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Meta-Analysis of Mobile Learning's Effect on High School Students' Physics Learning Outcomes: Data Analysis Using the JASP Application

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ABSTRACT

The development of digital technology drives the need for innovation in education, particularly regarding instructional media in high school physics. However, most research on implementing android-based mobile learning still yields varied and inconsistent results. Therefore, this meta-analysis synthesizes and evaluates the influence of Android-based mobile learning on the physics learning outcomes of high school students. Guided by PRISMA standards, 24 quasi experimental primary studies were collected and quantitatively analyzed using JASP software via a random-effects model. The analysis revealed a pooled effect size of 1.42 ($p < 0.001$), categorized as a very large effect. Although the heterogeneity index was remarkably high ($I^2 = 95.43\%$), a deeper examination indicated that effect sizes approaching zero or taking on negative values were driven by internal student factors and variations in methodological quality of primary studies, rather than limitations of android technology itself. Consequently, android-based mobile learning is highly effective in enhancing students' cognitive outcomes in physics. This study is expected to provide a scientific contribution and offers recommendations for practitioners to optimize android-based media by integrating it with active learning models and structured classroom management to foster self-regulated learning.

INTRODUCTION

Physics is a branch of natural science that studies natural phenomena through observation, experimentation, and scientific reasoning, enabling it to explain various natural phenomena systematically (Wea et al., 2023). For senior high school students, learning physics requires not only the ability to solve mathematical problems but also an understanding of the relationship between scientific principles and phenomena encountered in everyday life. One of the main challenges in learning physics is that many of its topics involve abstract concepts that cannot be observed directly, making visualization skills essential (Wati et al., 2025). Effective visualization of these abstract concepts enables students to build a deep understanding of underlying physical principles rather than relying merely on memorizing mathematical equations (Sriyani et al., 2023). In fact, a comprehensive understanding of concepts is one of the main indicators of students' learning success and academic achievement (Doyan et al., 2024; Wandi et al., 2023). Therefore, innovative learning media are needed to help students visualize physics concepts more concretely and understand them more easily.

The rapid development of digital technology has encouraged changes in learning strategies at various levels of education, including the use of mobile technology as a more adaptive and flexible learning medium (Fitriana et al., 2022). To meet the need for a more flexible learning process, android-based mobile learning has emerged as an alternative learning medium that is increasingly being used. The growing number of students who own smartphones has made it easier for them to access various learning resources independently, both at school and at home (Setuju et al., 2022). Through android-based mobile learning, abstract physics concepts can be presented in an interactive way, making it easier for students to understand and visualize these concepts. The integration of this technology based learning media has been shown to effectively increase students' active participation while improving their learning achievement (Atika et al., 2022). This potential has encouraged researchers to develop android-based mobile learning applications for physics education.

Integrating Android-based mobile learning is a widely implemented method to help students understand abstract physics concepts. Visual presentation through this medium facilitates a deeper understanding of physics phenomena difficult to observe directly. Applications have been developed across topics like static fluids, sound waves, light, optical instruments, and mechanics (Milinia et al., 2022; Rahmawati et al., 2021; Meilana et al., 2020). Android-based platforms provide easy access to learning resources and feature tools enabling dynamic student engagement with instructional material. Simulations, animations, and interactive media encourage a more independent, participatory learning experience. These elements increase student engagement, fostering better conceptual mastery and elevating physics academic achievement (Lisana & Suciadi, 2021; Polonia & Yuliati, 2019).

Although the implementation of android-based mobile learning platforms in physics is increasingly expanding, scholarly evaluations of its impact on learning outcomes continue to shows diverse research results. A number of studies report that the use of this medium is capable of improving student learning outcomes. The main factors supporting this improvement include students’ ease of access to learning materials, as well as the availability of interactive features such as simulations, animations, learning videos, and virtual laboratories. These features help visualize physics concepts that are difficult to observe directly (Nilsa & Sani, 2022).

On the other hand, research shows that Android-based mobile learning effectiveness does not always yield significant improvements, remaining limited under certain conditions. This variation is presumed to stem from factors including material characteristics, media quality, student digital literacy, intervention duration, and learning environment context (Abdullah et al., 2024; Anselmo et al., 2024; Siswanto et al., 2025; Sung et al., 2016). These diverse findings underscore the need for a thorough evaluation of Android mobile learning's influence on high school physics outcomes. Most previous studies were conducted under limited conditions regarding location, learning materials, and sample size. Consequently, their conclusions remain partial and unable to illustrate the overall magnitude of mobile learning’s impact.

To address the limitations of previous studies, meta-analysis has emerged as a relevant approach for integrating statistical findings from multiple independent studies.

Through this method, empirical data from various studies investigating similar topics can be combined and reanalyzed quantitatively. This integration allows for a more objective and reliable estimation of effect size. In addition, this approach helps minimize the analytical bias that often occurs in individual studies with small sample sizes. Therefore, meta-analysis can provide conclusions with a higher level of representativeness and generalizability.

Based on the findings and issues described, this study analyzes the effect of Android-based mobile learning on high school students' physics learning outcomes through a meta-analysis approach. The analysis integrated quantitative data from research articles meeting selection criteria to obtain a comprehensive overview of media effectiveness. Data processing was carried out using JASP software to generate objective effect size estimates and strengthen research conclusions. Altogether, 24 empirical articles meeting inclusion criteria served as data sources to quantify the effect magnitude of Android-based mobile learning on physics outcomes. Therefore, this study aims to synthesize empirical evidence and quantify the overall effect size of Android-based mobile learning on high school physics outcomes, providing an empirical reference for educators and curriculum developers.

METHODS

This study utilizes meta-analysis as its primary research design. This method enables the integration and synthesis of data from various previous empirical studies addressing similar themes, thereby facilitating the formulation of more comprehensive conclusions (Retnawati et al., 2010). Furthermore, since the effect size is calculated based on the synthesized results, the accuracy of the impact estimation is improved compared to individual studies. This approach is useful for determining whether findings from various previous studies indicate a consistent trend and for identifying factors that cause data variation across studies (Hansen et al., 2022; Paul & Barari, 2022). Through a review of published literature, this study aims to measure the effect size of the implementation of android-based mobile learning on senior high school students' physics learning outcomes.

The data collection procedure for this study follows the standard guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 protocol (Page et al., 2021). The screening of articles meeting the inclusion criteria was conducted systematically by accessing reputable databases such as Google Scholar and the Garuda Portal (SINTA). Given the rapid development of android-based mobile learning technology in physics education, the publication timeframe was limited to the last five years to ensure the relevance of the information used. The search for relevant literature was conducted using keywords connected by Boolean operators (AND and OR). The selected keywords in English included *"Mobile Learning", "Android", "Physics", and "learning outcomes"*. This systematic keyword selection aimed to identify research articles that present accurate data regarding the effectiveness of Android applications on the physics learning outcomes of senior high school students.

The data validity in this study is ensured through a rigorous article screening process that combines inclusion and exclusion criteria. Studies incorporated into the final dataset were required to fulfill the following four standard criteria: 1) the articles used are primary research results (experimental or quasi-experimental) published in accredited journals; 2) the research subjects are students at the senior high school level; 3) the media focus is on Android-based mobile learning; 4) the articles contain statistical data including Mean, Standard Deviation (N), or other statistical values that will be used to calculate the effect size. Conversely, articles must be excluded from the analysis process if they meet the exclusion criteria, namely: 1) the articles are in the form of review articles, proceedings, theses/dissertations, or books; 2) there is no control group in the study; 3) the quantitative data is incomplete so that it cannot be converted into effect size values. All of these criteria are necessary so that the alignment of the data with the research objectives can be well-maintained (Page et al., 2021).

The process of collecting and recording key information from the literature that meets the criteria is conducted systematically by following the data extraction procedure. This stage identifies the specific characteristics of each study and ensures consistency, structure, and accuracy in the subsequent data analysis and interpretation. The study is required to record identification information for each article, such as the author's name, publication year, physics topic discussed, and sample characteristics. The primary information extracted to calculate the effect size includes statistical data regarding both the experimental and control groups. These numerical parameters include the sample size (N), mean value, and standard deviation for both studied groups (Phillips & Barker, 2021). A pre-designed coding sheet is used to record all of these data, thereby ensuring a systematic and consistent approach for the next stage of analysis.

The data obtained from 24 articles will be analyzed to calculate the effect size value using the JASP (Jeffrey's Amazing Statistics Program) application. To determine the effect size, calculations are based on Cohen's categories using Hedges' (g) formula to correct for small sample bias.

Initial Cohen's d formula:

$$d = \frac{\bar{x}_e - \bar{x}_c}{SD_{pooled}} \tag{1}$$

Hedges' g correction for small samples:

$$g \approx d\left(1 - \frac{3}{4(n_e + n_c) - 9}\right) \tag{2}$$

The meta-analysis model is selected based on the characteristics of the data obtained from various research studies. Given the assumed variation or heterogeneity of characteristics across studies, a random effects model was selected to be applied to conduct the analysis in this study. The selection of the Random Effects Model is more relevant to use because not all studies have the same conditions, so the results or effect sizes obtained differ from one study to another(Kraft, 2019). Heterogeneity testing was conducted using the Q statistic and the I^2 index to determine the consistency of findings between one study and another. Then, the interpretation of the effect size refers to Cohen's criteria, namely $0{,}20 \leq g < 0{,}50$ (low), $0{,}50 \leq g < 0{,}80$ (medium) dan $g \geq 0{,}80$ (high) (Cohen, 1988). However, since even a small effect size can have significant practical value in learning, the context of educational research is also considered when interpreting the results (Kraft, 2020).

Following the computation of Hedges' g for each individual entry, cross-study variance was evaluated through a comprehensive heterogeneity assessment. This step clarifies whether fluctuations in effect magnitudes stem purely from random sampling errors or reflect structural differences in research features. Consequently, these test outcomes dictated the selection between a Fixed Effect or a Random Effects framework. To measure this variance, Cochran's Q statistic was calculated as follows:

$$Q = \sum_{i=1}^{k} w_i \,(ES_i - \overline{ES})^2 \tag{3}$$

In this equation, Q represents the primary heterogeneity value, while w_i denotes the specific weight allocated to the i-th investigation. Additionally, ES_i signifies the individual effect size, $\overline{ES}$ stands for the synthesized pooled effect, and k indicates the total number of included primary studies.

The I^2 index was further utilized to measure the exact proportion of variance, computed as follows:

$$I^2 = \frac{Q - df}{Q} \times 100\% \tag{4}$$

where the degrees of freedom are defined as $df = k - 1$

This I^2 metric reveals what portion of the total variance reflects genuine heterogeneity as opposed to arbitrary fluctuations. Adhering to the benchmarks established by Higgins (2008), thresholds at 25%, 50%, and 75% correspond to low, mid-tier, and pronounced heterogeneity tiers. A Fixed Effect approach suits datasets with minimal variance; however, given the detection of extensive heterogeneity here, a Random Effects framework was implemented to accommodate shifting true effects across distinct contexts. The entire statistical operation was executed via JASP.

RESULTS AND DISCUSSION

Results

In this study, a total of 24 selected articles were systematically categorized using identification codes ranging from A1 to A24. Each article was documented based on the author and publication year, physics learning topic, sample size, experimental and control group mean scores, as well as the calculated effect size. A comprehensive overview of these analyzed article characteristics is presented in a structured format in Table 1.

Table 1. Characteristics of Primary Studies Included in the Meta-Analysis

Code	Research (year)	Senior High School Physics Material	N_{sample}	$\bar{X}_E$	$\bar{X}_C$	*Effect Size*	Category
A1	Fathurohman et al (2023)	Dynamic Electricity	72	91.87	74.83	1.89	High
A2	Ningsih et al (2023)	Sound and Light Waves	60	79.5	71.5	0.9	High
A3	Yuliana et al (2020)	Impulse and Momentum	58	72.4	27.9	2.16	High
A4	Halmuniati et al (2022)	Mechanical Waves	48	77.58	73	0.64	Medium
A5	Mardiana et al (2025)	Optical Instruments	64	13.39	11.08	1.58	High
A6	Fatikasari et al (2020)	Work and Energy	60	88.67	79.83	1.24	High
A7	Revvina et al (2023)	Traveling and Stationary Waves	72	82.5	72	0.755	Medium
A8	Pratama, L. D., & Lestari (2020)	Electrical Resistance Circuits	64	80.03	76.53	0.958	High
A9	Akmaludin et al (2025)	Measurement	70	84.41	76.71	0.91	High

Code	Research (year)	Senior High School Physics Material	N_{sample}	$\bar{X}_E$	$\bar{X}_C$	*Effect Size*	Category
A10	Aisyah At. Thahirah et al (2025)	Work and Energy	60	74.33	53	2.78	High
A11	Jazirotunnisa & Wiyanto (2023)	Equilibrium of Rigid Bodies	58	45	45	0	No effect
A12	Sriyanti (2021)	Linear Motion	48	74	71.25	0.399	Low
A13	Ahmad Fahrudin (2022)	Waves	66	81.23	60.03	1.5	High
A14	Koilmo et al (2025)	Elasticity and Hooke's Law	32	85.38	75	1.3	High
A15	Maulida et al (2022)	Momentum and Impulse	59	86.84	75.87	1.48	High
A16	Tumba et al (2022)	Work and Energy	62	39.5	51.6	-0.83	Low and opposite direction
A17	Trenawati et al (2024)	Static Fluids	42	75	73	0.27	Low
A18	Amazihono et al (2022)	Measurement	60	82.44	69.11	1.43	High
A19	Pamangin (2025)	Work and Energy	83	15.64	14.75	0.35	Low
A20	Mahardika et al (2022)	Collisions	40	87.6	83.85	0.41	Low
A21	Noviatika et al (2019)	Momentum, Impulse, and Collisions	58	68.3	51.6	5.03	High
A22	Abdjul (2019)	Mechanical Waves	60	76.7	58.67	2.27	High
A23	Dwi Saputra et al (2024)	Waves	70	77.57	62.57	1.64	High
A24	Agustihana & Suparno (2018)	Thermodynamics	60	55.6	50.44	5.98	High
		Mean Effect Size				1.4	Very high

Based on Table 1, the overall mean effect size was 1.42, falling into the very high category. The highest effect size was 5.98 (A24), indicating that implementing android-based mobile learning in certain physics topics can significantly improve students' conceptual understanding. In contrast, the lowest effect size was -0.83 (A16), suggesting that media effectiveness does not occur automatically but is influenced by technical factors and student readiness. Nevertheless, most analyzed studies consistently reported that experimental groups achieved substantially higher average scores than control groups. Overall, these findings demonstrate that android-based media effectively help students construct an understanding of abstract physics concepts. Therefore, android-based mobile learning is proven to be a highly promising interactive medium for improving high school students' physics learning achievement.

After calculating the overall effect size, the next step was to examine heterogeneity across studies using the Residual Heterogeneity Test. This test determined whether effect size variation across studies was solely due to sampling error or influenced by potential moderator variables. Main parameters analyzed included the heterogeneity statistic (Qe), degrees of freedom (df), and significance level (p). The residual heterogeneity test results are summarized in Table 2.

Table 2. Heterogeneity Test Results

Heterogeneity Test		
Q_e	df	p
288.6	23	< 0.001

Based on Table 2, the residual heterogeneity test produced a Cochran's Q (Qe) value of 288.6 ($df = 23, p < 0.001$). Since the p-value was well below 0.05, effect size variation across studies was statistically significant, indicating substantial heterogeneity. This finding suggests that effect size differences among the 24 studies were not solely due to sampling error but influenced by substantive study differences. These differences included variations in physics topics, mobile application visualization quality, and experimental duration across schools. As a methodological consequence of this high heterogeneity, a random-effects model was selected to synthesize the data objectively and accurately.

Given the significant heterogeneity identified in the previous analysis, the pooled effect size was estimated using a random-effects model. This analysis was conducted to determine the overall effectiveness of android-based mobile learning on students' physics achievement. Main statistical parameters analyzed included the estimated effect size, standard error, t-statistic, degrees of freedom (df), and significance level (p). Summary statistical results for the pooled effect size analysis are presented in Table 3.

Table 3. Results of the Pooled Effect Size Test

Pooled Effect Size Test				
Estimate	Standard Error	t	df	p
1.42	0.29	4.87	23	< 0.001

Based on Table 3, the estimated pooled effect size was 1.42 with a standard error of 0.29 and a t-value of 4.87 (df = 23, p < 0.001). Since the significance level was well below 0.05, results indicate that android-based mobile learning had a statistically significant positive effect on students' physics achievement. The effect size of 1.42 falls into the very high category, indicating that this digital learning media substantially improved students' learning achievement compared to conventional methods. From a pedagogical perspective, this strong effect is attributed to android applications providing interactive visual simulations that help students understand abstract and complex physics concepts more easily. In addition, mobile learning accessibility and flexibility enable students to learn independently at their own pace, inside and outside the classroom. Therefore, these findings provide empirical evidence that integrating android-based mobile learning is a highly effective instructional strategy for improving high school students' physics achievement.

To strengthen pooled effect size reliability and assess cross-study variability, meta-analytic parameter estimation was conducted. This analysis evaluated the Confidence Interval (CI), Prediction Interval (PI), and heterogeneity measures (τ, τ^2, I^2, and H^2). Parameter estimates are summarized in Table 4.

Table 4. Meta-Analysis Estimate Parameters

Meta-Analytic Estimates					
		95% CI		95% PI	
	Estimate	Lower	Upper	Lower	Upper
Effect Size	1.424	0.82	2.03	-1.43	4.28
τ	1.348	1.05	2.02	–	–
τ^2	1.818	1.091	4.09	–	–
I^2	95.43	92.61	97.9	–	–
H^2	21.88	13.53	47.9	–	–

Based on Table 4, the estimated pooled effect size was 1.424, with a 95% Confidence Interval (CI) from 0.82 to 2.03. Since the entire confidence interval lies above zero, findings indicate that Android-based mobile learning consistently has a positive, statistically significant effect on students' physics achievement. In addition, the high I^2 value of 95.43% (95% CI [92.61, 97.90]) and H^2 of 21.88 indicate that 95.43% of total variance stems from true heterogeneity rather than sampling error. This substantial between-study variance (τ^2 = 1.818) is explained by contextual differences in physics topics, application features, and intervention duration. Meanwhile, the 95% Prediction Interval (PI) from -1.43 to 4.28 suggests that future effectiveness may vary depending on school facilities and learning environment readiness. Overall, these parameters provide empirical evidence supporting mobile learning effectiveness while emphasizing careful implementation in physics classes.

To provide a comprehensive visualization of the effect sizes from each primary study and the overall pooled effect, a forest plot was generated. This figure provides a graphical representation of the direction and magnitude of the effect of android-based mobile learning in each study included in the analysis. In addition to displaying the individual effect size estimates and their confidence intervals, the forest plot also presents the overall model summary and the prediction interval. The complete visualization of the effect size distribution is presented in Figure 1.

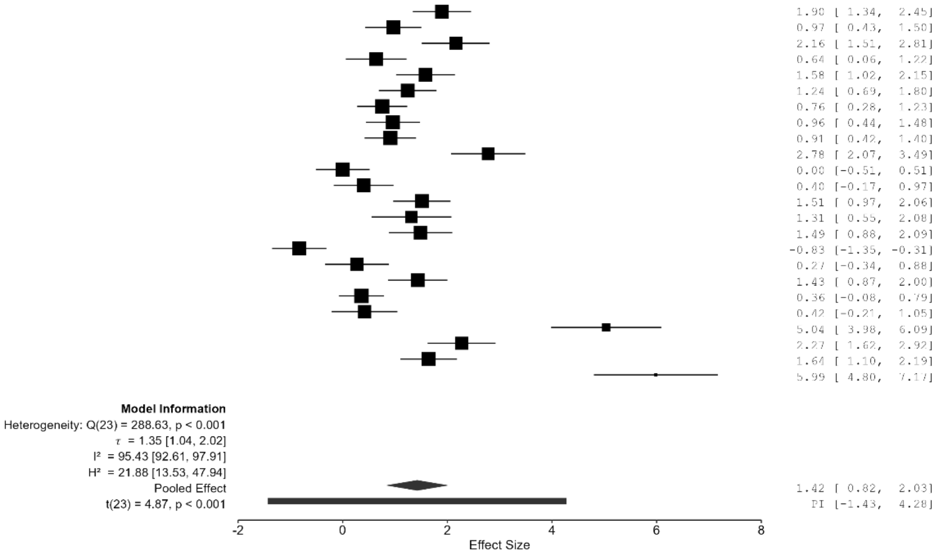

Figure 1. Forest Plot of Android Mobile Learning Effect Sizes

In Figure 1, the black squares represent the estimated effect sizes of the individual studies, while the horizontal lines indicate the corresponding 95% Confidence Intervals (CIs). The diamond at the bottom of the plot represents the pooled effect size of 1.42 (95% CI [0.82, 2.03]). Most of the 24 primary studies are located to the right of the zero line, with individual effect sizes reaching as high as 5.99, indicating that android-based mobile learning generally has a positive effect on students' physics learning achievement. However, a small number of studies are located close to or to the left of the zero line (e.g., -0.83), visually reflecting the high level of heterogeneity across the studies ($I^2 = 95.43\%$). The diamond, which lies entirely to the right of the zero line, further indicates that the overall effect of the intervention is statistically significant and consistently positive. Meanwhile, the long horizontal bar at the bottom of the plot represents the 95% Prediction Interval (PI), ranging from $-1.43\ to\ 4.28$, suggesting that the effectiveness of android-based mobile learning in future applications may vary depending on the conditions of the school environment. In summary, the forest plot confirms that although the results vary across studies, the overall evidence strongly supports the effectiveness of Android-based mobile learning in senior high school physics education.

Discussion

This study demonstrates that the implementation of android-based mobile learning has a significant positive effect on the physics learning outcomes of senior high school students. The meta-analysis synthesized an overall pooled effect size of 1.42, which is classified as a very large effect according to Cohen's criteria. This finding indicates that students who learned through android-based mobile learning consistently achieved higher learning outcomes than those receiving conventional instruction. The present finding is consistent with previous evidence showing that mobile learning improves students' academic achievement across education and enhances learning outcomes in high school physics classrooms (Tingir et al., 2017; Zhai et al., 2019).

Theoretically, this exceptional effectiveness is strongly anchored in Mayer's Cognitive Theory of Multimedia Learning and Sweller's Cognitive Load Theory (Mayer, 2024; Paas & Sweller, 2021). Senior high school physics is inherently dominated by abstract, microscopic, and dynamic concepts, such as static electricity, kinetic theory of gases, wave optics, and electromagnetic fields, that cannot be directly perceived through traditional instructional media. Conventional instruction often forces students into passive rote memorization without establishing genuine conceptual understanding (Doyan et al., 2024; Wandi et al., 2023). Android-based mobile applications resolve this cognitive barrier by integrating dual-coding visual stimuli, interactive simulations, dynamic animations, and virtual laboratories that convert abstract physics concepts into intuitive, concrete mental models (Atika et al., 2022; Clark & Mayer, 2016).

Furthermore, the ubiquity and portability of mobile devices foster self-regulated learning (SRL), as conceptualized by Zimmerman (2002). The seamless accessibility of Android learning tools breaks down spatial and temporal barriers, encouraging students to actively manage their learning pace, review challenging material autonomously, and engage in self-directed problem-solving (Broadbent & Poon, 2015; Sung et al., 2016). The synergy between interactive visual scaffolding and autonomous digital learning serves as the primary engine driving these substantial improvements in physics learning outcomes.

Although the overall synthesized effect size was strongly positive (ES = 1.42), this meta-analysis revealed an exceptionally high degree of statistical heterogeneity ($I^2 =$ 95.4%). This substantial heterogeneity indicates that the effectiveness of android-based mobile learning varies considerably across different instructional contexts and implementation conditions (Higgins et al., 2009). An examination of the characteristics of the primary studies revealed effect sizes ranging from highly positive effects to negligible effects (ES = 0 in Study A11) and even negative effects ($ES = -0.83$ in Study A16).

A zero-effect size (ES = 0) in Study A11 illustrates that technology integration does not automatically guarantee superior learning outcomes over conventional instruction. Evidence showed the Android application in Study A11 achieved high feasibility based on expert validation, scoring 85.83% (material) and 85.58% (media). Despite this high feasibility, qualitative findings indicated application effectiveness was constrained by students' internal characteristics and school environmental factors. Specifically, limited prior mathematical ability in analytical topics like rigid body equilibrium, combined with insufficient self-regulated learning skills, reduced students' ability to utilize interactive features effectively. Additionally, limited printed resources caused students to rely predominantly on teacher explanations, reducing independent learning opportunities through the Android application (Jazirotunnisa & Wiyanto, 2023).

Similarly, the negative effect size (ES = −0.83) in Study A16 reflects methodological limitations rather than Android m-learning ineffectiveness. In Study A16, the non-equivalent control group design exhibited baseline imbalance, as the control group held higher prior physics knowledge pre-intervention (Tumba et al., 2022). Descriptive gain analysis showed that the experimental group using Android animation media achieved a higher mean gain (+39.9 points) than the control group (+20.5 points). These findings suggest that the intervention itself contributed positively to students' learning progress. however, the calculated effect size may have been influenced by the initial differences between groups and inconsistencies in the reporting of the primary study (Borenstein et al., 2009; Tumba et al., 2022). Taken together, the findings from Studies A11 and A16 indicate that statistical heterogeneity in meta-analyses of android-based mobile learning is influenced not only by the instructional intervention itself but also by learner characteristics, educational context, and methodological quality.

The principal finding of this meta-analysis is that although Android-based mobile learning yields a very large overall effect size (ES = 1.42), its pedagogical effectiveness is not uniform and appears to be moderated by environmental and learner-related factors. Unlike previous studies that primarily emphasized the positive impact of educational technology on learning outcomes (Crompton & Burke, 2018; Sung et al., 2016), this study indicates that contextual factors, such as students' prerequisite mathematical competence, self-regulated learning skills, and the availability of supporting learning resources, may substantially influence the effectiveness of android-based mobile learning. Furthermore, this meta-analysis suggests that extreme negative effect sizes may partly reflect baseline differences between comparison groups in quasi-experimental studies rather than solely indicating instructional ineffectiveness (Higgins et al., 2009). These findings highlight that android-based mobile learning can serve as an effective catalyst for improving physics learning outcomes; however, its effectiveness remains dependent on appropriate pedagogical support and rigorous research design.

Despite its rigorous framework, several limitations of this meta-analysis should be acknowledged. First, included studies were limited to Android mobile learning in high school physics within specific educational and publication contexts. Consequently, generalizability of findings to other educational levels or disciplines should be interpreted with caution. Second, inconsistent reporting across primary studies prevented quantitative examination of potential moderator variables such as intervention duration, instructional design features (e.g., gamification versus simulation), and teacher digital competence which may have contributed to substantial residual heterogeneity (I^2 = 95.4%) (Higgins et al., 2009). Third, as with all meta-analyses, this study is susceptible to publication bias, as statistically significant findings are more likely published than non-significant results (Rothstein et al., 2005). Finally, several primary studies employed non-equivalent quasi-experimental designs, introducing baseline differences between comparison groups and influencing estimated effect sizes, as illustrated by Study A16 (Shadish et al., 2002; Tumba et al., 2022).

The pedagogical implications of this meta-analysis recommend the use of Android-based mobile learning as an effective instructional medium for senior high school physics. Nevertheless, the findings from studies A11 and A16 indicate that the successful implementation of this technology is heavily influenced by various supporting factors. In addition to providing high-quality applications, teachers must ensure that students possess the readiness necessary to utilize the technology effectively. Therefore, integrating mobile learning with active learning models, such as Problem-Based Learning, is essential to maximize overall instructional effectiveness.

Implementing android-based mobile learning for topics with a high level of mathematical complexity should begin with reinforcing relevant foundational skills through remedial or scaffolding strategies. Furthermore, teachers need to design instructional processes that integrate android-based media with active learning models, such as Problem-Based Learning (PBL) or inquiry learning, to foster students' self-regulated learning. Consequently, students will not merely act as passive listeners but will be actively engaged in the learning process.

CONCLUSION

Based on a statistical synthesis of 24 empirical studies using JASP, this meta-analysis confirms the positive impact of Android-based mobile learning. This digital intervention significantly enhances senior high school students' physics learning achievement. The analysis yielded a large pooled effect size ($ES = 1.40, p < 0.001$). This result demonstrates its superior efficacy compared to conventional instruction. Although high heterogeneity was observed ($I^2 = 95.4\%$), it does not indicate technical limitations of mobile devices. Instead, further examination shows that this variability stems from student baseline characteristics and methodological differences across primary studies. For this reason, integrating Android-based mobile learning is strongly recommended. However, its implementation should be paired with active learning models (e.g., PBL or inquiry-based learning) and adequate foundational mathematical support.

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