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Mental Models and Educational Technology in STEM-Physics Learning: A Systematic Literature Review

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Abstract: Developing accurate mental models is essential for enhancing students' conceptual understanding in STEM education, particularly in physics, where abstract concepts often challenge learners. This systematic literature review examines the role of educational technology in supporting the development of mental models within the context of physics learning in STEM. By analyzing 30 selected empirical studies published between 2015 and 2025, sourced from databases like Scopus, ERIC, and Google Scholar, the review evaluates how various digital tools have been employed to facilitate this process. The studies were filtered from an initial pool of 1,507 articles based on their relevance to the research question. The findings reveal that digital tools such as simulations, virtual laboratories, augmented reality (AR), and interactive multimedia are particularly effective in helping students construct and refine their mental models. These technologies provide students with hands-on experiences and real-time feedback, allowing for a deeper understanding of complex physical phenomena. The review concludes by discussing the implications of technology-enhanced instruction for STEM education, emphasizing how these tools can enhance conceptual understanding and problem-solving skills in physics. Finally, future research directions are suggested, focusing on further improving technology-mediated learning frameworks to support the development of mental models in STEM education.

Keywords: Mental models, STEM education, Educational technology, Physics learning, Systematic literature review

Introduction

In the 21st-century educational landscape, fostering deep conceptual understanding in STEM (Science, Technology, Engineering, and Mathematics) disciplines has become a critical priority. Among these, physics education poses unique cognitive challenges, as it demands learners to grasp abstract, often counterintuitive concepts such as force, energy, and electric circuits. To navigate these complexities, learners rely heavily on mental models internal cognitive structures that allow individuals to simulate, explain, and predict physical phenomena (Panasuk, 2022). These models are not static; they evolve with experience, instruction, and interaction with learning environments.

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Mental models have long been recognized as essential in science education due to their explanatory and predictive power. They serve as a bridge between a learner's prior knowledge and new scientific information, shaping the way students interpret problems and apply physics concepts (Treagust, Duit, & Fischer, 2020). However, many students arrive in physics classrooms with incomplete or inaccurate models formed through everyday experiences. If left unaddressed, these misconceptions can hinder the learning process and resist change even after formal instruction (Vosniadou, 2020).

The emergence and proliferation of educational technology including simulations, virtual labs, augmented reality (AR), and intelligent tutoring systems have introduced new dimensions to conceptual learning in physics. These tools have the potential to externalize abstract physics phenomena, offering dynamic, visual, and interactive representations that can facilitate the construction and refinement of mental models (Cheng & Yeh, 2021). For instance, dynamic simulations of electric circuits can help students visualize current flow and voltage changes in ways that traditional diagrams cannot. Augmented reality applications allow students to manipulate virtual forces or observe magnetic field lines in 3D, supporting spatial reasoning and conceptual engagement (Talan et al., 2022).

Over the past decade, research has increasingly examined how such technological interventions can scaffold learning by aligning instructional representations with learners' evolving mental models (Makransky & Mayer, 2022). In particular, design principles rooted in cognitive science such as coherence, redundancy avoidance, and signaling have been applied in educational technologies to improve cognitive processing and reduce mental load (Schroeder & Traxler, 2020). Despite these promising developments, the research landscape remains fragmented. Studies vary widely in their theoretical grounding, types of technology used, target concepts, and methods for assessing mental models. As such, there is a critical need to systematically review and synthesize recent literature that intersects mental model theory with technology-enhanced physics learning in STEM contexts. A comprehensive overview of this body of work can help clarify (1) how educational technologies are being used to support mental model development in physics, (2) what empirical evidence exists for their effectiveness, and (3) where gaps remain in current research.

Therefore, this systematic literature review aims to map and analyze empirical studies from the past five years (2015–2025) that explore the relationship between mental models and educational technology in physics learning within STEM education. By identifying prevailing trends, research methodologies, types of technologies, and conceptual focuses, this review seeks to inform educators, instructional designers, and researchers in their efforts to design effective learning environments that promote conceptual change and deeper understanding in physics.

Method

Research Design

This study employs a qualitative approach through a systematic literature review guided by the content analysis method. The research aims to analyze how educational technologies have been integrated into STEM physics learning to support the development of students' mental models. The research method used is in line with that applied by Susetyarini and Fauzi (2020), focusing on reviewing findings from peer-reviewed scientific journal articles. The review also adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework as suggested by Moher et al. (2015).

Data Source

The data for this study were obtained through a systematic review of literature focused on the use of educational technology in supporting the development of mental models within STEM physics learning. A comprehensive search was conducted across three major academic databases: Scopus, ERIC (Education Resources Information Center), and Google Scholar. These databases were selected due to their extensive indexing of peer-reviewed and empirical research in the fields of education, science, and instructional technology.

The initial search yielded a total of 1,507 articles published between 2015 and 2025. To ensure relevance to the research objective, the articles were screened based on predefined inclusion criteria, which focused on studies that: (1) examined the role of digital tools or educational technologies in physics education; (2) explicitly addressed mental models in the context of student learning; and (3) were empirical in nature, reporting data from classroom implementations or experimental studies. Articles that were theoretical, not related to physics education, or did not discuss mental model development were excluded from further analysis.

After a rigorous screening and selection process involving title and abstract review followed by full text analysis, 30 empirical studies were identified as meeting all inclusion criteria. These selected articles formed the primary data source for the literature review and were analysed to identify patterns in the use of technology such as simulations, virtual laboratories, augmented reality, and interactive multimedia in facilitating students' mental model development in physics. The data extracted from these studies were then synthesized using content analysis to address the overarching research questions of the review.

Table 1. Aspects and categories of content analysis in research

Aspects	Category
Types of Research (1a)	A.1 - R and D (Research and Development)
	C.3 - Qualitative Research
	D.4 - Quantitative Research
Types of Quantitative (1b)	B.1 - Observation Studies (OS)
	B.4 - Pre-Experimental Design (PED)
	B.5 - True Experimental Design (TED)
	B.6 - Quasi-Experimental Design (QED)
Research Subject	C.1 - X Grade SHS students
	C.2 - XI Grade SHS students
	C.3 - XII Grade SHS students
	C.4 - SHS in general
	C.5 - Undergraduate students

Inclusion: Selected articles are limited from 2015 to 2025 and are accompanied by the words, phrases, or sentences physics problem solving, pps, problem-solving skills, and problemsolving ability either in the title, abstract, or keywords. All of these stages are used to select articles to be reviewed, and the appropriate graph is shown in PRISMA which can be seen in FIGURE 1.

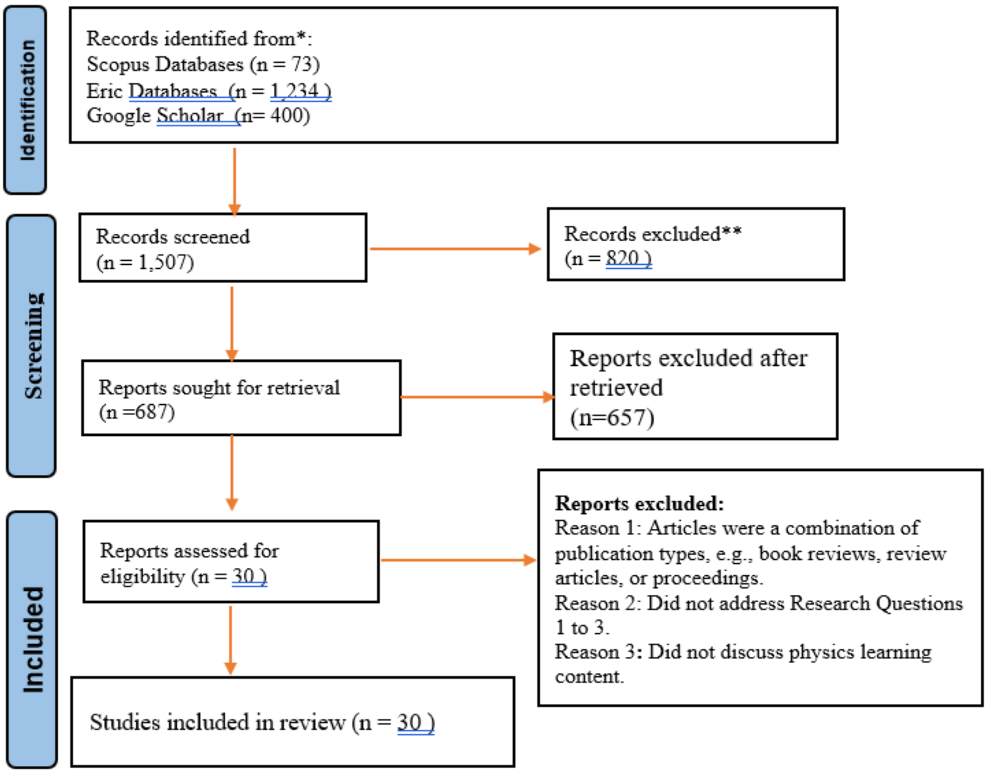

Figure 1. PRISM model graph

Research Instrument

In this study, the main research instrument was a data extraction sheet developed to systematically collect and analyze relevant information from each of the 30 selected articles. Guided by the PRISMA framework (Page et al., 2021), the sheet was designed to capture key elements such as authorship, publication year, research methodology, educational level of participants, types of digital technology used (e.g., simulations, virtual labs, AR, multimedia), and the specific role of these technologies in supporting the development of mental models in physics learning. Additionally, the instrument helped determine the relevance of each study to the research questions, ensuring that only studies aligned with the focus of this review were included in the final synthesis.

Data Analysis

The data were analyzed using qualitative content analysis by identifying key themes related to how educational technologies support mental model development in physics learning. Articles were coded based on research methods, types of digital tools used, educational levels, and outcomes. The findings were then grouped and interpreted to highlight patterns and draw conclusions relevant to the research questions.

Results and Discussion

An initial database search identified 1,507 articles related to the use of educational technology in supporting mental model development in STEM physics education. The articles were gathered from Scopus, ERIC, and Google Scholar databases. After applying inclusion criteria based on publication years (2015–2025), relevance to the research questions, and focus on physics learning content, the number of relevant articles was reduced to 30. These 30 articles were then fully analyzed and included in the systematic review, as shown in Table 2.

Table 2**.** Synthesized articles

No	Author	Source title	Title
1	Ubben & Bitzenbauer (2022)	Education Science MDPI	Two Cognitive Dimensions of Students' Mental Models in Science: Fidelity of Gestalt and Functional Fidelity.
2	Batlolona & Diantoro (2022)	Creativity Studies	Mental Models And Creative Thinking Skills In Students' Physics Learning
3	Bekaert et al. (2022)	Physical Review Physics Education Research	Identifying students' mental models of the apparent motion of the Sun and stars
4	Batlolona et al. (2020)	Jurnal Pendidikan Fisika Indonesia	Influence of Problem Based Learning Model on Student Mental Models
5	Batlolona et al. (2020)	Journal of Turkish Science Education	Students' Mental Models of Solid Elasticity: Mixed Method Study
6	Fratiwi et al. (2020)	European Journal of Educational Research	Developing MeMoRI on Newton's Laws: For Identifying Students' Mental Models.
7	Mansyur et al. (2022)	Journal of Turkish Science Education	Students' Mental Models about the Suspending Objects in Static Fluid
8	Glaudell (2020)	Conference Record of the IEEE Photovoltaic Specialists	Women in Physics, Math and Astronomy at Caltech: Supporting Women in STEM
9	Greene & Lopez (2019)	Journal of Physics: Conference Series	Evaluating a predictive model of student performance in introductory calculus-based physics
10	Anupam et al. (2018)	IEEE Transactions on Education	Particle in a Box: An Experiential Environment for Learning Introductory Quantum Mechanics
11	Anderson (2015)	Smart Innov. Syst. Technol.	M-MODEL: Design and implementation of an on-line homework system for engineering mechanics
12	Brewe et al. (2018)	Frontiers in ICT	Toward a neurobiological basis for understanding learning in university modeling instruction physics courses
13	Conradty et.al (2020)	Educ. Sci. MDPI	How creativity in STEM modules intervenes with self-efficacy and motivation
14	Dewi et al. (2018)	Journal of Physics: Conference Series	An analysis of students' mental models using temperature and heat transfer-diagnostic test(THT-DT)
15	Yuanphan & Nuangchalerm (2023)	Jurnal Penelitian dan Pembelajaran IPA	The Development of Grade 10 Students' Mental Models on Solutions Through Model-Centered Instruction

16	Amiruddin et al. (2023)	Journal of Education and Learning (EduLearn)	An analysis of first years senior high school students' mental models: a case study on the concept of uniform motion
17	Supriyatman et al. (2018)	Jurnal Pendidikan Fisika Indonesia	Design Of Experimental Problem Solving-Based Learning Program To Improve Mental Model And To Enhance Mental-Modeling Ability
18	Umar et al. (2024).	Journal of Science Learning	Developing Dispersion and Polarization Conceptual Inventory (DiPolCI) to Identify Students' Mental Model
19	Kafiyani et al. (2018)	Journal of Physics: Conference Series	Development of four-tier diagnostic test (FTDT) to identify student's mental models on static fluid
20	Ockhorst &Pols. (2023)	Journal of Physics: Conference Series	Development of the mental models of wave and particle as basis for wave-particle duality
21	Almadhoun & Parham-Mocello (2021)	Education Conference FIE	Exploratory Study on Accuracy of Students' Mental Models of a Singly Linked List
22	Sari et al. (2019)	Journal of Physics: Conference Series	Excavating the Quality of Vocational Students' Mental Models and Prediction on Heat Conduction
23	Ubben & Heusler (2019)	Research in Science Education	Gestalt and Functionality as Independent Dimensions of Mental Models in Science
24	Batlolona et al. (2020)	International Journal of Evaluation and Research in Education	Problem based learning: Students' mental models on water conductivity concept
25	Nongkhunsarn et al. (2018)	Journal of Physics	Grade 11 Student's Mental Model of Fluid and Analytical Thinking in Science Teaching Through Science Technology and Society (STS) Approach
26	Khasanah & Yulianti, 2016	Jurnal Pendidikan IPA Indonesia	Analysis Of Mental Model Of Students Using Isomorphic Problems In Dynamics Of Rotational Motion Topic
27	Dewi et al. (2023)	Jurnal Penelitian Pendidikan IPA	How Is Students' Mental Model In The Post-Pandemic Era? Work And Energy Concept Analysis Using The Wright Map
28	Hermita et al. (2020)	Universal Journal of Educational Research	Improving Prospective Primary School Teachers' Mental Models through Implementation of CDOI Supported by Multimode Visualization
29	Sánchez-A C et al. (2019)	ASEE Annual Conference and Exposition	ICT-based didactic strategies to build knowledge models in electronics in higher education
30	Dwandar. et al. (2019)	European Journal of Educational Research	Developing Of Computerized Adaptive Testing To Measure Physics Higher Order Thinking Skills Of Senior High School Students And Its Feasibility Of Use

Number of Publication

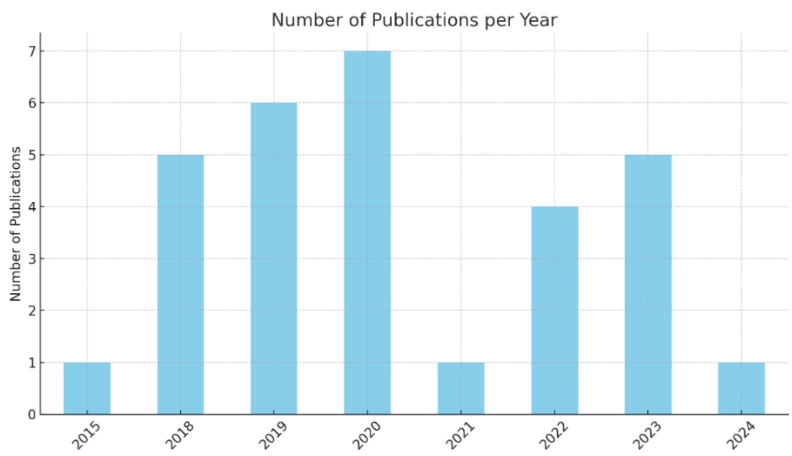

Figure 2. Trends in increasing number of research

Based on the displayed chart, it can be observed that the number of publications on topics related to physics and education has fluctuated over the years. The year 2020 recorded a relatively high number of publications, with many studies published in various journals focused on students' mental models and teaching approaches in the field of physics. Additionally, publications appear stable in the subsequent years, such as 2022, showing a growing trend in articles related to physics topics like mechanics, electromagnetism, and other concepts. The years 2019 and 2023 also recorded significant publications, although not as high as 2020. Overall, this chart provides an overview that research in this field continues to progress, with variations in the number of publications reflecting the interest and development of these topics over time.

Research Subject

The diagram provides an insightful distribution of research subjects in the field of education, with a clear emphasis on certain key areas. The largest portion, representing Mental Models in Science Education (53.3%), indicates a strong focus on understanding how students develop and apply mental models to comprehend scientific concepts. This area explores the cognitive frameworks students use to make sense of complex science topics and how these models influence their learning process.

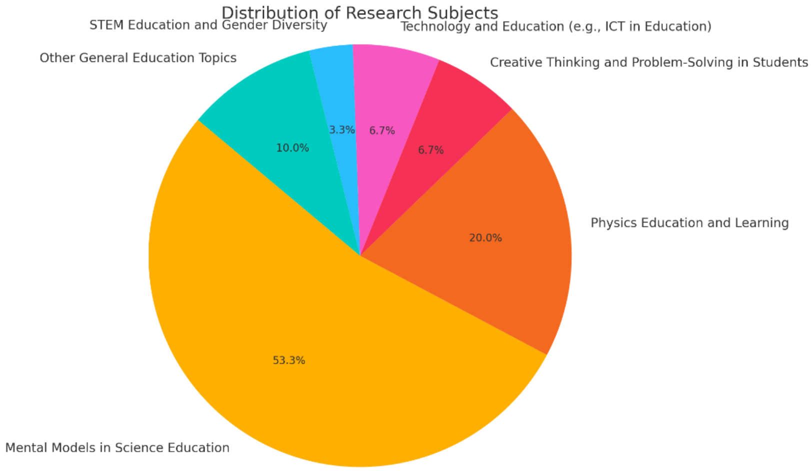

Figure 3. Trends in increasing research subject

Next, Physics Education and Learning makes up 20% of the chart. This section highlights the growing interest in physics education, investigating how students learn and engage with physics concepts. It likely involves exploring innovative teaching methods, student challenges in mastering physics, and the effectiveness of different educational strategies. The research on Creative Thinking and Problem-Solving in Students, which constitutes 6.7%, underscores the importance of nurturing students' abilities to think creatively and solve problems efficiently. In today's educational landscape, fostering such skills is vital for preparing students for real-world challenges, especially in an ever-evolving job market.

The Technology and Education section (10.0%) reflects the growing role of digital tools in the classroom. It examines how Information and Communication Technologies (ICT) can enhance learning, improve access to resources, and transform traditional educational practices to meet modern needs. STEM Education and Gender Diversity (3.3%) explores the intersection of STEM fields and gender, focusing on how to encourage greater gender diversity in science, technology, engineering, and mathematics education. This research area aims to promote inclusivity and ensure that both male and female students have equal opportunities to thrive in STEM disciplines.

Physics Topics for Research

The bar chart provides a clear visualization of the distribution of various physics topics in recent publications. Classical Mechanics emerges as the most prominent subject, with the highest number of publications, underscoring its continued relevance and importance in the field. This could indicate that researchers are still deeply engaged with foundational principles of physics, exploring new interpretations and applications. Astronomy follows closely behind, signalling a strong interest in the study of celestial bodies and the universe, an area that consistently attracts attention from both theoretical and observational perspectives. The recurring mention of Quantum and Elasticity further highlights the ongoing exploration of these fundamental concepts, particularly in the context of new technologies and their applications in modern science. Other topics such as Thermodynamics, Static Fluid, and Wave-Particle Duality are also represented, though less frequently. This suggests that while these areas are important, they may be more niche or specialized in their focus, reflecting specific research interests or emerging trends in physics education and application. Overall, the chart paints a picture of a dynamic and evolving field, with certain topics continuing to dominate, while others gain attention as new discoveries and advancements unfold.

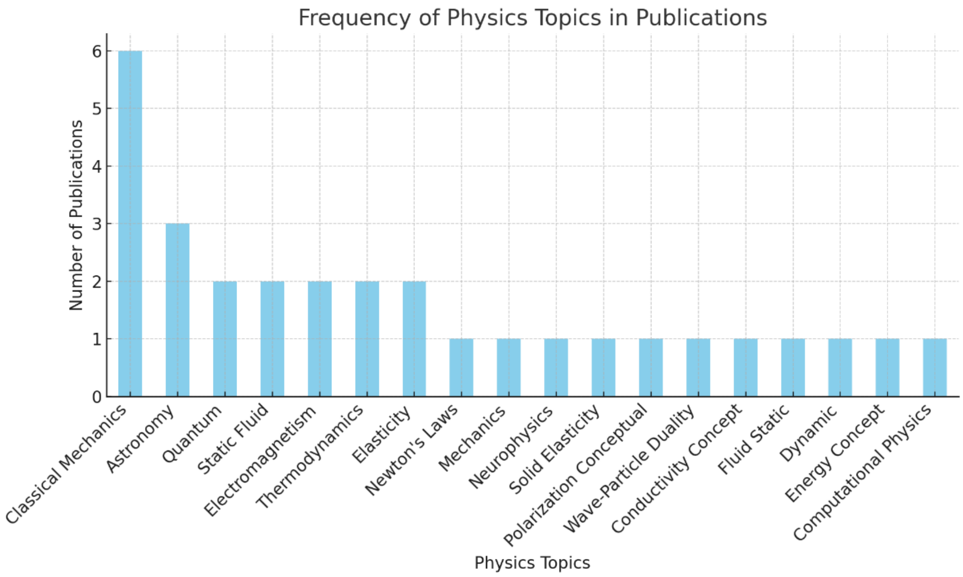

Figure 4. Trends in physics material in research

Conclusion

In conclusion, the systematic literature review on Mental Models and Educational Technology in STEM Physics Learning reveals the ongoing importance and evolution of key topics within the field of physics education. Classical Mechanics and Astronomy are the most frequently addressed subjects, reflecting their foundational role in STEM physics education. These topics continue to serve as a critical focus for researchers, as they underpin much of the curriculum and educational practices in physics. The review also highlights the prominent role of Quantum and Elasticity, areas that remain central to both theoretical exploration and the application of educational technologies. Advances in these topics are often intertwined with the integration of digital tools and innovative teaching methods, which aim to enhance students' understanding of complex physical concepts through interactive learning experiences. Additionally, subjects such as Thermodynamics, Wave-Particle Duality, and Energy Concept, though less prevalent, underscore the diversity in research areas, as educational technology continues to support the exploration of niche topics. These areas are gaining traction due to the growing interest in creating immersive and engaging educational environments that leverage digital platforms and simulations to facilitate deeper learning.

Recommendations

Based on the findings from this systematic literature review, future research should explore the impact of emerging educational technologies on the development of mental models in physics learning. While current studies have highlighted the role of digital tools like simulations and virtual labs, further investigation is needed to understand how specific technologies, such as augmented reality (AR) and virtual reality (VR), influence students' conceptual understanding. These technologies offer immersive experiences that may enhance students' ability to visualize and comprehend complex physics phenomena, warranting a deeper focus on their effectiveness in the classroom. Additionally, future studies should examine the long-term effects of educational technology on student learning outcomes. Most research to date has concentrated on short-term improvements in understanding, but there is limited knowledge about how sustained use of these tools impacts retention and application of physics concepts over time. Longitudinal studies could provide valuable insights into how digital learning platforms influence students' performance and mastery of the subject in the long run, ultimately guiding the development of more effective, technology-enhanced physics education strategies.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPESS journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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