



A Theory-Informed Framework for Interactive Digital Learning in Physics Education: A Systematic Literature Review

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ABSTRACT

Purpose: This study synthesizes evidence on interactive digital learning in physics education and addresses fragmented technology-specific reviews by proposing a theory-informed conceptual framework linking digital affordances, theoretical foundations, pedagogical design, learner processes and outcomes, and implementation conditions. **Methods:** Following PRISMA 2020 and PRISMA-S, literature published from January 2016 to June 2026 was retrieved from nine information sources and supplemented by backward and forward citation chasing. of 3,142 records identified, 66 publications met the eligibility criteria. Empirical studies were appraised using MMAT, with the JBI checklist additionally applied to quasi-experimental studies. Evidence was synthesized through thematic and abductive analysis. **Findings:** Five interconnected themes emerged: digital learning affordances, theoretical foundations, pedagogical design features, learner processes and outcomes, and implementation conditions. Learning benefits were associated with representational coherence, guided inquiry, scaffolding, feedback, reflection, and context-sensitive implementation. The synthesis does not establish causal mediation among framework components. **Conclusion:** The review proposes a theory-informed conceptual framework organizing recurring relationships across heterogeneous studies. **Research Implications:** The framework supports the design, implementation, evaluation, and empirical testing of coherent digital physics learning environments. **Originality:** The review integrates technological, theoretical, pedagogical, learner, outcome, and contextual dimensions across multiple digital modalities within a unified conceptual structure for future research.



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INTRODUCTION

Physics education aims to develop learners' conceptual understanding, scientific reasoning, problem solving, and representational competence through the study of natural phenomena that are often abstract, dynamic, invisible, and mathematically demanding. Unlike many other scientific disciplines, physics requires learners to coordinate multiple forms of representation, including mathematical equations, graphs, diagrams, experimental observations, simulations, and verbal explanations, to explain a single phenomenon coherently. Meaningful learning therefore depends not only on acquiring factual knowledge but also on learners' ability to construct, interpret, and integrate these complementary representations into coherent mental models. However, many students continue to experience difficulties in understanding abstract concepts, connecting multiple representations, and transferring conceptual knowledge to unfamiliar situations, resulting in persistent misconceptions and superficial learning (Marisda et al., 2022; Maruf et al., 2024; Munfaridah et al., 2021). These challenges have encouraged continuous efforts to design learning environments that support conceptual visualization, active inquiry, scientific reasoning, and meaningful knowledge construction.

Interactive digital learning has become an important pedagogical development in physics education because it enables learners to interact actively with scientific concepts that are otherwise difficult to observe through conventional instruction. Advances in educational technology have expanded opportunities for integrating interactive simulations,

virtual laboratories, augmented reality, virtual reality, mobile learning, digital modules, interactive multimedia, and web-based learning environments into physics classrooms. Although these digital environments differ in technological sophistication, interface design, and instructional implementation, they can provide pedagogical affordances that support conceptual visualization, manipulation of variables, integration of multiple representations, immediate feedback, guided inquiry, collaborative exploration, and self-paced learning (H J Banda & Nzabahimana, 2021; Lai & Cheong, 2022; Y. Wang et al., 2025). Their educational value therefore depends not on technological novelty alone but on how particular affordances are organized to support cognitive engagement, conceptual integration, and scientific reasoning. From this perspective, interactive digital learning is better understood as a pedagogical system in which technology creates opportunities for meaningful learning rather than as a collection of independent educational tools.

The rapid development of interactive digital learning has generated an extensive body of empirical research across diverse educational settings. Studies report improvements in outcomes such as conceptual understanding, academic achievement, motivation, scientific inquiry, self-efficacy, collaborative learning, practical laboratory skills, and higher-order thinking when digital technologies are integrated with appropriate pedagogical strategies (Anselmo et al., 2024; H J Banda & Nzabahimana, 2021; Herbert James Banda & Nzabahimana, 2023; S Cai et al., 2021; Georgiou et al., 2021; Lai & Cheong, 2022; Tsivitanidou et al., 2021). This evidence base has also stimulated systematic reviews of particular modalities, including augmented and virtual reality, virtual laboratories, mobile learning, simulation-based learning, and extended reality (Anselmo et al., 2024; Gumilar et al., 2025; Vidak et al., 2024; Y. Wang et al., 2025; Zatarain-Cabada et al., 2023). These reviews provide valuable technology-specific evidence, but their organizing logic generally remains centred on individual modalities, effectiveness questions, or implementation challenges. Consequently, they offer limited cross-technology explanation of the pedagogical mechanisms that recur across different interactive digital environments.

This fragmentation represents a conceptual limitation in the literature. Interactive simulations, virtual laboratories, augmented reality, virtual reality, mobile learning, and digital modules differ in their technical features, yet they often support overlapping learning activities such as visualizing abstract phenomena, coordinating representations, manipulating variables, conducting inquiry, receiving formative feedback, and reflecting on conceptual understanding. Existing reviews have mapped many of these benefits within specific technologies, but they have not systematically organized the recurring links among digital affordances, theoretical foundations, pedagogical design features, learner processes and outcomes, and implementation conditions within one physics-education framework. The gap addressed in this review is therefore not the absence of evidence that digital technologies can support physics learning, but the absence of a cross-modality conceptual synthesis that identifies transferable pedagogical principles and distinguishes technological opportunities from the theoretical, instructional, learner, and contextual conditions through which those opportunities may become educationally meaningful.

A theory-informed perspective provides a foundation for interpreting these recurring mechanisms because learning in digital environments emerges from interactions among technology, pedagogy, learner cognition, and instructional context. The Cognitive Theory of Multimedia Learning explains how learners select, organize, and integrate verbal and visual information to construct meaningful mental representations (R E Mayer, 2024), whereas Cognitive Load Theory emphasizes the management of limited working-memory capacity (Sweller et al., 2019). Constructivist learning theory, inquiry-based learning, experiential learning, problem-based learning, and self-regulated learning illuminate processes of exploration, experimentation, collaboration, reflection, and learner regulation. Representational competence is especially relevant to physics because students must coordinate equations, graphs, diagrams, simulations, verbal explanations, and experimental evidence. These perspectives are treated here as complementary lenses operating at different analytical levels rather than as interchangeable theories: cognitive theories address information processing, constructivist and inquiry perspectives address knowledge-building activity, representational competence addresses disciplinary meaning-making, self-regulation addresses learner control, and TPACK addresses teacher-level integration.

Accordingly, this systematic literature review adopts a theory-informed perspective to synthesize evidence on interactive digital learning in physics education published between January 2016 and June 2026. In contrast to reviews organized primarily around a single technology, this study integrates evidence across diverse interactive environments to: (1) map the landscape and recurring affordances of interactive digital learning; (2) identify theoretical foundations used to interpret digital physics learning; (3) synthesize pedagogical design features and reported learner processes and outcomes; (4) examine implementation conditions and contradictory or context-dependent findings; and (5) propose a Theory-Informed Framework for Interactive Digital Learning in Physics Education. The novelty of the framework lies in organizing these dimensions within a common cross-modality structure and in treating their links as theory-informed propositions for subsequent empirical testing rather than as established causal pathways.

METHOD

A. Research Design

This study employed a systematic literature review (SLR) to synthesize evidence on interactive digital learning in physics education and to develop a theory-informed conceptual framework describing proposed relationships among digital affordances, theoretical foundations, pedagogical design features, learner processes and outcomes, and implementation conditions. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA 2020) statement to support transparent reporting of study identification, screening, eligibility assessment, and inclusion (Page, McKenzie, et al., 2021). Search procedures were additionally documented with reference to the PRISMA Search Reporting Extension (PRISMA-S), which provides guidance for reporting information sources, search strategies, search dates, search fields, limits, and supplementary retrieval procedures (Rethlefsen et al., 2021).

A qualitative-dominant evidence synthesis was adopted because the literature on interactive digital learning in physics education is conceptually and methodologically heterogeneous, encompassing experimental, quasi-experimental, mixed-methods, qualitative, design-and-development, validation, review, and conceptual publications. A meta-analysis was not undertaken because the review did not address a single intervention-comparator-outcome configuration. Instead, the synthesis aimed to identify recurring patterns across digital modalities and to interpret them through an abductive framework-development process. The review protocol was not prospectively registered. However, the review questions, eligibility criteria, search concepts, screening procedures, extraction categories, appraisal approach, and synthesis plan were established before formal screening. The absence of prospective registration is treated as a methodological limitation and is considered when interpreting the reproducibility of the review.

B. Review Questions and Scope

The review was guided by four research questions designed to synthesise current evidence and support theory-informed framework development. The first question examined how interactive digital learning has evolved in physics education between January 2016 and June 2026. The second explored the theoretical perspectives underpinning the design, implementation, and evaluation of interactive digital learning. The third investigated the digital affordances, pedagogical design features, learner processes, learning outcomes, and implementation conditions reported across the included studies. The fourth synthesised these findings to identify transferable design principles and develop a theory-informed framework for interactive digital learning in physics education.

For this review, interactive digital learning was defined as the use of digital environments, platforms, media, or technologies that enable learners to actively explore, manipulate, visualise, simulate, experiment with, or respond to physics concepts, representations, phenomena, or problem-solving tasks. This definition encompassed interactive multimedia, digital learning environments, virtual laboratories, virtual experiments, interactive simulations, PhET simulations, augmented reality, virtual reality, mixed reality, extended reality, mobile learning, web-based learning, digital modules, electronic modules, interactive flipbooks, and digital game based learning. Digital resources that merely delivered static information without meaningful learner interaction were excluded because the review focused on pedagogically interactive learning environments rather than digital content delivery alone.

C. Information Sources and Search Strategy

Scopus was selected as the primary bibliographic database because of its broad coverage of physics education, science education, educational technology, engineering education, and the learning sciences. Additional structured searches were conducted in the Web of Science Core Collection, ERIC, and IEEE Xplore. To broaden coverage, searches were also conducted through the publisher platforms ScienceDirect, SpringerLink, Taylor & Francis Online, and Wiley Online Library. These publisher platforms were treated as supplementary discovery sources rather than equivalent bibliographic databases; records retrieved from them were pooled with database records and de-duplicated before screening to reduce overlap. Google Scholar was used as a supplementary search source, with screening limited to the first 200 records ranked by relevance because of its lower search transparency and reproducibility. Backward and forward citation chasing of key reviews and highly relevant studies was also undertaken to identify potentially eligible publications not retrieved through the structured searches (Haddaway et al., 2022). Thus, the review used nine information sources plus citation chasing rather than ten bibliographic databases.

The search covered publications from January 2016 to June 30, 2026. Only English-language publications were considered to ensure consistency throughout screening, appraisal, extraction, and synthesis. Eligible publication types included peer-reviewed journal articles and indexed conference proceedings that provided primary empirical or design

evidence. Systematic reviews, meta-analyses, and theoretically relevant review papers were retained only as secondary evidence for field mapping, theoretical interpretation, and citation chasing. They were not treated as independent confirmation of effects already represented by their constituent primary studies, thereby reducing the risk of double counting during evidence interpretation.

The search strategy was developed iteratively using two core concepts: interactive digital learning and physics education. Pilot searches were used to refine keywords and confirm retrieval of benchmark studies. The full Scopus search string was applied to titles, abstracts, and keywords as follows: TITLE-ABS-KEY (("interactive digital learning" OR "interactive multimedia" OR "digital learning environment" OR "virtual laboratory" OR "virtual lab" OR "virtual experiment" OR "interactive simulation" OR "PhET" OR "augmented reality" OR "virtual reality" OR "mixed reality" OR "extended reality" OR "mobile learning" OR "web based learning" OR "digital module" OR "electronic module" OR "interactive module" OR "interactive flipbook" OR "digital game based learning") AND ("physics education" OR "physics learning" OR "physics teaching" OR "physics instruction")). Equivalent concept blocks were adapted to the syntax and available search fields of the other sources. [Table 1](#) reports the source, search field or retrieval strategy, and number of records identified. Because verbatim platform-specific search strings and exact execution dates were not preserved in the submitted manuscript for every source, full line-by-line reproducibility is limited; this limitation is explicitly acknowledged rather than inferred retrospectively.

Table 1. Information Sources and Search Strategy

Source	Search field or retrieval strategy	Records identified
Scopus	Title, abstract, and keywords	734
Web of Science Core Collection	Topic search	512
ERIC	Title, abstract, and descriptor	146
IEEE Xplore	Metadata and abstract	268
ScienceDirect	Title, abstract, and keywords	426
SpringerLink	Title, abstract, and keywords	389
Taylor and Francis Online	Title, abstract, and keywords	214
Wiley Online Library	Title, abstract, and keywords	171
Google Scholar	First 200 records ranked by relevance	200
Backward and forward citation chasing	Key reviews and highly relevant studies	82
Total	Databases and supplementary sources	3,142

D. Eligibility Criteria

Eligibility criteria were established before screening to support transparent and consistent study selection. Primary empirical and design studies were eligible when they addressed physics education and provided extractable evidence on interactive digital learning. Systematic reviews, meta-analyses, and theoretically relevant reviews could also be retained, but only as secondary sources for field mapping, theoretical interpretation, and citation chasing; they were not treated as primary effect evidence in the thematic synthesis. The complete eligibility criteria are presented in [Table 2](#).

Table 2. Eligibility Criteria

Domain	Inclusion Criteria	Exclusion Criteria
<i>Educational context</i>	Studies focusing on physics education, physics learning, physics teaching, or physics instruction. Broader science education studies were included only when physics content or learning outcomes were clearly identifiable.	Studies focusing exclusively on disciplinary physics without an educational context or general digital education without a clear physics education component.
<i>Intervention</i>	Studies investigating interactive digital learning environments, platforms, tools, or instructional interventions, including interactive multimedia, virtual laboratories, virtual experiments, interactive simulations, PhET, augmented reality, virtual reality, mixed reality, extended reality, mobile learning, web based learning, digital modules, interactive flipbooks, and digital game based learning.	Studies using digital technology only for static content delivery or lacking meaningful learner interaction.
<i>Evidence</i>	Studies reporting empirical, theoretical, design, or implementation evidence relevant to learner processes, pedagogical design, learning outcomes, digital affordances, or implementation conditions.	Studies lacking extractable evidence relevant to framework development or providing insufficient methodological information.

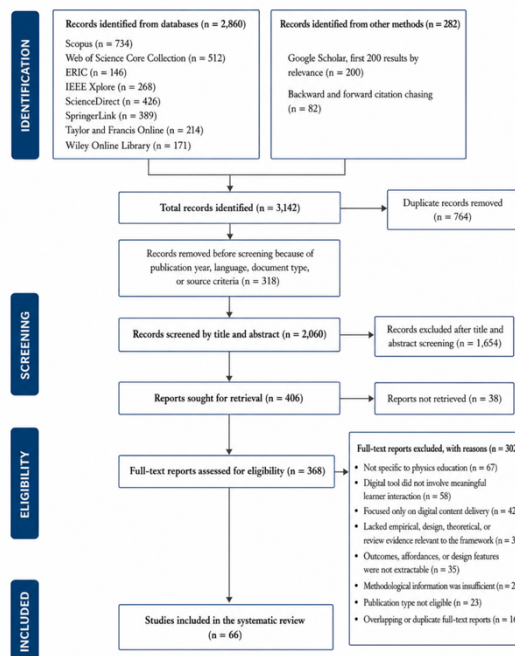
Domain	Inclusion Criteria	Exclusion Criteria
<i>Publication characteristics</i>	English language publications published between January 2016 and June 30, 2026 with accessible full text.	Publications outside the specified period, non English publications, or inaccessible full text.
<i>Study type</i>	Peer-reviewed journal articles and indexed conference proceedings reporting primary empirical or design evidence. Systematic reviews, meta-analyses, and theoretically relevant review papers were retained only as secondary evidence for contextual mapping, theoretical interpretation, and citation chasing; they were not treated as independent primary-effect evidence.	Duplicate publications, editorials, book reviews, short communications, dissertations, theses, magazine articles, and other publication types not meeting the eligibility criteria.

E. Study Selection Procedure

Study selection followed the four stages of PRISMA 2020: identification, screening, eligibility, and inclusion. A total of 3,142 records were identified through the nine information sources and supplementary citation-chasing procedures. Of these, 2,860 records were retrieved from Scopus, Web of Science, ERIC, IEEE Xplore, ScienceDirect, SpringerLink, Taylor & Francis Online, and Wiley Online Library, while 282 additional records were retrieved through Google Scholar screening and backward/forward citation chasing. All records were subsequently pooled for de-duplication and eligibility screening (Page, McKenzie, et al., 2021; Page, Moher, et al., 2021).

All retrieved records were exported to a reference management system before being imported into Rayyan, which was used to facilitate duplicate detection, title and abstract screening, reviewer decision management, and documentation of the screening process (Ouzzani et al., 2016). Prior to formal screening, 764 duplicate records were removed, followed by the exclusion of 318 records that fell outside the publication period, were not written in English, were not peer reviewed, or clearly failed to meet the predefined source criteria. The remaining 2,060 records were independently screened by two reviewers from titles and abstracts using the predefined eligibility criteria. Before screening commenced, both reviewers completed a calibration exercise on an initial sample of studies to ensure a consistent interpretation of the eligibility criteria. Disagreements were resolved through discussion, and unresolved cases were adjudicated by a third reviewer. Following title and abstract screening, 1,654 records were excluded and 406 reports were sought for full-text retrieval.

Figure 1. PRISMA 2020 Flow Diagram for the Systematic Review of Framework for Interactive Digital Learning in Physics Education, 2016 to 2026.



Publication period: January 2016 to June 2026. Review reported in accordance with PRISMA 2020.

Figure 1. PRISMA 2020 Flow Diagram for the Systematic Review of Interactive Digital Learning in Physics Education (2016–2026)

During the eligibility assessment, 38 reports could not be retrieved because of inaccessible full texts, inactive publication links, or institutional access limitations. The remaining 368 full-text reports were assessed independently against the predefined eligibility criteria. Of these, 302 reports were excluded because they were not specific to physics education, lacked meaningful learner interaction, focused solely on static digital content delivery, did not provide relevant empirical, theoretical, or design evidence, contained insufficient methodological information, presented non-extractable findings, represented ineligible publication types, or duplicated another full-text report. Detailed reasons for exclusion are presented in Table 3. Following the eligibility assessment, 66 studies met all inclusion criteria and were retained for quality appraisal, structured data extraction, thematic synthesis, and theory-informed framework development. The complete study selection process is illustrated in [Figure 1](#).

The final 66 included studies represented multiple forms of interactive digital learning in physics education, including PhET simulations, interactive simulations, virtual laboratories, virtual experiments, augmented reality, virtual reality, mobile learning, digital modules, interactive flipbooks, digital games, and web-based extended reality. These studies were retained for quality appraisal, data extraction, thematic synthesis, and theory-informed framework development.

F. Quality Appraisal

The methodological quality of primary empirical studies was appraised to assess the credibility of the evidence used in interpretation. Given the methodological diversity of the empirical literature, the Mixed Methods Appraisal Tool (MMAT) 2018 was used to appraise qualitative, randomized quantitative, non-randomized quantitative, quantitative descriptive, and mixed-methods studies ([Hong et al., 2018](#)). For quasi-experimental studies, the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Quasi-Experimental Studies was additionally used to examine group comparability, exposure, outcome measurement, follow-up, and potential confounding ([Barker et al., 2024](#)). Secondary reviews, meta-analyses, and conceptual papers were not assigned MMAT or JBI quasi-experimental scores because these tools are not designed for those publication types; such publications were used only for contextual mapping and theoretical interpretation and were not treated as primary empirical evidence supporting effect claims.

Quality appraisal was conducted independently by two reviewers, with disagreements resolved through discussion until consensus was reached. Appraisal was used qualitatively rather than converted into a single numerical hierarchy. 'Greater analytical weight' was operationalized in three ways: (1) direct empirical claims and recurring cross-study patterns were preferentially grounded in studies that met a larger proportion of design-appropriate appraisal criteria; (2) studies with notable methodological limitations were retained for contextual, theoretical, or implementation insights but were not used as the sole support for a proposed framework relationship; and (3) contradictory findings were interpreted in relation to study design, context, and methodological limitations. No study was excluded solely on the basis of appraisal because the objective was conceptual synthesis rather than pooled effect estimation. The lack of a complete study-level appraisal table in the original submission limits independent auditing and is acknowledged as a reporting limitation.

G. Data Extraction and Synthesis

A structured data extraction form was developed before the review to support consistency across included publications. The extraction framework recorded bibliographic information, study context, participant characteristics, physics topic, type of interactive digital learning, research design, theoretical foundation, pedagogical strategy, key design features, learner interactions, outcome measures, principal findings, study limitations, and implications for framework development. Data extraction was conducted by one reviewer and independently verified by a second reviewer; discrepancies were resolved through discussion and re-examination of the original publication. During synthesis, extracted material was additionally classified as (a) directly reported study evidence, (b) cross-study interpretive synthesis, or (c) a new theoretical proposition introduced by the review authors. This distinction was used to avoid presenting abductively derived framework relationships as direct causal findings of the included studies.

The evidence was synthesised using thematic synthesis because the included studies differed substantially in technology type, educational context, theoretical orientation, research design, participant characteristics, and reported outcomes ([Thomas & Harden, 2008](#)). The synthesis was complemented by thematic analysis to support the identification, refinement, and interpretation of recurring patterns across heterogeneous evidence ([Braun & Clarke, 2006](#)). Rather than aggregating findings statistically, the analysis sought to explain how interactive digital learning supports meaningful learning in physics education across different technological environments.

The analytical process consisted of four iterative stages. First, extracted data were subjected to descriptive coding based on technology type, instructional context, theoretical perspective, digital affordances, pedagogical design features, learner processes, learning outcomes, and implementation conditions. Second, related codes were grouped

into broader descriptive themes representing common patterns across studies. Third, these themes were interpreted through relevant theoretical perspectives, including the Cognitive Theory of Multimedia Learning, Cognitive Load Theory, constructivist learning theory, inquiry-based learning, problem based learning, experiential learning, self-regulated learning, Technological Pedagogical Content Knowledge (TPACK), and representational competence, enabling the development of higher order analytical themes. Finally, relationships among digital affordances, pedagogical design, learner processes, learning outcomes, and implementation conditions were synthesised through an abductive analytical process to construct a Theory-Informed Framework for Interactive Digital Learning in Physics Education.

Framework development proceeded iteratively between empirical evidence and theoretical interpretation. Emerging conceptual relationships were continuously compared across different forms of interactive digital learning, including interactive simulations, virtual laboratories, augmented reality, virtual reality, mobile learning, digital modules, interactive flipbooks, digital game-based learning, and web based learning environments. Contradictory findings and negative cases were examined throughout the analysis to minimise confirmation bias and ensure that the resulting framework reflected both convergent and divergent evidence. The synthesis was considered conceptually complete when additional studies no longer generated substantively new analytical categories relevant to framework development.

H. Methodological Rigor and Ethical Considerations

Methodological rigor was strengthened through several strategies to enhance the credibility, transparency, and reproducibility of the review. Review questions, eligibility criteria, search strategies, quality appraisal procedures, data extraction protocols, and synthesis methods were established before formal screening. Multiple bibliographic databases and supplementary citation chasing were employed to maximise retrieval coverage. Study selection and quality appraisal were conducted independently by two reviewers, with disagreements resolved through consensus discussion and, when necessary, consultation with a third reviewer. Structured data extraction, systematic quality appraisal, and the examination of contradictory findings further strengthened the credibility and trustworthiness of the synthesis. This review analysed previously published literature and did not involve human participants, personal data, or experimental interventions; therefore, formal ethical approval was not required. Ethical standards were upheld by applying transparent eligibility criteria, systematically documenting review decisions, accurately representing the findings of the included studies, acknowledging methodological limitations, and citing all sources in accordance with APA guidelines.

RESULTS

The thematic synthesis indicates that interactive digital learning in physics education has evolved from isolated digital tools to more integrated pedagogical environments that combine visualization, manipulation, simulation, experimentation, feedback, inquiry, and learner interaction. Across the 66 publications retained under the eligibility criteria, five organizing themes were identified: (1) the landscape and affordances of interactive digital learning, (2) theoretical foundations, (3) pedagogical design features, (4) learner processes and learning outcomes, and (5) challenges and implementation conditions. These five themes are used consistently in the narrative and in Figure 2. Because the included literature is heterogeneous and the review did not conduct meta-analysis, frequency-like expressions and comparative-effect claims are interpreted cautiously; the synthesis emphasizes recurring patterns and proposed relationships rather than causal or quantitative rankings.

Theme 1. Landscape of Interactive Digital Learning in Physics Education

The synthesis revealed a rapidly expanding landscape of interactive digital learning in physics education, characterised by increasing diversity in both technological modalities and pedagogical functions. Rather than relying on a single form of digital instruction, recent studies have adopted a wide range of interactive environments, including PhET simulations, interactive simulations, virtual laboratories, virtual experiments, augmented reality, virtual reality, mobile learning, digital modules, interactive flipbooks, web based extended reality, and digital game based learning. Despite differences in technological sophistication and learning contexts, these modalities share a common educational purpose: enabling learners to visualise, manipulate, investigate, and explain physics phenomena that are otherwise abstract, invisible, dynamic, hazardous, or difficult to access through conventional instruction.

Across the reviewed literature, simulation-based learning was frequently investigated. PhET simulations and related interactive environments allow students to manipulate variables, observe immediate consequences, test predictions, and connect visual changes with physical principles. Studies have reported gains in conceptual

understanding, motivation, and academic achievement when these environments are embedded within guided or inquiry-oriented instruction rather than used only as stand-alone visualization tools. Meta-analytic and review evidence also suggests positive learning effects, while indicating that reported effects vary across educational levels, physics topics, instructional designs, and outcome measures (H J Banda & Nzabahimana, 2021; Herbert James Banda & Nzabahimana, 2023; Fadillah et al., 2026; Pranata, 2024). These findings support a conditional rather than universal interpretation of simulation-based learning benefits.

The landscape has also broadened through technologies that extend learning beyond conventional simulations. Virtual laboratories and virtual experiments provide opportunities for repeated experimentation, procedural practice, inquiry, and experimental reasoning where access to physical laboratories is limited by equipment, safety, time, or institutional resources. Augmented reality enriches learning by connecting digital representations with physical environments, thereby strengthening contextual visualisation, spatial reasoning, and situated inquiry. Virtual reality contributes immersive learning experiences that enable students to investigate inaccessible or counterintuitive physics phenomena, including modern physics topics, through experiential exploration supported by reflection and inquiry. Meanwhile, mobile learning, web based extended reality, digital modules, and interactive flipbooks increase flexibility by supporting self paced learning, structured multimedia content, repeated practice, learner autonomy, and continuous access across formal and informal learning settings. Collectively, these technologies demonstrate that interactive digital learning has expanded from classroom based multimedia toward more flexible, immersive, and learner centred digital ecosystems (Su Cai et al., 2021; Canright & White Brahmia, 2024; Georgiou et al., 2021; Gumilar et al., 2025; Hidayati et al., 2024; Lai & Cheong, 2022; Marisda, Sultan, et al., 2025; Vidak et al., 2024; C. Wang et al., 2021; Yusuf et al., 2024; Zatarain-Cabada et al., 2023). Table 3 summarises the principal digital modalities identified in the review, together with their dominant pedagogical functions, representative evidence, and implications for the proposed framework.

Table 3. Analytical Evidence for the Landscape of Interactive Digital Learning in Physics Education

Digital modality	Dominant pedagogical function	Representative evidence	Implication for framework development
PhET and interactive simulations	Supporting variable manipulation, prediction testing, conceptual visualization, and immediate observation of physical relationships	Banda and Nzabahimana (2021, 2023), Pranata (2024), Fadillah et al. (2026)	Simulations should be positioned as affordance rich environments for guided conceptual exploration rather than as stand alone visualization tools
Virtual laboratories and virtual experiments	Expanding access to experimental learning, repeated practice, guided inquiry, and procedural reasoning	Y. Wang et al. (2025), Yusuf et al. (2024)	Virtual experimentation should be treated as a complementary learning environment that connects access, inquiry, and experimental reasoning
Augmented reality	Supporting contextual visualization, spatial reasoning, haptic engagement, collaborative inquiry, and situated learning beyond the classroom	Cai et al. (2021), Lai and Cheong (2022), Vidak et al. (2024), Gumilar et al. (2025)	Augmented reality should be integrated into the framework as a modality that connects physical contexts with digital representations
Virtual reality	Providing immersive, experiential, and epistemic engagement with abstract or inaccessible physics phenomena	Georgiou et al. (2021), Tsivitanidou et al. (2021), Canright and White Brahmia (2024)	Virtual reality should be understood as an epistemic learning space when immersion is aligned with inquiry, conceptual reasoning, and reflection
Mobile learning and web based extended reality	Enabling flexible access, learner autonomy, interactive practice, and learning beyond formal classroom settings	Anselmo et al. (2024), Zatarain Cabada et al. (2023)	Flexible digital access should be incorporated as a condition that supports self regulated and distributed physics learning
Digital modules and interactive flipbooks	Structuring content, multimedia learning, feedback, exploratory tasks, and flexible engagement with physics concepts	Hidayati et al. (2024), Marisda et al. (2025)	Structured digital materials should be positioned as pedagogical environments that organize interaction, representation, and reasoning

The evidence presented in Table 3 demonstrates that interactive digital learning should be understood as an affordance based pedagogical ecosystem rather than as a collection of independent technologies. Although PhET simulations, virtual laboratories, augmented reality, virtual reality, mobile learning, digital modules, and interactive flipbooks differ

in interface, accessibility, and technological sophistication, they can provide a common set of pedagogical affordances, including visualization, manipulation, experimentation, feedback, representational support, learner control, and inquiry. Consequently, the educational value of interactive digital learning appears to depend not only on the specific technology employed than by the extent to which its affordances are orchestrated to promote conceptual understanding, inquiry, experimental reasoning, critical thinking, and meaningful engagement with physics concepts. This synthesis establishes the first conceptual layer of the proposed framework by demonstrating that the diversity of digital technologies converges around a shared set of pedagogical functions rather than distinct technological categories.

Theme 2. Theoretical Foundations and Pedagogical Affordances

The synthesis identified a diverse but interconnected body of learning theories that explain how interactive digital learning supports meaningful physics learning. Across the reviewed studies, digital environments were most frequently interpreted through the Cognitive Theory of Multimedia Learning (CTML), Cognitive Load Theory (CLT), constructivist learning theory, inquiry based learning, experiential learning, problem based learning, self regulated learning, Technological Pedagogical Content Knowledge (TPACK), embodied cognition, cognitive conflict, and representational competence. Collectively, these perspectives explain how digital environments facilitate conceptual visualisation, manipulation, prediction, experimentation, representational coordination, learner regulation, and conceptual understanding. However, the review also revealed considerable variation in theoretical explicitness. While some studies clearly articulated the learning mechanisms underpinning digital design, others focused primarily on technological implementation or learning outcomes without explicitly explaining why particular forms of interactivity supported physics learning.

Among these perspectives, CTML and CLT constitute the dominant theoretical foundation for interactive digital physics learning. Physics instruction frequently requires students to coordinate equations, graphs, diagrams, animations, simulations, verbal explanations, and experimental evidence simultaneously. Within this context, effective digital learning depends on instructional designs that help learners select relevant information, organize verbal and visual representations, integrate new knowledge with prior understanding, and minimize unnecessary cognitive processing. Contemporary work by Mayer and by Girwidz and Kohnle consistently argues that multimedia environments become educationally effective only when instructional design is grounded in established cognitive principles rather than technological capability alone (Raimund Girwidz & Kohnle, 2021; Richard E. Mayer, 2024). The reviewed evidence therefore indicates that multimedia principles and cognitive load management provide the cognitive architecture through which digital affordances become educationally meaningful.

A second theoretical cluster is represented by constructivist, inquiry based, and problem based perspectives, which explain learning as an active process of knowledge construction through exploration, experimentation, and evidence based reasoning. Interactive simulations, PhET environments, and virtual laboratories consistently encourage learners to manipulate variables, formulate predictions, observe outcomes, compare evidence, and refine explanations. These activities demonstrate that digital interactivity functions educationally valuably when embedded within guided inquiry rather than unrestricted exploration. Instead of serving as channels for information delivery, interactive environments become spaces in which learners investigate physical phenomena and construct conceptual explanations through iterative cycles of prediction, experimentation, and reflection (H J Banda & Nzabahimana, 2021; Herbert James Banda & Nzabahimana, 2023; Gezer et al., 2021; Yusuf et al., 2024).

The reviewed studies also highlighted the growing importance of experiential learning, embodied cognition, and representational competence. Immersive technologies, particularly augmented reality and virtual reality, create opportunities for students to experience abstract or inaccessible phenomena through spatial interaction, contextual visualization, and embodied exploration. At the same time, digital environments increasingly integrate equations, graphs, animations, diagrams, numerical data, and verbal explanations within a single learning space. Consequently, meaningful learning depends not only on immersive experiences but also on learners' ability to coordinate multiple representations into coherent conceptual understanding. The evidence therefore suggests that representational coherence should be regarded as a fundamental pedagogical affordance rather than merely a multimedia design feature (Su Cai et al., 2021; Georgiou et al., 2021; Munfaridah et al., 2021; Tsivitanidou et al., 2021).

A fourth cluster concerns theories addressing implementation and learner regulation. TPACK explains how teachers integrate technological, pedagogical, and disciplinary knowledge to orchestrate meaningful digital learning, whereas self-regulated learning emphasizes learners' capacity to control pacing, monitor understanding, revisit materials, and use feedback independently. Closely related perspectives, including cognitive conflict and problem-based learning, explain how digital environments facilitate conceptual change by confronting intuitive misconceptions through structured cycles of prediction, observation, explanation, and reflection. Collectively, these theories

demonstrate that the effectiveness of interactive digital learning depends not only on digital affordances but also on the pedagogical orchestration that enables learners to regulate, evaluate, and reconstruct their understanding (Anselmo et al., 2024; Hidayati et al., 2024; Mgeladze & Kapanadze, 2025; Mufit et al., 2024). Table 4 summarises the principal theoretical perspectives identified across the reviewed studies, together with the pedagogical affordances they explain, representative evidence, and their implications for the proposed framework.

Table 4. Analytical Evidence for Theoretical Foundations and Pedagogical Affordances

Theoretical foundation	Pedagogical affordance explained	Representative evidence	Implication for framework development
Cognitive theory of multimedia learning and cognitive load theory	Supporting selection, organization, integration, signaling, segmentation, cognitive load management, and meaningful processing of verbal and visual information	Mayer (2024), Girwidz and Kohnle (2021), Vidak et al. (2024), Anselmo et al. (2024)	The framework should explain how interactive digital learning supports physics understanding by managing cognitive processing and reducing unnecessary load
Constructivist learning and inquiry based learning	Supporting variable manipulation, prediction testing, observation, experimentation, evidence interpretation, and explanation building	Banda and Nzabahimana (2021), Y. Wang et al. (2025), Yusuf et al. (2024), Hidayati et al. (2024)	The framework should position interactivity as guided inquiry rather than unguided exploration
Experiential learning and embodied cognition	Supporting immersive, spatial, contextual, and experiential engagement with abstract or inaccessible physics phenomena	Cai et al. (2021), Georgiou et al. (2021), Tsivitanidou et al. (2021), Canright and White Brahmia (2024)	The framework should explain how immersion and embodiment become meaningful when connected to conceptual reasoning and reflection
Representational competence	Supporting coordination among equations, graphs, diagrams, animations, verbal explanations, numerical data, and physical meanings	Munfaridah et al. (2021), Marisda et al. (2025), Hidayati et al. (2024)	The framework should treat representational coherence as a core condition for meaningful digital physics learning
TPACK and collaborative learning	Supporting teacher competence, pedagogical orchestration, collaborative inquiry, and technology integration in physics instruction	Mgeladze and Kapanadze (2025), Rizki et al. (2024)	The framework should include teacher readiness and pedagogical integration as enabling conditions
Self regulated learning	Supporting flexible access, learner autonomy, pacing, monitoring, feedback use, and repeated engagement	Anselmo et al. (2024), Zatarain Cabada et al. (2023), Marisda et al. (2025)	The framework should explain how digital access and learner control support autonomous physics learning when guided by structure and feedback
Cognitive conflict and problem based learning	Supporting misconception confrontation, conceptual change, prediction, observation, explanation, and reflective reconstruction	Mufit et al. (2024), Hidayati et al. (2024), Rizki et al. (2024)	The framework should explain how digital environments can challenge intuitive reasoning and promote conceptual revision

The synthesis presented in Table 4 demonstrates that no single learning theory sufficiently explains interactive digital learning in physics education. Instead, the reviewed literature converges toward a complementary theoretical architecture in which cognitive theories explain information processing, constructivist and inquiry perspectives explain knowledge construction, experiential and representational theories explain interaction with complex physics phenomena, and implementation-oriented theories explain the pedagogical and contextual conditions required for successful integration. Taken together, these perspectives establish the second conceptual layer of the proposed framework by demonstrating that the educational value of interactive digital learning arises from the interaction between digital affordances and theoretically grounded learning mechanisms rather than from technological innovation alone.

Theme 3. Design Features for Meaningful Physics Learning

The synthesis suggests that the educational value of interactive digital learning is closely associated with both pedagogical design and technological affordances. Across simulations, virtual laboratories, augmented reality, virtual

reality, digital modules, and interactive flipbooks, recurring design features were linked to conceptual reasoning, inquiry, representational understanding, and cognitive engagement. Because the included studies differ in design and quality and no comparative meta-analysis was conducted, the review does not claim that pedagogy is statistically more important than technology. Instead, the evidence supports the more cautious proposition that technological sophistication alone is insufficient without coherent instructional design.

Among these features, representational coherence emerged as one of the most consistently reported design principles. Physics learning requires students to coordinate equations, graphs, diagrams, animations, numerical data, verbal explanations, and physical meaning. Although interactive digital environments can integrate these representations within a single learning space, learners do not automatically recognize the relationships among them. Consequently, effective instructional designs explicitly guide students to compare, translate, and integrate multiple representations through visual cues, explanatory prompts, embedded questions, and structured learning tasks. The reviewed evidence therefore suggests that representational coherence functions not merely as a multimedia characteristic but as a pedagogical mechanism that supports conceptual integration across different forms of representation (Hidayati et al., 2024; Marisda et al., 2024; Munfaridah et al., 2021).

A second group of recurring design features involves guided exploration, instructional scaffolding, and formative feedback. Interactive digital environments enable students to manipulate variables, investigate relationships, and observe immediate consequences of their actions. However, the synthesis suggests that unrestricted exploration rarely produces deep conceptual understanding. Instead, meaningful learning occurs when digital interaction is structured through guiding questions, prediction tasks, inquiry prompts, explanatory feedback, and opportunities for reflection. Studies involving PhET simulations, virtual laboratories, and digital Predict Observe Explain modules collectively demonstrate that scaffolding transforms digital manipulation into conceptual reasoning by helping learners connect observations with underlying scientific explanations (H J Banda & Nzabahimana, 2021; Herbert James Banda & Nzabahimana, 2023; Hidayati et al., 2024; C. Wang et al., 2021; Yusuf et al., 2024).

The synthesis further highlights the importance of conceptual conflict, reflective inquiry, and collaborative learning as mechanisms that promote higher order thinking. Many physics concepts challenge learners' intuitive beliefs, making conceptual reconstruction an essential component of instruction. Interactive digital environments support this process by encouraging students to compare predictions with empirical evidence, identify inconsistencies, discuss alternative explanations, and revise their understanding through structured reflection. Collaborative and problem oriented activities strengthen these processes by promoting argumentation, evidence evaluation, and shared meaning making. Consequently, digital interactivity becomes educationally valuable not because it increases activity, but because it organises productive cycles of prediction, observation, explanation, discussion, and conceptual revision (Hidayati et al., 2024; Mufit et al., 2024; Rizki et al., 2024).

Another recurring finding concerns the need for cognitive manageability and instructional alignment. Although highly interactive environments often increase learner engagement, they may also impose unnecessary cognitive demands when interfaces become visually complex, navigation is unclear, or learner control exceeds students' prior knowledge. These concerns are particularly evident in immersive environments such as augmented and virtual reality, where visual richness can simultaneously facilitate and hinder conceptual understanding. The reviewed studies commonly recommend instructional strategies including signaling, segmentation, progressive task sequencing, coherent interface design, and gradual release of learner control to maintain cognitive efficiency. Equally important, digital interaction should remain closely aligned with intended learning objectives, reasoning processes, inquiry activities, and assessment strategies so that technological engagement directly contributes to conceptual learning rather than becoming an end in itself (R Girwidz & Kohnle, 2022; Lai & Cheong, 2022; Marisda, Tolla, et al., 2025; R E Mayer, 2024; Vidak et al., 2024). Table 5 summarises the principal pedagogical design features identified across the reviewed studies, together with their educational functions, representative evidence, and implications for the proposed framework.

Table 5. Analytical Evidence for Design Features for Meaningful Physics Learning

Design feature	Pedagogical function	Representative evidence	Implication for framework development
Representational coherence	Helps students connect equations, graphs, diagrams, animations, text, numerical data, and physical meaning	Munfaridah et al. (2021), Hidayati et al. (2024), Marisda et al. (2025)	The framework should position representational coherence as a core condition for meaningful digital physics learning

Design feature	Pedagogical function	Representative evidence	Implication for framework development
Guided exploration	Turns digital manipulation into inquiry through prediction, observation, comparison, explanation, and revision	Banda and Nzabahimana (2021, 2023), Y. Wang et al. (2025), Yusuf et al. (2024)	The framework should clarify that interactivity requires guidance to support conceptual understanding
Feedback and scaffolding	Supports error recognition, conceptual progress, reflective thinking, and explanation building	Hidayati et al. (2024), Y. Wang et al. (2025), Yusuf et al. (2024)	The framework should treat feedback and scaffolding as proposed links between digital affordances and learner processes
Conceptual conflict and reflective prompting	Helps students confront misconceptions, compare predictions with evidence, and reconstruct understanding	Mufit et al. (2024), Hidayati et al. (2024)	The framework should explain how digital environments can support conceptual change through structured cognitive tension
Collaborative and problem oriented activity	Supports discussion, argumentation, evidence evaluation, problem solving, critical thinking, and shared meaning making	Rizki et al. (2024), Banda and Nzabahimana (2023)	The framework should include collaborative and problem based learning as pedagogical structures that activate digital affordances
Cognitive load management	Reduces unnecessary processing and supports attention to relevant physics concepts	Mayer (2024), Girwidz and Kohnle (2021), Lai and Cheong (2022), Vidak et al. (2024)	The framework should explain that digital learning must be cognitively manageable to become pedagogically effective
Alignment with learning objectives	Ensures that digital interaction supports targeted concepts, reasoning processes, outcomes, and assessments	Marisda et al. (2025), Hidayati et al. (2024), Yusuf et al. (2024)	The framework should connect technology use with instructional goals, learning tasks, and assessment alignment

The synthesis presented in Table 5 indicates that meaningful interactive digital learning is better interpreted as design-centred rather than technology-centred. Across diverse modalities, recurring pedagogical features included representational coherence, guided inquiry, scaffolding, formative feedback, conceptual conflict, collaborative reasoning, cognitive-load management, and constructive alignment. These features provide plausible links between digital affordances and learner activity, but the qualitative synthesis does not establish mediation in a causal-statistical sense. Accordingly, this theme forms the third conceptual layer of the proposed framework by identifying pedagogical design features that may connect digital opportunities with learner processes and subsequent outcomes.

Theme 4. Learner Processes and Learning Outcomes

The synthesis indicates that the educational value of interactive digital learning extends beyond improvements in academic performance to encompass the cognitive, affective, behavioral, practical, and higher-order processes through which students learn physics. Across the reviewed studies, conceptual understanding, academic achievement, motivation, and engagement were the most frequently reported outcomes. However, the evidence also highlights critical thinking, problem solving, scientific reasoning, self efficacy, practical competence, cognitive load regulation, epistemic development, conceptual change, and self regulated learning. Collectively, these findings suggest that interactive digital learning should be evaluated not only by measurable learning outcomes but also by the learner processes that generate those outcomes.

Across the included studies, conceptual exploration emerged as the central learning process underlying effective interactive digital learning. Interactive simulations and PhET environments allow students to manipulate variables, test predictions, observe dynamic relationships, and revise explanations through immediate visual feedback. These opportunities have been reported to support conceptual understanding and academic achievement when embedded within structured inquiry activities rather than unrestricted exploration. Meta analytical evidence further confirms that simulation based learning produces substantial educational benefits, although the magnitude of these effects varies according to educational level, instructional design, physics topic, and assessment domain (H J Banda & Nzabahimana, 2021; Fadillah et al., 2026; Hidayati et al., 2024).

A second recurring learner process involves self regulated and reflective learning. Mobile learning environments, digital modules, and interactive flipbooks provide flexible access, repeated engagement, learner controlled pacing, and structured multimedia resources that encourage students to monitor their understanding, revisit difficult concepts, and make productive use of feedback. Rather than functioning solely as repositories of instructional content, these digital

environments organize learning through sequential reasoning, reflection, and independent regulation. The reviewed evidence therefore suggests that learner autonomy becomes educationally meaningful when supported by structured guidance, feedback, and coherent learning pathways rather than unrestricted independence (Anselmo et al., 2024; Hidayati et al., 2024; Marisda et al., 2024; Zatarain-Cabada et al., 2023).

The synthesis also demonstrates that immersive and inquiry based experiences support distinctive forms of learning that are difficult to achieve through conventional instruction. Augmented reality and virtual reality strengthen spatial reasoning, embodied interaction, and experiential understanding by enabling learners to engage directly with abstract, microscopic, or inaccessible physics phenomena. Virtual laboratories similarly extend opportunities for experimental reasoning by allowing repeated experimentation, procedural practice, data interpretation, and inquiry in contexts where physical laboratory access is limited. These environments contribute not only to conceptual understanding but also to practical competence, scientific reasoning, self efficacy, and productive engagement with experimental physics (Su Cai et al., 2021; Canright & White Brahmia, 2024; Georgiou et al., 2021; Tsivitanidou et al., 2021; C. Wang et al., 2021; Yusuf et al., 2024).

Although higher order outcomes were reported less frequently than conceptual understanding and achievement, the reviewed literature suggests their growing importance. Critical thinking, problem solving, epistemic reasoning, conceptual change, and cognitive load regulation emerged when interactive digital environments incorporated guided inquiry, conceptual conflict, collaborative reasoning, and structured reflection. Nevertheless, considerable variation in theoretical perspectives, research designs, and measurement instruments limits direct comparison across studies. This inconsistency suggests that future research should move beyond documenting outcome improvements toward examining the mechanisms through which digital interaction promotes higher order thinking and durable conceptual change (Anselmo et al., 2024; Canright & White Brahmia, 2024; Mufit et al., 2024; Rizki et al., 2024). Table 6 summarises the principal learner processes and outcome domains identified across the reviewed studies, together with representative evidence and their implications for the proposed framework.

Table 6. Analytical Evidence for Learner Processes and Outcomes in Interactive Digital Physics Learning

Outcome domain	Associated learner processes	Representative evidence	Implication for framework development
Cognitive outcomes	Conceptual exploration, variable manipulation, prediction, observation, representational reasoning, and explanation building	Banda and Nzabahimana (2021, 2023), Fadillah et al. (2026), Hidayati et al. (2024), Marisda et al. (2025)	The framework should connect digital interaction with conceptual understanding, achievement, and representational learning
Affective outcomes	Motivation, engagement, self efficacy, learner perception, attitude formation, and productive participation	Cai et al. (2021), Tsivitanidou et al. (2021), Canright and White Brahmia (2024), Anselmo et al. (2024)	The framework should explain how interactive digital learning may be associated with students' motivation, confidence, and engagement with physics
Practical and inquiry outcomes	Experimental access, procedural reasoning, data interpretation, repeated experimentation, inquiry, and evidence based explanation	Y. Wang et al. (2025), Yusuf et al. (2024), Mustari et al. (2025)	The framework should include virtual experimentation as a pathway for supporting inquiry and practical reasoning
Higher order outcomes	Critical thinking, problem solving, scientific reasoning, epistemic development, conceptual change, and self regulation	Rizki et al. (2024), Mufit et al. (2024), Canright and White Brahmia (2024), Anselmo et al. (2024)	The framework should move beyond achievement and conceptual understanding toward mechanism based evaluation of higher order learning
Cognitive load related outcomes	Attention management, reduction of extraneous load, support for germane processing, and cognitive efficiency	Mayer (2024), Girwidz and Kohnle (2021), Vidak et al. (2024), Anselmo et al. (2024)	The framework should treat cognitive manageability as a condition that links digital design with meaningful learning
Self regulated learning outcomes	Flexible pacing, repeated access, monitoring of understanding, feedback use, and independent learning	Anselmo et al. (2024), Zatarain Cabada et al. (2023), Marisda et al. (2025)	The framework should explain how learner control and accessibility support autonomous learning when guided by structure and feedback

The synthesis presented in Table 6 demonstrates that learning outcomes are best understood as the consequence of interconnected learner processes rather than isolated instructional effects. Conceptual understanding, achievement, motivation, practical competence, and higher order thinking emerge through cycles of conceptual exploration,

representational reasoning, inquiry, feedback processing, self regulation, and reflective explanation. Accordingly, this theme establishes the fourth conceptual layer of the proposed framework by explaining how pedagogically designed digital affordances are translated into multidimensional learning outcomes through identifiable cognitive, affective, inquiry based, and self regulatory processes.

Theme 5. Challenges and Conditions for Effective Implementation

The synthesis demonstrates that the effectiveness of interactive digital learning is determined not only by the quality of digital technologies or pedagogical design but also by the conditions under which those innovations are implemented. Across the reviewed studies, successful implementation consistently depended on the interaction among cognitive, pedagogical, technological, institutional, and contextual factors. Rather than functioning as external constraints, these conditions shape whether digital affordances can be transformed into meaningful learning experiences within authentic physics classrooms.

A recurring implementation challenge concerns cognitive manageability. Although interactive environments increase opportunities for visualization, manipulation, and learner engagement, they may also generate excessive cognitive demands when interfaces become overly complex, visual information is excessive, navigation is unclear, or learner control is insufficiently structured. This challenge is particularly evident in augmented reality, virtual reality, and extended reality environments, where immersive experiences can simultaneously facilitate and hinder conceptual understanding. Across the reviewed studies, effective implementations consistently incorporated signaling, segmentation, coherent interface design, progressive task sequencing, and structured scaffolding to minimize extraneous cognitive load while maintaining meaningful engagement with physics concepts (Raimund Girwidz & Kohnle, 2021; Lai & Cheong, 2022; Richard E. Mayer, 2024; Vidak et al., 2024).

The review also highlights the importance of learner readiness, teacher competence, and pedagogical integration. Students benefit from interactive digital learning only when they possess sufficient digital literacy, technical confidence, and opportunities for sustained engagement. Likewise, teachers require technological pedagogical content knowledge to integrate digital tools with instructional goals, inquiry activities, classroom interaction, and assessment. The evidence suggests that digital technologies become educationally meaningful when teachers actively orchestrate learning through guidance, feedback, questioning, and collaborative discussion rather than relying on technology alone. Conversely, studies reporting less favorable outcomes commonly describe situations in which digital tools were implemented without adequate pedagogical support or learner (Anselmo et al., 2024; H J Banda & Nzabahimana, 2021; Mgeladze & Kapanadze, 2025; Ng & Chua, 2023; Rizal et al., 2025).

A further condition concerns contextual and institutional support. Virtual laboratories and other interactive environments substantially expand opportunities for experimentation where access to physical laboratory facilities is limited. However, sustainable implementation requires reliable technological infrastructure, curriculum alignment, technical support, professional development, and long-term institutional commitment. These factors influence whether interactive digital learning becomes an integrated component of physics education or remains an isolated technological innovation. The reviewed evidence therefore demonstrates that implementation should be understood as a systemic process involving interactions among technology, pedagogy, learners, teachers, curriculum, and institutional resources rather than as the simple adoption of digital tools (Mgeladze & Kapanadze, 2025; Mustari et al., 2025; C. Wang et al., 2021; Yusuf et al., 2024). Table 7 summarises the principal implementation conditions identified across the reviewed studies, together with representative evidence and their implications for the proposed framework.

Table 7. Analytical Evidence for Challenges and Conditions for Effective Implementation

Implementation condition	Main challenge or function	Representative evidence	Implication for framework development
Cognitive manageability	Prevents overload caused by complex interfaces, excessive visual information, and unguided learner control	Lai and Cheong (2022), Vidak et al. (2024), Mayer (2024), Girwidz and Kohnle (2021)	The framework should include cognitive load management as a condition for effective digital learning
Student readiness and access	Shapes whether learners can use digital tools confidently and consistently	Anselmo et al. (2024), Rizal et al. (2025)	The framework should recognize access, usability, and technical skills as enabling conditions
Teacher readiness and TPACK	Supports meaningful integration of technology, pedagogy, and physics content	Mgeladze and Kapanadze (2025), Rizki et al. (2024)	The framework should position teacher competence as a key implementation factor

Implementation condition	Main challenge or function	Representative evidence	Implication for framework development
Pedagogical integration	Ensures that digital tools are connected to objectives, inquiry tasks, feedback, and assessment	Banda and Nzabahimana (2023), Ng and Chua (2023), Hidayati et al. (2024)	The framework should explain that technology requires instructional structure to support learning benefits
Laboratory access and contextual needs	Expands opportunities for experimentation where physical laboratory resources are limited	Y. Wang et al. (2025), Yusuf et al. (2024), Mustari et al. (2025)	The framework should treat virtual experimentation as a contextual response to access and resource limitations
Institutional support	Sustains implementation through infrastructure, technical assistance, professional development, and curriculum alignment	Y. Wang et al. (2025), Mgeladze and Kapanadze (2025), Mustari et al. (2025)	The framework should include institutional readiness as a condition for sustainable digital physics learning

The synthesis presented in [Table 7](#) demonstrates that implementation conditions constitute an integral component of interactive digital learning rather than a set of external limitations. Cognitive manageability, learner readiness, teacher competence, pedagogical integration, technological accessibility, curriculum alignment, and institutional support collectively can shape whether digital affordances, theoretically informed design, and learner processes can generate meaningful educational outcomes. Accordingly, this theme establishes the fifth conceptual layer of the proposed framework by positioning implementation conditions as enabling mechanisms that sustain effective, scalable, and context responsive digital physics learning.

Synthesis toward a Theory-Informed Framework for Interactive Digital Learning in Physics Education

The thematic synthesis demonstrates that interactive digital learning in physics education cannot be adequately explained by technological innovation alone. Across the reviewed studies, digital technologies consistently function as educational tools whose effectiveness depends on interactions among technological affordances, theoretically informed pedagogical design, learner engagement, and contextual implementation. Although previous studies have reported positive effects of individual technologies such as interactive simulations, virtual laboratories, augmented reality, virtual reality, mobile learning, and digital modules, the evidence remains fragmented because these technologies are frequently investigated as independent interventions rather than as interconnected components of a broader learning system. The synthesis presented in this review therefore moves beyond technology specific findings by integrating empirical evidence into a coherent theoretical framework that explains how interactive digital learning supports meaningful physics learning across diverse instructional contexts.

The proposed framework organizes the synthesis into five interdependent conceptual components that correspond to the five themes and Figure 2: (1) digital affordances, (2) theoretical foundations, (3) pedagogical design features, (4) learner processes and learning outcomes, and (5) implementation conditions. The relationships among these components are proposed conceptual links derived from thematic-abductive synthesis and should not be interpreted as empirically established causal pathways.

The first component comprises digital affordances, including visualization, interactivity, experimentation, simulation, immediate feedback, learner control, multimodal representation, and flexible accessibility. These affordances create opportunities for learners to engage with abstract or inaccessible physics phenomena, but they do not imply learning effects by themselves. Their educational significance depends on how they are interpreted through theory, incorporated into pedagogical design, and enacted in particular learning contexts.

The second component comprises theoretical foundations. CTML and Cognitive Load Theory provide lenses for interpreting multimedia processing and cognitive manageability; constructivist, inquiry-based, problem-based, and experiential perspectives address active knowledge construction; representational competence addresses physics-specific coordination of representations; self-regulated learning addresses learner monitoring and control; and TPACK addresses teacher-level integration of technology, pedagogy, and physics content. These theories operate at different analytical levels and are used to interpret, rather than causally prove, patterns in the evidence base.

The third component comprises pedagogical design features, including representational coherence, guided inquiry, scaffolding, formative feedback, conceptual conflict, collaborative reasoning, cognitive-load management, and alignment among objectives, activities, and assessment. The synthesis suggests that these features are plausible links through which digital affordances can be organized into meaningful instructional experiences. Because most included studies do not test mediation directly, these relationships are framed as theory-informed propositions for future empirical examination.

The fourth component integrates learner processes and learning outcomes. Reported learner processes include conceptual exploration, representational reasoning, prediction, experimentation, reflection, self-regulation, collaborative discussion, and evidence-based explanation. Reported outcomes include conceptual understanding, academic achievement, motivation, engagement, practical competence, scientific reasoning, critical thinking, problem solving, conceptual change, self-efficacy, and cognitive-load-related outcomes. Combining processes and outcomes in one component maintains consistency with Figure 2 while retaining their analytical distinction.

The fifth component consists of implementation conditions, including cognitive manageability, learner readiness, teacher competence, pedagogical integration, technological accessibility, curriculum alignment, and institutional support. These conditions may enable, constrain, or modify how digital affordances and pedagogical designs are enacted. Figure 2 therefore represents reciprocal and context-sensitive conceptual relationships rather than a linear causal sequence; empirical testing is required to determine whether, when, and to what extent the proposed relationships hold across physics topics, educational levels, and digital modalities.

Taken together, this synthesis contributes a theory-informed conceptual framework that extends beyond technology-centred classifications. Rather than claiming to identify a universally superior technology or a proven causal mechanism, the framework organizes recurring evidence into a common cross-modality structure and advances testable propositions about how digital affordances, theory, pedagogical design, learner activity and outcomes, and implementation conditions may relate in interactive physics learning.

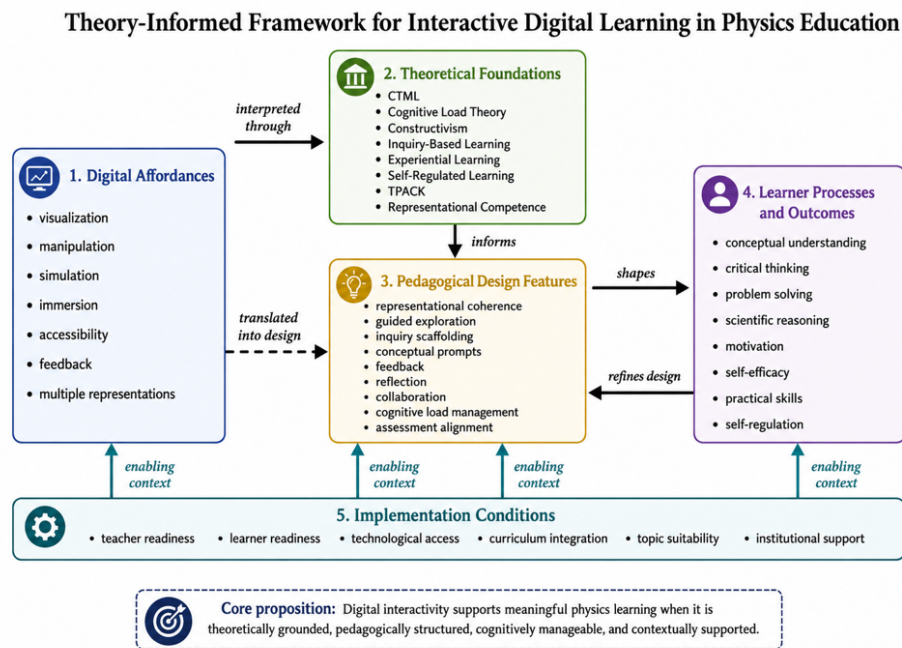


Figure 2. Theory-Informed Framework for Interactive Digital Learning in Physics Education.

DISCUSSION

The present review supports interpreting interactive digital learning in physics education as a pedagogically orchestrated learning system rather than as a collection of educational technologies. Positive outcomes have been reported for simulations, virtual laboratories, augmented reality, virtual reality, mobile learning, and digital modules, but heterogeneity in study designs, contexts, outcomes, and methodological quality prevents a simple comparative ranking of technologies or mechanisms. The most defensible synthesis-level interpretation is therefore conditional: digital affordances create educational opportunities whose value is associated with theoretically informed design, learner engagement, and implementation context.

This interpretation represents a conceptual shift from treating digital technologies as independent instructional interventions toward examining shared pedagogical functions across modalities. The evidence directly supports the recurrence of affordances such as visualization, variable manipulation, feedback, experimentation, and multiple representations across different environments. The further proposition that these affordances become educationally

meaningful through theory-informed design is an interpretation of the synthesis rather than a statistically demonstrated comparative effect.

The proposed framework also brings multiple theoretical perspectives into a single structure, but their integration requires explicit functional boundaries. CTML and Cognitive Load Theory operate primarily at the level of information processing and cognitive manageability; constructivist, inquiry-based, problem-based, and experiential perspectives address learner activity and knowledge construction; representational competence addresses physics-specific coordination of equations, graphs, diagrams, simulations, and verbal explanations; self-regulated learning addresses learner monitoring and control; and TPACK addresses teacher-level integration of technology, pedagogy, and disciplinary content.

These perspectives therefore should not be treated as interchangeable or cumulatively causal. Their value in the framework lies in explaining different analytical levels and boundary conditions. Overlap is possible—for example, guided inquiry may simultaneously influence cognitive processing, representational coordination, and self-regulation, but the review does not assume that combining more theories necessarily produces stronger learning. Instead, theory selection should be matched to the instructional problem, learner process, and implementation level being examined.

The review extends previous evidence syntheses by addressing the conceptual fragmentation that characterizes research on interactive digital learning in physics education. Technology-specific reviews have generated important findings about simulations, virtual laboratories, augmented reality, virtual reality, mobile learning, and extended reality. This review does not replace those syntheses; it reorganizes their recurring pedagogical insights together with primary-study evidence into a cross-modality framework that distinguishes digital opportunities, theoretical explanations, design features, learner processes and outcomes, and implementation conditions.

Across modalities, recurring pedagogical features include representational coherence, guided inquiry, scaffolding, formative feedback, reflective prompting, conceptual conflict, collaborative reasoning, cognitive manageability, and alignment with learning goals. Their recurrence supports the interpretation that technically different environments can offer comparable pedagogical functions. However, because the review did not conduct comparative meta-analysis and because study quality varies, statements about relative strength or superiority are not warranted. These features are therefore treated as recurring evidence patterns and candidate mechanisms rather than quantified determinants of effectiveness.

The synthesis also reveals negative and context-dependent findings that qualify positive interpretations. Complex interfaces and immersive environments can increase extraneous cognitive demands; unrestricted exploration may fail to generate deep conceptual understanding; students differ in digital access, readiness, and self-regulatory capacity; teachers may lack the pedagogical knowledge required to integrate technology with inquiry and assessment; and institutional infrastructure can constrain sustainable implementation. Such divergent evidence helps explain why similar technologies may yield different outcomes across contexts and supports the inclusion of implementation conditions as an integral part of the framework.

Accordingly, the framework shifts future research from asking only whether a particular technology works toward testing which affordances and design features are associated with particular learner processes and outcomes, for whom, and under what implementation conditions. Importantly, the arrows in Figure 2 should be read as proposed relationships generated through thematic-abductive synthesis. Longitudinal, experimental, quasi-experimental, and structural-modeling studies are needed before mediation, moderation, or causal language can be justified.

For instructional design, the synthesis suggests prioritizing pedagogical coherence alongside technological capability. Because no comparative meta-analysis was performed, the review does not conclude that pedagogical design is statistically more influential than technological sophistication. Instead, the evidence indicates that advanced technology alone does not guarantee learning benefits and that technology selection should be aligned with conceptual reasoning, inquiry, representational coordination, feedback, and meaningful learner interaction.

A second implication concerns theory use in design. Rather than combining theories indiscriminately, designers can select theoretical perspectives according to the instructional problem and level of analysis. Multimedia and cognitive-load principles can guide information presentation; inquiry, constructivist, problem-based, and experiential perspectives can structure learning activity; representational competence can guide coordination of physics representations; self-regulated learning can inform learner control and feedback; and TPACK can guide teacher-level integration. This role differentiation reduces the risk of theoretical eclecticism while preserving the integrative character of the framework.

The review further highlights the continuing role of teachers in orchestrating interactive digital learning. Digital environments may provide feedback, learner control, and adaptive support, but classroom implementation still depends on guidance, questioning, reflection, discussion, curriculum alignment, and assessment. Professional development

should therefore extend beyond technical proficiency to include the pedagogical use of digital affordances within disciplinary physics teaching.

For curriculum development, the framework offers a structured way to align digital affordances, theoretical rationale, pedagogical design, learner processes and outcomes, and implementation conditions. Such alignment can guide the design of digital teaching materials, virtual laboratories, interactive modules, and blended learning environments while allowing adaptation to educational level, physics topic, learner characteristics, available infrastructure, and institutional priorities.

Several limitations qualify the interpretation of this review. The included literature is heterogeneous in educational level, physics topic, research design, sample characteristics, theoretical explicitness, outcome measures, and methodological quality. English-language and accessible-full-text eligibility may introduce language and access bias. Google Scholar was limited to the first 200 relevance-ranked results, and searches conducted through publisher platforms are less reproducible than searches in bibliographic databases. Secondary reviews were used only for contextual mapping and theoretical interpretation to reduce double counting, but overlap with primary evidence remains a potential concern. The protocol was not prospectively registered, and the original submission did not provide a complete study-level characteristics and appraisal table, limiting independent auditability. Finally, the relationships depicted in the framework were generated through thematic-abductive synthesis and have not yet been empirically validated.

CONCLUSION

This systematic literature review synthesizes interactive digital learning in physics education as a system comprising five consistently organized dimensions: digital affordances, theoretical foundations, pedagogical design features, learner processes and learning outcomes, and implementation conditions. Across heterogeneous digital modalities, recurring evidence highlights the importance of representational coherence, guided inquiry, scaffolding, feedback, reflection, cognitive manageability, and alignment with instructional goals. These patterns indicate that the educational value of digital technologies is context- and design-dependent rather than a direct consequence of technological sophistication.

The principal contribution of the review is a proposed theory-informed conceptual framework that organizes these dimensions and their possible relationships within a common cross-modality structure. The framework should be interpreted as a set of theoretically grounded propositions, not as a validated causal model. Its interpretation is limited by heterogeneity across studies, English-language and full-text restrictions, search-source reproducibility constraints, the absence of prospective protocol registration, and incomplete study-level appraisal reporting in the original submission. Future research should empirically test the proposed relationships across physics domains, educational levels, and cultural contexts; examine contradictory and boundary conditions; and develop measures capable of distinguishing learner processes from learning outcomes. Such work can refine the framework and establish the extent to which its proposed relationships are supported empirically.

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DM contributed to the conceptualization of the study, development of the methodology, investigation process, formal data analysis, data curation, visualization, and preparation of the original manuscript draft. AS was involved in the investigation and validation processes and contributed to reviewing and editing the manuscript. MW contributed to data curation, formal analysis, visualization, and manuscript review and editing. RR was responsible for validation and supervision and also participated in reviewing and editing the manuscript. AR contributed to the validation process and manuscript review and editing. NH provided supervision, managed project administration, and contributed to reviewing and editing the manuscript. All authors read and approved the final version of the manuscript.

AI DISCLOSURE STATEMENT

The authors used ChatGPT (OpenAI) during the preparation of this manuscript to assist with language refinement, improving clarity and coherence, strengthening the academic structure, and enhancing the presentation of the manuscript. All conceptualization, review protocol development, literature search strategy, study selection, quality appraisal, evidence synthesis, interpretation of findings, development of the theory-informed explanatory framework, and final editorial decisions were conducted, critically evaluated, and approved by the authors. All AI-assisted content was thoroughly reviewed, revised, and verified for accuracy, originality, and scholarly integrity. The authors accept full responsibility for the content of this publication.

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