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Vector Learning in Vocational and Engineering Education: A Systematic Review, Narrative Synthesis, and Limited Meta-Analysis Using JASP

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Abstract: Vector learning is a fundamental component of physics and engineering but is often perceived as difficult due to its abstract concepts. This study aims to map publication trends, instructional models, and the effectiveness of vector learning from 2016 to 2025 through a systematic literature review and limited meta-analysis. Twenty-one articles from Scopus, Sinta 1–2, and DOAJ were analyzed using the PRISMA protocol. Seven quantitative studies were synthesized through meta-analysis using JASP, while fourteen were reviewed narratively. The findings show a steady increase in publications, with notable peaks in 2018 and 2020. Problem-based learning and augmented reality emerged as the most widely implemented instructional approaches. The pooled effect size indicates a large impact (d = 1.01), with augmented reality (d = 0.74) and blended learning (d = 0.62) showing high effectiveness. Narrative synthesis highlights conceptual difficulties, ongoing media innovation, and the development of supporting teaching materials. The study concludes that vector learning research remains active but requires further exploration in AI integration, web-based gamification, and long-term retention assessment.

Keywords: Augmented reality; Meta-analysis; Problem-based learning; Systematic literature review; Vector learning

Introduction

Vector learning is fundamental in mathematics and engineering education, supporting the understanding of advanced topics such as particle dynamics, electromagnetic fields, and fluid mechanics (Hoyer & Girwidz, 2024; Choi & Yun, 2019; Zavala & Barniol, 2010). Nevertheless, students frequently struggle with vector operations, spatial representations, and transitions among symbolic, graphical, and geometric forms, compounded by misconceptions like conflating scalar and vector addition or misinterpreting dot and cross products, which impede conceptual understanding in STEM courses (Hoyer & Girwidz, 2024; Addae, 2025; Chhabra & Das, 2023; Bahtaji, 2023; Zavala & Barniol, 2010; Rodríguez-Nieto et al., 2024).

To address these challenges, instructional innovations such as dynamic visualization tools, augmented reality (AR), tangible robotics, and gamified learning environments have been implemented to enhance conceptual reasoning and engagement (Muñoz et al., 2016; Ziatdinov & Valles, 2022; Arbain & Shukor, 2025). Web-based learning media also improve understanding of abstract concepts and problem-solving in STEM subjects, including physics topics like sound waves (Maryani et al., 2022; Zulfira et al., 2024; Zamista & Azmi, 2023).

Despite these advances, comparative evaluations remain limited, particularly in technical disciplines such

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as mining and mechanical engineering. Research from 2016–2025 shows growth in vector learning studies, driven by emerging technologies and interdisciplinary approaches. AR enhances spatial visualization and problem-solving, while tangible robots support learners' transition from concrete to abstract reasoning (Volodin et al., 2025; Guntur & Setyaningrum, 2021). In Indonesia, physics education research largely focuses on cognitive learning outcomes using quantitative and quasi-experimental approaches at the secondary education level (Nabilah & Jumadi, 2022), a trend also confirmed by recent systematic literature reviews (Fitriah et al., 2025).

A preliminary scan of Scopus and Web of Science shows increased publications and citations, yet studies are fragmented, focusing on isolated methods, single-level populations, or context-specific implementations, with few quantifying effect sizes via meta-analysis. Prior reviews are outdated, limited to theory, or lack statistical synthesis, highlighting the need for a comprehensive, evidence-based overview to inform pedagogy, curriculum, and future research.

This study's novelty lies in combining a systematic literature review with a limited meta-analysis of vector learning research (2016–2025), mapping instructional models such as AR, blended learning, and PBL, while providing pooled effect sizes. It integrates multiple educational contexts, highlights contemporary innovations, identifies persistent difficulties, and uncovers underexplored areas like AI integration, web-based gamification, and long-term retention. Guided by PRISMA (Moher et al., 2009), this study addresses four research questions: publication trends, instructional models and outcomes, most effective methods, and implications for future research and practice.

Overall, consolidating a decade of diverse research offers educators, researchers, and policymakers structured evidence to design effective, technology-enhanced vector learning strategies, clarifying what works, for whom, and under which conditions, thereby advancing STEM and engineering education.

Method

Research design and method should be clearly defined. This study employed a Systematic Literature Review (SLR) combined with a limited meta-analysis to address the research questions. The literature search was conducted in three major databases: Scopus (via Publish or Perish), Sinta (rank 1–2), and DOAJ, covering publications from 2016 to 2025. The keywords used were *"Vector learning," "Vector education,"* and *"Teaching vector."*

The initial search identified 233 articles from Scopus (filtered to 6 relevant studies), 5 articles from Sinta, and 10 articles from DOAJ (from an initial 144). After deduplication and screening using predefined inclusion–exclusion criteria, a total of 21 articles were retained for analysis. Among these, seven quantitative studies were subjected to a meta-analysis using JASP software, while the remaining fourteen studies were analyzed through narrative synthesis.

The inclusion criteria were as follows: (1) published between 2016–2025; (2) the main topic focused on vector learning; (3) published in Scopus- or Sinta 1/2-indexed journals; (4) written in English or Indonesian; (5) discussing instructional models, media, learning outcomes, or educational trends; and (6) empirical in nature (quantitative, qualitative, or R&D). The exclusion criteria were: (1) not primarily focused on vector learning; (2) not a journal article; (3) full text not available; (4) lacking empirical data; or (5) published outside the defined time frame.

The article selection process was visualized using a PRISMA flow diagram (Figure 1), illustrating the four stages of *identification, screening, eligibility,* and *inclusion*.

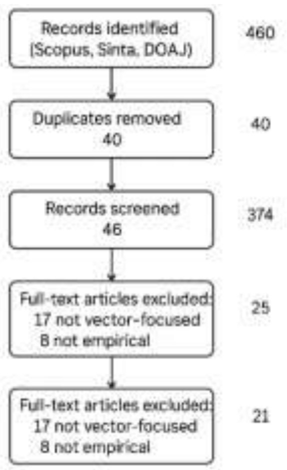

Figure 1. PRISMA flowchart of the study selection process

From an initial 460 records identified across databases, 40 duplicates were removed, leaving 420 articles for screening. At this stage, 46 records were excluded, resulting in 50 full-text articles assessed for eligibility. Of these, 25 were excluded (17 did not focus on vector learning and 8 were not empirical studies). Finally, 21 articles met the inclusion criteria and were retained for review.

A bibliographic summary of the included studies is presented in Table 1, which provides an overview of the article titles, years of publication, authors, and source databases. Further details, such as research design, instructional models, media, and reported learning outcomes, were analyzed but are not displayed in the table for clarity. These data served as the basis for the descriptive analysis, meta-analysis, and narrative synthesis presented in the subsequent sections.

Table 1. Summary of 21 Selected Articles (Condensed Version)

Authors (year)	title (shortened)	database / doi
Mushlihuddin, Nurafifah & Irvan (2018)	Problem-based learning on vector analysis	DOI: 10.1088/1742-6596/948/1/012028
Dubey & Barniol (2023)	Personalized adaptive learning for vectors	DOI: 10.1088/1361-6404/ace826
Puri, Jumadi & Wiyatmo (2025)	PBL-SSI worksheet on sand mining	https://jurnal.ustjogja.ac.id/index.php/compton
Campos, Hidrogo & Zavala (2022)	Virtual reality in vector learning	DOI: 10.3389/feduc.2022.965640
Asshaari et al. (2024)	Cooperative learning in vector calculus	DOI: 10.17576/jkukm-2024-36(6)-12
Sharifov (2020)	Head-to-tail method in physics tasks	DOI: 10.15294/jpfi.v16i2.25395
Pratama, Larasati & Khotimah (2020)	TORIQ: Android-based vector learning	DOI: 10.1088/1742-6596/1613/1/012052
Tasman et al. (2021)	Blended learning in calculus vector	DOI: 10.1088/1742-6596/1742/1/012006
Saifullah, Sutopo & Wisodo (2017)	Students' difficulties in impulse & momentum	DOI: 10.15294/jpii.v6i1.9593
Suana et al. (2017)	Schoology-based blended learning media	DOI: 10.15294/jpii.v6i1.7205
Atsnan (2016)	CPS-based vector learning device	DOI: 10.21831/jrpm.v3i1.10406
Argarini & Sulistyorini (2018)	Prezi-based media for vector analysis	Google Scholar
Jana & Sugiyarta (2018)	Flashcard-assisted active learning in vectors	Google Scholar
Saumi, Muliani & Amalia (2022)	AR-based e-module for vector	Google Scholar
Subali et al. (2019)	Teaching aids for resultant force vectors	Google Scholar
Zhao (2024)	Concreteness fading in vector addition	Google Scholar
Fernández-Cézar et al. (2020)	Teaching vector spaces from real problems	Google Scholar
Heckler & Mikula (2016)	Factors affecting computer-based vector math	Google Scholar
Bollen et al. (2016)	Students' use of divergence & curl	Google Scholar
Klein et al. (2020)	Eye-tracking in visual interpretation of divergence	Google Scholar
Veasna (2020)	Students' difficulty in geometry & vectors	Google Scholar

Result and Discussion

Publication Trends

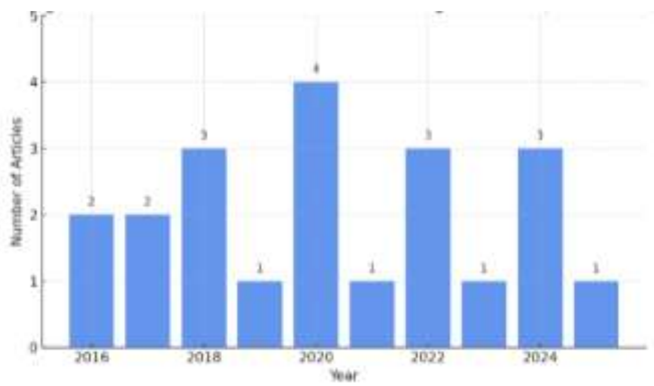

Figure 2. Publication trend of vector learning research during 2016–2025

Analysis of the selected articles indicates a steady growth of research on vector learning between 2016 and 2025, with notable peaks in 2018 (3 articles) and 2020 (4 articles) (Figure 2). This reflects increasing scholarly concern with the conceptual difficulties students face in mastering vectors, particularly in directionality, operations, and representation. Several studies (Sabah, 2023; Khumaidi et al., 2022) highlight persistent misconceptions, suggesting that conventional teaching methods are insufficient. In response, innovative approaches such as 3D models (McNaughtan et al., 2021) and simulation-based learning (Lasisi et al., 2025) have emerged, emphasizing the shift toward technology-supported instruction.

Learning Models and Learning Outcomes

Problem-Based Learning (PBL) and its variants (PBL-SSI, PBL-NP) dominated the reviewed studies and consistently yielded moderate-to-high N-Gain scores, improving both problem-solving and conceptual understanding. For example, Mushlihuddin et al. (2018) reported significant gains in vector analysis, while Wijnia et al. (2024) observed higher motivation and achievement in experimental groups. Alongside PBL, technology integration played a crucial role. Studies using Augmented Reality (AR), Virtual Reality (VR), Android apps, and presentation tools (e.g., Prezi) reported enhanced spatial reasoning and comprehension (Guntur & Setyaningrum, 2021; Langer et al., 2020). Other strategies—blended learning, cooperative learning, flashcards, and concreteness fading (Zhao, 2024)—further scaffolded students' transition from concrete to abstract thinking.

Figure 3 summarizes the distribution of instructional models, showing PBL as dominant, followed by blended learning, digital media, and representational scaffolds. Reported outcomes include improved conceptual mastery, problem-solving, and motivation, alongside validation of the practicality and effectiveness of instructional materials.

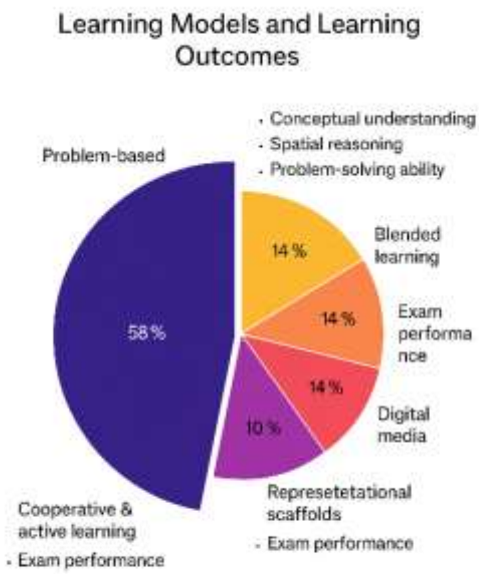

Figure 3. Distribution of instructional models in reviewed studies

Effectiveness of Instructional Models

Seven quantitative studies qualified for meta-analysis, yielding a pooled effect size of d = 1.01 (95% CI = 0.693–1.328; $p < .001$), categorized as large (Cohen, 1988). This underscores the substantial impact of PBL and digital media integration on vector learning. The result aligns with earlier findings in STEM education (Hake, 1998) and is consistent with individual studies such as Mushlihuddin et al. (2018), which reported significant improvements in mathematical problem-solving.

The heterogeneity test (Q_e = 0.932, df = 6, p = 0.988; τ^2 = 0) indicates negligible variation, suggesting consistent effectiveness across contexts. This robustness is echoed in Zhao (2024), who found concreteness fading to be effective across diverse groups.

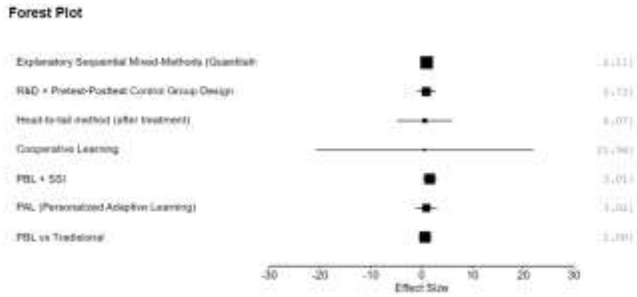

Figure 4. Forest plot of meta-analysis on effect sizes of vector learning models

Recommendations for Future Research and Practice

While current evidence supports the effectiveness of problem-based and technology-enhanced models, gaps remain. Most studies emphasize short-term outcomes, with limited attention to long-term retention. Technology use is largely confined to AR, VR, and mobile apps, with little exploration of web-based gamification, AI, or adaptive learning. Research contexts are also concentrated in high schools and early university cohorts, with few vocational or cross-cultural studies.

Future work should investigate long-term learning retention, expand into underrepresented contexts, and explore novel tools such as gamified web platforms and AI-driven adaptive learning. Practically, educators are encouraged to integrate PBL with interactive visual media (AR/VR) and formative online assessments to foster deeper conceptual understanding, motivation, and sustained engagement.

Discussion

The meta-analysis shows a large overall effect size (d = 1.01) for innovative vector learning approaches, particularly Augmented Reality (AR), Blended Learning, and Problem-Based Learning (PBL) (Cohen, 1988; Dubey & Barniol, 2023; Tasman et al., 2021; Mushlihuddin et al., 2018). AR demonstrates the strongest impact on spatial visualization and conceptual understanding (Guntur & Setyaningrum, 2021; Langer et al., 2020), while PBL effectively promotes active knowledge construction and problem-solving (Magaji, 2021; Wijnia et al., 2024; Yanti, Rahmad, & Azhar, 2023; Dewi et al., 2023). Blended learning offers moderate but consistent gains.

Effectiveness appears to vary by educational context. Most studies were conducted at senior high school and early university levels, with limited evidence in vocational or engineering-specific settings (Veasna, 2024; Subali et al., 2019). Web-based gamification, such as mobile TORIQ media, shows promising engagement and learning outcomes compared to conventional approaches (Pratama et al., 2020; Sharifov, 2020; Silfiani, Jasruddin, & Amin, 2022; Matsun et al., 2022; Setiaji et al., 2025; Rahman et al., 2021).

Despite positive results, most studies rely on short-term post-tests, and quasi-experimental designs dominate, limiting insight into long-term retention and cognitive processes (Sabah, 2023; Saifullah et al., 2017; Heckler & Mikula, 2016). Future research should examine interactions between instructional methods, learner profiles, and STEM disciplines.

Practically, educators should integrate AR, PBL, and blended learning to strengthen conceptual understanding and problem-solving (Campos et al., 2022; Susilawati et al., 2022; Mushlihuddin et al., 2018). Media developers and curriculum designers can align tools with cognitive principles, especially for spatial topics (Ziatdinov & Valles, 2022; Zhao, 2024). Expanding studies into vocational and engineering contexts will enhance relevance for technical disciplines (Volodin et al., 2025; Saumi et al., 2022).

Conclusion

This review analyzed 21 studies on vector learning published between 2016 and 2025. The findings show an increasing research trend, with Problem-Based Learning, Augmented Reality, and blended learning emerging as the most widely used instructional models. Meta-analysis results indicate a large pooled effect ($d = 1.01$), confirming that innovative and technology-supported approaches significantly improve students' conceptual understanding and spatial reasoning. These results align with cognitive learning theory, which emphasizes the role of interactive and multimodal representations in supporting abstract reasoning. Although the findings are promising, most studies remain limited to general STEM contexts, affecting the generalizability of the results. Practically, this review suggests that educators integrate active and technology-enhanced methods to strengthen vector learning outcomes. Future research is encouraged to explore AI-based adaptive systems, web-based gamification, and long-term retention assessment, especially in vocational and engineering education where vector competence is essential.

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Author Contributions
Denal Mulia contributed to the conceptualization of the study, literature review, data analysis, and drafting of the manuscript; Fadhilah contributed to research supervision, methodology refinement, correspondence with the journal, and critical revision of the manuscript; Dedy Irfan contributed to data interpretation, validation of findings, and technical review of the manuscript.

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Conflict of Interest
The authors declare no conflict of interest.

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