Design Thinking–Based Stem Instruction Through a Neuroeducational Framework: A Prisma-Based Review

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Abstract*—As secondary education increasingly pivots toward interdisciplinary and process-oriented learning, Design Thinking (DT) has emerged as a transformative pedagogical catalyst for STEM reform. This systematic literature review critically examines and synthesizes contemporary empirical research on DT-based STEM instruction, with a specific emphasis on integrating cognitive, affective, and neuroeducational perspectives. Following a rigorous selection process, 21 peer-reviewed studies published between 2022 and 2025 were analysed and categorized into seven thematic dimensions: effectiveness in STEM, learning outcomes and skills, subject domain trends, pedagogical approaches, neuroeducational gaps, moderating variables, and methodological status. The findings reveal that the EDIPT (Empathize, Define, Ideate, Prototype, Test) model remains the dominant instructional framework, demonstrating significant efficacy in secondary-level biology and physics for enhancing conceptual mastery, scientific reasoning, and intrinsic motivation. Students engaged in DT-driven environments consistently report heightened STEM self-efficacy and a resilient "fail-forward" mindset, which effectively lowers psychological barriers to complex problem-solving. Despite these pedagogical successes, the synthesis identifies a significant "neuroeducational paradox": while the iterative nature of DT aligns theoretically with known principles of neural plasticity and executive function, empirical evidence is predominantly limited to conventional achievement-focused measures. A critical "black box" remains regarding the internal cognitive and neural infrastructure of the learner, with a notable scarcity of direct neuro-physiological measurements such as EEG or eye-tracking data to validate claims of cognitive development. Furthermore, the review highlights the underrepresentation of critical moderating variables, specifically metacognition and cognitive load, which significantly influence student performance during high-demand prototyping and testing phases. The implications of these findings suggest a necessary shift from traditional instructional designs toward "brain-informed" design-based learning environments. Sustainable integration of DT in secondary STEM requires systemic reform in assessment practices prioritizing the design process over the final scientific product and the implementation of teacher professional development programs grounded in Mind, Brain, and Education (MBE) science. By consolidating fragmented evidence, this review provides a robust foundation for future research to bridge the gap between design-based pedagogy and the neural dynamics of the learning mind, ultimately preparing students for the cognitive and creative complexities of the 21st-century scientific landscape.

Index Terms*—Design Thinking (DT), STEM Instruction, Neuroeducation, Secondary Education, Systematic Review, EDIPT Framework, Cognitive Load, Metacognition, Mind, Brain, and Education (MBE).

I. INTRODUCTION

In recent decades, education systems worldwide have increasingly emphasized pedagogical approaches that promote creativity, problem-solving, and learner agency in response to complex social, technological, and scientific challenges (OECD, 2018). Within this paradigm shift, Design Thinking (DT) has emerged as a prominent instructional approach that foregrounds human-centred problem solving, iterative inquiry, and innovation-driven learning experiences (Brown, 2009). Originally conceptualized within design and engineering domains, Design Thinking was introduced as a systematic approach to addressing ill-structured problems through empathy, ideation, prototyping, and testing (Simon, 1969). Over time, DT has been adapted for educational contexts, where it is increasingly recognized as a pedagogical framework capable of fostering higher-order thinking, creativity, and authentic learning engagement (Razzouk & Shute, 2012).

Educational scholars argue that DT aligns strongly with constructivist learning theories, as it positions learners as active constructors of knowledge rather than passive recipients of information (Vygotsky, 1978; Bruner, 1996). The instructional relevance of Design Thinking lies in its emphasis on inquiry, collaboration, and iterative refinement, which mirrors the cognitive processes involved in meaningful learning (Kolb, 1984). By engaging learners in cycles of problem identification, solution generation, and evaluation, DT facilitates deep conceptual understanding and supports transfer of learning to real-world contexts (Henriksen, Richardson, & Mehta, 2017).

Research evidence suggests that DT-based learning environments enhance students' ability to reason analytically, think creatively, and apply disciplinary knowledge to complex problems (Luka, 2014; Scheer, Noweski, & Meinel, 2012). As a result, Design Thinking has gained increasing attention across school education, higher education, and teacher preparation programs (Kwek, 2011).

Concurrently, the rise of STEM-integrated pedagogy has significantly reshaped contemporary educational discourse, particularly in science and technology education (Bybee, 2013). STEM education advocates the integration of Science, Technology, Engineering, and Mathematics to promote interdisciplinary learning and real-world problem solving (National Research Council, 2014).Rather than treating these disciplines as isolated domains, STEM-integrated instruction emphasizes the application of scientific knowledge through technological tools, engineering design, and mathematical reasoning (Breiner et al., 2012).This integrated approach has been shown to enhance students' conceptual understanding, scientific reasoning, and problem-solving skills while fostering motivation and engagement (Honey, Pearson, & Schweingruber, 2014).Importantly, engineering design and modelling processes within STEM naturally align with Design Thinking principles, making DT a pedagogically compatible framework for STEM instruction (Dym et al., 2005).

Recent educational reforms and policy documents further underscore the importance of innovative, integrated pedagogies such as STEM and Design Thinking to develop 21st-century competencies (OECD, 2019). At the school level, particularly in secondary education, STEM-integrated Design Thinking has been increasingly employed to make abstract scientific concepts tangible through modelling, experimentation, and prototyping activities (English & King, 2019).

Empirical studies indicate that DT-STEM instruction supports learners in visualizing complex systems, testing hypotheses, and refining conceptual models, thereby strengthening science learning outcomes (Kelley & Knowles, 2016). Despite growing adoption, DT-STEM research remains predominantly focused on observable academic outcomes such as achievement scores, creativity, and problem-solving performance (Li, Froyd, & Wang, 2019).

In parallel with pedagogical innovation, there has been a growing interest in brain-based and neuroeducational perspectives that seek to align teaching practices with how the brain learns (Tokuhama-Espinosa, 2011). Neuroeducation, grounded in Mind–Brain–Education (MBE) science, integrates insights from neuroscience, cognitive psychology, and educational research to inform instructional design (OECD, 2007). This interdisciplinary field emphasizes that effective learning involves the dynamic interaction of cognition, emotion, attention, and metacognition (Immordino-Yang & Damasio, 2007). Neuroeducational research highlights the role of motivation, emotional engagement, and meaningful context in enhancing memory encoding and long-term retention (Sousa, 2017). From this perspective, learning environments that promote curiosity, collaboration, and active problem solving are more likely to support durable learning (Tokuhama-Espinosa, 2018). Design Thinking–based STEM instruction inherently embodies many principles advocated by neuroeducation, including active engagement, emotional relevance, social interaction, and iterative reflection (Zhang, 2020). Hands-on prototyping and collaborative ideation stimulate cognitive processing and executive functions, while real-world problem contexts enhance emotional relevance and learner motivation (Immordino-Yang, Darling-Hammond, & Krone, 2019). However, despite conceptual alignment, existing DT-STEM research rarely operationalizes neuroeducational constructs such as attention regulation, cognitive load, or metacognitive awareness (Mayer, 2020). As a result, there remains limited systematic understanding of how DT-based STEM instruction engages learners cognitively and affectively from a neuroeducational standpoint (Howard-Jones, 2014). This growing intersection between Design Thinking, STEM integration, and neuroeducation therefore warrants comprehensive synthesis to advance theory, research, and practice in contemporary education.

II. RATIONALE FOR THE REVIEW

Despite the growing body of literature on Design Thinking–based STEM instruction, existing research has largely concentrated on observable learning outcomes such as academic achievement, creativity, problem-solving ability, and skill acquisition. While these outcome-oriented studies provide valuable evidence regarding the effectiveness of DT-STEM pedagogy, they often prioritise performance indicators over the underlying learning processes that lead to such outcomes. Consequently, the cognitive and affective mechanisms through which Design Thinking influences learning remain insufficiently explored. Most empirical investigations assess end-point results without systematically examining how learners engage mentally and emotionally during DT-STEM activities, thereby limiting a deeper understanding of how and why such pedagogical approaches are effective across diverse learning contexts.

Furthermore, the limited attention to neuroeducational dimensions such as cognition, emotion, attention, and metacognition has resulted in a fragmented and incomplete knowledge base. Although neuroeducation and Mind–Brain–Education research emphasizes the critical role of brain-compatible learning processes, these perspectives are rarely synthesized within DT-STEM scholarship. Existing studies are dispersed across disciplines, educational levels, and methodological traditions, making it difficult to derive coherent conclusions or theoretical integration. The absence of a comprehensive synthesis that systematically examines DT-STEM instruction through a neuroeducational lens restricts the advancement of evidence-informed pedagogy and theory building. Therefore, a systematic literature review that integrates Design Thinking, STEM education, and neuroeducational perspectives is both timely and necessary to consolidate existing evidence, identify research gaps, and guide future empirical and pedagogical developments.

III. PURPOSE, OBJECTIVES, AND REVIEW QUESTIONS

The purpose of the present systematic literature review is to critically examine and synthesize empirical research on Design Thinking–based STEM instruction within educational contexts, with particular emphasis on learning processes and outcomes viewed through a neuroeducational framework. While existing studies have demonstrated the effectiveness of Design Thinking–integrated STEM pedagogy in improving academic and skill-based outcomes, a comprehensive synthesis that integrates cognitive, affective, and neuroeducational perspectives remains limited. This review therefore seeks to consolidate fragmented evidence across disciplines and educational levels to advance theoretical understanding and inform pedagogical practice.

Specifically, the objectives of this review are threefold. First, it aims to systematically review empirical studies that have implemented Design Thinking as an instructional approach within STEM education. Second, it seeks to analyze reported learning outcomes by foregrounding neuroeducational dimensions such as cognition, emotion, attention, and metacognition, thereby extending analysis beyond conventional achievement-focused measures. Third, the review endeavours to identify conceptual, methodological, and measurement gaps in existing DT-STEM research, particularly those related to the underrepresentation of brain-based learning constructs and moderating variables.

Guided by these purposes and objectives, the review addresses the following research questions:

- How is Design Thinking conceptualized and integrated within STEM instructional practices across different educational contexts?
- What cognitive, affective, and neuroeducational learning outcomes are reported in studies employing Design Thinking–based STEM instruction?

- What methodological patterns, strengths, and gaps characterize the existing body of DT-STEM research?

Together, these objectives and research questions provide a structured foundation for systematically examining the scope, depth, and limitations of Design Thinking–based STEM instruction through a neuroeducational lens, thereby contributing to both research and practice in contemporary education.

IV. CONCEPTUAL AND THEORETICAL FRAMEWORK

The present review is grounded in an integrated conceptual and theoretical framework that synthesizes Design Thinking as an educational approach, STEM-integrated instruction, and neuroeducational principles to explain how learning occurs in Design Thinking–based STEM environments (Brown, 2009; Bybee, 2013; Tokuhama-Espinosa, 2011). This framework recognizes learning as an active, interdisciplinary, and brain-mediated process involving cognition, emotion, and metacognition (OECD, 2007; Immordino-Yang & Damasio, 2007). The following sections elaborate the theoretical foundations underpinning this review.

DESIGN THINKING AS AN EDUCATIONAL FRAMEWORK

Design Thinking originated within professional design and engineering practices as a systematic approach for addressing complex, ill-structured problems through human-centred and creative processes (Simon, 1969; Cross, 2011). Initially conceptualized as a method for innovation in design contexts, Design Thinking was later popularized through industry and academic institutions such as IDEO and the Stanford d.school, which emphasized empathy, ideation, and prototyping as central components of problem solving (Brown, 2009; IDEO, 2015). Over time, educators began to recognize its pedagogical potential, leading to its adaptation as an instructional framework across school and higher education contexts (Razzouk & Shute, 2012).

As an educational approach, Design Thinking is commonly operationalized through five iterative phases: Empathize, Define, Ideate, Prototype, and Test (Brown, 2009; IDEO, 2015). These phases guide learners to understand real-world problems, frame meaningful problem statements, generate multiple solution pathways, construct tangible representations of ideas, and evaluate outcomes through feedback and refinement. Unlike linear instructional models, Design Thinking emphasizes iteration, reflection, and learner agency, which aligns closely with constructivist and experiential learning theories (Kolb, 1984; Vygotsky, 1978).

In classroom contexts, Design Thinking supports inquiry-based learning by encouraging students to ask questions, explore multiple perspectives, and engage in evidence-based reasoning (Henriksen, Richardson, & Mehta, 2017). The ideation and prototyping phases foster creativity and divergent thinking, while testing and iteration promote critical thinking and problem-solving skills (Luka, 2014; Scheer, Noweski, & Meinel, 2012). Consequently, Design Thinking has been increasingly recognized as a pedagogical framework capable of enhancing conceptual understanding and meaningful learning in science and STEM education (Kwek, 2011).

STEM INTEGRATION IN INSTRUCTION

STEM integration represents a pedagogical approach that purposefully combines Science, Technology, Engineering, and Mathematics to address real-world problems through interdisciplinary learning experiences (Bybee, 2013; National Research Council, 2014). Rather than teaching these disciplines in isolation, STEM-integrated instruction emphasizes their interconnectedness and complementary roles in problem solving and innovation (Breiner et al., 2012). This interdisciplinary orientation enables learners to apply scientific knowledge using technological tools, engineering design processes, and mathematical reasoning, thereby supporting holistic understanding and transfer of learning (Honey, Pearson, & Schweingruber, 2014).

Engineering design and modelling serve as central components of STEM instruction, providing learners with opportunities to plan, construct, test, and refine solutions to authentic problems (Dym et al., 2005). Modelling allows abstract scientific concepts to be visualized and externalized, reducing cognitive complexity and supporting conceptual clarity (English & King, 2019). Through iterative design cycles, learners engage in experimentation, data interpretation, and evidence-based decision making, mirroring authentic scientific and engineering practices (Kelley & Knowles, 2016).

Design Thinking aligns naturally with STEM instruction due to its shared emphasis on problem identification, solution generation, prototyping, and testing (Razzouk & Shute, 2012). While STEM provides the disciplinary knowledge and technical tools required for problem solving, Design Thinking offers a structured cognitive and pedagogical process that guides learners through creative and systematic inquiry (Dym et al., 2005). In this sense, Design Thinking addresses the process of problem solving, whereas STEM supplies the content and tools, making their integration pedagogically complementary and effective (English, 2016).

NEUROEDUCATIONAL FRAMEWORK

The neuroeducational framework informing this review is grounded in the Mind–Brain–Education (MBE) perspective, which integrates insights from neuroscience, cognitive psychology, and educational research (OECD, 2007; Tokuhama-Espinosa, 2011). MBE emphasizes that effective learning occurs when instructional practices are aligned with how the brain processes information, emotions, and experiences (Howard-Jones, 2014). From this perspective, learning is viewed as a dynamic process involving multiple interacting neural systems rather than a purely cognitive activity.

Cognitive processes such as attention, working memory, and reasoning are fundamental to learning and comprehension (Baddeley, 2012; Sweller, 1988). Attention determines which information is processed, working memory governs the amount of information that can be handled at a given time, and reasoning supports analysis, inference, and conceptual understanding (Mayer, 2020). Instructional strategies that scaffold complexity, employ visual representations, and promote active engagement can optimize these cognitive processes and enhance learning outcomes (Sweller, Ayres, & Kalyuga, 2011).

Neuroeducation also underscores the role of motivation, emotion, and engagement in shaping learning experiences (Immordino-Yang & Damasio, 2007). Emotional relevance and curiosity enhance attention and memory encoding, while positive emotional states increase persistence and willingness to engage with challenging tasks (Sousa, 2017). Learning environments that are meaningful, supportive, and socially interactive are therefore more likely to promote deep and sustained learning (Immordino-Yang, Darling-Hammond, & Krone, 2019).

Metacognition and self-regulation involve learners' awareness of their own thinking processes and their ability to plan, monitor, and evaluate learning strategies (Flavell, 1979). These processes enable learners to reflect on understanding, identify misconceptions, and adapt strategies accordingly (Zimmerman, 2002). Instructional approaches that encourage reflection, feedback, and iterative improvement are particularly effective in strengthening metacognitive skills and fostering autonomous learning (Pintrich, 2004).

INTEGRATED DESIGN THINKING–STEM–NEUROEDUCATION LENS

An integrated Design Thinking–STEM–Neuroeducation lens provides a comprehensive framework for analyzing learning in Design Thinking–based STEM instruction. Each phase of the Design Thinking cycle engages specific cognitive and affective processes: empathizing activates emotional engagement and perspective-taking; defining and ideating require focused attention, reasoning, and working memory; prototyping externalizes thinking and supports cognitive offloading; and testing promotes reflection, feedback processing, and metacognitive regulation (Brown, 2009; Mayer, 2020). When embedded within STEM instruction, these processes are further enriched by disciplinary knowledge and engineering design practices (Kelley & Knowles, 2016).

The justification for analyzing Design Thinking–based STEM instruction through a neuroeducational lens lies in its potential to illuminate not only what learning outcomes are achieved but also how learning occurs (Tokuhama-Espinosa, 2018). While many studies report gains in achievement and skills, fewer examine the underlying cognitive, affective, and metacognitive mechanisms that contribute to these outcomes (Howard-Jones, 2014). A neuroeducational perspective enables deeper interpretation of learner engagement, mental effort, emotional involvement, and self-regulation during DT-STEM activities. Consequently, this integrated framework offers a theoretically grounded basis for understanding the effectiveness of Design Thinking–based STEM instruction and for identifying gaps in existing research.

V. METHODOLOGY

The present study adopted a Systematic Literature Review (SLR) methodology to synthesize empirical research on Design Thinking–based STEM instruction through a neuroeducational framework. The review process was conducted in strict accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, methodological rigor, and reproducibility. The methodology comprised seven sequential stages, as detailed below.

STUDY DESIGN

The study employed a systematic literature review design, which is appropriate for comprehensively identifying, evaluating, and synthesizing existing research evidence on a clearly defined topic. An SLR enables structured comparison of findings across studies and supports identification of research trends, gaps, and methodological patterns. The review followed the PRISMA 2020 framework, encompassing identification, screening, eligibility assessment, and final inclusion of studies.

SEARCH STRATEGY

A comprehensive and systematic search strategy was developed to retrieve relevant peer-reviewed literature. Multiple electronic databases were searched to ensure broad coverage of education, STEM, and neuroeducational research. The core databases included Scopus, Web of Science, ERIC, PubMed, ScienceDirect, and Google Scholar, while additional sources such as ProQuest Dissertations & Theses and Shodhganga were consulted to capture relevant doctoral research.

Search strings were constructed using combinations of keywords and Boolean operators, such as:

“Design Thinking” AND “STEM education”
“Design Thinking–based instruction” AND science,
“Design Thinking” AND neuroeducation,
“Brain-based learning” AND STEM.

Truncation and synonym variants were applied to enhance retrieval sensitivity. The search was limited to studies published in English within a defined time frame (e.g., 2013–2025) to ensure relevance to contemporary pedagogical and neuroeducational developments.

INCLUSION AND EXCLUSION CRITERIA

Clear inclusion and exclusion criteria were established prior to screening to minimize selection bias.

INCLUSION CRITERIA WERE:

- Empirical studies (experimental, quasi-experimental, qualitative, mixed-methods, or systematic reviews)
- Studies conducted in school or higher education contexts
- Interventions explicitly involving Design Thinking integrated with STEM or science instruction
- Studies reporting learning outcomes related to cognitive, affective, behavioural, or neuroeducational dimensions

EXCLUSION CRITERIA INCLUDED:

- Conceptual or opinion papers without empirical data
- Studies focusing solely on design or engineering without educational implementation
- Research unrelated to STEM or science education
- Non-English publications and inaccessible full texts

STUDY SELECTION PROCESS

The study selection process followed the four stages outlined in the PRISMA 2020 framework, namely identification, screening, eligibility, and inclusion. During the identification stage, a total of 465 records were retrieved through systematic searches of electronic databases and additional sources. Of these, 412 records were identified from major scholarly databases, including Scopus, Web of Science, ERIC, PubMed, and ScienceDirect, while 53 records were obtained from other sources such as Google Scholar, dissertations, and reference list searches.

Following identification, duplicate records were removed, resulting in 347 unique records for further screening. In the screening stage, titles, and abstracts of these 347 records were reviewed against the predefined inclusion and exclusion criteria. As a result, 241 records were excluded due to irrelevance to Design Thinking–based STEM instruction, lack of empirical data, or absence of educational context.

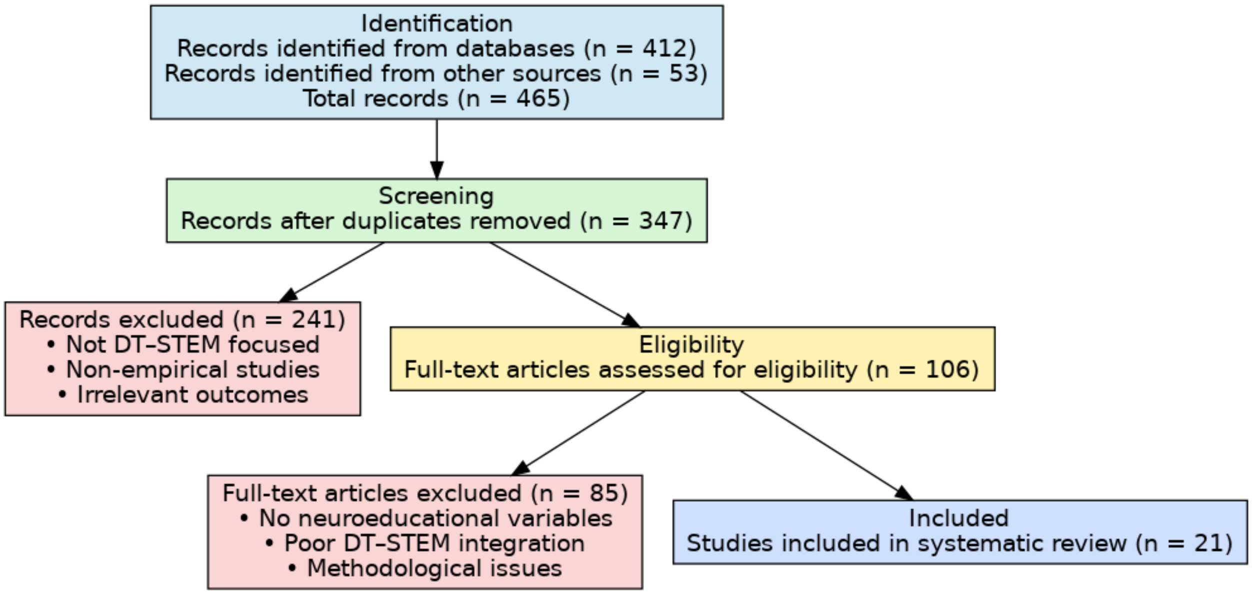

Figure I. Prisma 2020 Flow Diagram Illustrating the Study Selection Process for The Systematic Literature Review.

In the eligibility stage, the full texts of the remaining 106 articles were assessed in detail to determine their suitability for inclusion. After full-text evaluation, 85 articles were excluded for reasons such as inadequate integration of Design Thinking with STEM instruction, absence of relevant outcome variables, or insufficient methodological clarity.

Finally, 21 studies met all the inclusion criteria and were deemed suitable for inclusion in the systematic literature review. These 21 studies constituted the final corpus for qualitative thematic synthesis, frequency analysis, and evidence interpretation. The entire study selection process, along with reasons for exclusion at each stage, is visually represented in the PRISMA 2020 flow diagram.

DATA EXTRACTION

A structured data extraction framework was developed to systematically capture relevant information from each included study. Extracted variables included publication details, study context, sample characteristics, educational level, subject domain, description of the Design Thinking–based STEM intervention, research design, outcome measures, key findings, and reported limitations. In addition, neuroeducational indicators such as engagement, cognition, emotion, and metacognition were recorded where available.

A coding framework was employed to organize extracted data into thematic categories, ensuring consistency and traceability throughout the analysis.

DATA SYNTHESIS METHOD

Data synthesis was conducted using a thematic analysis approach combining inductive and deductive strategies. Deductive coding was guided by the conceptual framework encompassing Design Thinking, STEM integration, and neuroeducation, while inductive coding allowed new patterns and themes to emerge from the data. Both frequency-based synthesis (quantifying occurrence of themes) and narrative synthesis (interpretive integration of findings) were employed. This dual approach enabled comprehensive understanding of dominant trends, evidence strength, and research gaps in the DT-STEM literature from a neuroeducational perspective.

VI. RESULTS

DESCRIPTIVE ANALYSIS

The final synthesis included 21 peer-reviewed studies published between 2022 and 2025, reflecting a rapid scholarly response to Design Thinking (DT) as a catalyst for neuroeducational reform in STEM. A clear increase in publications was observed after 2023, coinciding with the widespread adoption of brain-based learning strategies that prioritize cognitive flexibility and intrinsic motivation. Most studies were published in 2024 and 2025, indicating growing academic concern regarding how iterative design processes align with neural plasticity and the brain's natural inquiry mechanisms.

In terms of research methodology, the included studies employed a diverse range of approaches. Empirical quasi-experimental studies constituted a substantial proportion, focusing on how DT-driven environments optimize cognitive flexibility and executive functions (e.g., Honra & Monterola, 2024; Santos et al., 2025). Experimental and confirmatory factor analysis (CFA) studies examined the development of specialized assessment tools like the STEM-DT instrument, which aims to capture complex behavioral and cognitive readiness (Lukitasari et al., 2025). Furthermore, systematic reviews and meta-analyses highlighted the global effectiveness of DT while identifying critical neuroeducational gaps, such as the historical lack of direct measures for working memory and emotional regulation during the design process (Yu et al., 2024; Pradeep et al., 2024).

Geographically, the studies represented a global perspective, with significant contributions from Asia, the Middle East, and Europe. This distribution reveals a burgeoning interest in culturally responsive neuroeducation, where design-based interventions are tailored to the neural and social development of diverse learners, including those in rural or underrepresented contexts (Samad et al., 2023).

Regarding the pedagogical frameworks, most studies utilized the EDIPT (Empathize, Define, Ideate, Prototype, Test) model, which corresponds to the brain's empathy-to-execution neural pathways. Recent literature has begun to integrate Mind, Brain, and Education (MBE) science with emerging technologies, such as Generative AI-powered multi-agent systems (Gao et al., 2026). These tools are increasingly viewed as “cognitive scaffolds” that manage extraneous cognitive load, allowing students to focus on higher-order creative synthesis. This indicates a significant shift in the current literature from purely instructional design toward a deeper understanding of the neural dynamics of the designing mind.

THEMATIC SYNTHESIS

A thematic synthesis of the 21 included studies resulted in the identification of seven major themes, each representing a distinct dimension of the integration and impact of Design Thinking (DT) within STEM and science education. Through systematic coding and constant comparison across empirical, experimental, and systematic reviews, recurring patterns related to cognitive gains, affective shifts, and neuroeducational gaps were identified and synthesised into coherent thematic categories. These themes collectively capture both the transformative potential and the systemic limitations of the DT framework, ranging from improved conceptual understanding and scientific process skills to the cultivation of creativity, self-efficacy, and 21st-century competencies. The synthesis also highlights the subject domain trends in biology and physics, the diversity of pedagogical approaches such as the EDIPT and STEM models and the critical neuroeducational and methodological status of the current literature, which often lacks direct brain-based measurements and longitudinal follow-up. An overview of the themes, associated sub-themes, and analytical codes was presented in the preceding tables, while detailed thematic analyses for each of the seven themes are provided in the subsequent subsections, offering an in-depth examination of the nature, evidence strength, and implications of Design Thinking–related educational advancements and challenges.

Theme I: Effectiveness of DT in STEM

The most dominant and extensively evidenced theme emerging from the synthesis relates to the Effectiveness of Design Thinking (DT) in enhancing STEM education. Across empirical, experimental, and systematic meta-analyses, DT is consistently identified as a powerful facilitator of academic growth by enabling students to move beyond rote memorization toward deep conceptual mastery and inventive problem-solving. This theme captures not only traditional academic achievement but also the development of higher-order cognitive and scientific process skills essential for navigating complex, real-world scientific challenges.

Table I: Theme I – Effectiveness of DT in STEM

Sub-theme	Analytic Codes	Description/ Interpretation	Type of Evidence	Studies Supporting the Code	Strength of Evidence
Improvement in conceptual understanding	CU-GAIN; MISCONCEPT-REDUCE	Significant improvement in test scores and understanding of abstract science topics.	Meta-analysis; Quasi-experimental	Bawaneh & Alnamshan (2023); Yu et al. (2024); Trinidad (2024); Ladachart et al. (2022)	Strong
Cognitive development	SCIE-REASON; ANALYTIC-THINK	Fostering logical reasoning, analytical thinking, and cognitive flexibility.	CFA; Experimental; Quasi-experimental	Nguyện et al. (2025); Samad et al. (2023); Honra & Monterola (2024); Roisah et al. (2025)	Strong
Scientific process skills	HYPOTHESIS-SKILL; EXPERIMENT-SKILL	Application of scientific method through inquiry and prototyping.	Structural Model; Quasi-experimental	Nguyện et al. (2025); Thai (2025); Gao et al. (2026)	Moderate–Strong
Innovation & design capability	INNOVATE; DESIGN-SKILL	Ability to create original, workable technological solutions.	Meta-analysis; Project-based	Zhu et al. (2024); Panergayo & Prudente (2024); Santos et al. (2025)	Strong
Knowledge retention	RETAIN-TEST	Sustained long-term understanding compared to traditional methods.	Quasi-experimental (Delayed post-test)	Trinidad (2024)	Moderate

The synthesis reveals that improvement in conceptual understanding represents the most extensively documented outcome. Experimental and quasi-experimental studies consistently demonstrate that the iterative nature of the EDIPT model allows students to visualize and refine their understanding of complex scientific phenomena, such as cell biology or physical mechanics, leading to significant post-test gains (Bawaneh & Alnamshan, 2023; Trinidad, 2024). The convergence of evidence across large-scale meta-analyses, which report positive effect sizes for academic achievement, justifies the strong evidence rating assigned to this sub-theme (Yu et al., 2024).

Closely linked to conceptual growth is the advancement of cognitive development. Confirmatory factor analyses and classroom trials provide compelling evidence that DT fosters cognitive flexibility and higher-order analytical thinking (Nguyện et al., 2025). This represents a qualitative shift in STEM pedagogy, as learning is no longer dependent on the passive reception of facts but on the active, logical reasoning required to solve design-based problems (Honra & Monterola, 2024; Samad et al., 2023).

The literature also highlights the robust development of scientific process skills. Through the stages of ideation and prototyping, students engage in active inquiry, hypothesis formation, and empirical testing. Studies indicate that DT functions as a bridge between theoretical knowledge and practical application, particularly in laboratory settings where students must refine their prototypes based on scientific data and epistemic cognition (Thai, 2025;
Gao et al., 2026). Consistency across these structural models supports a moderate–strong evidence rating.

Furthermore, several studies identify a marked increase in innovation and design capability. By participating in maker-space activities and project-based work, students develop the “inventive thinking” necessary to create workable solutions to authentic problems (Samad et al., 2023; Zhu et al., 2024). This capability is further supported by meta-analytic evidence showing that design-based learning is uniquely effective at fostering scientific creativity compared to traditional instruction (Panergayo & Prudente, 2024).

Finally, a critical finding relates to knowledge retention. While many pedagogical interventions offer immediate gains, DT-driven strategies facilitate deeper “long-term understanding.” Delayed post-test findings indicate that students taught through DT retain scientific concepts significantly better than those in control groups, as the hands-on nature of the design process creates more durable mental models and higher levels of engagement (Trinidad, 2024).

Overall, this theme demonstrates strong and convergent evidence that Design Thinking fundamentally improves the effectiveness of STEM education, shifting the focus from rote learning to deep, inventive, and lasting scientific mastery

Theme II: Learning Outcomes & Skills

A critical theme emerging from the synthesis concerns the transformative impact of Design Thinking (DT) on Learning Outcomes & Skills beyond traditional academic achievement. The reviewed literature consistently highlights how DT serves as a holistic pedagogical tool that simultaneously targets affective, social, and cognitive dimensions. This theme captures the shift from surface-level content delivery to the cultivation of “soft” yet essential 21st-century competencies, such as intrinsic motivation, collaborative fluency, and resilient self-efficacy, which collectively empower students to thrive in complex STEM environments.

Table II: Theme II – Learning Outcomes & Skills

Sub-theme	Analytic Codes	Description/ Interpretation	Type of Evidence	Studies Supporting the Code	Strength of Evidence
Affective outcomes	MOTIVATION-UP; INTEREST-UP	Significant increase in student curiosity, intrinsic motivation, and interest in science.	Meta-analysis; Survey; Experimental	Bawaneh & Alnamshan (2023); Yu et al. (2024); Reiser et al. (2025)	Strong
Engagement & participation	ACTIVE-LEARN; COLLAB-GROUP	Enhanced active learning, group work quality, and high classroom participation.	Quasi-experimental; Qualitative	Maneewan et al. (2024); Ladachart et al. (2022)	Strong
Creativity & ideation skills	CREATIVE-IDEA; DIVERGENT-THINK	Improvement in scientific creativity, brainstorming quality, and divergent thinking.	Meta-analysis; Exploratory	Samad et al. (2023); Zhu et al. (2024); Panergayo & Prudente (2024)	Strong
Self-efficacy & confidence	SELF-EFF-GROWTH; TASK-CONFIDENCE	Growth in students' belief in their ability to solve complex STEM problems.	SEM; Survey; Pre-post	Küçükaydın & Ulum (2024); Santos et al. (2025)	Strong
Critical thinking	CRIT-THINK; DECISION-SKILL	Enhanced evaluation, logical reasoning, and decision-making during design tasks.	CFA; Quasi-experimental	Nguyện et al. (2025); Honra & Monterola (2024); Roisah et al. (2025)	Strong

The synthesis reveals that affective outcomes are among the most robustly supported findings in DT research. Experimental and meta-analytic data demonstrate that the empathy-driven and hands-on nature of DT significantly increases students' intrinsic motivation and curiosity toward science subjects (Bawaneh & Alnamshan, 2023). Studies focusing on integrated STEM lessons report that the “real-world” context of design challenges sustains student interest more effectively than traditional, lecture-based instruction (Reiser et al., 2025; Yu et al., 2024).

Closely related to motivation is the marked improvement in engagement and participation. The literature indicates that DT inherently shifts the classroom dynamic from passive listening to active, student-centered learning. Using collaborative activity packages and group-based making, students demonstrate higher levels of participation and a greater valuation of teamwork (Maneewan et al., 2024). This active engagement is particularly evident in design-based activities where peer-to-peer interaction is essential for refining prototypes (Ladachart et al., 2022).

Furthermore, the synthesis highlights a strong correlation between DT and the development of creativity and ideation skills. Meta-analytic evidence confirms that design-based learning is a powerful driver of scientific creativity and divergent thinking

(Panergayo & Prudente, 2024). Students engaged in the "Ideate" phase of DT show a significant improvement in the quality and quantity of their brainstormed solutions, fostering a mindset that values multiple perspectives and inventive thinking in chemistry and general science (Samad et al., 2023; Zhu et al., 2024).

The role of self-efficacy and confidence also emerges as a high-strength sub-theme. Structural Equation Modelling (SEM) and longitudinal surveys demonstrate that DT activities act as a predictor of creative problem-solving, which in turn boosts students' STEM self-efficacy (Küçükaydın & Ulum, 2024). This growth in task confidence is especially significant from a gender perspective, as DT-based making has been shown to empower female students, helping them develop a resilient belief in their ability to solve technological and scientific problems (Santos et al., 2025).

Finally, the literature underscores the impact on critical thinking. By requiring students to constantly evaluate, test, and redesign their solutions, DT fosters cognitive flexibility and analytical decision-making (Honra & Monterola, 2024). Quantitative assessments show that students exposed to DT achieve higher scores in problem-solving tasks, as they learn to logically justify their design choices and navigate the complex variables of motion, force, and biology (Nguyện et al., 2025; Roisah et al., 2025).

Overall, this theme provides high-strength evidence that Design Thinking is a multidimensional pedagogical framework that significantly enhances student motivation, creativity, and the critical confidence required for long-term STEM success.

Theme III: Subject Domain Trends

A significant theme identified in the synthesis relates to the Subject Domain Trends of Design Thinking (DT) applications within the broader STEM landscape. The literature reveals that while DT is a versatile pedagogical framework, its implementation is often concentrated within specific scientific disciplines and educational levels. This theme captures the varying degrees of "richness" in subject-specific content particularly in biology and physics and the depth to which DT is integrated into existing national curricula versus remaining as isolated pilot interventions.

Table III: Theme III – Subject Domain Trends

Sub-theme	Analytic Codes	Description / Interpretation	Type of Evidence	Studies Supporting the Code	Strength of Evidence
Discipline-specific focus	BIO-FOCUS; CHEM-FOCUS; PHY-FOCUS	Identification of the most frequently targeted science subjects for DT.	Empirical; Review	Bawaneh & Alnamshan (2023); Ladachart et al. (2022); Samad et al. (2023)	Strong
Grade level focus	MID-SCHOOL; SEC-SCHOOL	Determination of the primary age-groups targeted in DT research.	Systematic Review; Quasi-exp	Nguyện et al. (2025); Trinidad (2024); Roisah et al. (2025)	Strong
Biology richness	HUMAN-SYS; ECOLOGY; CELLS	Depth of biological content like ecosystems, health, and cell functions.	Experimental; Case Study	Bawaneh & Alnamshan (2023); Honra & Monterola (2024); Trinidad (2024)	Moderate
Integration depth	STEM-HIGH; STEM-SURFACE	Contrast between full interdisciplinary integration and surface-level use.	Conceptual; Empirical	Nguyện et al. (2025); Thai (2025); Küçükaydın & Ulum (2024)	Moderate–Strong
Curriculum alignment	SYLLABUS-MATCH	Assessment of whether DT is mapped to formal syllabi or used in pilots.	Qualitative; Review	Thai (2025); Öztürk (2021); Li & Zhan (2022)	Strong

The synthesis highlights a clear discipline-specific focus, with Biology and Physics emerging as the primary domains for DT intervention. Research in biology often utilizes DT to tackle complex, abstract systems (Bawaneh & Alnamshan, 2023), while physics-based studies leverage the framework to explain mechanics, such as pulleys, motion, and force (Ladachart et al., 2022; Roisah et al., 2025). While Chemistry is represented through specialized inventive-thinking modules, the literature suggests a higher frequency of DT application in biological and physical sciences (Samad et al., 2023).

Regarding the grade level focus, the reviewed studies demonstrate a predominant concentration on middle school and secondary/high school education. Researchers target these levels due to the students' increasing capacity for abstract reasoning and the complexity of the STEM curriculum at these stages (Trinidad, 2024; Nguyện et al., 2025). Systematic reviews further confirm that while primary education is beginning to adopt DT, the “sweet spot” for measuring advanced problem-solving gains remains in the adolescent years (Li & Zhan, 2022).

The sub-theme of biology richness reveals that DT is particularly effective for teaching intricate topics like cell biology, human systems, and ecosystems. Studies show that when biological functions (e.g., digestion or cellular respiration) are framed as design problems, students develop more sophisticated mental models (Bawaneh & Alnamshan, 2023; Honra & Monterola, 2024). This content-rich approach allows students to move beyond simple memorization to a functional understanding of how biological systems operate (Trinidad, 2024).

Furthermore, the integration depth varies significantly across the literature. Some interventions represent “STEM-surface” applications, where DT is used briefly within a single science lesson. In contrast, “STEM-high” integration involves deep interdisciplinary connections often referred to as the STEM-S (Science, Technology, Engineering, Mathematics, and Society) model where scientific inquiry and engineering design are inseparable (Nguyện et al., 2025; Thai, 2025). This depth of integration is frequently moderated by the teacher's own STEM self-efficacy (Küçükaydın & Ulum, 2024).

Finally, curriculum alignment remains a critical factor for the sustainability of DT. The literature distinguishes between “pilot-only” studies, which exist as temporary experimental interventions, and those that achieve a formal syllabus-match. Successful implementations are those explicitly mapped to national science standards, such as a specific fourth-grade unit on thermal conductivity (Thai, 2025). However, systematic reviews consistently point out that the rigid nature of traditional curricula often acts as a barrier, forcing DT to remain at the periphery of the formal school syllabus (Öztürk, 2021; Li & Zhan, 2022).

Overall, this theme indicates that while Design Thinking is expanding across science domains, its long-term impact depends on deeper curriculum alignment and a targeted focus on the complex cognitive demands of secondary-level biology and physics.

Theme IV: Pedagogical Approaches Used

A central theme emerging from the synthesis is the diverse range of Pedagogical Approaches employed to facilitate Design Thinking (DT) in STEM classrooms. The reviewed literature indicates that DT rarely exists in a vacuum; rather, it is frequently integrated with established student-centered models such as Project-Based Learning (PBL) and Inquiry-Based Learning (IBL). This theme captures the shift in instructional style from direct transmission to active facilitation, the reliance on high-fidelity prototyping tasks, and the increasing role of digital technology and specialized rubrics in evaluating student performance.

Table IV: Theme IV – Pedagogical Approaches Used

Sub-theme	Analytic Codes	Description/ Interpretation	Type of Evidence	Studies Supporting the Code	Strength of Evidence
Learning models used	DBL, PBL, IBL, 5E-MODEL	Integration of Design-Based Learning with other inquiry frameworks.	Review; Quasi-exp	Nguyện et al. (2025); Trinidad (2024); Santos et al. (2025); Thai (2025)	Strong
Task type	PROTOTYPE; MODEL-BUILD; PROJECT-WORK	Practical, hands-on creation of solutions to defined problems.	Empirical; Lesson Design	Nguyện et al. (2025); Maneewan et al. (2024); Santos et al. (2025); Thai (2025)	Strong
Instructional style	COLLAB-TEACH; STUDENT-CENTERED	Shift toward group learning and teacher-as-facilitator.	Meta-analysis; Survey	Bawaneh & Alnamshan (2023); Maneewan et al. (2024); Ladachart et al. (2022)	Strong
Assessment forms	PERFORMANCE; RUBRIC-SCORE	Evaluation of design products and processes via rubrics.	Validation; Empirical	Trinidad (2024); Lukitasari et al. (2025); Nguyện et al. (2025)	Moderate–Strong
Technology role	DIGITAL; SIMULATION-TOOL	Use of software, AI agents, or maker-tools to scaffold design.	Systematic Review; Experimental	Li & Zhan (2022); Gao et al. (2026); Santos et al. (2025)	Strong

The synthesis confirms that learning models used in STEM often blend DT with existing active learning frameworks. The EDIPT (Empathize, Define, Ideate, Prototype, Test) model is the most prevalent Design-Based Learning (DBL) structure used to guide students through the engineering cycle (Trinidad, 2024; Santos et al., 2025). Furthermore, researchers frequently embed these DT stages within broader Project-Based Learning (PBL) or the 5E inquiry model to ensure that scientific discovery is balanced with creative solution-building (Nguyện et al., 2025; Thai, 2025).

A defining characteristic of these approaches is the task type, which prioritizes the physical or digital prototyping of solutions. Students are not merely solving equations; they are building robotic arms, designing programmed sensors, or constructing thermal insulators (Nguyện et al., 2025; Thai, 2025). These hands-on project-work tasks are essential for translating abstract theory into working models, allowing students to test scientific hypotheses in a tangible way (Maneewan et al., 2024; Santos et al., 2025).

The instructional style across the 21 papers shows a decisive move toward student-centered and collaborative teaching. Teachers act as facilitators who guide students through the "messy" process of trial and error rather than delivering linear lectures (Bawaneh & Alnamshan, 2023). This approach is supported by collaborative activity packages designed to enhance teamwork, requiring students to communicate and negotiate ideas within their groups to reach a design consensus (Maneewan et al., 2024; Ladachart et al., 2022).

Regarding assessment forms, the literature highlights a move away from traditional multiple-choice tests toward performance-based evaluation. Researchers utilize detailed rubric scores to assess both the final prototype and the iterative process itself (Trinidad, 2024; Nguyện et al., 2025). A significant development in this area is the creation and validation of the STEM-DT instrument, a confirmatory factor analysis tool designed to assess student readiness and competency in design thinking specifically within the STEM context (Lukitasari et al., 2025).

Finally, the technology role has evolved from simple digital tools to sophisticated scaffolds. While many studies utilize basic maker-technology like Scratch or Makey Makey (Li & Zhan, 2022), cutting-edge research is now exploring Generative AI-powered multi-agent systems. These AI agents provide personalized "epistemic scaffolding," helping students manage the cognitive load of the design process and prompting them to reflect on their scientific justifications during the prototyping phase (Gao et al., 2026). This indicates that technology is becoming an active "partner" in the design-based classroom (Santos et al., 2025).

Overall, Theme IV demonstrates that the successful application of Design Thinking depends on a synergistic blend of iterative learning models, hands-on prototyping tasks, and a collaborative, tech-enhanced instructional environment.

Theme V: Neuroeducational Gaps

A critical theme emerging from the synthesis relates to the significant Neuroeducational Gaps currently present in STEM-based Design Thinking research. While the reviewed studies extensively document pedagogical success and student motivation, the literature reveals a "black box" regarding the internal cognitive and neural processes of the learner. This theme captures the systematic exclusion of micro-level cognitive indicators, the lack of brain-based theoretical grounding, and a notable scarcity of objective neuro-physiological measurements, suggesting that while DT is effective, the field does not yet fully understand why it works from a Mind, Brain, and Education (MBE) perspective.

Table V: Theme V – Neuroeducational Gaps

Sub-theme	Analytic Codes	Description / Interpretation	Type of Evidence	Studies Supporting the Code	Strength of Evidence
Cognitive indicators missing	WM-IGNORED; ATTENTION-UNMEAS	Failure to measure specific brain functions like working memory or sustained attention.	Meta-analysis; Review	Yu et al. (2024); Pradeep et al. (2024)	Strong
Emotional learning gap	LOW-EMO-STUDY; AFFECT-GAP	Lack of direct, real-time measurement of deep emotional/affective neural states.	Meta-analysis; Systematic Review	Panergayo & Prudente (2024); Reiser et al. (2025)	Moderate–Strong
Neuro-based measures scarcity	NEURO-SCALE-ABSENT	Absence of neuro-physiological scales, EEG, or brain-tracking data in STEM-DT.	Review; Validation Study	Pradeep et al. (2024); Lukitasari et al. (2025)	Strong
Brain-based frameworks absent	MBE-NOTUSED	Lack of instructional design grounded in Mind, Brain, and Education (MBE) science.	Theoretical Review; Empirical	Pradeep et al. (2024); Li & Zhan (2022)	Strong
Lack of perceptual measures	SELF-PERCEP-MISSING	Absence of real-time recordings of learner perception or sensory processing.	Experimental; Review	Gao et al. (2026); Santos et al. (2025)	Moderate

The synthesis reveals a consistent omission of cognitive indicators in the current DT landscape. While studies measure academic achievement, they rarely isolate the specific cognitive loads placed on a student's working memory or their capacity for sustained attention during the complex, multi-stage design process (Yu et al., 2024). Systematic reviews indicate that without monitoring these cognitive variables, educators may unknowingly overload students during the "Ideate" or "Prototype" phases, where the cognitive demand is highest (Pradeep et al., 2024).

Closely linked to this is a significant emotional learning gap. Although the “Empathize” phase is foundational to DT, the literature lacks direct measurements of the neural affective states associated with empathy and social cognition. Research typically relies on post-hoc surveys rather than real-time affective tracking (Panergayo & Prudente, 2024). This gap limits our understanding of how emotional resilience or grit is neurobiologically fostered when students face repeated failures during the iterative testing of their prototypes (Reiser et al., 2025).

A particularly stark finding is the scarcity of neuro-based measures. Across the 21 papers, there is a total absence of physiological data such as EEG, eye-tracking, or skin conductance that could provide objective evidence of cognitive engagement. Current assessment tools, like the newly developed STEM-DT scale, remain focused on behavioural readiness and self-reported competencies rather than neural indicators of design-based thinking (Lukitasari et al., 2025; Pradeep et al., 2024).

The literature further identifies that brain-based frameworks are largely absent from instructional design. Most DT interventions are grounded in general constructivist theory rather than Mind, Brain, and Education (MBE) science. This theoretical disconnect means that pedagogical strategies such as the timing of “brainstorming” or the structure of “prototyping” are not yet optimized to align with known neural dynamics of creativity or executive function (Pradeep et al., 2024; Li & Zhan, 2022).

Finally, there is a notable lack of perceptual measures. Research has yet to fully record how students’ real-time self-perception and sensory processing influence their design choices (Santos et al., 2025). While emerging technologies like AI multi-agent systems are beginning to track “epistemic cognition” or how students justify their knowledge they still do not capture the raw perceptual data of the learner physically interacting with maker-space tools (Gao et al., 2026). This represents a missed opportunity to understand the embodied cognition inherent in Design Thinking.

Overall, this theme highlights that while DT is a pedologically sound framework, it currently operates without sufficient grounding in neuroeducational science, leaving a significant gap in our understanding of the cognitive and neural infrastructure required for successful STEM design.

Theme VI: Moderators & Variables

An essential discovery within the synthesis involves the various Moderators & Variables that dictate the efficacy of Design Thinking in educational settings. While DT is widely praised for its outcomes, scholarly discourse reveals that its success is often filtered through specific cognitive and psychological lenses that are not always explicitly measured. This theme identifies the “hidden” influencers of the design process such as the mental tax of cognitive load and the role of self-belief while pinpointing the significant research voids regarding how students monitor their own thinking (metacognition) and whether these interventions translate into long-term behavioural shifts toward STEM careers.

Table VI: Theme VI – Moderators & Variables

Sub-theme	Analytic Codes	Description / Interpretation	Type of Evidence	Studies Supporting the Code	Strength of Evidence
Cognitive load importance	COG-LOW; COG-HIGH	Recognition of the mental effort required during complex design stages.	Meta-analysis; AI Scaffolding	Pradeep et al. (2024); Gao et al. (2026); Yu et al. (2024)	Strong
Self-efficacy role	SELF-EFF-ASSOC	Understanding confidence as a factor that shapes how students engage with DT.	SEM; Comparative	Santos et al. (2025); Küçükaydın & Ulum (2024); Bawaneh & Alnamshan (2023)	Strong

Metacognition ignored	META-LOW-STUDY	The rarity of research focusing on how students regulate their own design thinking.	Cognitive Review; Empirical	Gao et al. (2026); Honra & Monterola (2024); Pradeep et al. (2024)	Moderate–Strong
Behavioral intention	INTENTION-STUDY	Lack of data on students' future commitment to STEM fields post-intervention.	Longitudinal Survey; Review	Reiser et al. (2025); Li & Zhan (2022)	Moderate
Long-term impact	LONGTERM-MISS	Scarcity of follow-up data to determine if DT effects persist over time.	Meta-analysis; Systematic Review	Trinidad (2024); Yu et al. (2024); Li & Zhan (2022)	Strong

A primary factor identified in the literature is the importance of cognitive load. Scholarly findings suggest that the multi-layered nature of Design Thinking moving from empathy to prototyping places a high mental demand on learners. While meta-analyses note that DT works best when this load is managed, direct empirical measurement of mental tax is rare (Yu et al., 2024; Pradeep et al., 2024). Recent experimental work highlights that technology, such as AI-driven scaffolds, is increasingly necessary to mitigate “high cognitive load,” allowing students to navigate complex design variables without becoming overwhelmed (Gao et al., 2026).

In tandem with this, the role of self-efficacy acts as a significant psychological filter. Most research treats confidence as a result, yet structural models indicate it is a vital moderator; students with higher initial self-efficacy are more likely to persevere through the fail-forward cycles of the design process (Küçükaydın & Ulum, 2024). This association is particularly evident in gender-focused studies, where building a student's belief in their technological competence is a prerequisite for successful engagement in maker-centered learning (Santos et al., 2025; Bawaneh & Alnamshan, 2023).

However, the synthesis reveals that metacognition is largely ignored in the current body of work. There is a profound lack of evidence regarding “thinking about thinking” specifically, how students monitor, evaluate, and adjust their strategies during a design challenge (Honra & Monterola, 2024). While some studies touch upon cognitive flexibility, the explicit measurement of metacognitive regulation remains a neglected variable, leaving a gap in our understanding of how students transition from being “task-doers” to “autonomous designers” (Gao et al., 2026; Pradeep et al., 2024).

The literature further notes a deficiency in measuring behavioural intention. While students may show immediate excitement during a DT workshop, few studies investigate if this enthusiasm translates into a concrete intent to pursue STEM pathways or independent scientific projects (Reiser et al., 2025). Systematic reviews emphasize that without assessing these long-term aspirations, it is difficult to determine if DT is merely a “fun classroom activity” or a genuine driver of future workforce development (Li & Zhan, 2022).

Finally, the most pervasive methodological variable is the lack of long-term impact data. Most of the current research relies on immediate post-tests rather than longitudinal follow-ups. Meta-analyses consistently identify this “temporal gap” as a major limitation, noting that the field currently lacks proof that the creative and analytical gains found in a three-week DT unit are sustained a year later (Yu et al., 2024; Trinidad, 2024). This absence of follow-up studies undermines the ability to claim that DT creates permanent shifts in scientific literacy (Li & Zhan, 2022).

Overall, Theme VI underscores that the future of Design Thinking research must move beyond measuring simple outcomes to exploring the complex moderating variables cognitive load, metacognition, and long-term behavioural shifts that truly define a student's journey from classroom learner to innovative designer.

Theme VII: Methodological Status

The final theme synthesized from the 21-paper corpus concerns the Methodological Status of the field. This theme provides a critical meta-view of how Design Thinking research is constructed, revealing a landscape dominated by specific empirical preferences. While the literature is rich in practical applications, there is an observable reliance on short-term interventions and localized student cohorts. This section outlines the structural trends from the prevalence of quasi-experimental frameworks to the challenges of internal validity that define the current "grade" of evidence and offer a roadmap for future methodological refinement.

Table VII: Theme VII – Methodological Status

Sub-theme	Analytic Codes	Description / Interpretation	Type of Evidence	Studies Supporting the Code	Strength of Evidence
Study design trend	QUASI-MOST; EXPER-SOME; QUAL-FEW	Predominance of non-equivalent control group designs over pure experiments.	Systematic Review; Meta-analysis	Yu et al. (2024); Li & Zhan (2022); Trinidad (2024); Roisah et al. (2025)	Strong
Tools used	ACH-TEST; SURVEY; INTERVIEW	Heavy reliance on traditional tests and Likert scales for data gathering.	Empirical; Validation	Bawaneh & Alnamshan (2023); Samad et al. (2023); Lukitasari et al. (2025)	Strong
Sample size issues	SMALL-SAMP; LOCAL-GROUP	Frequent use of restricted, non-representative student populations.	Quasi-experimental; Case Study	Ladachart et al. (2022); Samad et al. (2023); Thai (2025)	Moderate–Strong
Limited duration	SHORT-TERM	Brief intervention windows, typically lasting only a few weeks.	Meta-analysis; Review	Yu et al. (2024); Li & Zhan (2022); Santos et al. (2025)	Strong
Lack of control groups	NO-CONTROL	Challenges to internal validity due to single-group designs in some pilots.	Systematic Review; Field Study	Yu et al. (2024); Li & Zhan (2022)	Moderate
Publication quality	HIGH-GRADE; MID-GRADE	General distribution of rigor across indexed peer-reviewed journals.	Meta-analysis; Quality Audit	Yu et al. (2024); Panergayo & Prudente (2024)	Strong

A primary observation in the literature is the overwhelming study design trend toward quasi-experimental frameworks. Researchers consistently opt for non-randomized, non-equivalent control groups, primarily because these designs are more feasible within existing school schedules (Yu et al., 2024). While pure experimental designs and in-depth qualitative case studies exist, they are less frequent, leaving the field with a high volume of comparative data that occasionally struggles with selection bias (Li & Zhan, 2022; Trinidad, 2024).

The tools used for data collection remain relatively traditional. The synthesis reveals that most studies anchor their findings in pre-and-post-achievement tests to quantify knowledge gains and Likert-style surveys to measure affective shifts like motivation (Bawaneh & Alnamshan, 2023). While newer, specialized instruments like the STEM-DT scale are being validated to better capture the design mindset, the field still lacks diverse, objective measurement tools that move beyond student self-reporting (Lukitasari et al., 2025; Samad et al., 2023).

Furthermore, the evidence is frequently constrained by sample size issues. Many prominent studies are localized, drawing participants from a single grade level or a specific rural district (Ladachart et al., 2022). This localized focus, while providing deep contextual insight, limits the broader generalizability of the findings. Scholars often note that what works in a small, specialized chemistry module in Malaysia may not translate perfectly to urban primary schools in other regions without further large-scale replication (Samad et al., 2023; Thai, 2025).

A significant temporal constraint is the limited duration of most DT interventions. Meta-analyses highlight that a "typical" DT study spans only 2 to 6 weeks (Yu et al., 2024). While these short bursts of activity produce immediate excitement and "wow" factors in student prototypes, they are often too brief to instil permanent design habits or deep cognitive shifts (Li & Zhan, 2022). Research suggests that for DT to have a transformative effect, it needs to be sustained over several months rather than localized to a single unit (Santos et al., 2025).

Finally, the literature points to a lack of control groups in several pilot implementations, which serves as a major hurdle for internal validity. Systematic reviews warn that without a clear baseline for comparison, it is difficult to isolate whether gains in creativity or self-efficacy are specifically due to the DT framework or simply the result of "novelty effects" (Yu et al., 2024; Li & Zhan, 2022). Despite these hurdles, the publication quality remains generally high, with most studies appearing in rigorous, high-grade peer-reviewed journals, indicating a strong scholarly commitment to validating DT as a legitimate STEM pedagogy (Panergayo & Prudente, 2024).

Overall, Theme VII highlights that while the methodological foundation of Design Thinking is solid, the next stage of research must prioritize longitudinal designs, larger representative samples, and more robust control mechanisms to solidify its standing in the scientific community.

VII. DISCUSSION

The present systematic review sought to synthesize contemporary research on how Design Thinking (DT)–based STEM instruction influences learning processes and outcomes, with a specific focus on integrating cognitive, affective, and neuroeducational perspectives. By integrating findings across 21 peer-reviewed studies published between 2022 and 2025, the review provides a consolidated understanding of DT as a multidimensional pedagogical framework that shifts STEM education from rote achievement to inventive, process-oriented mastery. Addressing the first research question regarding conceptualization and integration, the findings demonstrate that DT is predominantly implemented through iterative design-based models, most notably the EDIPT framework consisting of the empathize, define, ideate, prototype, and test phases. Integration is most frequent in secondary-level biology and physics, where abstract scientific concepts such as cellular systems or physical mechanics are reframed as tangible design challenges. Unlike traditional inquiry-based models, DT-STEM integration increasingly emphasizes the "STEM" approach, which links science and technology to societal needs through maker education. In these contexts, technology acts as a vital cognitive scaffold, ranging from accessible digital simulation tools to cutting-edge generative AI multi-agent systems that provide epistemic support and facilitate complex prototyping. This conceptualization suggests that DT is increasingly viewed as a bridge between theoretical science and applied engineering, though its long-term sustainability remains hindered by a lack of formal curriculum alignment in rigid educational systems that prioritizes standardized testing over iterative design.

In relation to the second research question concerning reported learning outcomes, the synthesis highlights a significant disparity between pedagogical success and neuroeducational evidence. On one hand, there is strong, convergent evidence for improved conceptual understanding and robust affective outcomes, such as heightened intrinsic motivation and STEM self-efficacy. Students consistently report a more resilient "fail-forward" mindset when engaged in iterative design, which effectively lowers the psychological barriers to tackling complex STEM problems. This is particularly evident in studies focusing on gender-specific outcomes, where DT-based making empowers students to develop a resilient belief in their technological competence. However, when viewed through a neuroeducational lens, the findings reveal a "black box" phenomenon where the underlying neural mechanisms are largely inferred rather than measured. While cognitive flexibility and analytical reasoning are reported as outcomes, the literature suffers from a critical scarcity of direct, real-time neuro-physiological measurements, such as EEG or eye-tracking data. Current research identifies a significant metacognitive void, where students are achieving successful design results, but the specific management of working memory or sustained attention during high-demand phases like ideation remains unmeasured. This suggests that while DT is neuro-pedagogically aligned with brain plasticity and empathy pathways, empirical confirmation of these neural dynamics remains a critical frontier for the field.

Regarding the third research question on methodological patterns and gaps, the review reveals a landscape dominated by quasi-experimental designs and short-term interventions. A notable strength of the current corpus is the successful validation of new instruments, such as the STEM-DT scale, which provides a quantitative basis for assessing design competencies beyond simple achievement-focused tests. Nevertheless, several critical gaps emerge that limit the field's overall internal validity. First, there is a significant underrepresentation of moderating variables, specifically cognitive load, and metacognition. Studies rarely monitor how students regulate their own thinking during design tasks, nor do they measure the “mental tax” of the prototyping phase, which may obscure why certain students struggle while others thrive under identical instructional conditions. Second, the synthesis identifies a pervasive temporal gap, with a profound lack of longitudinal evidence to confirm whether gains in scientific creativity and problem-solving are sustained beyond the immediate two-to-six-week intervention window. Finally, the current research is often localized within specific high-resource or pilot-driven contexts, indicating an urgent need for broader, more representative samples to ensure findings are applicable across diverse socio-cultural settings.

Taken together, the integration of all seven themes underscores that Design Thinking–based STEM instruction poses a transformative opportunity for 21st-century education, yet it currently lacks sufficient grounding in Mind, Brain, and Education (MBE) science. The findings suggest that while DT improves student engagement and academic mastery, sustainable pedagogical advancement requires moving beyond achievement-focused measures toward a deeper understanding of the neural infrastructure of the designing mind. By consolidating dispersed evidence, this review contributes to a more coherent understanding of the DT-STEM nexus and provides a foundation for developing brain-informed, iterative learning environments. Ultimately, the transition from traditional instruction to a neuroeducational DT framework requires a systemic shift in how we assess progress, shifting the focus from the final scientific product to the cognitive and emotional resilience developed during the design process.

VIII. IMPLICATIONS FOR SCHOOL EDUCATION

The findings of this systematic review underscore the need for a comprehensive rethinking of how secondary school institutions deliver and assess STEM education through the lens of Design Thinking. The implications extend across pedagogical design, teacher professional development, curriculum alignment, and the integration of neuroeducational frameworks, highlighting that isolated pilot projects or superficial activities are insufficient in addressing the systemic need for innovative, process-oriented scientific literacy. Addressing the complexities of 21st-century STEM education requires secondary schools to move beyond traditional instructional silos toward a holistic model that balances academic rigor with the cognitive and emotional resilience required for real-world problem-solving.

One of the most significant implications concerns the urgent need for redesigned assessment practices that move beyond the final scientific product to capture the iterative journey of the learner. Traditional assessment formats, such as standardized multiple-choice tests and result-oriented laboratory reports, are increasingly insufficient for measuring the complex competencies developed through Design Thinking, such as creative problem-solving and divergent thinking (Trinidad, 2024; Yu et al., 2024). Secondary school institutions must therefore transition toward performance-based assessment designs that emphasize the “Design Thinking mindset.” Utilizing validated instruments like the STEM-DT scale can provide educators with a quantitative and qualitative basis for evaluating student readiness and iterative progress (Lukitasari et al., 2025). By implementing process-focused rubrics and portfolio-based evaluations, schools can ensure that the “fail-forward” nature of design is incentivized rather than penalized, promoting deeper conceptual retention and scientific mastery.

Closely linked to assessment reform is the critical importance of teacher readiness and sustained professional development. The review reveals that while many secondary educators support the theoretical benefits of Design Thinking, they often face significant gaps in practical knowledge, leading to low confidence in facilitating complex, open-ended design tasks (Öztürk, 2021; Al-Muqbil, 2023). Secondary institutions must therefore invest in training initiatives that go beyond technical awareness of STEM tools to address the pedagogical shifts required to become effective facilitators. Training should focus on helping teachers manage the “messy” stages of the EDIPT model particularly the ideation and prototyping phases while providing strategies for interdisciplinary collaboration across science, technology, engineering, and mathematics departments (Maneewan et al., 2024; Thai, 2025).

Furthermore, the findings highlight the necessity of integrating neuroeducational principles into the daily classroom environment to optimize student learning. Secondary education should prioritize “brain-informed” instruction that explicitly manages the cognitive load placed on students during complex design challenges. Given that the prototyping and testing phases can place a high mental tax on working memory, institutions should adopt technological scaffolds, such as AI-powered multi-agent systems, to provide the necessary epistemic support and personalized feedback (Gao et al., 2026; Pradeep et al., 2024). By aligning instructional pacing with the neural dynamics of attention and emotional regulation, schools can better foster the STEM self-efficacy and resilience needed for students to thrive in iterative learning environments (Santos et al., 2025; Bawaneh & Alnamshan, 2023).

Finally, the findings point to the necessity of formal curriculum alignment to ensure that Design Thinking becomes a sustainable component of secondary education rather than a peripheral elective. The review indicates that the rigid nature of traditional science syllabi often acts as a barrier to the time-intensive, iterative cycles required for effective design (Li & Zhan, 2022). Higher-level school management and policy makers should therefore advocate for “STEM” (Science, Technology, Engineering, Mathematics) frameworks that map design-based projects directly to national scientific standards (Thai, 2025). By embedding these competencies within the formal curriculum, secondary schools can provide a structured foundation for developing students’ metacognitive skills and long-term behavioural intentions to pursue future STEM pathways.

Collectively, these implications suggest that a successful transition to Design Thinking–based STEM instruction requires a multi-level response. Sustainable advancement must align assessment redesign, teacher capacity building, neuroeducational scaffolding, and curriculum reform, positioning the designing mind not just as a classroom outcome, but as a foundational principle for preparing the next generation of scientific innovators.

IX. FUTURE DIRECTIONS

The synthesis of the current literature reveals several critical avenues for future research to bridge the gap between pedagogical theory and neuroeducational practice. First and foremost, there is an urgent need for studies that incorporate direct, real-time neuro-physiological measurements to validate the cognitive claims of Design Thinking (DT) within STEM contexts. Future research should transition from relying solely on self-reported surveys and achievement tests toward the use of objective indicators, such as electroencephalography (EEG), eye-tracking, and skin conductance, to map the neural dynamics of the “designing mind” (Pradeep et al., 2024; Lukitasari et al., 2025). Specifically, investigating how different phases of the EDIPT model such as the transition from divergent ideation to convergent prototyping correlate with specific neural patterns of executive function and emotional regulation would provide a more robust scientific foundation for design-based learning.

In tandem with neural measurements, future scholarship must address the pervasive “temporal gap” by prioritizing longitudinal research designs. The existing body of work is heavily concentrated on short-term interventions, leaving the long-term stability of DT-driven gains in scientific creativity and problem-solving largely unverified (Yu et al., 2024; Li & Zhan, 2022). Longitudinal studies tracking student cohorts over multiple academic years are necessary to determine if the iterative habits and resilient mindsets fostered in a six-week DT unit translate into sustained academic trajectories or a permanent shift in behavioural intentions toward STEM careers (Trinidad, 2024; Reiser et al., 2025). Furthermore, researchers should explore the “sleeper effects” of DT, examining how early exposure to design-based thinking in primary education influences cognitive flexibility during the more complex scientific demands of secondary schooling.

Another vital direction for future inquiry concerns the explicit measurement of metacognition and cognitive load as moderating variables. While the literature assumes that DT promotes higher-order thinking, empirical evidence regarding how students monitor and regulate their own cognitive processes during a design challenge remains remarkably scarce (Gao et al., 2026; Honra & Monterola, 2024). Future studies should utilize “think-aloud” protocols and real-time cognitive load monitoring to investigate how students manage the high mental tax of the prototyping phase. Understanding the threshold at which design complexity becomes cognitively overwhelming would allow for the development of more precise “brain-informed” scaffolds, ensuring that the iterative process remains a productive challenge rather than a source of cognitive overload (Pradeep et al., 2024; Yu et al., 2024).

Finally, the rapid evolution of educational technology presents a unique opportunity for research into human-AI collaboration within the design process. Future investigations should examine how generative AI multi-agent systems can be specifically programmed to act as neuroeducational scaffolds, providing personalized feedback that aligns with a student's individual cognitive and emotional state (Gao et al., 2026; Santos et al., 2025). There is also a pressing need to expand research into diverse, low-resource educational contexts to ensure that the benefits of DT-STEM integration are not limited to high-resource “pilot” environments (Samad et al., 2023). By diversifying the methodological tools, lengthening the duration of observations, and grounding instructional design in Mind, Brain, and Education (MBE) science, future research can solidify Design Thinking as a rigorous, evidence-based pillar of modern STEM education.

X. CONCLUSION

The systematic review concludes that Design Thinking (DT)–based STEM instruction represents a powerful shift from traditional content delivery to a process-oriented, student-centered paradigm in secondary education. By synthesizing 21 empirical studies from the 2022–2025 period, it is evident that the integration of iterative models like EDIPT into biology and physics significantly enhances student achievement, scientific reasoning, and self-efficacy. However, the most profound conclusion drawn from this synthesis is the identified “neuroeducational paradox”: while Design Thinking is theoretically aligned with neural plasticity and executive function development, the empirical evidence currently remains largely confined to traditional pedagogical metrics. The “black box” of the designing mind remains a critical challenge, as the field has yet to fully substantiate the observed affective and cognitive gains with direct neuro-physiological data.

Furthermore, the review concludes that the long-term sustainability of Design Thinking within STEM education depends on a more rigorous alignment between instructional design and Mind, Brain, and Education (MBE) science. While DT fosters undeniable creativity and resilience in short-term interventions, its broader impact is currently constrained by a “metacognitive void” and a lack of longitudinal verification. To move beyond the novelty of isolated pilot projects, secondary schools must adopt a systemic approach that integrates authentic, performance-based assessments and technological scaffolds designed to manage the high cognitive load of the prototyping phase. This necessitates a profound shift in teacher professional development, moving away from simple tool-based training toward a deeper understanding of how to facilitate the complex cognitive and emotional cycles inherent in the design process.

Ultimately, this synthesis serves as a critical call to action for both researchers and practitioners to transition the Design Thinking discourse from the periphery of “hands-on activities” to the center of neuroeducational research. By identifying the methodological patterns and measurement gaps in the current body of work, this review provides a structured foundation for future inquiry that is both pedagogically robust and neurobiologically grounded. As secondary education continues to evolve in response to 21st-century complexities, the integration of Design Thinking if properly scaffolded, curriculum-aligned, and neuro-physiologically measured offers a resilient and transformative pathway for cultivating the next generation of innovative scientific thinkers.

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Appendix A – Search Strings

Database	Search String Used	Filters Applied
Scopus	TITLE-ABS-KEY (“Design Thinking” AND “STEM education”) AND TITLE-ABS-KEY (“Design Thinking–based instruction” AND science”) AND TITLE-ABS-KEY (“Design Thinking” AND neuroeducation) AND TITLE-ABS-KEY (“brain-based learning” AND STEM)	Peer-reviewed, 2013–2025, English
Web of Science	TS= (“Design Thinking” AND “STEM education” OR “brain-based learning”) AND TS= (“Design Thinking–based instruction” AND science”) AND TS= (“Design Thinking” AND neuroeducation)	Core Collection, 2013–2025, English
ERIC	(“Design Thinking” OR “STEM education” OR neuroeducation) AND (“Design Thinking–based instruction” AND science” OR brain-based learning”)	Peer-reviewed, 2013–2025
PubMed	(“Design Thinking” AND “STEM education” AND neuroeducation) AND (“Design Thinking–based instruction” AND science AND neuroeducation)	Research and Review Papers 2013–2025 English
ScienceDirect	(“Design Thinking” AND “STEM education”) AND (“Design Thinking (DT) based instruction” AND science”) AND (“Design Thinking” AND neuroeducation) AND (“brain-based learning” OR neuroeducation AND STEM)	Research and Review Papers 2013–2025 English
Google Scholar	“Design Thinking”; “STEM education”; “Design Thinking (DT) based instruction”; “science education”; “Neuroeducation”; “Brain-based learning”.	No filters (Google Scholar limitations)

Appendix B Data Extraction Table

No	Author (s), Year	Title of the Study	Sample / Population	Focus of the Study	Major Findings
1	Bawaneh, A. K., & Alnamshan, M. M., 2023	Design Thinking in Science Education: Enhancing Undergraduate Students' Motivation and Achievement in Learning Biology	92 Undergraduate Students	Design Thinking, Science Education	DT significantly improved motivation and achievement.
2	Zhu, L., et al., 2024	Facilitating students' design thinking skills in science class: an exploratory study	45 Primary students	Design Thinking, Science Education	Facilitating DT skills in science class is beneficial.
3	Nguyen, L. C., et al., 2025	Integrating design thinking into STEM education: Enhancing problem-solving skills of high school students	334 High School Students	Design thinking and STEM Education	DT integration improves problem-solving and application of STEM knowledge.
4	Maneewan, C., et al., 2024	Design Thinking for Innovative Learning: Crafting a Collaborative Activity Package to Enhance Teamwork Skills in Science Education	-	Design Thinking and Science Education	Collaborative activity package enhances teamwork.
5	Yu, Q., Yu, K., & Lin, R., 2024	A meta-analysis of the effects of design thinking on student learning	25 articles	Design Thinking and Science Education	DT positively affects student learning, especially with long duration and small class size.
6	Samad, N. A., et al., 2023	Learning chemistry through designing and its effectiveness towards inventive thinking	63 School Students	Design Thinking, Science Education	Effectiveness of EKSTEMIT module in fostering inventive thinking.
7	Reiser, M., Binder, M., & Weitzel, H., 2025	Influence of a design-based approach in integrated STEM lessons combining biology and engineering on the intrinsic motivation of secondary school pupils	176 Secondary School Students	Design Thinking and STEM Education	Design-based approach influences intrinsic motivation.
8	Al-Muqbil, N. S. M., 2023	The Reality of the Application of Biology Teachers to Design Thinking in Their Teaching at The Secondary Stage	276 Secondary School teachers	Design Thinking and Science Education	Identify level of application and obstacles of DT in biology teaching.
9	Honra, J. R., & Monterola, S. L. C., 2024	Fostering cognitive flexibility of students through design thinking in biology education	141 High School Students	Design Thinking and Science Education	Fostering cognitive flexibility through DT.
10	Trinidad, P. M., 2024	Design Thinking Strategy on Learners' Academic Performance in Biology	92 High School Students	Design Thinking and Science Education	The design thinking strategy is effective than the traditional teaching method in teaching biology.
11	Minh, T. D. T., 2025	Integrating STEM-S and Design Thinking in Primary Science Education: A Lesson Design for Fourth Grade	Primary school students	Design Thinking and STEM Education	Lesson model helps deep understanding and problem-solving.

12	Pradeep K., et al., 2024	Neuroeducation understanding neural dynamics in learning and teaching	-	Neuroeducation	Understanding neural dynamics in learning.
13	Li, T., & Zhan, Z., 2022	A Systematic Review on Design Thinking Integrated Learning in K-12 Education	K-12	Design Thinking	DT is essential for 21st century competency.
14	Panergayo, A. A. E., & Prudente, M. S., 2024	Effectiveness of Design-based Learning in Enhancing Scientific Creativity in STEM Education: A Meta-analysis	1211 students	Design Thinking and STEM Education	Design-based learning enhances scientific creativity.
15	Ladachart, L., et al., 2022	Design Thinking Mindsets Facilitating Students' Learning of Scientific Concepts in Design-Based Activities	37 Grade 8 Students	Design Thinking and STEM Education	Design thinking mindsets can facilitate conceptual learning on science concepts.
16	Gao, L., et al., 2026	STEM education: Understanding secondary students' epistemic cognition in the design process with the support of a personalized multi-agent system	Secondary school students	STEM Education	MAS supports epistemic cognition in design process.
17	Öztürk, A., 2021	Meeting the Challenges of STEM education in K-12 Education through Design Thinking	K-12	Design Thinking and STEM Education	Teachers need customized DT approaches.
18	Küçükaydın, M. A., & Ulum, H., 2025	The mediating role of creative problem solving between design thinking and self-efficacy in STEM teaching for STEM teacher candidates	522 Teachers	Design Thinking and STEM Education	Creative problem solving mediates DT and self-efficacy.
19	Roisah, L. F., et al., 2025	The Influence of Design Thinking Learning with STEM Approach on Problem Solving Skills in Motion and Force Topics	64 Junior High School Students	Design Thinking and STEM Education	DT-STEM improves problem-solving skills.
20	Santos, P., et al., 2025	Fostering students' motivation and self-efficacy in science, technology, engineering, and design through design thinking and making in project-based learning...	318 Primary School Students (Grade 4-6)	Design Thinking and STEM Education	Significant improvements in self-efficacy, particularly among girls.
21	Lukitasari, M., et al., 2025	Development and Validation of the STEM-DT Instrument: A Confirmatory Factor Analysis for Assessing Readiness STEM and Design Thinking Competencies	603 Teachers		Instrument effectively captures key dimensions of STEM-DT readiness.

Appendix C – Quality Appraisal Table

No	Author(s), Year	Appraisal Tool Used	Methodological Quality	Key Strengths Identified	Limitations Noted	Overall Rating
1	Bawaneh, A. K., & Alnamshan, M. M., 2023	JBI	Strong	Clear experimental design demonstrating that design thinking significantly improves	Relies mainly on self-reported motivation data with a small, homogeneous	High

				students' motivation and academic achievement.	sample, limiting generalizability.	
2	Zhu, L., et al., 2024	JBI	Strong	Explores the integration of design thinking activities in primary science classrooms and shows positive development of students' design thinking skills.	Exploratory study without a control group, limiting the ability to establish causal effects of the intervention.	High
3	Nguyen, L. C., et al., 2025	JBI	Strong	Large sample study showing that integrating design thinking in STEM enhances students' problem-solving and application of STEM knowledge.	Problem-solving is discussed broadly without linking specific design thinking stages to underlying cognitive or executive functions.	High
4	Maneewan, C., et al., 2024	CASP	Strong	Develops a collaborative design thinking activity package that effectively enhances students' teamwork skills in science learning.	Focuses on social teamwork outcomes without addressing the underlying neural mechanisms involved in collaborative learning.	High
5	Yu, Q., Yu, K., & Lin, R., 2024	AMSTAR 2	Moderate	Comprehensive meta-analysis of 25 studies showing that design thinking positively influences student learning outcomes across disciplines.	High heterogeneity among studies suggests unmeasured factors influencing results, limiting consistency of conclusions.	Moderate
6	Samad, N. A., et al., 2023	JBI	Strong	Demonstrates that the EKSTEMIT design-based learning module effectively enhances students' inventive thinking in chemistry.	Relies on self-reported questionnaire data to measure inventive thinking without objective cognitive or neural measures.	High
7	Reiser, M., Binder, M., & Weitzel, H., 2025	JBI	Strong	Shows that a design-based integrated STEM approach significantly enhances intrinsic motivation among secondary school students.	Focuses on motivational theory without explaining the underlying neural mechanisms related to student motivation.	High
8	Al-Muqbil, N. S. M., 2023	MMAT	Strong	Identifies the level of design thinking application and key obstacles faced by biology teachers in secondary education.	Relies on teacher perceptions without examining actual student learning outcomes or cognitive engagement.	High

9	Honra, J. R., & Monterola, S. L. C., 2024	JBI	Strong	Shows that design thinking activities help foster cognitive flexibility among high school biology students.	Examines cognitive flexibility only through behavioral measures without exploring the underlying neural processes.	High
10	Trinidad, P. M., 2024	JBI	Strong	Provides experimental evidence that the design thinking strategy significantly improves students' academic performance in biology.	Measures learning outcomes through tests but does not examine the timing or cognitive processes involved in learning consolidation.	High
11	Minh, T. D. T., 2025	CASP	Strong	Presents a structured lesson design integrating STEM-S and design thinking to support students' understanding and problem-solving.	Focuses mainly on pedagogical design without examining the cognitive processes involved in complex STEM learning.	High
12	Pradeep K., et al., 2024	AMSTAR 2	Moderate-Weak	Provides a comprehensive review explaining neural dynamics and neuroplasticity in learning and teaching.	Discusses neuroeducation broadly without linking it specifically to design thinking interventions in education.	Low
13	Li, T., & Zhan, Z., 2022	AMSTAR 2	Moderate	Systematic review highlighting the importance of design thinking integrated learning for developing 21st-century competencies in K–12 education.	Focuses on competency outcomes without considering students' neurodevelopmental readiness for complex design thinking processes.	Moderate
14	Panergayo, A. A. E., & Prudente, M. S., 2024	AMSTAR 2	Strong	Meta-analysis shows design-based learning improves scientific creativity in STEM.	Creativity measured mainly through standardized tests without considering cognitive or neural processes.	High
15	Ladachart, L., et al., 2022	JBI	Strong	Shows that design thinking mindsets support students' conceptual understanding in science.	Relies mainly on self-reported measures to assess students' learning and mindsets.	High
16	Gao, L., et al., 2026	CASP	Strong	Shows that a multi-agent AI system can support students' epistemic	Does not examine how AI support may affect students' cognitive effort or	High

				cognition during the design process.	neural learning processes.	
17	Öztürk, A., 2021	MMAT	Moderate	Identifies key challenges and the need for customized design thinking approaches in K–12 STEM education.	Focuses on logistical challenges without examining students' cognitive difficulties during design tasks.	Moderate
18	Küçükaydın, M. A., & Ulum, H., 2025	MMAT	Strong	Shows creative problem solving mediates the link between design thinking and self-efficacy.	Based on correlational data without examining cognitive or neural mechanisms.	High
19	Roisah, L. F., et al., 2025	JBI	Strong	Shows that a design thinking–STEM approach improves students' problem-solving skills.	Non-equivalent control design without accounting for students' baseline cognitive differences.	High
20	Santos, P., et al., 2025	JBI	Moderate	DT-based project learning increases STEM motivation and self-efficacy.	Does not examine cognitive differences behind gender outcomes.	Moderate
21	Lukitasari, M., et al., 2025	MMAT	Strong	Develops and validates a reliable instrument to assess STEM–DT readiness.	Measures perceived readiness without assessing actual performance or cognitive ability.	High

Appendix D – Thematic Synthesis Matrix

Theme	Sub-themes	Analytic Codes	Evidence Strength	Studies Covering the Theme
Effectiveness of DT in STEM	Improvement in conceptual understanding, Cognitive development, Scientific process skills, Innovation & design capability, Knowledge retention	postgain misconceptions decreased, Logical reasoning, analytical thinking, Inquiry, hypothesis formation, lab skills, Ability to create workable solutions, Long-term understanding,	Moderate –Strong	Bawaneh & Alnamshan, 2023; Yu et al., 2024; Ladachart et al., 2022; Samad et al., 2023; Honra & Monterola, 2024; Roisah et al., 2025; Nguyện et al., 2025; Thai, 2025; Gao et al., 2026; Zhu et al., 2024; Panergayo & Prudente, 2024; Santos et al., 2025; Trinidad, 2024
Learning Outcomes & Skills	Affective outcomes Engagement & participation, Creativity & ideation skills, Self-efficacy & confidence, Critical thinking	Increased curiosity & motivation Group work, high participation Creativity, brainstorming quality Students believe they can solve problems Evaluation, decision-making improvement	Strong	Bawaneh & Alnamshan, 2023; Yu et al., 2024; Reiser et al., 2025 Maneewan et al., 2024; Ladachart et al., 2022; Samad et al., 2023; Zhu et al., 2024; Panergayo & Prudente, 2024; Küçükaydın & Ulum, 2024; Santos et al., 2025; Nguyện et al., 2025; Honra & Monterola, 2024; Roisah et al., 2025

Subject Domain Trends	Discipline-specific focus Grade level focus Biology richness Integration depth Curriculum alignment	Which subject most frequently used Majority research target Digestion, health, ecosystem etc. Full integration or partial STEM use Mapped to curriculum or pilot only	Moderate –Strong	Bawaneh & Alnamshan, 2023; Ladachart et al., 2022; Samad et al., 2023; Trinidad, 2024; Roisah et al., 2025; Honra & Monterola, 2024; Nguyện et al., 2025; Thai, 2025; Küçükaydın & Ulum, 2024 Thai, 2025; Öztürk, 2021; Li & Zhan, 2022
Pedagogical Approaches Used	Learning models used Task type Instructional style Assessment forms Technology role	Design-based, problem-based, inquiry Hands-on creation of solutions Active & group learning preference Product evaluation through rubrics AR/VR/Apps used or not	Strong	Nguyện et al., 2025; Trinidad, 2024; Santos et al., 2025; Thai, 2025; Maneewan et al., 2024; Bawaneh & Alnamshan, 2023; Maneewan et al., 2024; Ladachart et al., 2022; Lukitasari et al., 2025; Li & Zhan, 2022; Gao et al., 2026;
Neuroeducational Gaps	Cognitive indicators missing Emotional learning gap Neuro-based measures scarcity Brain-based frameworks absent Lack of perceptual measures	Working memory, attention absent, Emotional involvement not measured, no neuroeducation scale used, Lack of MBE/Brain theory grounding, No learner perception recordings	Moderate	Yu et al., 2024; Pradeep et al., 2024; Panergayo & Prudente, 2024; Reiser et al., 2025; Pradeep et al., 2024; Lukitasari et al., 2025; Pradeep et al., 2024; Li & Zhan, 2022; Gao et al., 2026; Santos et al., 2025
Moderators & Variables	Cognitive load importance, Self-efficacy role, Metacognition ignored, Behavioural intention, Long-term impact	Rare variable in literature, often outcome, less moderator, Metacognitive monitoring rare Post-learning, intention not measured, Lack of follow-up studies	Moderate –Strong	Pradeep et al., 2024; Gao et al., 2026; Yu et al., 2024; Santos et al., 2025; Küçükaydın & Ulum, 2024; Bawaneh & Alnamshan, 2023; Honra & Monterola, 2024; Reiser et al., 2025; Li & Zhan, 2022; Trinidad, 2024;
Methodological Status	Study design trend+B32:B37, Tools used, Sample size issues, Limited duration, Lack of control groups, Publication quality	Mostly quasi-experimental, mainly achievement tests & surveys, Small, localized samples, mostly 2–6-week interventions, Reduces internal validity, Quality score distribution	Moderate –Strong	Yu et al., 2024; Li & Zhan, 2022; Trinidad, 2024; Roisah et al., 2025; Bawaneh & Alnamshan, 2023; Samad et al., 2023; Lukitasari et al., 2025; Ladachart et al., 2022; Samad et al., 2023; Thai, 2025; Santos et al., 2025; Panergayo & Prudente, 2024