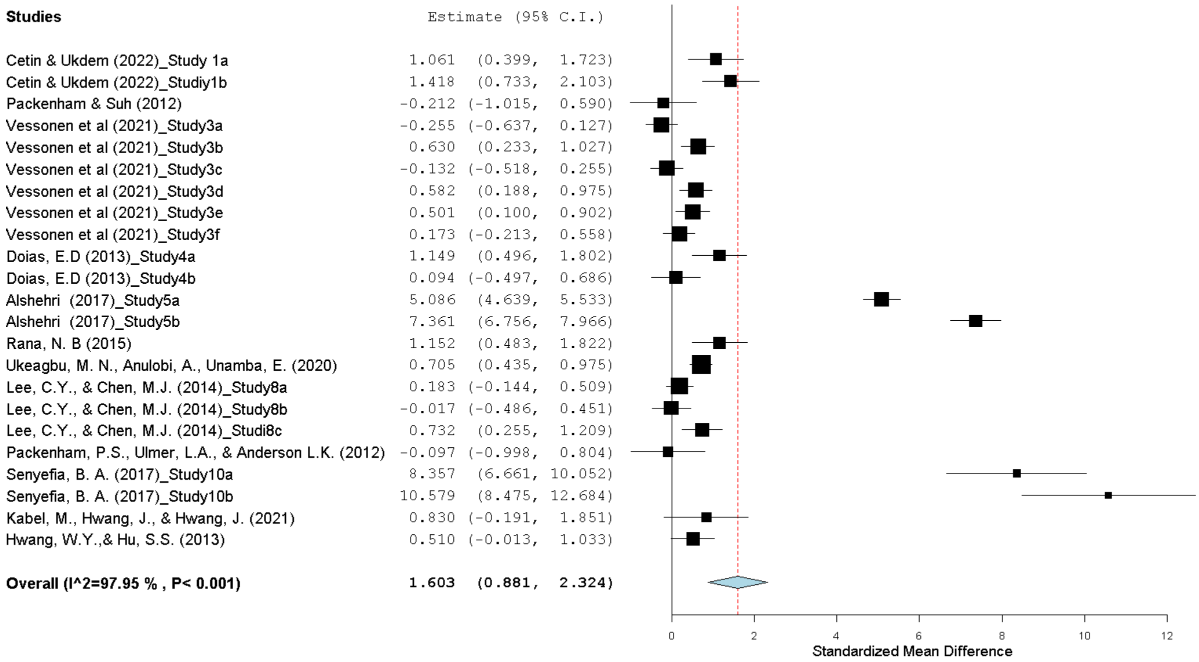

Figure 2. Effect Size from Each Primary Study

There are five negative effect sizes. This indicates that, in this study, the control group outperformed the experimental group. There were 18 positive effects, which showed that the experimental group was better than the control group. These outputs indicate variations in results in the application of mathematics learning, which were divided into learning using virtual manipulatives and those not using virtual manipulatives.

The next step is to check publication bias. The aim was to check whether there was a tendency for articles to publish only significant studies, leading to meta-analysis results that do not describe the actual conditions of the population (Retnawati, Apino, Kartianom, Djidu, & Anazifa, 2018). Publication bias can be identified by examining the funnel plot. If the distribution of effect sizes is symmetrical between the vertical lines, it can be concluded that there is no publication bias. A good meta-analysis is free of publication bias.

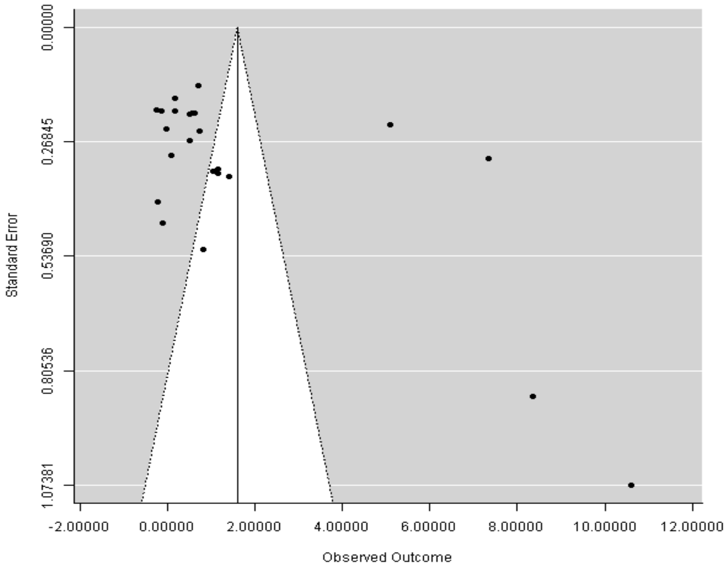

Figure 3. Funnel Plot Effect Size

Based on Figure 3, the distribution of effect sizes appears asymmetric. An asymmetrical funnel plot suggests the presence of publication bias. According to Rosenthal (Setiawan & Phillipson, 2019), if the funnel plot is not symmetrical, determining whether there is publication bias must be done using the Fail Save N (FSN) method. If the FSN value / (5k + 10) > 1 (k indicates the number of studies), then the meta-analysis results are resistant to publication bias (Purnamasari et al., 2023; Setiawan & Phillipson, 2019). With the help of the OpenMEE application, the FSN value is 3621. Based on the formula, it is 3621/ (5 * 23 + 10) = 28.97. Because 28.97 > 1, the meta-analysis is resistant to publication bias.

To support this, an Egger's regression test was performed, with the following results.

Table 3 . Egger's Regression (Weighted Regression) Test

Weighted Regression Test for Funnel Plot Asymmetry

	Asymmetry Test			Limit Estimate μ		
Estimates	**t**	**df**	**p**	**Estimate**	**Lower 95% CI**	**Upper 95% CI**
23	1.888	21	.073	-0.710	-2.603	1.182

Based on Egger's regression test table (*Weighted Regression Test for Funnel Plot Asymmetry*), the p-value was found to be 0.073. Since this value is greater than the standard significance threshold of 0.05, Egger's regression intercept is not statistically significant. This indicates that there is no firm evidence of publication bias or small-study effects in the meta-analysis. This means that the primary study data are sufficient to conduct a meta-analysis. Next, the results and discussion regarding the calculation of the overall effect size and analysis of moderator variables or study characteristics are provided.

3.1 Calculations of Summary Effect Size

If a single effect size is calculated for each study, then the overall effect size is calculated by involving all effect sizes from a single research simultaneously (Dincer, 2018). The strength of the summary effect in meta-analysis is much bigger than the strength of the impact in one of the primary studies (Borenstein et al., 2009). With the summary effect, the actual impact of using virtual manipulative in mathematics learning can be seen. Summary effect findings calculated based on the random-effects model are given in Table 4, along with lower and upper bounds according to standard errors and at 95% confidence intervals.

Table 4. Summary Effect Size

Estimate	**955 Confidence interval**		**Std. error**	**p-Value**
	Lower bound	**Upper bound**		
1.603	0.881	2.324	0.368	< 0.001

As can be seen in Table 4, the summary effect size is d=1.603 with a standard error of 0.368, lower limit of 0.881 and upper limit of 2.324, and this value is significant ($p<0.05$). Based on Cohen et al (2018), the effect size of 1,603 is in the strong category. This effect size shows that the mathematics learning achievement of the experimental class is higher than that of the control class. In other words, this also shows that the mathematics achievement of students who learn using virtual manipulative is higher than that of students who use traditional or concrete manipulative. The research findings show that the use of virtual manipulative has a significant effect on students' mathematics learning achievement.

This research result is consistent with many other studies reporting on the effectiveness of virtual manipulatives in supporting mathematics learning achievement. For instance, the use of virtual manipulatives supports students' conceptual knowledge and problem-solving skills (Moyer-Packenham & Westenskow, 2013). This is further supported by the scaffolding theoretical model of Wood, Bruner, & Ross (1976). In this sense, virtual manipulatives are viewed as digital scaffolds that help students develop a deeper understanding of the theoretical content of mathematics. Unlike the physical manipulatives that often do not show dynamic dimensions of their existence, the virtual manipulative features the ability to interact (e.g., students can drag or rotate) or to see tools changing perspective or zooming in or out. This allows the student greater flexibility to investigate and work with mathematical objects.

3.2 Analysis of Moderator Variables

Meta-analysis with moderator analysis allows a more in-depth exploration of possible reasons behind the observed differences (Alabbasi et al., 2023; Pietro, 2023). This research determined the education level and type of control class as moderator variables. The results of the analysis assessing whether there are significant differences in effect sizes by education level are presented in Table 5.

Table 5. Effect Size Based On Education Level

Education Level	**n**	**Effect size (d)**	**95% Confidence interval**		**Std. error**	**p-Value**
			Lower bound	**Upper bound**		
Primary School	13	1.280	0.147	2.412	0.578	0.027
Secondary School	10	1.810	1.019	2.602	0.404	<0.001

Based on Table 5, the effect size for the primary school level is d=1.280 and for the secondary school d=1.810. This result is also significant (p<0.05). The effect size is bigger at the secondary school level. This means that the use of virtual manipulative in secondary school has a greater influence on learning achievement than in primary school. The efficacy of virtual manipulatives in secondary schools is based primarily on a few salient theories of learning. It is important to note that this argument is rooted in Piaget's Theory of Cognitive Development (formal operational stage). By now, students are no longer dependent on the manipulation of solid objects, they have learned to reason abstractly, and hypothetically. Virtual manipulatives are an effective bridge, as they enable students to see and manipulate concepts such as algebraic expressions or geometric transformations in a fluid manner consistent with their emergent capacity for abstraction.

Furthermore, whether the differences between the two are significant can be seen in the following forest plot results:

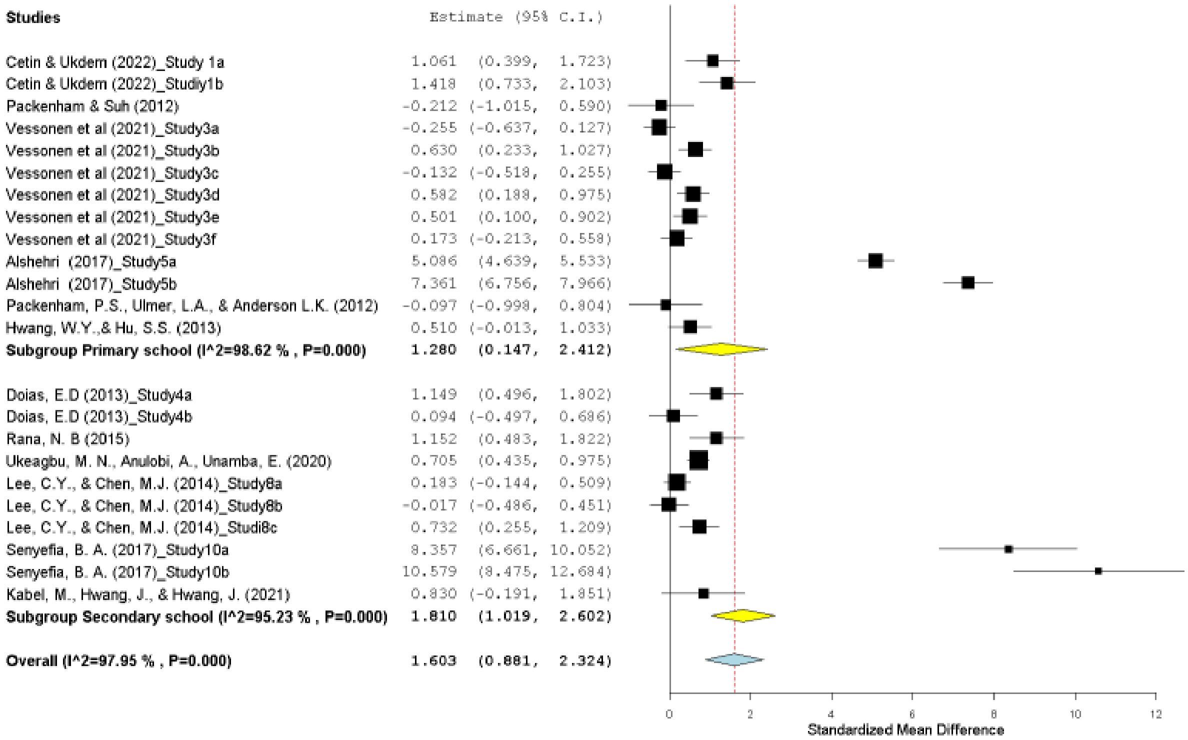

Figure 4. Subgroup Forest Plot Effect Size Base On Education Level

Based on Figure 4, it can be seen that the effect sizes grouped at primary and secondary school education levels (denoted by yellow rectangles) intersect each other and intersect the red line. The vertical dotted red line shows the location of the summary effect. This shows that the difference in the influence of using virtual manipulative in the two groups is not too big.

Referring to the primary study data used in this meta-analysis, in a study conducted by Ukdem & Cetin (2022) virtual manipulative has a significant influence when implemented in primary schools, both when compared with traditional methods or with concrete teaching aids. Likewise, in the secondary school level, virtual ma-nipulative provide effective use in mathematics learning compared to traditional methods (Hwang & Hu, 2013). This means that at both primary and secondary school levels, the use of virtual manipulatives provides benefits in mathematics learning, especially in improving learning achievement.

The results of the analysis to determine whether there are significant differences between effect sizes according to the type of control group are presented in Table 6.

Table 6. Effect Size Based on Type of Control Class

Type of Control Class	n	Effect size (d)	95% Confidence interval		Std. error	*p*-Value
			Lower bound	Upper bound		
Traditional (T)	5	1.979	0.674	3.284	0.666	0.003
Concrete Manipulative (CM)	18	1.473	0.596	2.351	0.448	0.001

Meta-analysis research addresses mathematics learning with virtual manipulatives. In connection with the data required for meta-analysis, the primary study used must contain a control class in determining the effectiveness of the virtual manipulative. The control class in the primary study used are divided into traditional and concrete manipulatives. What is meant by traditional class in this research is learning mathematics without using teaching aids or manipulative and only relying on textbooks and explanations from the teacher. Class with concrete manipulative is mathematics learning using physical objects or concrete manipulative to help understand concepts through direct experience and exploration. Concrete manipulative belongs to objects used to help to understand material in learning (Byrne, Jensen, Thomsen, & Ramchandani, 2023). Based on Table 5, the effect size of the use of virtual manipulative in research with traditional control class is $d = 1.979$. Meanwhile, the effect size of the use of virtual manipulative in research with a control class using concrete manipulative is $d = 1.473$. These results are statistically significant ($p < 0.05$).

The effect size of the use of virtual manipulative in research with a traditional control class (T) is greater than the use of virtual manipulative in research with control class using concrete manipulative (CM). This means that the use of virtual manipulative with traditional control class (T) has a greater effect or greater effectiveness compared to if the control uses concrete manipulative (CM). This means that concrete manipulative can be used as an alternative to traditional methods if there are no facilities to access virtual manipulative.

This indicates that the use of virtual manipulative basically can improve learning performance. This is in line with Gamit (2023) opinion that technology in mathematics learning is used to improve traditional methods by adding new functions or ways of thinking. Learning using technology enhances students' academic performance in mathematics, and it is concluded that learning with technology is better than traditional teaching methods (Rizada & Rey, 2023). Virtual manipulatives can also provide scaffolding features that are not available on concrete manipulative (Bassette & Bouck, 2023). In conclusion, virtual manipulative can be an option in improving students' understanding and performance in mathematics (Ismail et al., 2023).

Furthermore, whether the differences between the two are significant can be seen in the following forest plot results:

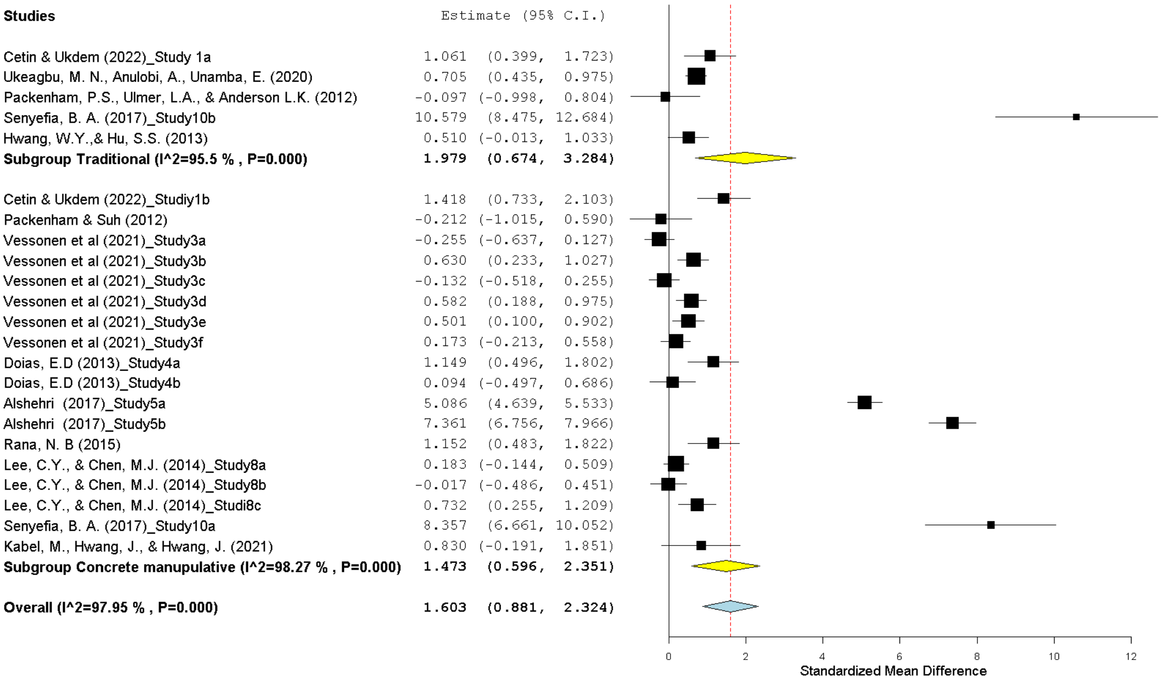

Figure 5. Subgroup Forest Plot Effect Size Base on Type Of Con-trol Class

As shown in Figure 5, the locations of the effect sizes grouped into traditional control (T) and concrete manipulative control (CM) (denoted by yellow rectangles) intersect with one another and with the red line. This shows that although the effect size of the virtual manipulative for T is greater than for CM, the difference in the influence of using the virtual manipualtive in the two groups is not too great or they remain equally effective. In the end, the meta-analysis concluded that the use of virtual manipulative, whether compared to traditional methods or concrete manipulative, was still equally effective and had a strong effect. Therefore, the use of virtual manipulative can be done in mathematics learning to improve student learning achievement.

The present investigation has some significant limitations that should be considered. First, language and publication bias are possible as the literature search was limited to studies published in english. This has the severe constraint of being a data scope, possibly missing points included in other than english language. Second, the included studies had to be quantitative and provide full statistical data (e.g. means and sample sizes). This method excludes findings from qualitative research or studies that didn't provide complete data, which would influence the analysis of results and reduce insight into why virtual manipulatives may be effective. Lastly, the heterogeneous intervention length of studies included in this review complicates direct comparison and precludes any meaningful conclusions on long-term effectiveness. These limitations make the data sources for meta-analysis limited.

4. CONCLUSION

The results of this research conclude that the use of virtual manipulatives in mathematics learning has a significant impact on student learning achievement with an effect size of 1.603, and it is in the strong category. It shows that the effect is substantial and cannot be ignored. The use of virtual manipulatives makes a significant and positive difference in students' mathematics learning achievement. Education level and type of control class were determined as moderator variables. The subgroups for education level were divided into primary school and secondary school, while the subgroups for type of control class were divided into traditional class and class using concrete manipulatives. Based on the analysis of the educational level, the effectiveness of virtual manipulatives tends to be greater at the secondary school (d=1.810) than at the primary school level (d=1.280). However, the use of virtual manipulatives is equally effective in mathematics learning achievement. Based on the type of control class, the effectiveness of using manipulatives tends to be greater when compared to traditional (d=1.979), than when compared to concrete manipulatives (d=1.473). However, the use of virtual manipulatives is equally effective in mathematics learning achievement.

These findings have the following important practical implications for educators and curriculum designers. These findings recommend that educators use virtual manipulatives as an effective tool to enhance students' mathematics learning achievement. Educators are invited to incorporate virtual manipulatives as tools for student-centered learning, rather than simply using them to replicate physical manipulatives in a virtual world. These dynamic features, including the ability to modify the generated data and observe perturbations in allowances in real time, can enable students to develop a more conceptual understanding of the model. In addition, professional development is needed to support teachers in using these tools appropriately in mathematics instruction.

Moreover, this study presents promising avenues for further investigation. Future research will likely overcome these limitations by using larger samples and data from multiple languages and cultures while decreasing publication bias. Additional analysis can also be conducted on the effectiveness of virtual manipulatives on mathematics learning achievement by involving more primary studies and moderator variables. Future studies with a mixed approaches design should be conducted in order to provide further evidence on the long-term impact of virtual manipulatives. Research can be extended to determine how the use of virtual manipulatives influences student motivation and self-reports of effectiveness, as well as their achievement.

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